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Sofia, 2026

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APPLYING REORDERED HEURISTICS FOR EFFICIENCY ENHANCEMENT IN SITUATIONAL ANALYSIS WHEN SOLVING PROBLEMS CONTAINING MORE THAN ONE CONDITION IN SPACE MISSION ANALYSIS

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Key words: *situational analysis, reordered heuristics, space mission analysis and design, orbital events prediction*

Abstract

Situational analysis deals with verifying conditions of a geometric or physical nature during satellites' movement in their orbits. This analysis is applied to determine time intervals optimal for the execution of specific satellite operations. Situational problems are solved at various stages of the preparation and operational phases of the satellite missions. The most interesting cases are when a situational problem contains multiple conditions. Each situational problem is solved by sequential verifications of the conditions involved. Verifications can be terminated when an unfulfilled condition is detected (Horner's rule) to improve the efficiency of the analysis. Calculations are repeated for subsequent time steps. Solving such a situational problem may be time-consuming when multi-variant and multi-satellite simulations are performed.

A heuristic approach is proposed for the efficiency enhancement of situational analysis for problems including multiple conditions. This approach is based on the reordering of condition checks. The approach is algorithmized and incorporated into the situational analysis solver that was previously developed. The efficiency of the proposed heuristic is evaluated based on examples with different numbers of situational conditions. This approach shows better efficiency than applying Horner's rule.

Introduction

The rapid advancement of space technology has led to a significant increase in the spacecraft population orbiting the Earth. Furthermore, satellites are becoming increasingly smaller. Multi-satellite missions are designed and implemented in various scientific and applied fields. These and other trends are well-represented in the scientific literature [1, 2].

Limitations are imposed on the preparation time, cost, and reliability of operational use when designing and preparing space missions, regardless of the number and type of satellites. Computer programs are used at different stages from

the preparation to the realisation of space missions. Various aspects of space missions are simulated to meet the ever-increasing requirements. It is important to note that, in addition to well-known programs designed for commercial distribution (STK¹, FreeFlyer², ASTOS³ – or open source program GMAT⁴), some organisations develop their own programs to meet specific needs. Some of these internal programs extend beyond satellite dynamics simulations [3–6]. Wertz & Larson [7] suggest using programs tested in numerous missions created and supported by specialised companies. Nonetheless, he highlights that developing one's own programs allows for a deeper understanding of the underlying problems. Chagas [8] emphasises the importance of applying a comprehensive set of modelling and simulation toolkits to develop complex space missions. Applying multi-physics environments is crucial to tame the complex problems in space mission design [9].

The situational analysis deals with the determination of time intervals optimal for the implementation of certain satellite operations (performing measurements with various sensors, communication with ground stations, and special or general satellite operations). The fulfilment of specific conditions is verified for separate moments throughout the simulation time in the framework of this analysis. This analysis examines the environmental conditions under which satellites operate. We assume that the corresponding orbital event occurs when one or a combination of several conditions is met. Situational analysis, along with orbital analysis, satellite operations planning, and various engineering/mechatronic-oriented analyses, plays a critical role in optimising satellite missions. Applying this analysis is crucial at different stages of the preparation and execution of space missions.

At the Space Research and Technology Institute, BAS, work is being done on creating and improving the Parallel Situational Analysis Solver (PSAS) [10]. A reordered heuristic applicable to solving situational problems with several conditions is proposed in the present work.

The rest of the paper is organized as follows: The second section describes some types of missions and the specific situational conditions used in each of them; The third section presents the idea of situational problems composed of several conditions and their solution; The fourth section explains the approach for efficiency enhancement; The fifth section tells about parallel situation analysis solver; The sixth section shows application examples and an estimation of the efficiency of the proposed heuristic; Some comments about algorithmic complexity are presented in the seventh section and the eighth section concludes the article and indicates some possible developments and applications.

¹ STK [Online]. Available at: <https://www.ansys.com/content/dam/amp/2023/november/asset-creation/stk-capabilities.pdf>

² FreeFlyer [Online]. Available at: <https://ai-solutions.com/freeflyer-astrodynamic-software/>

³ ASTOS [Online]. Available at: <https://www.astos.de/products/astos>

⁴ GMAT [Online]. Available at: <https://gm.atlassian.net/wiki/spaces/GW/overview>

Related Work

Determining the optimal time intervals for observation and measurement is crucial at the initial stage of space mission preparation. Performing a situational analysis is indispensable for assessing the feasibility and realism of any mission. At the next stages, parameters related to various satellite subsystems and instruments can be optimised. These time intervals are used as input resources when planning and scheduling payload operations at the operation stage of a satellite mission [11].

The ability to make observations and measurements depends on the platform's location in orbit and various other conditions that either allow or prohibit them. These conditions are related to the visibility of the objects being monitored (or from the disposition of in-situ measurement instruments to be in suitable spatial areas) and any sources of disturbance or prohibitions caused by other objects or phenomena.

Forecasting the optimal time intervals for observations in the frame of astrophysical missions necessitates the assessment of various factors, some of them related to the positions of the Sun, Moon, and satellite platform [12–17]. Additionally, physical factors such as the satellite's position relative to the South Atlantic Anomaly and polar cusps must also be considered [16, 18]. The presence of high levels of radiation background in certain segments of the orbits above these areas is a significant issue, as it can lead to electrical discharges, scientific instrument damage, and background enhancement in images obtained by optical instruments with SSD detectors. Constraints related to passing through radiation belt passages regarding XMM-Newton⁵ and Chandra missions are applied [19]. Thus, an analysis of geometrical and physical factors is essential when selecting the appropriate observation intervals, especially when dealing with sensitive scientific instruments and image acquisition systems. Bernacca et al. [20] present examples of how to simulate star visibility and tracking by a telescope attached to the main truss of the International Space Station. Additionally, to determine the visibility of the studied stars, solar panels are considered as structural elements in this work.

Interesting and current tasks arise regarding space debris tracking with space-based optical sensors. Scott and Thorsteinson [16] consider different constraints regarding NEOSat Space-Based space situational *awareness*. Mission representing a microsatellite space telescope designed to track resident space objects and perform asteroid astronomy. Orbital conditions related to constraints related to the satellite platform and its orientation relative to the Sun and the Earth, the observation objects, and the mutual position of the platform and the observed objects (resident space objects) are considered in detail. Further constraints are applied to the telescope's field of view – avoiding the galactic centre and

⁵ "XMM-Newton Users Handbook", Issue 2.22, 2024 (ESA: XMM-Newton SOC). Available on: https://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/XMM_UHB.pdf

containing background stars. Du et. al. [21] and Du et. al. [22] presented results from computer simulations to evaluate the performance of multi-satellite space debris cataloguing missions. In both cases, in addition to geometric constraints to estimate visibility, an illuminance estimate is added, based on the shape and albedo of the space debris. Li et al. [23] apply the same constraints in their analysis.

Experimental observations of the anomalous fluxes of fast charged particles, disturbances of quasi-steady and ULF–VLF magnetic field components, and thermal plasma ion fluxes have been considered using the data of the active space experiment during electron beam injection in the frame of the Apex mission [24]. A DOK-S charged particle spectrometer installed at the subsatellite measured the differential fluxes of fast electrons and protons in eight energy intervals. The conditions for executing the experiment are based on the angle between the injection direction and the magnetic field vector, the characteristics of the environment, as well as the possibilities of observations with instruments located on a sub-satellite or on the Earth's surface.

In magnetospheric research missions, it is necessary to know when the satellites pass through the different regions (polar cusp, polar oval, bow shock, or/and magnetopause) for preliminary analysis and measurement planning. These regions are described with geometric models of surfaces [25] and determine the conditions for the operation of the instruments.

The visibility of objects and areas of the Earth's surface depends on the parameters of the Earth's orbit and its rotation in remote sensing missions. The ability to observe the Earth's surface depends on the spectral ranges of instruments. For observations in the visible spectral range, the objects must be illuminated by the Sun. Observations of the unilluminated part of the Earth's surface are carried out in the infrared spectral range, as the satellite may be in the umbra [26]. Kosari et al. [27] involve additional considerations of conditions related to pixel elongation and lighting (concerning the Sun) constraints.

Within the framework of the Korean space program, tools are being developed to predict orbital events [3, 28] – satellite contact time in specific ground stations, eclipses due to the Earth and moon, satellite pass time at the equator, pole, apogee, and perigee, satellite earth sensor interferences due to the sun and moon, Satellite attitude manoeuvre for imaging.

Concept of situation analysis

As pointed out above, situational analysis is applied to the space mission analysis at the initial stages of its preparation. During the operational stage, this analysis provides planning and scheduling for satellite operations, with appropriate time intervals for their execution. Each situational problem SP is composed of one or a conjunction of several situational conditions sc_i of different types:

$$(1) \quad SP = sc_1 \wedge sc_2 \wedge \dots \wedge sc_n = \bigwedge_1^n sc_i,$$

Applying Horner's rule, we can write

$$(2) \quad SP = (... (... (sc_1 \wedge sc_2) \wedge ...) \wedge sc_m ... \wedge sc_{n-1}) \wedge sc_n = \bigwedge_1^m sc_i, (m \leq n)$$

where m is the index of the first unfulfilled condition among the ordered n conditions of the situational problem. While the algorithmic complexity of representation Eq. (1) is $O(n)$, that of Eq. (2) is $O(m)$ ($m \leq n$). The conditions themselves are predicate functions accepting values of **true** or **false**. They can be generally represented as:

$$sc_i = sc_i(\{\vec{R}\}, \{\alpha\}, \{\beta\}, t)$$

where $\{\vec{R}\}$ is a set of radius vectors of satellites, $\{\alpha\}$ – is a set of parameters of the mathematical model describing the situational condition, and $\{\beta\}$ – is a set of specific constraints. The sets of parameters $\{\alpha\}$ and constraints $\{\beta\}$ are specific for each situational condition. In some cases, they are explicitly entered when composing the situational task (conditions 1 and 4 in Table 1). They are defined by models in other cases. This is the case of conditions 2 and 3 in Table 1. The radius vectors of the Sun and Moon are parameters of the geometric models of the corresponding situational conditions, which are calculated based on models of their movements. In this formulation, solving a situational problem represents a verification of the feasibility of a logical function at appropriate moments.

Enhancement of situational analysis efficiency

Basics

Improving the effectiveness of situational analysis is important for the following reasons:

- A large number of situational problems must be solved; the large number of problems is a result of the number of satellites, scientific instruments, objects to study, and scientific tasks to solve;
- Solving problems with several situational conditions each requires more calculations;
- Multiple solving while varying different parameters (orbital parameters, parameters of satellite subsystems) in order to optimise them;
- Running computer simulations over a long time horizon.

There are some standard ways to increase the efficiency of situational analysis:

- Optimisation related to mathematical models for verifying situational conditions;
- Use of compilers generating efficient code;
- Application of parallel calculations.

In addition to the previously mentioned ways for enhancing the efficiency of situational analysis, we will focus on one more.

Enhancing the efficiency of situational analysis by reordering the heuristic

Heuristics are ways of solving problems based on practical or intuitive assumptions about optimality. Unlike methods, they are not associated with rigorous evidence. Here, a heuristic to enhance the efficiency of solving multi-condition situational problems by reordering them is proposed – the reordered heuristic.

Instead of the direct problem SP to verify Eq. (1) or Eq. (2), let us consider the opposite problem [29]:

$$(3) \quad \overline{SP} = \overline{sc(t)_1 \wedge sc(t)_2 \wedge \dots \wedge sc(t)_n}$$

According to (1) or (2), we look for time intervals when all conditions are met. In the opposite task (3), we look for time intervals when at least one of the conditions is not fulfilled. Applying de Morgan's law, we can represent the opposite problem Eq. (3) as follows

$$(3') \quad \overline{SP} = \overline{sc(t)_1} \vee \overline{sc(t)_2} \vee \dots \vee \overline{sc(t)_k} \vee \dots \vee \overline{sc(t)_n}$$

To solve the opposite problem $\overline{SP}$ it is enough that only one of the conditions $\overline{sc(t)_k}$ is fulfilled. After finding the k^{th} condition ($\overline{sc(t)_k} = true$) sufficient to solve the problem, one can proceed with verifications in the next steps by applying the following heuristic:

$$(4) \quad \overline{SP} = \overline{sc(t+\Delta t)_k} \vee \overline{sc(t+\Delta t)_1} \vee \dots \vee \overline{sc(t+\Delta t)_{k-1}} \vee \overline{sc(t+\Delta t)_{k+1}} \vee \dots \vee \overline{sc(t+\Delta t)_n}$$

The meaning of reordering the conditions is related to the fact that the situational conditions themselves are slowly changing functions with respect to the time step with which the simulation model is discretised. In fact, moving the k^{th} unfulfilled condition in the first place causes verifications to interrupt already on the very first condition for a large number of time steps.

Development of a situational analysis solver

Situational problems editor

A dialogue editor is developed for composing situational problems. Depending on the type of satellite mission, a set of possible situational conditions is proposed to choose from. With appropriate dialogue controls, situational conditions are selected, and their parameters are entered to compose a situational problem. With check control, it is indicated that the current problem will be solved without or based on a reordered heuristic.

After compiling all situational problems, an actual solver is created to solve them at each step of the system/simulation time. For this purpose, a special

subroutine is used, which in turn calls system functions to create computational threads. In addition, two objects of type event are created for each thread. These events are used for synchronisation between the solver threads and a special thread (parent thread) that manages the simulation process. Here, we briefly note that the entire simulation process can include different types of parallel solvers. The handlers of the threads and the mentioned events are stored in a two-dimensional array and represent pool parameters.

When solving numerous situational problems (hundreds and thousands) it is important to avoid overload. Managing the thread pool consumes computational resources; therefore, taking only one task is inefficient. For this purpose, an integer variable is created – “granularity”. It determines the number of situational problems that are taken by the threads to solve at once. When these problems are solved, the thread can try to take the next portion of the problems. One more object of type “event” is created for all solver threads. It is used by each thread when solving several situational problems (the number is specified with the parameter “granularity”). When a thread needs to take on situational problems for solving, it changes the state of this event and takes certain actions. Until these actions are completed and the thread returns the previous state of the event, access to the situational problems by other threads is forbidden. This prevents situational problems from being solved by different threads. A situational problem counter is also necessary for the thread pool to function. It counts the situational problems taken for solving.

In addition to the situational problem descriptor, the coordinates of the satellites are also needed to solve situational problems. Depending on the type of situational conditions, the coordinates of other objects or environmental parameters may be required. All necessary data, or their memory addresses, are obtained from the Space mission dynamic solver descriptor (SMDSD) (Fig. 1a). This descriptor is necessary for the interpreter of the simulation model to start the situational solver at each time step. This is shown in Fig. 1b with the bidirectional connections between “Interpretation thread of a simulation model” and “pool of threads control” subroutine. The descriptor contains heterogeneous information about the pull of the thread of the solver and situational problems. Information from this descriptor is used when creating functional models of satellite subsystems.

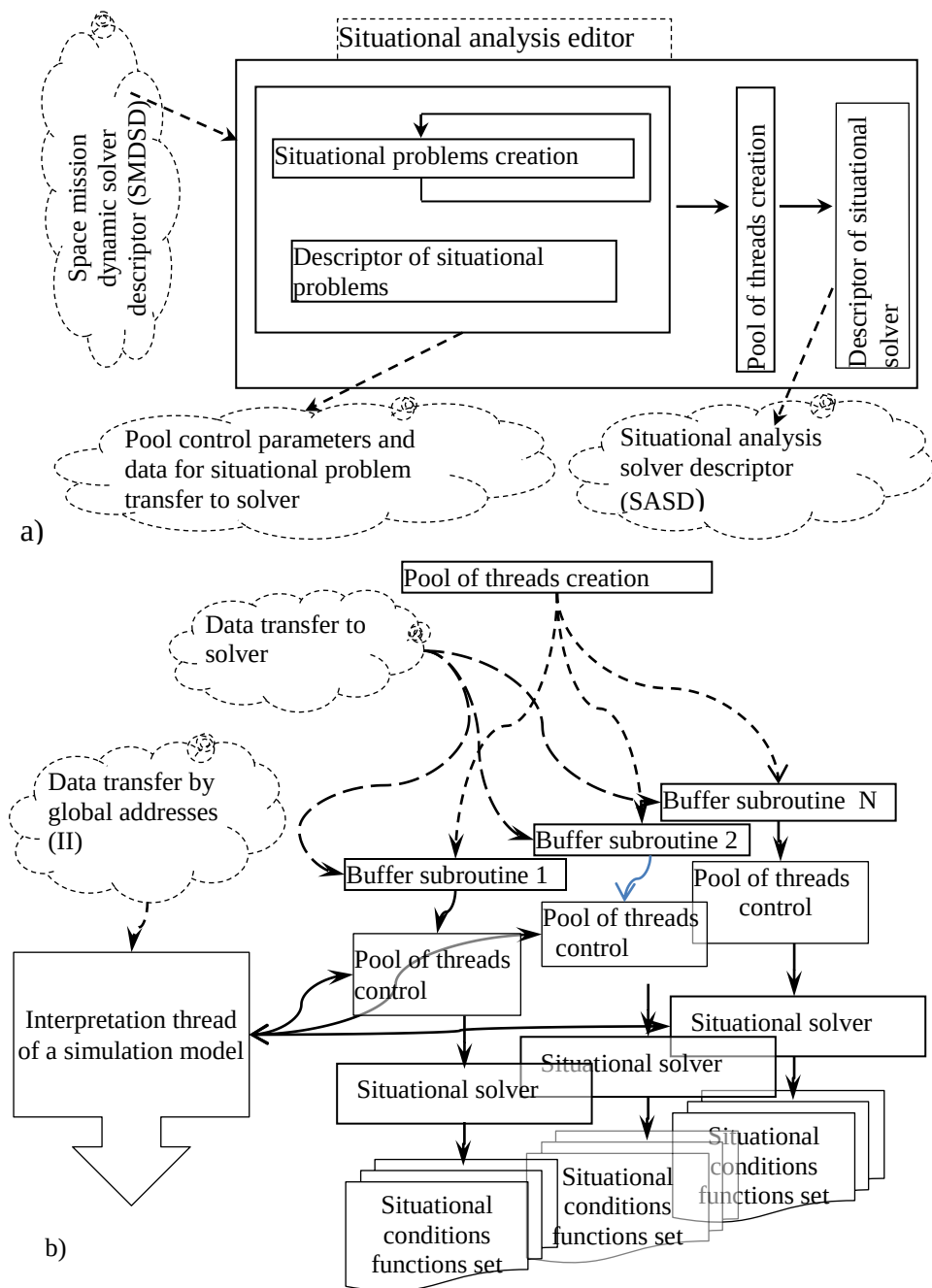


Fig. 1. Structural schemes of: (a) Situational Problems Editor and (b) Situational Problems Solver composed of N threads

Parallel situational analysis solver

A parallel solver of situational problems was developed [10]. The "thread pool" model is used for parallelisation [30]. "Parallelism across the situational problem" is applied as the parallelisation approach. The solver threads are synchronised for each time step with the parent thread (Fig. 1b). Depending on the particular problems, the number of threads is selected, as well as the "granularity", i.e., the degree of fragmentation of the entire set of situational problems. The number of threads for each individual solver should conform to the number of processors/cores in the computer system. Within a simulation model, different actual solvers (created with different parameters) can be created to solve specific sets of problems.

Each solver receives the necessary control parameters and data via a buffer subroutine. This buffer subroutine is the main one for the solver. It accepts the data from the situational editor (mentioned above) via global data (common block in the Fortran language) and then calls a thread pool supervising (management) subroutine. Each buffer subroutine contains a specific name of the main subroutine used in a particular solver. The thread pool management subroutine has polymorphic properties and can be called from buffer subroutines of a variety of parallel solvers.

Situational problem descriptor

Each situational problem is described by a descriptor – a one-dimensional array of a derived type (Atanassov, 2016). The null element of the array contains information about the situational problem (Appendix A). The following elements describe the situational conditions, according to the order of their input by the situational editor. The descriptors of all situational problems related to a specific space (single-satellite or multi-satellite) mission are combined into a two-dimensional array. The **efficiency** parameter, which indicates the efficiency-enhancing approach in solving each situational problem is included in the null element (Appendix A). The value of this parameter is determined at the stage of composing the situational problem. At a value of 0, Horner's rule applies. A reordered heuristic is used if the value of 1 is set. Other values of the **efficiency** parameter can be used for other algorithms in the future.

Program implementation of the reordered heuristic

When an unfulfilled condition included in a situational problem is detected, subroutine **Conditions_reordering** is called (Fig. 2). This subroutine reorders some elements in the task descriptor. The null element does not participate in the reordering. The element matching the detected unfulfilled condition is moved to the first position, and all others before it are shifted to one position. The remaining elements do not change their original positions.

```

SUBROUTINE   Conditions_reordering (iadr_sci_task, max_cond,no_meet)
USE DFlib
USE RN,ONLY:SitCond,sit_task
   type   (sit_task)          sci_task(0:max_cond)
   type   (SitCond)   Sit_Cond,temp_Sit_Cond(no_meet-1)
POINTER(iadr_sci_task,sci_task)
AUTOMATIC Sit_Cond,temp_Sit_Cond

      IF(sci_task(0)%opt_level.EQ.1) THEN ! reordered heuristic
        IF(no_meet.EQ.1) RETURN
          Sit_Cond= sci_task(no_meet)%sit_cond
          DO   i=no_meet,2,-1
            sci_task(i)%sit_cond= sci_task(i-1)%sit_cond
          END DO
          sci_task(1)%sit_cond= Sit_Cond
      ELSEIF(sci_task(0)%opt_level.EQ.2) THEN ! other heuristic
        IF(no_meet.EQ.1) RETURN
      ENDIF

END SUBROUTINE optimization

```

Fig. 2. The "optimisation" subroutine implementing the "reordered heuristic"

Examples of applications

Situational problem compilation

Let's consider a situational problem composed of several types of conditions (Table 1):

Table 1. Example of a situational problem

Numerical identifier	Titles of the types of situational conditions that are used below
1	The satellite is in the Earth's shadow
2	The Moon is below the horizon
3	The satellite passes over a circular area of Earth's surface with geographic coordinates of its centre (φ, λ) and angular radius δ .
4	A circular area on the Earth's surface (with geographic coordinates of its centre (φ, λ) and angular radius δ) is fully illuminated

Such situational problems arise in remote sensing missions. The situational conditions mentioned in Table 1 are included in the situational problem editor and the situational solver.

Evaluation of the efficiency depending on the order of the conditions

Three numerical experiments are conducted to evaluate the efficiency of the proposed heuristic. Both experiments simulated the motion of a satellite in an orbit with the following parameters: semi-major axis $a = 7\,000\,000$ m, eccentricity $e = 0.001$, and inclination i of 5° . It is verified whether the satellite passes above a circular area on the surface of the Earth with geographical coordinates of the centre at $(0^\circ, 0^\circ)$, and an angular radius of $\delta = 10^\circ$. Additionally, it is verified whether the satellite is in the shadow of the Earth [31], and if the Moon is below the horizon [32]. The integration of the equations of motion of the satellite and the checks of the conditions are performed within a time horizon of thirty days with a step $dt = 10$ s.

Table 2 contains results regarding the number of verified conditions when solving the situational problem based on a static ordering of the conditions applying Horner's rule (2) and when applying the reordered heuristic.

Table 2. Number of condition verifications performed – first situational problem

Variants of the conditions ordering	Verified conditions with Horner's rule	Verified conditions with heuristic	Efficiency [%]
1-2-3	277 635	263 919	4.94
1-3-2	277 588	263 916	4.92
2-1-3	358 035	263 918	26.29
2-3-1	389 388	263 919	32.22
3-1-2	358 320	263 915	26.35
3-2-1	389 720	263 920	32.28

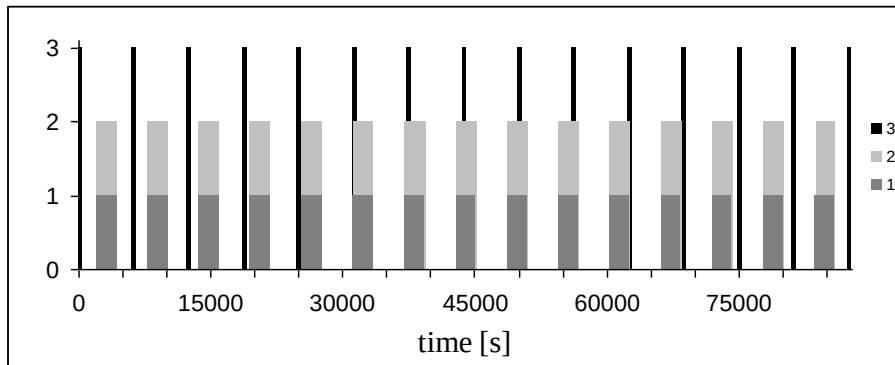


Fig. 3. Time diagrams of situational conditions are shown:

1 – the satellite is in the Earth's shadow, 2 – the satellite is in the shadow of the Moon, and 3 – the satellite passes over a circular region

Fig. 3 shows a timing diagram of the situational conditions for the considered time horizon. The three situational conditions are fulfilled simultaneously in the following time intervals: (31 200, 31 410), (37 340, 37 670), (43 580, 43 920), (49 840, 50 170), (56 100, 56 410), and (62 360, 62 430).

In the second experiment, an additional fourth condition is checked to see if the entire above-mentioned area is unlit by the Sun. In one case, time intervals are searched in which three conditions are met simultaneously, and in the other case, four conditions are met.

Table 3. Number of condition verifications performed – second situational problem

Variants of the conditions ordering	Verified conditions with Horner's role	Verified conditions with heuristic	Efficiency [%]
1-2-3-4	279 574	265 858	4.91
1-2-4-3	282 598	265 859	5.92
1-3-2-4	279 527	265 855	4.89
1-3-4-2	279 945	265 856	5.03
1-4-2-3	284 395	265 854	6.52
1-4-3-2	281 789	265 851	5.66
2-1-3-4	359 974	265 857	26.14
2-1-4-3	362 998	265 858	26.76
2-3-1-4	391 327	265 858	32.06
2-3-4-1	407 843	265 857	34.81
2-4-1-3	405 197	265 855	34.39
2-4-3-1	418 689	265 856	36.50
3-1-2-4	360 259	265 854	26.20
3-1-4-2	360 677	265 855	26.29
3-2-1-4	391 659	265 859	32.12
3-2-4-1	408 175	265 867	34.86
3-4-1-2	403 060	265 852	34.04
3-4-2-1	419 158	265 853	36.57
4-1-2-3	400 503	265 853	33.62
4-1-3-2	397 897	265 850	33.19
4-2-1-3	440 905	265 854	39.70
4-2-3-1	454 397	265 855	41.49
4-3-1-2	438 436	265 851	39.36
4-3-2-1	454 534	265 852	41.51

A simulation experiment was conducted with two satellites. The orbital parameters are as follows: for the first satellite, the semi-major axis is $a_1 = 7\,000\,000$ m, eccentricity $e_1 = 0.001$, and inclination $i_1 = 5^\circ$; for the second satellite, $a_2 = 7\,500\,000$ m, $e_2 = 0.005$, and $i_2 = 15^\circ$.

Table 4 shows the results of the checks performed for two cases of initial orders of the situational conditions. The number of possible orders under six conditions is 720 and cannot be shown. In these and other cases, the number of checks based on Horner's rule varies significantly between cases. When applying reordering, much fewer checks are performed, close to those shown in Tables 2 and 3.

Moreover, in this experiment, the conditions are more than those in the second, and given the applied reordered heuristic, the probability of fulfilling more conditions in one time step is smaller than that with fewer conditions. Therefore, the number of checks performed decreases with an increase in the number of conditions when applying this heuristic!

Table 4. The number of checks for problems, including three conditions for each companion for an interval of one month, is shown

Variants of the conditions ordering	Verified conditions with Horner's role	Verified conditions with heuristic	Efficiency [%]
1(1), 2(1), 3(1), 1(2), 2(2), 3(2)	279 637	260 902	6.7
2(1), 3(1), 2(2), 3(2), 1(1), 1(2)	408 989	260 918	36.20

In Table 4 and Table 5, the ordering variants are denoted by two numbers – the first digit indicates the situational condition, while the second digit (in the brackets) refers to the corresponding satellite.

Solving the same situational problem for three ten-day periods of the selected time horizon and results for a randomly chosen order of conditions are shown in Table 5. The differences in the efficiency in solving the situational problem for the three time intervals are due to the irregularities related to changes in the positions of the Sun and Moon.

Table 5. The number of checks performed for the second task from Table 4, but for a consecutive ten-day period

Variants of the conditions ordering	Verified conditions with Horner's role	Verified conditions with heuristic	Efficiency [%]
<u>1-10 Apr 2022</u>			
2(1), 3(1), 2(2), 3(2), 1(1), 1(2)	145 520	86 931	40.26
<u>10-20 Apr 2022</u>			
2(1), 3(1), 2(2), 3(2), 1(1), 1(2)	118 857	86 701	27.05
<u>20-30 Apr 2022</u>			
2(1), 3(1), 2(2), 3(2), 1(1), 1(2)	140 428	86 897	38.1

Effectiveness of the proposed heuristics

Let us note that terminating the verifications upon failure of the next checked condition in (2) increases the efficiency of solving the situational problem compared to initially solving all predicate functions sc_i and computing the situational problem as $SP = \bigwedge_1^n sc_i$. Let us note that when solving situational problems, applying Horner's rule as $SP = \bigwedge_1^k sc_i$, $k < n$, instead of checking all conditions as $SP = \bigwedge_1^n sc_i$ improves the efficiency in obtaining the final result. Applying (1) within a thirty-day simulation interval with a 10-sec step will lead to 777,600 and 1,036,800 checks for each of the first two situational problems, respectively.

Table 2 and Table 3 show the performance when applying these two approaches – Eq. (2) and Eq. (4), evaluated for different initial orderings of conditions in the two situational problems. It can be seen that the initial order of conditions affects the efficiency when applying Horner's rule. Applying the proposed heuristic results in nearly equalising the number of checks.

Even with an increase in the number of conditions in situational problems, the number of checks is decreasing. When applying Horner's rule, the number of checks is sensitive to the order of situational conditions and the orbital parameters of the satellite. The value of the orbital parameters of the satellites, as well as the position of the Sun and the Moon, determines the geometric configuration with which the situational conditions are associated. The reordered heuristic minimises this and other irregularities.

Discussion

Solving a situational problem involving several conditions, for an extended interval of simulation time, is not based on an exact algorithm, even when applying Horner's rule. The number of verified conditions for different moments of time t varies. Thus, the algorithmic complexity changes depending on the checked conditions – $O(m(t))$. Only for the time interval when all conditions are fulfilled, the complexity is $O(n(t))$. Applying conditions reordering, the algorithmic complexity is $O(1)$ for long segments along the time axis!

Conclusion and outlook

The proposed approach for efficiency enhancement of the situational analysis is implemented within the framework of the developed PSAS. The latest version of the situational solver is designed for use in a multiphysics environment for space mission simulations. The application of this approach turns the solver into a powerful analysis tool, increasing the efficiency of simulations.

Future development of the parallel situational analysis solver involves developing and including other types of situational conditions and algorithms to enhance its efficiency. Given the formal nature of the presented approach for

situational analysis, a search for other application possibilities is also foreseen. For example, work is being done on applying the situational solver to problems related to the self-shadowing of solar panels on structurally complex space platforms.

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The author would like to express his gratitude to fortune for the opportunity to collaborate, many years ago, with Dr Alexander Sukhanov from the Space Research Institute at the Russian Academy of Sciences, which subsequently led to the idea proposed in this manuscript.

Appendix A

```

type SitCond
  integer sit_code ! Code of the situation condition type
  integer sat_num ! The identification number of a satellite is concerned
                  ! with this situational condition
  logical begin_sit ! The situational interval begins
  logical fl_results ! If .true. - end of the situational interval
  real duration ! Duration of a current situational condition/event
  real dt_sit ! Accumulates duration of situational condition
union
  map ! Sit__1: Passing over circular region of Earth surface
    integer reg_num ! Number of regions- actual number
    real lati_r , longi_r ! Geographic coordinates of the centre
    real angle_r ! Angular radius of the region
  end map
  map ! Sit__6: Circular geographic region - day/[night] time
    real lati_6,longi_6 ! Coordinates of the centre
    real angle_6 ! Angular radius
  end map
  map ! Sit_76,77: The moon is under horizon
    logical Moon_under ! Moon's "umbra"
    logical Moon_horizon ! Moon on horizon (rise/set)
    logical Moon_over ! Moon's light
  end map
  map ! Sit_78/79: satellite in conic shadow
    real num_sat_79
    logical umbra ! If .true. - <umbra>
    logical penumbra ! If .true. - <penumbra>
    logical sunligh ! If .true. - penumbra=.false, umbra=.false.
  end map
end union
end type SitCond

```



```

type    sit_problem
union
  map                                ! For the zero element; only for solving process control
    integer  SP_type                ! Type of situation problem
    integer  max_cond              ! Maximum number of conditions in the problem
    integer  efficiency            ! Efficiency-improving algorithm: 0- none, 1/2/3
    logical  begin_sit
    logical  fl_results            ! If is .true. - end of time window
    real*8   t1,t2                 ! Time interval where the situation is satisfied
    real     duration,dt_sit       ! Duration of the situational problem time window
    real     t_task_total          ! Accumulates total durations for the simulation period
  end map
  map
    type (SitCond) sit_cond
  end map
end union
end type sit_problem

```

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ПРИМЕНЕНИЕ ПЕРЕСТАВЛЕННОЙ ЭВРИСТИКИ ДЛЯ ПОВЫШЕНИЯ ЭФФЕКТИВНОСТИ СИТУАЦИОННОГО АНАЛИЗА ПРИ РЕШЕНИИ ЗАДАЧ, СОДЕРЖАЩИХ БОЛЕЕ ОДНОГО УСЛОВИЯ, В АНАЛИЗЕ КОСМИЧЕСКИХ МИССИЙ

Атанас Атанасов

Резюме

Ситуационный анализ занимается проверкой условий геометрического или физического характера во время движения спутников по орбитам. Этот анализ применяется для определения временных интервалов, оптимальных для выполнения конкретных операций со спутниками. Ситуационные задачи решаются на различных этапах подготовки и эксплуатации спутниковых миссий. Наиболее интересными являются случаи, когда ситуационная задача содержит несколько условий. Каждая ситуационная задача решается путем последовательной проверки соответствующих условий. Проверки могут быть прекращены при обнаружении невыполненного условия (правило Хорнера) для повышения эффективности анализа. Вычисления повторяются для последующих временных шагов. Решение такой ситуационной задачи может быть трудоемким при проведении многовариантных и многоспутниковых симуляций. Предлагается эвристический подход для повышения эффективности ситуационного анализа задач, включающих несколько условий. Этот подход основан на переупорядочивании проверок условий. Подход алгоритмизирован и интегрирован в ранее разработанный решатель ситуационного анализа. Эффективность предложенной эвристики оценивается на примерах с различным количеством ситуационных условий. Этот подход демонстрирует большую эффективность, чем применение правила Хорнера.

CORIMIA IONIZATION MODEL – 2+1 INTERVAL APPROXIMATION FOR COSMIC RAY NUCLEI ($Z > 1$)

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Abstract

This paper considers the ionisation model CORIMIA (Cosmic Ray Ionisation Model for Ionosphere and Atmosphere) in its two-interval 2+1 approximation with a charge-decreasing interval of the ionisation loss function. Increasing the number of approximation intervals is the next step in improving the model. The final stage will be the introduction of a 5-interval approximation of the Bohr-Bethe-Bloch formula with a charge-decreasing interval. This version introduces integration limits over an arbitrary energy interval.

Introduction. Particles with Charge $Z > 1$

In [1], the case of cosmic-ray protons ($Z = 1$), which constitute the majority of their composition [2–4], was considered (see Table 1 below). Particles with charge $Z > 1$ can be divided into several groups according to their nuclei. This classification is possible because experimental studies (Dorman, 2004) [5]; (Toptigin, 1985) [6] have shown that the fluxes of cosmic rays composed of nuclei with similar charges are approximately equal. Table 1 presents the fluxes of the different nuclear groups in the composition of cosmic rays. Experimental results cited by Dorman [5] and Toptigin (in parentheses) [6] are shown.

Table 1: Groups of Nuclei in Cosmic Rays – The first column of the table presents the different nuclear groups found in cosmic rays. The second column shows the nuclear charge Z of the groups, and the third column provides experimental data on the flux ϕ ($\text{m}^{-2}\cdot\text{ster}^{-1}\cdot\text{s}^{-1}$) for energies $E > 2.5$ GeV/nuc. Data without brackets are from Dorman (2004), and those in brackets are from Toptigin (1985).

Table 1.

Nuclear group from CR	Charge Z	Flux ϕ ($\text{m}^{-2} \cdot \text{ster}^{-1} \cdot \text{s}^{-1}$) for energies $E > 2.5$ GeV/nuc
Protons p	1	1300 (1300)
Helium nuclei α	2	88 (94)
Light nuclei L	3–5	1.9 (2)
Medium nuclei M	6–9	5.6 (6.7)
Heavy nuclei H	10–19	2.5 (2)
Very heavy nuclei VH	≥ 20	0.7 (0.3)

Model approximation

In describing the model for calculating the rate of ion pair production due to the passage of charged cosmic ray particles with $Z > 1$, a double integral approximation of the ionisation loss function is used. Equation (2) [1] applies in this case. However, besides the two characteristic energy limits of the integral, there is another interval related to the charge reduction of the ionising particle: $[E_a; E_b][E_{-a}; E_{-b}]$, where the upper bound E_a is defined as [7, 8]:

$$(1) \quad E_a = 0.15 \times Z^2.$$

Here, E_a is the initial energy at which the particle starts to reduce its charge. E_{-b} is the lower bound of the charge reduction interval, when the particle has a charge $Z = 1$ and is described by:

$$(2) \quad E_b = 0.15.$$

From equations (1) and (2), the effective charge of the incoming particle is given by:

$$(3) \quad Z^* = \left(\frac{E}{0.15}\right)^2, \quad 0.15 \leq E \leq E_a.$$

Substituting this expression for the effective charge Z^* into the ionisation loss function (equation (2)) [1], we obtain:

$$(4) \quad \frac{1}{\rho} \frac{dE}{dh} = 242 \times Z^2 \times E^{-3/4} = 242 \frac{E}{0.15} E^{-3/4} = 1613.3 E^{1/4}, \quad 0.15 \leq E \leq E_a.$$

The final form of equation (2) [1] becomes:

$$(5) \quad -\frac{1}{\rho} \frac{dE}{dh} = \begin{cases} 1613.3 E^{1/4}, & 0.15 \leq E \leq E_a, & \text{Interval 1}^* \\ 242 Z^2 E^{-3/4}, & E_a \leq E \leq 600 \text{ MeV}, & \text{Interval 1} \\ 2 Z^2, & 600 < E \leq 5 \times 10^6 \text{ MeV}, & \text{Interval 2.} \end{cases}$$

where Interval 1* represents the region of charge reduction of an incoming charged particle in the Earth's atmosphere. The reason for this charge reduction is detailed in Dorman (2004) [5] and is related to the process of electron attachment.

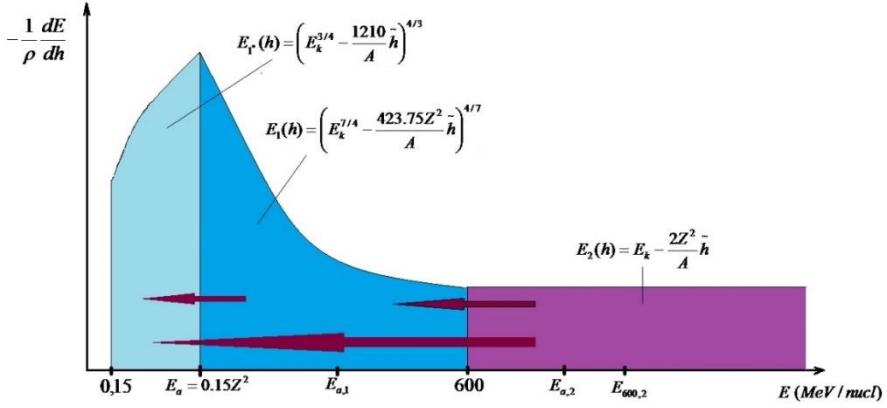


Fig. 1. Double-integral (2+1) approximation of the ionisation loss function for charged cosmic ray particles with charge $Z > 1$

The figure shows the segmentation of energy losses into different intervals $E1^*(h)$, $E1(h)$, $E2(h)$, as well as the segment boundaries at the respective energies when the particle crosses between intervals: $E11(h)$, $E21(h)$, $E31(h)$.

The first step in model development is to determine the energy loss functions for the different intervals in equation (5). As in the case of particles with charge $Z = 1$, we will use the quantity of transferred matter h .

The amount of transferred matter h in Interval 1* can be expressed as [7]:

$$(6) \quad \tilde{h} = \tilde{h}_{1^*} = \frac{1}{1613.3} \int_{E(h)}^{E_k} \frac{AdE}{E^{1/4}} = \frac{A}{1613.3} \frac{4}{3} \left(E_k^{3/4} - E^{3/4}(h) \right),$$

where A is the atomic mass of the particle with charge Z . From equation* (6), the energy losses law in Interval 1* can be written as:

$$(7) \quad E_{1^*}(h) = \left(E_k^{3/4} - \frac{1210}{A} \tilde{h} \right)^{4/3}.$$

For the transferred matter in Interval 1, we have:

$$(8) \quad \tilde{h} = \tilde{h}_1 = \frac{1}{242} \int_{E(h)}^{E_k} \frac{AdE}{Z^2 E^{-3/4}} = \frac{A}{Z^2 242} \frac{4}{7} \left(E_k^{7/4} - E_1^{7/4}(h) \right).$$

From expression (8), we can express the energy loss law in Interval 1 as:

$$(9) \quad E_1(h) = \left(E_k^{7/4} - \frac{423.75Z^2}{A} \tilde{h} \right)^{4/7}.$$

In a similar way, we can derive the energy losses law in the final interval – Interval 2. The amount of transferred matter $h_{\sim}$ is given by:

$$(10) \quad \tilde{h} = \tilde{h}_2 = \frac{A}{2Z^2} \int_{E(h)}^{E_k} dE = \frac{A}{2Z^2} (E_k - E_2(h)).$$

The energy losses law in Interval 2 is:

$$(11) \quad E_2(h) = E_k - \frac{2Z^2}{A} \tilde{h}.$$

The next important step is to derive analytical expressions for the atmospheric cut-off thresholds $E_{Aj}E_{\sim}\{Aj\}E_{Aj}$ in the different intervals. The transferred matter for Interval 1* can be expressed as:

$$(12) \quad \tilde{h} = \tilde{h}_{1^*} = \frac{A}{1613.3} \int_{E(h)=0.15}^{E_{A1^*}(h)} \frac{dE}{E^{1/4}} = \frac{A}{1613.3} \frac{4}{3} \left(E_{A1^*}^{3/4}(h) - 0.15^{3/4} \right).$$

The atmospheric cut-off for Interval 1* is then defined by:

$$(13) \quad E_{A1^*}(h) = \left(0.15^{3/4} + \frac{1210}{A} \tilde{h} \right)^{4/3} \leq E_a.$$

Similarly, the remaining two cut-off thresholds can be expressed. The transferred matter in Interval 1 is:

$$(14) \quad \tilde{h} = \tilde{h}_{1^*} + \tilde{h}_1 = \frac{A}{1613.3} \int_{0.15}^{E_a} \frac{dE}{E^{1/4}} + \frac{A}{242Z^2} \int_{E_a}^{E_{A1}} \frac{dE}{E^{-3/4}} = \frac{A}{1210} \left(E_a^{3/4} - 0.15^{3/4} \right) + \frac{A}{423.75Z^2} \left(E_{A1}^{7/4} - E_a^{7/4} \right).$$

From equation (14), the cut-off threshold for Interval 1 can be expressed as:

$$(15) \quad E_{A1}(h) = \left(423.74 \frac{Z^2}{A} \tilde{h} - 0.35Z^2 \left(E_a^{3/4} - 0.15^{3/4} \right) + E_a^{7/4} \right)^{4/7}.$$

The transferred matter for the final Interval 2 is the sum of the transferred matter across all intervals, and is given by:

$$(16) \quad \tilde{h} = \tilde{h}_{1^*} + \tilde{h}_1 + \tilde{h}_2 = \frac{A}{1613.3} \int_{0.15}^{E_a} \frac{dE}{E^{1/4}} + \frac{A}{242Z^2} \int_{E_{A2}(h)}^{600} \frac{dE}{E^{-3/4}} + \frac{A}{2Z^2} \int_{600}^{E_{A2}(h)} dE = \frac{A}{1210} \left(E_a^{3/4} - 0.15^{3/4} \right) + \frac{A}{423.75Z^2} \left(600^{7/4} - E_a^{7/4} \right) + \frac{A}{2Z^2} (E_{A2}(h) - 600).$$

The final expression for the atmospheric cut-off for Interval 2 is:

$$(17) \quad E_{A2}(h) = 2 \frac{Z^2}{A} \tilde{h} - 0.002Z^2 \left(E_a^{\frac{3}{4}} - 0.15^{\frac{3}{4}} \right) - 0.005 \left(600^{\frac{7}{4}} - E_a^{\frac{7}{4}} \right) + 600$$

The effective reflection threshold is determined by taking into account the increase in the geomagnetic cut-off ER and atmospheric cut-off EA .

Upon entering the atmosphere, a cosmic ray particle with charge Z begins to lose energy according to the energy loss laws for the different intervals in equation (5). In other words, its kinetic energy E_k changes based on the loss mechanisms and charge reduction processes, depending on the interaction it undergoes.

When the particle crosses a boundary between energy intervals, it is necessary to derive specific energy loss laws for each case. Using double integral approximations of the Bohr-Bethe-Bloch ionisation loss function and accounting for the charge reduction interval, the following boundary conditions are possible [7–9]:

- $E_{1*1}(h)$ – when the particle crosses the boundary between Interval 1 and Interval 1* (at energy E_a);
- $E_{21}(h)$ – when the particle crosses the boundary between Interval 2 and Interval 1 (at 600 MeV);
- $E_{31}(h)$ – when the particle crosses both the boundary between Interval 2 and Interval 1 (600 MeV), and the boundary between Interval 1 and Interval 1* (at E_a).

To derive the energy loss laws at the interval boundaries, the transferred matter h is used.

If the energy of the incoming particle crosses the boundary E_a , we have:

$$(18) \quad \tilde{h} = \tilde{h}_{1*} + \tilde{h}_1 = \frac{A}{1613,3} \int_{E_{11*}(h)}^{E_a} \frac{dE}{E^{1/4}} + \frac{A}{242Z^2} \int_{E_a}^{E_k} \frac{dE}{E^{-3/4}} = \frac{A}{1210} \left(E_a^{3/4} - E_{11*}^{3/4} \right) + \frac{A}{423,75Z^2} \left(E_k^{7/4} - E_a^{7/4} \right).$$

The energy loss law in this case is:

$$(19) \quad E_{11*}(h) = \left(\frac{2,85}{2Z^2} - \left(E_k^{7/4} - E_a^{7/4} \right) - \frac{1210}{A} \tilde{h} + E_a^{3/4} \right)$$

When the incoming particle's energy crosses the boundary at 600 MeV, the transferred matter h can be expressed as:

$$(20) \quad \tilde{h} = \tilde{h}_1 + \tilde{h}_2 = \frac{A}{242Z^2} \int_{E_{21}(h)}^{600} \frac{dE}{E^{-3/4}} + \frac{A}{2Z^2} \int_{600}^{E_k} dE = \frac{A}{423,75Z^2} \left(600^{7/4} - E_{21}^{7/4} \right) + \frac{A}{2Z^2} (E_k - 600).$$

From equation (20), we can derive the energy loss law when the incoming particle's energy crosses the 600 MeV boundary:

$$(21) \quad E_{21}(h) = \left(211,88(E_k - 600) - \frac{423,75Z^2}{A} \tilde{h} + 600^{7/4} \right)^{4/7}$$

If the kinetic energy E_k of the incoming particle crosses both boundaries – at 600 MeV and at $E_a = 0.15 \times Z^2$ – then the total transferred matter is:

$$(22) \quad \tilde{h} = \tilde{h}_{1^*} + \tilde{h}_1 + \tilde{h}_2 = \frac{A}{1613,3} \int_{E_{21^*}(h)}^{E_a} \frac{dE}{E^{\frac{1}{4}}} + \frac{A}{242Z^2} \int_{E_a}^{600} \frac{dE}{E^{-\frac{3}{4}}} + \frac{A}{2Z^2} \int_{600}^{E_k} dE = \frac{A}{1210} (E_a^{3/4} - E_{21^*}^{3/4}) + \frac{A}{423,75Z^2} (600^{7/4} - E_a^{7/4}) + \frac{A}{2Z^2} (E_k - 600).$$

The final energy loss law when both thresholds (600 MeV and E_a) are crossed becomes:

$$(23) \quad E_{21^*}(h) = \left(E_a^{\frac{3}{4}} + \frac{2,85}{2Z^2} \left(600^{\frac{7}{4}} - E_a^{\frac{7}{4}} \right) + \frac{605}{Z^2} (E_k - 600) - \frac{1210}{A} \tilde{h} \right)^{4/3}$$

Based on the derived energy loss laws for each interval (equations (7, 9, 11) 4.33, 4.35, 4.37) and for cases when boundaries between intervals are crossed (equations (19, 21, 23) 4.45, 4.47, 4.49), we can now express the ionisation loss function from equation (5, 4.31) as follows:

For Interval 1*:

$$(24) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_{1^*} = 1613,3 E_{1^*}^{1/4} = 1613,3 \left(E_k^{3/4} - \frac{1210}{A} \tilde{h} \right)^{1/3}$$

$$(25) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_1 = 242Z^2 E_1^{-3/4} = 242Z^2 \left(E_k^{7/4} - \frac{423,75Z^2}{A} \tilde{h} \right)^{-3/7}$$

$$(26) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_2 = \frac{2Z^2}{A}$$

$$(27) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_{11^*} = 1613,3 E_{11^*}^{1/4} = 1613,3 \left(\frac{2,85}{2Z^2} (E_k^{7/4} - E_a^{7/4}) - \frac{1210}{A} \tilde{h} + E_a^{3/4} \right)^{1/3}$$

$$(28) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_{21} = 242Z^2 E_{21}^{-3/4} = 242Z^2 \left(211,88(E_k - 600) - \frac{423,75Z^2}{A} \tilde{h} + 600^{7/4} \right)^{-3/7}$$

$$(29) \quad \frac{1}{\rho} \left(\frac{dE}{dh} \right)_{21^*} = 1613,3 E_{21^*}^{1/4} = 1613,3 \left(\frac{2,85}{2Z^2} (600^{7/4} - E_a^{7/4}) - \frac{605}{Z^2} (E_k - 600) - \frac{1210}{A} \tilde{h} + E_a^{3/4} \right)^{1/3}$$

Based on the previous considerations, we can express the explicit form of the model for calculating the electron production rate $q(h)q(h)q(h)$ – the general formula [4]. When determining the form of the general formula, it is necessary to account for different possible cases depending on the energy of the effective reflection threshold, as well as on the differences in atmospheric cut-off energies for the separate intervals.

Case 1.

The energy of the effective reflection threshold is less than the upper boundary of Interval 1*:

$$0.15 < EA1 \leq E_{eff} \leq Ea < E_{\infty} < 600 \text{ MeV.}$$

In this case, the general formula (4) becomes:

(30)

$$\begin{aligned} q(h) = & \frac{\rho(h)}{Q} \left(\int_{E_{eff}}^{E_a} D(E) \left(\frac{dE}{dh} \right)_{1*} dE_k + \int_{E_a}^{E_{a\infty}} D(E) \left(\frac{dE}{dh} \right)_{11*} dE_k + \int_{E_{a\infty}}^{600} D(E) \left(\frac{dE}{dh} \right)_1 dE_k \right. \\ & \left. + \int_{600}^{E_{600}} D(E) \left(\frac{dE}{dh} \right)_{21} dE_k + \int_{E_{600}}^{\infty} D(E) \left(\frac{dE}{dh} \right)_2 dE_k \right) \\ = & \frac{1613,3\rho(h)}{Q} \int_{E_{eff}}^{E_a} D(E) \left(E_k^{3/4} - \frac{1210}{A} \tilde{h} \right)^{1/3} dE_k \\ & + \frac{1613,3\rho(h)}{Q} \int_{E_a}^{E_{a\infty}} D(E) \left(\frac{2.85}{Z^2} (E_k^{7/4} - E_a^{7/4}) - \frac{1210}{A} \tilde{h} \right. \\ & \left. + E_a^{3/4} \right)^{1/3} dE_k \\ & + \frac{242Z^2\rho(h)}{Q} \int_{E_{a\infty}}^{600} D(E) \left(E_k^{7/4} - \frac{423,75Z^2}{A} \tilde{h} \right)^{-3/7} dE_k \\ & + \frac{242Z^2\rho(h)}{Q} \int_{600}^{E_{600}} D(E) \left(211,88(E_k - 600) - \frac{423,75Z^2}{A} \tilde{h} \right. \\ & \left. + 600^{7/4} \right)^{-3/7} dE_k + \frac{2Z^2\rho(h)}{Q} \int_{E_{600}}^{\infty} D(E) dE_k \end{aligned}$$

Where:

- E_k is the energy at infinity (initial kinetic energy,
- E_a is the energy threshold defined by the energy loss law for Interval 1:

$$(31) \quad E_{a\infty}(h) = \left(E_a^{7/4} + \frac{423,75Z^2}{A} \tilde{h} \right)$$

E_{600} is the energy at infinity at the 600 MeV boundary, which follows from the energy loss law for Interval 2 and is given in the expression [4, 7–11]:

$$(32) \quad E_{600} = 600 + \frac{2Z^2}{A} \tilde{h}$$

Case 2a.

The energy of the effective reflection threshold is greater than the upper boundary of Interval 1*, but less than the 600 MeV boundary. The energy at infinity (initial energy) is less than 600 MeV:

$$E_a < E_{eff} < E_{\infty} < 600 < E_{600} \text{ MeV.}$$

Then the general equation [4] takes the form:

$$\begin{aligned}
 (33) \quad q(h) &= \frac{\rho(h)}{Q} \left(\int_{E_{eff}}^{E_{a\infty}} D(E) \left(\frac{dE}{dh} \right)_{11^*} dE_k + \int_{E_{a\infty}}^{600} D(E) \left(\frac{dE}{dh} \right)_1 dE_k + \right. \\
 &+ \int_{600}^{E_{600}} D(E) \left(\frac{dE}{dh} \right)_{21} dE_k + \int_{E_{600}}^{\infty} D(E) \left(\frac{dE}{dh} \right)_2 dE_k = \\
 &= \frac{1613.3\rho(h)}{Q} \int_{E_{eff}}^{E_{a\infty}} D(E) \left(\frac{2.85}{Z^2} (E_k^{7/4} - E_a^{7/4}) - \frac{1210}{A} \tilde{h} + E_a^{3/4} \right)^{1/3} dE_k + \\
 &+ \frac{242Z^2\rho(h)}{Q} \int_{E_{a\infty}}^{600} D(E) \left(E_k^{7/4} - \frac{423.75Z^2}{A} \tilde{h} \right)^{-3/7} dE_k + \\
 &+ \frac{242Z^2\rho(h)}{Q} \int_{600}^{E_{600}} D(E) \left(211.88(E_k - 600) - \frac{423.75Z^2}{A} \tilde{h} + 600^{7/4} \right)^{-3/7} dE_k + \\
 &+ \frac{2Z^2\rho(h)}{Q} \int_{E_{600}}^{\infty} D(E) dE_k.
 \end{aligned}$$

Case 2b.

The energy of the effective reflection threshold is greater than the upper boundary of Interval 1*, but less than the 600 MeV boundary. The energy at infinity (initial energy) is greater than 600 MeV:

$$E_a < E_{eff} < 600 < E_{a\infty} < E_{600} \text{ MeV.}$$

Then the general equation [4] becomes:

$$\begin{aligned}
 (34) \quad q(h) &= \frac{\rho(h)}{Q} \left(\int_{E_{eff}}^{600} D(E) \left(\frac{dE}{dh} \right)_1 dE_k + \int_{600}^{E_{a\infty}^*} D(E) \left(\frac{dE}{dh} \right)_{21^*} dE_k \right. \\
 &+ \int_{E_{a\infty}^*}^{E_{600}} D(E) \left(\frac{dE}{dh} \right)_{21} dE_k + \int_{E_{600}}^{\infty} D(E) \left(\frac{dE}{dh} \right)_2 dE_k = \\
 &= \frac{1613.3\rho(h)}{Q} \int_{E_{eff}}^{600} D(E) \left(E_k^{7/4} - \frac{423.75Z^2}{A} \tilde{h} \right)^{1/3} dE_k + \\
 &+ \frac{1613.3\rho(h)}{Q} \int_{600}^{E_{a\infty}^*} D(E) \left(\frac{2.85}{Z^2} (600^{7/4} - E_a^{7/4}) - \right. \\
 &- \frac{605}{Z^2} (E_k - 600) - \frac{1210}{A} \tilde{h} + E_a^{3/4} \left. \right)^{1/3} dE_k + \\
 &+ \frac{242Z^2\rho(h)}{Q} \int_{E_{a\infty}^*}^{E_{600}} D(E) \left(211.88(E_k - 600) - \frac{423.75Z^2}{A} \tilde{h} + 600^{7/4} \right)^{-3/7} dE_k + \\
 &+ \frac{2Z^2\rho(h)}{Q} \int_{E_{600}}^{\infty} D(E) dE_k
 \end{aligned}$$

$E_{a\infty}^*$ is expressed by the energy loss law of a particle crossing the boundaries at 600 MeV and E_a , and is given by [7–9]:

$$(35) \quad E_{a\infty}^* = \frac{1}{212} \left(127200 - 600^{7/4} + E_a^{7/4} + 423.75\tilde{h} \right).$$

Case 3.

The energy of the effective reflection threshold is greater than the 600 MeV boundary but less than $E_{a\infty}^*$: $600 < E_{eff} < E_{a\infty}^* < E_{600}$ MeV. In this case, we have:

$$(36) \quad q(h) = \frac{\rho(h)}{Q} \left(\int_{E_{eff}}^{E_{a\infty}^*} D(E) \left(\frac{dE}{dh} \right)_{21^*} dE_k + \int_{E_{a\infty}^*}^{E_{600}} D(E) \left(\frac{dE}{dh} \right)_{21} dE_k + \right. \\ \left. + \int_{E_{600}}^{\infty} D(E) \left(\frac{dE}{dh} \right)_2 dE_k = \right. \\ = \frac{1613.3 \rho(h)}{Q} \int_{E_{eff}}^{E_{a\infty}^*} D(E) \left(\frac{2.85}{Z^2} (600^{7/4} - E_a^{7/4}) - \right. \\ \left. - \frac{605}{Z^2} (E_k - 600) - \frac{1200}{A} \tilde{h} + E_a^{3/4} \right)^{1/3} dE_k + \\ + \frac{242Z^2 \rho(h)}{Q} \int_{E_{a\infty}^*}^{E_{600}} D(E) \left(211.88(E_k - 600) - \frac{423.75Z^2}{A} \tilde{h} + 600^{7/4} \right)^{-3/7} dE_k + \\ \left. + \frac{2Z^2 \rho(h)}{Q} \int_{E_{600}}^{\infty} D(E) dE_k \right.$$

Case 4.

The energy of the effective reflection threshold is greater than the 600 MeV boundary, as well as $E_{a\infty}^*$ and E_{600} : $600 < E_{a\infty}^* < E_{600} < E_{eff} < \infty$.

The rate of electron production due to the passage of charged cosmic rays is:

$$(37) \quad q(h) = \frac{\rho(h)}{Q} \int_{E_{eff}}^{\infty} D(E) \left(\frac{dE}{dh} \right)_2 dE_k = \frac{2Z^2 \rho(h)}{Q} \int_{E_{eff}}^{\infty} D(E) dE_k$$

With these four cases, the model for calculating the rate of free electron production due to the passage of charged cosmic rays is completed, using the double-integral approximation of the ionisation loss function based on the Bohr-Bethe-Bloch formula. Fig. 1 illustrates the double-integral approximations of the ionisation loss function in the case of ionising particles with charge $Z > 1$.

Conclusion

The results obtained have been applied to the calculation of ionisation profiles in the ionosphere, ionisation and electrical parameters in the atmosphere of the Earth, planets and their satellites [12–14], in the propagation of radio waves [4], in various geophysical events [15–21]. There are possible connections between ionisation by cosmic rays in the atmosphere and some climatic parameters.

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МОДЕЛЬ ИОНИЗАЦИИ CORIMIA – 2+1 ИНТЕРВАЛЬНОЕ ПРИБЛИЖЕНИЕ ДЛЯ ЯДЕР КОСМИЧЕСКИХ ЛУЧЕЙ ($Z > 1$)

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Аннотация

В данной статье рассматривается модель ионизации CORIMIA (Cosmic Ray Ionization Model for Ionosphere and Atmosphere) в ее двухинтервальном 2+1 приближении с интервалом убывания заряда функции ионизационных потерь. Увеличение числа интервалов аппроксимации является следующим шагом в совершенствовании модели. Заключительным этапом станет введение 5-интервального приближения формулы Бора-Бете-Блоха с интервалом убывания заряда. Эта версия включает введение пределов интегрирования в произвольном интервале энергии.

THERMODYNAMIC HYPOTHESIS IN COSMOLOGY

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Key words: cosmology; thermodynamics; time evolution

Abstract

SUMMARY: We summarise the principles of thermodynamics. We present a new way of describing time in physics – we consider time as a main manifold. We analyse its behaviour as a basic state in spacetime thermodynamics. We develop the cascading concept in the thermodynamic interpretation of the cosmological development of time and the spatial-temporal manifolds originating in it, considering them as new thermodynamic states.

We discuss how the behaviour of entropy as a leading parameter is reflected in the complicating evolutionary picture.

Introduction

There is no reason in the laws of physics that time moves only in one direction. Most processes and interactions are symmetrical in a time reversal. The only exceptions are the irreversible processes. They require a relaxation time until the previous state is restored. This is the reason, although in principle, both direct and reverse phenomena are permissible, they differ in the frequency with which they happen. In reality, reverse phenomena occur so rarely that we can postulate/to summarize, as time does not turn back and time has no closed curves anywhere. The relaxation time in practice requires an additional path until the exact event is restored. Therefore, one can never reach one's own past, only a neighbouring solution.

We will propose a thermodynamic interpretation that does not impose a cosmic caesura in the cosmology, but predicts/suggests a priority direction in the naturally universe/s development.

Thermodynamics (TD) considers the reversible and irreversible processes that occur as a result of the energy change – the exchange, the connections, and their transformation into other forms. At this time, the thermodynamics conceptually unites quantum and relativistic physics. They have contact points in the field of thermodynamics, and their mathematical physics manages, if not to unite them completely, but to adequately fit them together for an appropriate description of the natural processes and laws.

Formulations of the TD-principles for a temperatureless medium

1. *The Zero Principle – generalisation of the TD-Spacetime (TDST)*

If two thermodynamic systems are in a (energetic) equilibrium separately, with a third system, then they are also in equilibrium between them. All systems, which are in TD-equilibrium with each other, have the same energetic characteristics.

2. *The First Principle – generalisation of the TD-Spacetime*

The internal energy of a closed system is conserved.

The internal energy of an open system depends on additional factors, one of which is the number change of the subsystems.

3. *The Second Principle – generalisation of the TD-Spacetime*

The entropy of an isolated thermodynamic system can only increase or remain the same. Boltzmann gives a suitable summary: Nature moves from states of lower probability to states of higher probability.

4. *The Third Principle – generalisation of the TD-Spacetime*

The entropy of a system tends to a constant value when the system state tends to the (absolute) minimum energy level. The constant value is called the residual entropy of the system. It/Entropy relates to the number of possible eigenstates and may not be zero.

A more general form of the law exists for with more than one minimum energy level: Example – the universe onto instanton-tor has at least two absolute minimum energy levels!

The third law of thermodynamics applies only to equilibrium states.

Based on the second law, the minimum entropy can be determined only to within an arbitrary constant. The third law of thermodynamics allows the determination of the unknown constant, and thus the exact determination of the minimum entropy.

Central hypothesis

Postulate 1. *In a thermodynamic interpretation, we propose Time as a basic fundamental TD-state [1]. In such quality, the Time represents an active medium with its own energy and an unlimited number of dimensions, which has nonlocal properties and spontaneous flexibility, does not obey rotational symmetries (has no closed time curves anywhere and never), and can interact with the objects within itself, if any.*

1. *Time as a thermodynamic object. Dual nature*

Theoretical studies [2–4] and available observations indicate that the light speed constant undergoes centuries-long variation over cosmological epochs. If the

light speed varies, then time precedes the birth of our (and other) space-time manifolds, is older than the Universe, and will remain after it.

- Then Time can be considered as a background, but also as a basic (minimum) thermodynamic state – an analogue of absolute (true) vacuum*.

The time origin as a fundamental manifold without spatial dimensions is a purely theoretical problem of abstract mathematics. Therefore, we will refer to Gödel's First and Second Incompleteness Theorems, and we will accept that the mathematical fundamentals are unprovable and leave this question open. We will limit ourselves to a TD interpretation.

As a TD-object, Time can exist in two possible pure states, which belong as regions to the general manifold:

- Ordered time – the dimensions in these sections are orthogonal and linearly independent of each other; or

- Chaotic time where dimensions are randomly interwoven.

It is assumed that spatial manifolds arise only in the first type of time.

As a basic TD-state, time has a dual nature:

- ✓ it can be considered as a quantum environment with energetic info-structures without a causal relationship;

- ✓ but also as a continuous medium – an energy background, whose info-structures freely pass through each other, and information is rearranged in them without causing TD-recoil: $E \sim (*) \sim \text{information}$. Since info-structures are open systems, they can be shifted in different degrees, in different directions of Time, moving through each other without creating disturbances in the basic manifold.

The Time system is a two-sided open TD system: above to infinity, and below to indeterminacy – each finite interval of time can be divided into countless infinitely small intervals.

- In such an infinite-dimensional environment, any recoilless rearrangement of information in the main manifold can create a new timeline (it is not an arrow, has no cause-and-effect relationships), i.e., to release a new time dimension and thus increase its infinity. Each newly emerged dimension appears but cannot disappear. Because even if the timeline in question is erased, in the manifold, instructions remain (information/energy is not lost), how to restore it again (hidden dimensions).

2. Transition theory

As a basic state, time is in equilibrium. However, there is no reason to consider this equilibrium sustainable. Time is very flexible. Time dimensions are elastic, and most natural disturbances are smoothing out. However, there is a possibility that a given disturbance is effective enough to cause self-intersection in some time component. Then time transmutes – an instanton is born. This is a particular solution of a standing wave in time and represents a region of purely/only time dimensions covered with a spatial envelope (similar around the

black hole horizon/ergosphere [5, 6]). Spatial dimensions are plastic. Plastic deformation, unlike elastic deformation, is irreversible and leads to an irreversible phase transition. Thus, through a phase transition in the thermodynamics of space-time, a primary multiverse (local multiverse) arises – a new Universe.

- Every space-time system is bounded (or closed) below by the primary instanton radius R_{in0} . (The initial scale function of the manifold coincides with the time scale at the moment of closure (here $R_{in0} = 10^{-43} \text{ cm} \equiv t_{pl} \rightarrow 10^{-43} \text{ s}$). Subsequently, the lag/lead G-function [7] regulates centuries-long variation in the light speed. The G-function acts in such a way that no rupture occurs in the manifold.

- Local multiverses are self-contained systems that do not depend (have no causal relationships) but interact with the environment. Resemble quantum structures (particles in a vacuum) in time. Similar to the type I and type II populations of galaxies, which are interpenetrating systems, independent of each other, but they interact gravitationally.

Time does not obey rotational symmetries, and this is the reason for forming instantons upon self-intersection [8, 9]. In the sense of the TDST second principle, the probability of the transition of pure time into space-time is infinitely large since this is a transition from a state with zero entropy (absent) to increasing entropy, and the entropy gradient is always positive. The entropy from the self-intersection (the entanglement of freedom degrees [10–12]) can argue a basic mechanism for the emergence of space-time. The loss of symmetry in the Time-manifold leads to the emergence of classical connected space-times.

The time arrow direction in the manifold coincides with the direction of the outer instanton normal at each moment of the expansion.

Surface gravity is constant throughout the instanton at the moment of formation. This fact reflects the TDST Zero Law, which states that a system in equilibrium has uniformly distributed energy characteristics.

The formation of instanton(s) through an irreversible phase transition changes the configuration from the main state to a new TD-state in which the first entropies arise. When an instanton is born, the surface itself is an entropy, and its birth is an irreversible transition in the sense of the generalisation of the TDST Second Law.

3. Consequences

By analogy with the event horizon of black holes, an instanton is also formed, but here the environmental conditions create formation peculiarities. This is a different type of instanton that arose not by nonlinearity in the space-time fabric, but as a consequence of the transmutation of one type of dimension into another. By analogy with the elements synthesis – the transformation of pure time into space-time during the transition from the basic to the next TD-state, encapsulates the remainder of the "energy of transmutation" in the new structure.

Consequence 1: *The encapsulated energy has a small non-zero value: It represents the locked-in instanton shell (minimal rotational surface [13]) spatial fabric, which is essentially the dark matter [9] (DM) and corresponds to the minimal entropy at the moment of its closure. Unlike ordinary matter, DM does not obey rotational symmetries – DM-particles in the manifold walls do not have spin.*

Consequence 2: *As a consequence of the closure at about one [Planck] time, gravity separates, and dark energy (DE) arises as a primary thermodynamic recoil – the own dynamics of the manifold:*

- (1) $a = f(\Lambda)$,
- (2) $a = \text{const}(\Lambda)$, (Λ in our Universe); [8]

In [14], early dark energy is considered as a cosmological constant. Moreover, [15] suggests that the scalar field potential that drives inflation would act as a cosmological constant that decreases with time.

In our considerations, dark energy is a thermodynamic recoil, an inertia, a consequence of the emergence. It represents its own manifold dynamics and, as such, is assumed to be constant and corresponds to the cosmological constant in general, and not only at the beginning. DE is a very small constant, and therefore, in the early epochs, its action is negligible. In the following epochs, the particles' materialisation (birth-annihilation) releases spatial density and illuminates it in the manifold. The manifold surface tension weakens [16] and becomes more and more difficult to resist the emergence of inertia. Therefore, although the dark energy is constant, the expansion is accelerating (the Hubble constant undergoes a centuries-long variation). The agreement of the processes with what we observe (in our Universe) leads to the conclusion that the expansion is stable, $a_A = \text{const}$, and the expansion rate has a nearly parabolic growth function, with a very small correction in the degree, far beyond the decimal point.

When the instanton is formed, it has m -number of unfolded spatial dimensions, n -number of broken/compactified * and ∞ -number of time dimensions (inside and outside). In the local multiverse, the folding fractal is characteristic (Kaluza-Klein solutions [17]), and n is a finite number. The number of unfolded dimensions m ($= 3$ here) is constant, since they belong to the spatial envelope of the instanton formed in the transition.

Cascading construction of new TD-states

1. Primary and secondary manifolds

Primary manifolds arise through a phase transition in the TD-Space-time, when a time component self-intersects and breaks the symmetry in the main manifold. The born instantons (space-like manifolds) generate secondary manifolds in the process of their evolution.

A necessary condition for the emergence of a primary manifold is that it does not rotate, because time dimensions do not obey rotational symmetries, but this is not enough of a condition.

If a manifold tunnels to an absolute (true) vacuum, then it has no basic spatial state. This statement is a possible candidate for a sufficient condition for a given manifold to be primary.

Secondary manifolds are the result of a critical nonlinearity in some dimension in a primary manifold. Then a pole appears in the primary manifold, which is an embryo that forms an instanton [18]. A black hole (BH) is a formed pole in the space-time manifold.

When a Universe rotates, it is a sufficient condition to conclude that it belongs to a secondary manifold – a generated Universe.

2. Type of the manifold – Dynamic classification

According to whether and how the topology and spectra of the inner and outer derivatives change at a fixed point of the local manifold, the manifold and its structures can be classified into the following dynamical classes:

- Stationary manifold with static metric.
- A stationary manifold with a non-stationary metric is a contradiction. A non-stationary metric implies dynamics in some time dimension. In addition, even if it is external (oscillations of the horizon/surface of the instanton) to the manifold, there is no way that the spectres of the derivatives can remain unchanged to keep the manifold stationary.
- Dynamically flexible manifold with "static" topology and quasi-stationary metric * – soft Swiss cheese (here).
- Dynamic manifold with non-stationary metric – (the only basic manifold – Time).

3. The complexity Levels – structuring and self-organisation

Time – basic level – infinite-dimensional dual manifold without spatial dimensions.

I. Primary manifold – through a phase transition, by the transmutation of time into space-time, a local multiverse is born. Every dynamic manifold evolves and can stratify:

– The primary cleavage upon closure in rotationally mobile branches (universes families) is a Secondary TD-recoil of the second type; Parallel are those branches of the stratification whose external invariants do not change from point to point [19].

The branches are not connected spatially-continuously along the orthogonal timeline (may be tunnels between them, but they are rotationally mobile and not glued together), so there is no violation of the stability condition of the manifold for two or more time directions.

– Each branch is copied into specific realities -> quantum cloning in layer-alternatives (the Universes) – each primary branch is a kind of complex of subspace trestles with its own spectrum of bifurcation points.

II. Secondary manifolds – offshoots from the local multiverse – generated Universes.

III. Swarming – detachment from the Mother Universe.

4. The TD-recoils

The formation rearrangement and the secondary manifolds displacement lead to TD-recoil in the main/primary manifold:

Primary TD-recoil is long-lasting, in the multiverse's own lifetime ~ 1 Planck time, the instanton is born, and dark energy arises as a reaction to the closure of the instanton. The gravity separated.

Secondary TD-recoil of the first type is short-term. That is the inflation and the χ -boson appearance.

10^{-35} – 10^{-32} s – interrupts the cord with the mother universe and the wormhole closes; follows a secondary TD-recoil of the inflation. The strong interaction separated;

10^{-10} s – the χ -boson breaks away from the manifold walls, and the particles acquire mass. The last splitting in the force so far occurs: the weak and electromagnetic interactions separated.

Secondary TD-recoil of the second type is caused by internal-structural shifts in the local multiverse, such as:

The primary branches split upon closure, and

The rearrangement in the frequencies of a momentary reality*.

Entropy

In the sense of the II principle of the TDST, the transition probability from the main state to a state with non-zero to increasing entropy is always different from zero [1].

In the new state, each subsystem space-time bounded (or closed) below by the primary instanton radius. We will consider trees of space-time manifolds as individual quantum objects. Each has its own dynamic "arrow of time"*. The energy is grouped at another level through an irreversible transition – the new structures are discrete, and they lose the properties of a continuum.

The loss of symmetry in the basic manifold is an irreversible process. Irreversibility always reduces the amount of free energy. When an instanton is born, part of it is encapsulated in the new structure, and the “transmutation energy” will not be restored until the end of the local multiverse. An irreversible process that changes the configuration from the main state. The attenuation of the interaction in a particle system is an irreversible process. Entanglement is also a form of attenuation, i.e., irreversibility. The entropy of a self-intersection [8–9]

(the entanglement of freedom degrees [10–12]) is only a primary result in the thermodynamic evolution of time. The irreversibility of the processes in the next levels is mainly associated with two aspects:

In the local manifold, the emergence and displacement of the bifurcation points relative to their initial location, due to the mobility of the space-time fabric, is caused by the inherent dynamics (expansion) of a manifold.

Swarming from the universe's mothers leads to TD-recoil, but also expands the population of the main manifold with secondary manifolds. In an open system, such as time, which depends on the number of changes of its subsystems, this is essential due to the following important circumstances:

The secondary manifolds can rotate. Primary manifolds are rotationally mobile, but their momentum is zero because they arise from pure time, and time dimensions do not obey rotational symmetries;

Also possible for them to be born together, observing certain symmetries between each other, or

Too quickly die, if the primary TD recoil is so powerful, i.e., DE has too high a value and the expansion is exponential:

$$(3) \quad a = f(\Lambda) \neq \text{const},$$

Time as an open system should be able to self-structure itself in such a way that entropy decreases. This raises the question: how much the entropy increase in cascades is regulated by the number of short-lived local multiverses, whose demise restores some of the lost symmetries in the main manifold. Also, can the regions' chaotic time provide a buffer mechanism for regulating entropy in the orderly time regions?

Conclusions and Discussion

In conclusion, we will note that the TD-hypothesis does not impose any restrictions on m and n (except for being finite), the fractal shape, and its compactification radius in the local manifold. Therefore, in this way, the TDPV second principle guarantees the diversity of local multiverses, since the probability that the unfolded dimensions are the same number or are arranged in the same way $\rightarrow 0$! Moreover, the folding fractal in compactified volumes is different.

We will also note that it is extremely important to acquire the appropriate tools and measurable physical quantities that allow adequate testing of the theory.

Spectra bifurcation points related to the universe's fundamental constants. Types of symmetries are broken at bifurcation points. In different universes, they are broken in different ways.

Spectra Frequencies of a momentary reality could be cosmological sources of the gravitational waves included in the background cosmic noise. It has long

been theorised that it consists of individual signals that are too weak to be detected, but combined create a static background noise [20].

Information transferred through special points (regions) between the manifolds is preserved, but has no memory of the initial state and therefore does not impose a restriction on the initial conditions of the generated Universes. The irretrievable loss of information contradicts one of the basic postulates of quantum mechanics. According to the Schrödinger equation, physical systems that change in time cannot create or destroy information – a property known as unitary. However, the Laws are not violated because only the reflected information (Hawking radiation) has degraded, and the direct information to the daughter manifold has the potential to preserve its memory of the IC, albeit in an incomplete form (distorted/deformed, but in a precisely defined way – a modulation from whose signature additional concretisations about previous states can be extracted).

All of these tools are subjective, related to a local manifold, and can be predicted theoretically within the framework of the mathematics developed for the corresponding geometry of the local manifold.

The general mathematical framework of the basic manifold will require continuous adaptation in relation to the fact that time is the fourth type by the dynamic classification, and its geometry changes with the diversity of the subsystems arising in the gradation of the levels.

Appendix

(*) – Without spatial dimensions, there is no mass expression for the energy.

Absolute (true) vacuum – complete lack of space and spatial dimensions.

Compactified dimensions begin the transmutation (they are no longer time dimensions), but they fail to complete it. They remain enclosed within themselves (ordered structures in fractals) – the Kaluza-Klein solutions [<https://arxiv.org/pdf/hep-th/9906064>].

Dynamic time arrow – the arrow direction coincides with the direction of the instanton normal at each moment of the expansion.

Frequency of a momentary reality – the location, shape, and oscillations of the brane-alternative compared to the other structures in the local multiverse, at a particular moment in the expansion.

Quasi-stationary metric – the metric undergoes negligible changes, the accumulation of which leads to noticeable physical effects that can no longer be ignored.

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ТЕРМОДИНАМИЧНА ХИПОТЕЗА В КОСМОЛОГИЯТА

К. Янкова

Резюме

Обобщаваме принципите на термодинамиката. Представяме нов начин за описание на времето във физиката – разглеждаме времето като основно многообразие. Анализираме поведението му като основно състояние в пространствено-времевата термодинамика. Развиваме каскадната концепция в термодинамичната интерпретация на космологичното развитие на времето и произлизащите от него пространствено-времеви многообразия, разглеждайки ги като нови термодинамични състояния.

Обсъждаме как поведението на ентропията като водещ параметър се отразява в усложняващата се еволюционна картина.

QUASI-PERIODS IN THE LIGHT CURVE OF THE LBV STAR AF ANDROMEDAE REVEALED BY THE SEF METHOD

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Key words: *Time series; Periods; LBV stars; AF And*

Abstract

We analyse the B-band historical light curve of AF And (1918–19901) using our Structure Eminence Function (SEF) method. It extracts and characterises repetitive structures (patterns) responsible for quasi-periods (QPs) in time series. SEF is the dependence of structural eminence on the structure length. The positions of the SEF peaks indicate QPs. An advantage of the SEF method is its ability to represent the QP profile (the shape of the repetitive structure). The skewness of the profile may hint at the QP's nature, e.g., "obscure" or "flash". In this study, we describe and apply 4 variants of the SEF method. We emphasise 2 QPs at 3.90 and 4.55 yr (± 0.05 yr). The profile of QP at 4.55 yr poses positive skewness. Compared to Eta Car, where in our recent work we found two QPs, the SEF humps of AF And are about 1.5 times less prominent. For the present, we are unable to associate some of these QPs with the established periodic phenomenon of AF And. However, the similarity between pairs of QPS of Eta Car and AF And hints at the possible binarity of AF And.

Introduction

Recently, we analysed B- and V-band light curves (LCs) of the Galactic LBV Eta Carinae over the time interval 1823–2023 (Georgiev et al. 2025, G+25). Using our Structure Eminence Function (SEF) (Georgiev 2023, G23), we found two photometric quasi-periods (QPs). We also applied the periodogram methods CLEAN and Lomb-Scargle in a comparative framework. The well-prominent QP of 5.6–5.7 yr can be linked to the established orbital period of 5.54 yr. While the mass loss rate of this system is about $10^{-3} M_{\odot} \text{ yr}^{-1}$, such a notable increase in the orbital period over a century may be real. The less prominent QP of 4.9 yr may be explained somewhat with emissivity in the optical that originates in a large volume (G+25).

The LBV AF And belongs to the most luminous stars in M31. The mass of such a star is 50–120 $M_{\odot}$. Probably because of its dense stellar wind, its peculiar emission line spectrum is very similar to the spectrum of Eta Car. In the last century, AF And shows complicated variability in the B-band interval of 15.5–17.6 mag, as well as more than 10 outbursts. In the quiescent state, the absolute magnitude is

about -8.2 mag and the spectral class is Of or WR (Humphreys et al. 2014). Then the temperature is about 33 000 K and the mass loss rate is about $2.2 \times 10^{-4} M_{\odot} \text{ yr}^{-1}$ (Joshi 2019). During an outburst, the luminosity becomes about $10^5 L_{\odot}$. Gallagher et al. (1981) maintained that "the evolution of a massive star to its core helium-burning phase at AF And's position in an interarm region of M31 supports a binary interpretation". The radius of AF And as a single star is estimated to be $63 R_{\odot}$ (Szeifert et al. 1996).

Earlier, we began testing our SEF method on the historical LC of AF And (Georgiev et al. 2024, G+24). In this paper, we continue describing and applying the method. This text contains: 1. SEF method and its 4 variants; 2. QPs in the LC of AF And; 3. SEF profiles of QP structures; 4. Supplementary illustrations; 5. Summary. The abbreviations used are as follows:

AV – average value;	QP – quasi-period;
BP – beat period;	RLC – residual LC;
dp – data point number;	SD – standard deviation;
LC – light curve;	SEF – structure eminence function;
PE – power exponent;	TS – time step;
PGF – periodgraph function;	WS – window size of smoothing.

1. The SEF method in 4 variants

The SEF method (Fig. 1) reveals and characterises repetitive structures (patterns) responsible for LC QPs. SEF is a dependence of the eminence (amplitude) of the structure on the length of time of the structure. Any prominent repetitive structure causes the maximum SEF "SEF build"). Further, our Periodograph Function (PGF), a "derivative" of SEF, shows clearly the SEF structure. The PGF is an SEF after subtraction of the SEF background and normalization to this background (see "PGF build"). The PGF humps are a spectrum of the QPs, like the results of other periodogram methods.

Preparatory procedures ensure a dense and flat input LC for the SEF build (if needed). Aiming for dense enough LC, we may perform resampling of the original LC by linear interpolation with a suitable constant time step (TS) (Figs. 2a, 3a, 5a, 7a). The resampling procedure omits local noise peaks and produces a somewhat smoothed LC. We may also perform the completion of the original LC, adding interpolated data in the large LC gaps (Figs. 2b, 4a, 6a, 8a). This procedure keeps the noise peaks. The output of the resampling or completing procedure is the input LC for the detrending procedure (Fig. 1).

The SEF method requires **flat (detrend) LC**, i.e. LC with zero average value (AV). We may perform **local detrend** (removal of short-scale trend). The code smooths the LC "point-by-point" with a moving average. The code extracts the smoothed LC from the input LC and derives residual LC (RLC) (Figs. 3b–6b).

The smoothing window size (WS) is chosen to ensure good protrusion of the humps in the initial part of the PGF (see also Fig. 12). We may also perform **global detrend** (removal of long-scale trend). The code fits the LC by a low-degree polynomial, extracts the fit from the LC, and derives RLC (Figs. 7a, 8a). The RLC is characterised by zero AV and some standard deviation (SD). After local or global detrend, the result RLC is a flattened version of the LC, which is the input LC for SEF build (Fig. 1, Figs. 3c–8c).

SEF build is based on extracting and averaging RLC segments with length $L = L_{\min} \dots L_m$ and deriving their signal and noise profiles. The relevant SEF value is $E_L = A_L/D_L$, where A_L and D_L are suitable AV and SD characteristics of the signal and noise profiles.

Let's (t_i, z_i) , $i = 1 \dots N$ be a **uniformly sampled RLC**, dense and flat, with TS δt , zero AV, and relevant SD. For SEF¹, build our code to search for repetitive structures, checking RLC segments with length L data points (dp) or time length (QP) $tL = (L - 1) \times \delta t$, between $L_{\min}$ and $L_{\max}$, as follows. For every current L , the code pulls up the first L RLC data z_i , $i = 1 \dots L$, and puts them into an initially empty 1D set x_j with cell numbers $j = 1 \dots L$. Then, it adds over there the next L data z_i , $i = L + 1 \dots L + L$ from the RLC. Later, it adds the next L data, etc. The (integer) number of possible additions is $k = N/L$. In the end, for the current L , every cell x_j contains k adds and has relevant AVs a_j and SDs d_j . Further, the code continues with the next segment length L , etc. So, each structure with length L dp is described by signal profile a_j and noise profile d_j (see also Fig. 10a). For the SEFs in Figs. 3c–8c, we specify $L_{\min} = 20$ dp or $t_{\min} = 1$ yr with TS $\delta t = 0.05$ yr. For statistical significance of signal and noise profiles, we need at least $k = 3$ additions of segments for every L . Therefore, the code extracts and adds segments of maximum length $L = N/3$ dp. For example, the RLC in Fig. 5b has $N = 932$ dp. So, in Fig. 5c we use $L_{\max} = 310$ dp or $t_{\max} = 15.5$ yr. There, the segment with length 20 dp (1 yr) contains $k = 932/20 = 46$ additions.

Now, let (t_i, z) , $i = 1 \dots N$ be an **arbitrary sampled RLC**, dense and flat, with zero AV and relevant SD. In the previous case, we used a 1D set x_j with L cells to accumulate uniformly sampled RLS segments. Now, a 2D area (x_j, y_j) with N cells is necessary for collecting arbitrary sampled RC segments with their values and times. The code checks the system of time segments $t_i = t_{\min} \dots t_{\max}$ with a step of increasing δt . Similarly to the previous case, we supply $t_{\min} = 1$ yr and $\delta t = 0.05$ yr. Again, for at least $k = 3$ additions, the code uses $t_{\max} = t_{RLC}/3$. For the extraction of segments, the code derives the left bounds of the k -th positions of the current segment with length t_L in the RLC, $b_k = t_{\min} + (k - 1) \delta t$. Then, for every t_L , the code pulls up the available n_1 RLC data starting with the time length t_L and places them in an empty 2D set at $x_i = t_i - b_1$, $y_i = z_i$, $i = 1 \dots n_1$, with cell numbers $j = 1 \dots n_1$. After that, it transfers the next n_2 data from the second RLC position of the segment to the 2D area: $x_{n_1 + 1} = t_i - b_2$, $y_i = z_i$, $i = n_1 \dots n_1 + n_2$, etc. For every t_L , the data in the 2D area has to be sorted by time x_{thtt} . The sorted data covers a segment

with length t_L , and there is a "raw profile" of the structure with length t_L . Later, the raw profile is smoothed by a moving average with TS 0.1 yr and WS 0.4 yr. (Applying TS of 0.05 yr and WS 0.2 yr is not applicable here because of the low density of the available completed RLC). The result is the signal profile a_j and the noise profile d_j . Further, the code checks the next segment, with length t_{L+1} , etc. As in the case with resampling, every structure with time length t_L is described by a signal profile a_j and a noise profile d_j (see also Figs. 10b, 10c).

Later, in both RLC cases, for every L or t_L , the code derives average signal $A_L = \langle |a_j| \rangle_L$ and average noise $D_L = \langle d_j \rangle_L$. Note that A_L gathers absolute values $|a_j|$, i. e. A_L is a one-sided average signal of the structure. Every prominent repetitive structure in the RLC produces a local maximum in the signal function A and a local minimum in the noise function D (G23). Therefore, we ought to define the **dimensionless SEF** (Figs. 3c–8c) as follows: $E_L = A_L/D_L$ or $E(t) = A(t)/D(t)$. In this study, the division by D "increases" the signal by about 3.8 times (Fig. 9a).

PGF build is a transformation of the SEF by background removal, aiming to better reveal the QPs. We consider the SEF background to be the curve that encloses 90% of the SEF data points from below. Generally, the SEF fit E_F (Figs. 3c–8c, dashed curves) is a power function and a linear function on the log-log scale. Therefore, the background is easily derived by shifting the relevant SEF straight line downward. Later, after transformation back into the linear scale, the SEF background straight line becomes a power function E_B (Figs. 3–8c, solid curves), with the same power exponent. So, we define the **dimensionless PGF** using the SEF values E and SEF background E_B as follows: $G_L = (E - E_B)/E_B$ or $G(t) = (E(t) - E(t)_B)/E(t)_B$. The PGF value characterises the relative height of the SEF value above the SEF background. Each PGF value represents a form of signal-to-noise ratio.

Basic QP p may be suspected among QPs by (i) a high peak in the initial part of the PGF and (ii) the presence of its large counterparts $2p$, $3p$, etc. But, in this study, we find 3 prominent QPs (Figs. 3c–8c, 3d–8d). In Figs. 3c, 4c large counterparts are visible up to $8p$. In the cases of RLC with high resolution and low noise, short counterparts $p/2$, $p/3$, etc. may be seen (in G23 – up to $p/7$). The protruding of default short counterparts is especially modelled in G23. Furthermore, (iii) the profile (shape) a_j of the basic QP is single, i.e., it contains one minimum and one maximum. Such are also the profiles of $p/2$, etc., but they are faint (G23). However, the profiles of the large counterparts are double, triple, etc. (G23, G+25; bottom panels in Figs. 3–8). Finally, (iv) the basic QP may be recognised as a real period if its physical reason is clear. Unfortunately, in this study, we don't have such a true period.

Note that in the SEF build, the number of segment additions k is an integer and a part of the RLC, near its end, becomes unusable. To suppress this effect, we build SEF, QP profiles, and PGF twice, by direct and reverse processes of the RLC. The average profiles and PGFs results are always regarded (Fig. 11).

Fig. 1 presents a schematic overview of 4 variants (v1–v4) of the SEF method. The variants are arranged in vertical succession, as follows.

v1 includes (i) resampling of the original LC with a constant time step, (ii) local detrending by moving AV with a suitable WS, and (iii) SEF^I build.

v2 includes (i) filling the gaps in the original LC to achieve suitable data density, (ii) local detrending as in V1, and (iii) SEF^{II} build.

v3 includes (i) resampling as in v1, (ii) global detrend by smoothing the resampled LC using a low-degree polynomial, and (iii) SEF^I build.

v4 includes (i) filling the gaps as in v2, (ii) global detrending of the completed LC as in v3, and (iii) SEF^{II} build.

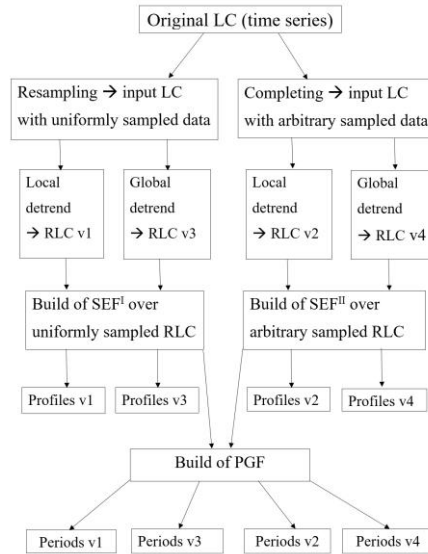


Fig. 1. Scheme of the procedures in the SEF 4 versions. See the text.

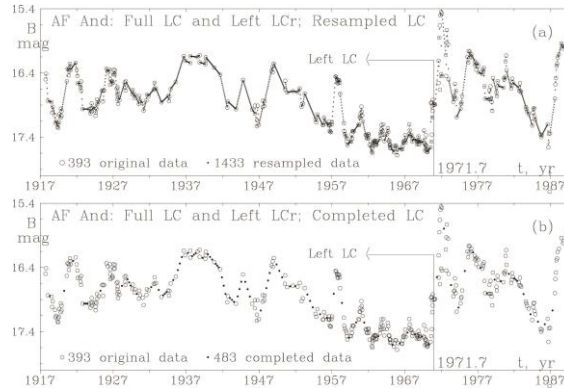


Fig. 2. Historical LC of AF And with resampled (a) or completed (b) version. See the text.

2. QPs in the LC of AF And

Fig. 2 shows the *B*-band LC (1917.7–1989.4; 71.7 yr), collected by Gantchev et al. (2017). The original LC (circles) contains 393 dp with an AV TS of 0.183 yr and a maximal data gap of 1.52 yr. In Fig. 2a, the original LC is resampled by linear interpolation with a TS of 0.05 yr. The result LC contains 1433 dp (dots only). In Fig. 2b, large gaps in the original LC are filled with interpolated data. The result LC contains 483 dp (circles and dots). The AV TS is 0.15 yr, and the maximal gap width is 0.4 yr. Further, the "Full LC" is analysed in Fig. 3, Fig. 4, while the "Left LC", 54 yr long, before the eruptions in 1971–1973, is analysed in Figs. 5–8. The rRight part of the full LC is too short for separate SEF analysis.

Figs. 3a–8a show by dots (1) the input LCs, resampled or completed from the original LC. Their parameters are time episode T , number of data N , AV and SD in magnitudes, as well as TS or average TS ($\langle TS \rangle$). The dashed lines show the levels of AV and $AV \pm SD$. The dots of the curves (2) are the smoothed input LC according to the applied SEF variant, v1–v4.

Figs. 3b–8b show the RLC, derived as the difference between the input LC and its smoothed version. Note that for convenience, when the brightness increases, the RLC value must also increase. Therefore, working with input and smoothed LCs in magnitudes, B_I and B_S , respectively, we use everywhere the RLC with opposite sign: $\Delta B(t) = -[B_I(t) - B_S(t)]$. The RLC parameters, as in panel (a), are N , SD, and time episode. The dashed lines show the zero level and zero $\pm$ SD. In Figs. 3b–6b, the local smoothing WS is shown by a bar. The choice of WS of 6.45 yr or 129 dp is illustrated in Fig. 12. Due to the local smoothing, the edges of the input LC, each of length WS/2, are lost, and the episode is shorter. In Figs. 7b, 8b, after global smoothing (by a second-degree polynomial), the entire length of the input LC is used. Due to the smoothing effect of resampling, the SD of the RLC (Figs. 3b, 5b, 7b) is about 0.03 mag lower than that of the completed RLC (Figs. 4b, 6b, 8b).

Figs. 3c–8c show SEF^I derived from uniformly sampled RLC (Figs. 3c, 5c, 7c) or SEF^{II} derived from arbitrarily sampled RLC (Figs. 4c, 6c, 8c). The curves E_F and E_B represent the power fit models of the SEF and SEF background. Power exponent (PE) is implemented. The suspected exemplary basic QP is $p = 3.9$ yr. Its large counterparts, 2p, 3p, etc., are visible up to 8p in Figs. 3c, 4c, and. up to 4p in Figs. 5c–8c. The SEFs begin from $\{t_{\min} = 1 \text{ yr or } L_{\min}\} = 20 \text{ dp}$ and ends at $t_{\max} = t_{RLC}/k$, where k is the number of the segment added to the AV profile; here, $k_{\min} = 3$. In Figs. 5c, 6c, the SEF length is 15.5 yr, and in Figs. 7c, 8c, it is 17.5 yr, respectively. Especially in Figs. 3c, 4c, for $k_{\min} = 2$, the SEF $t_{\max}$ is 27.5 yr. The reason is searching for beat periods (see below). The SEF increase F is due to covering stronger LC variations. The PEs' values, 0.8–1.0, show that here the SEFs are slightly convex.

Figs. 3d–8d show the initial parts of the PGFs $G(t)$, derived from the relevant SEFs. The hump resolution of the SEF method may be estimated by the half-width at half of the hump maximum. Here, for a QP of 3.9 yr, it is about 4 dp or 0.2 yr. The relative hump resolution is about 5% of the QP value, as in G+24 and G+25.

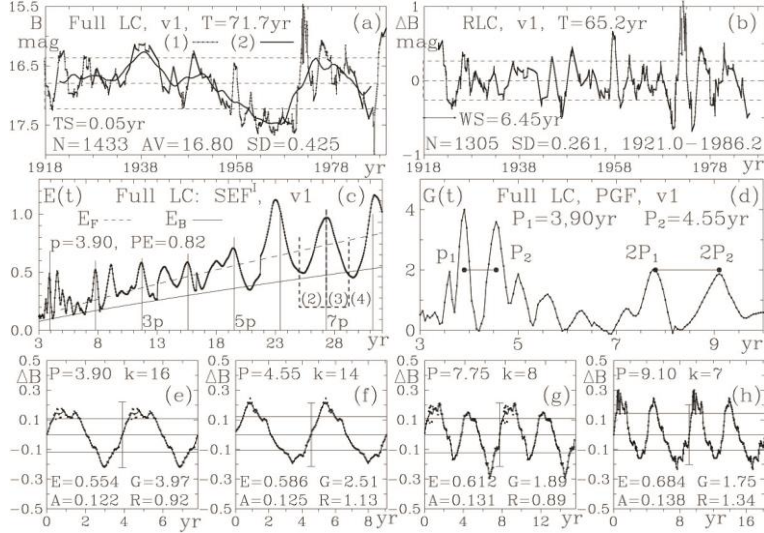


Fig. 3. SEF v1 analysis of Full LC. See the text.

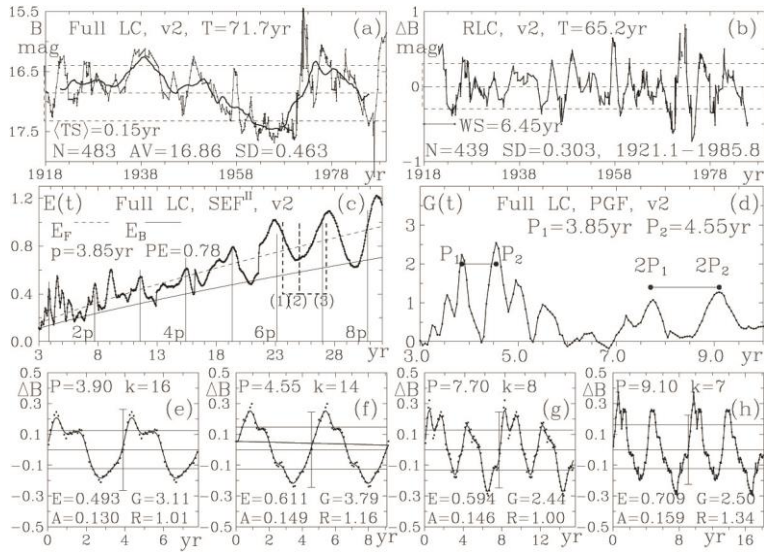


Fig. 4. SEF v2 analysis of Full LC. See the text.

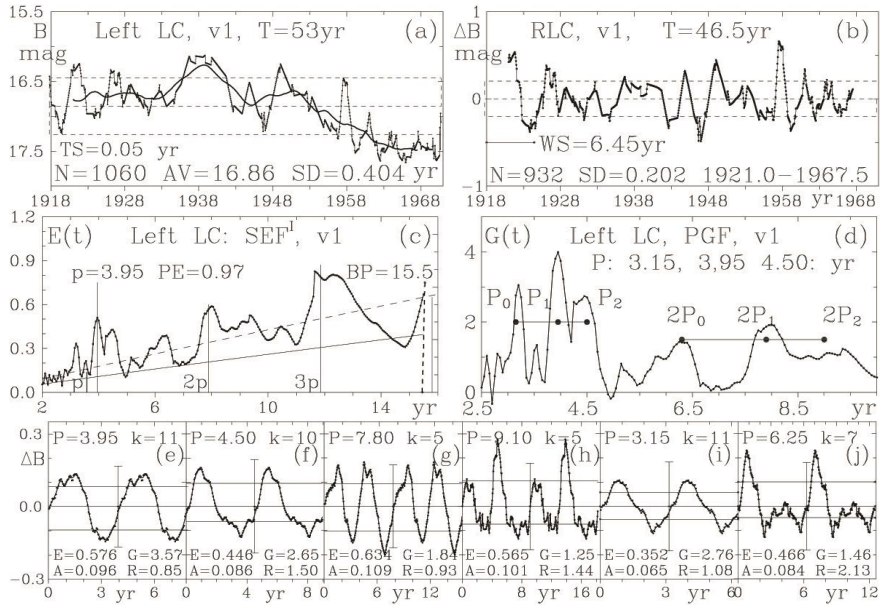


Fig. 5. SEF v1 analysis of Left LC. See the text.

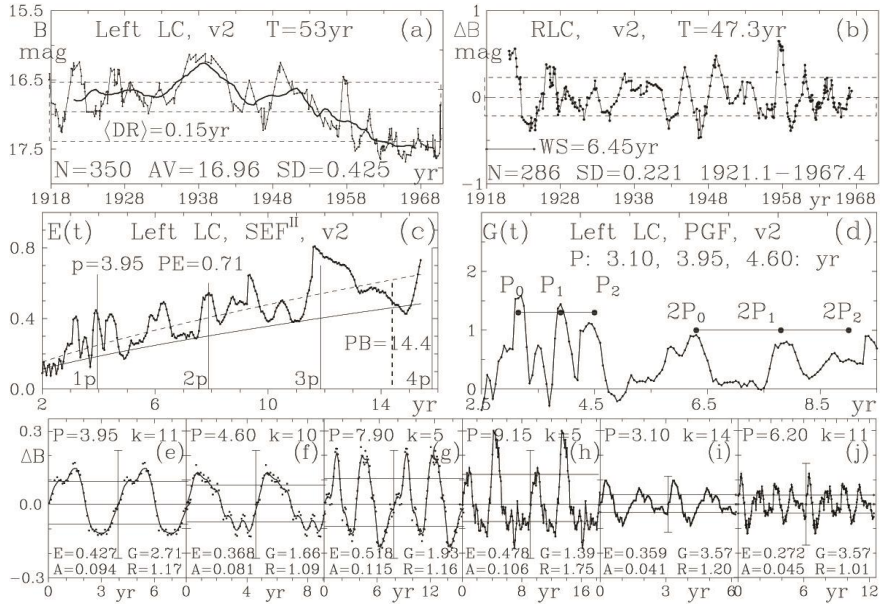


Fig. 6. SEF v2 analysis of Left LC. See the text.

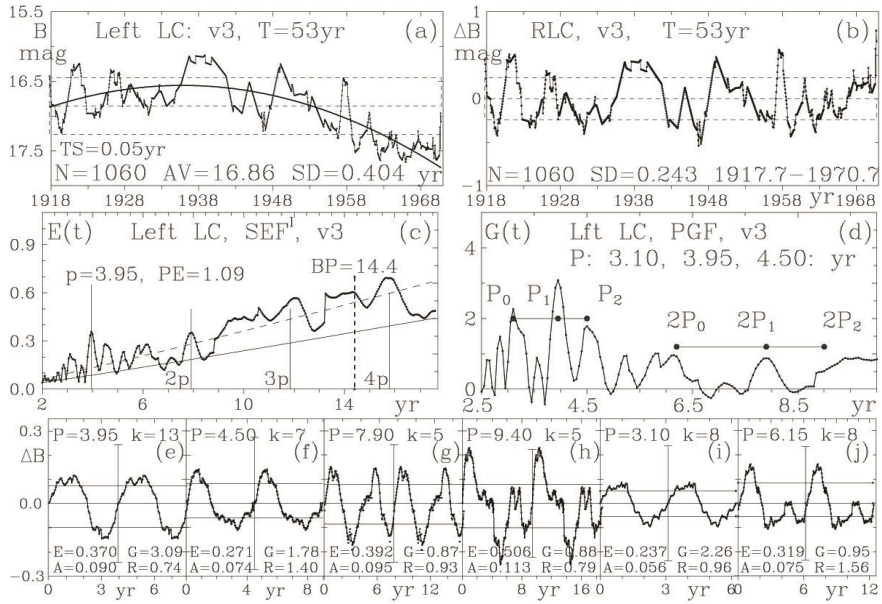


Fig. 7. SEF v3 analysis of Left LC. See the text.

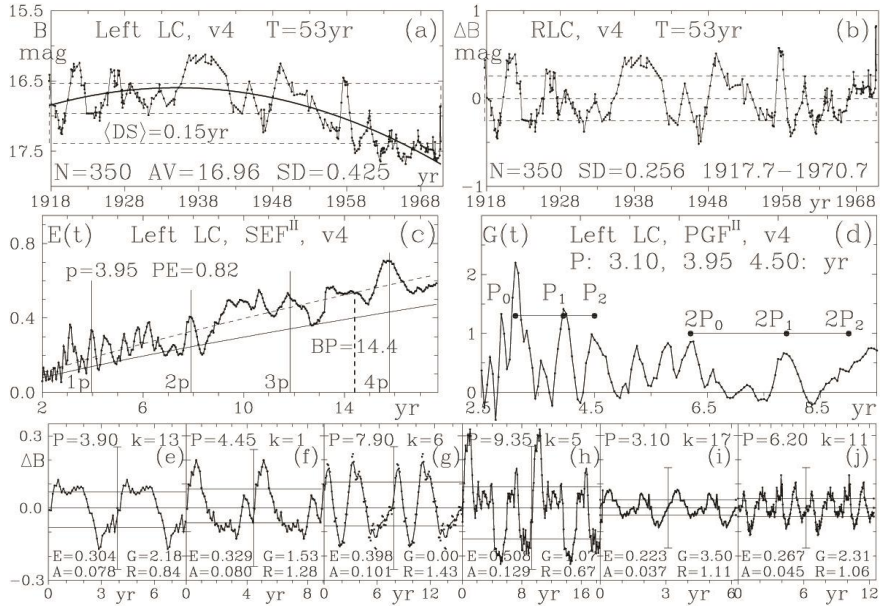


Fig. 8. SEF v4 analysis of Left LC. See the text.

In Figs. 3d–8d, the widths of the PGF humps of the large counterparts $2p$ are twice as large, but the relative hump width is again about 5%. However, the QP resolution is higher than the hump resolution. In Figs. 3d–8d, the prominent QPs are marked with dots. The QP value, measured by peak position or by the centre of the hump, varies within ± 1 dp or ± 0.05 yr. So, the QP error is 0.05 yr.

In Figs. 3d–8d, we reveal **3 prominent QPs**. The QPs at $P_1 = 3.90$ yr and $P_2 = 4.55$ yr are present everywhere. similar to the QP pair of Eta Car (4.9 and 5.6–5.7 yr) (G+25). Here, the QP 4.55 yr profile poses positive skewness, similar to the QP of 5.6–5.7 yr of Eta Car. AF And is known as a single LBV star, but the found QPs hint that it may be a binary LBV, as maintained by Gallagher et al. (1981). The orbital period should be about 4.5 yr. The QP at $P_0 = 3.10$ yr is absent in the Full LC (Figs. 3d–6d) but is clearly visible in the Left LC (Figs. 7d, 8d). We found additionally that the QP P_0 is variable and strongly prominent in 1940–1960 yr. For the present, the origin of the prominent QPs in AF And is unknown.

Two prominent QPs must have "**beat QPs**". The beat period (BP) p_b from two periods p_1 and p_2 follows the formula $1/p_b = 1/p_1 - 1/p_2$ ($p_1 < p_2$). In Figs. 3c, 4c, the possible BPs are marked by triads of dashed vertical lines, (1), (2), (3). Four possibilities for p_1 , p_2 , and p_0 are considered. (1): 3.85, 4.60, 23.6; (2): 3.85, 4.55, 25.0; (3): 3.9, 4.55, 27.3; (4): 3.9, 4.5, 29.2. According to the QP values of P_1 and P_2 in Figs. 3d, 4d, the realistic cases are (3) and (2). So, the BPs, marked by the middle vertical lines, are 27.3 yr in Fig. 3c and 25.0 yr in Fig. 4c. The first BP coincides with $7P_1$. The second has a separate hump, but its prominence is weak. In Figs. 5c–8c, the BPs for the QPs P_0 and P_1 are marked by vertical dashed lines. They are close to the large counterparts $4P_1$. So, the beat periods are not remarkable.

3. SEF profiles of QP structures

Figs. 3(e–j)–8(e–j) show QP profiles, i. e., profiles of SEF structures, corresponding to the SEF peak values. For the visualisation, they are drawn twice. The profile may provide a hint about its reason, e.g., "obscure" or "flash". In spite of the nosed LC, different SEF variants produce similar profiles. The bottom panels in Figs. 3–8 show profiles a_j (here as ΔB) and their parameters. The dots represent raw profiles, and the curves show profiles that are smoothed through the AV of 5 neighbour points. P is the QP, i.e., the peak position in the PGF. k is the number of segments added for the profile. E and G are the peak values of SEF and PGF of the presented QP. A is the "one-side" AV of the profile a_j . The vertical bar represents the AV SEF noise D of the profile. The ratio $R = A_1/|A_2|$, where A_1 and A_2 are AVs of the positive and negative parts of the profile, characterises the vertical asymmetry of the profile a_j . Positive R shows that the profile maximum (sometimes high and narrow) is more prominent than the profile minimum (sometimes shallow and wide) (see Figs. 3f–8f). Horizontal lines correspond to the A_1 , zero, and A_2 levels.

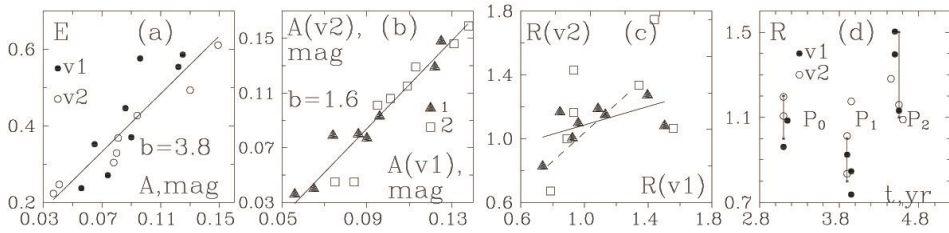


Fig. 9. Juxtaposition of profile parameters. See the text.

Fig. 9 juxtaposes parameters of QP profiles. The relevant linear fits with slope coefficients b are shown. In Figs. 9a, 9d, only data about the basic QPs (P_0 , P_1 , P_2), 8 dp from v1 (after resampling) and 8 dp from v2 (after completion) are used. In Fig. 9a, SEF values E are about 3.8 times higher than the average signal A . The reason is the division of the average signal A by the average noise D . In Fig. 9d, typical values of the ratio R for the QPs P_0 , P_1 , and P_2 are about 1.1, 1.0, and 1.3, respectively. The vertical asymmetries in these profiles differ slightly. In Fig. 9b, the ratio of signals $A(v2)/A(v1)$ for the basic QPs (1) and for $2p$ counterparts (2) is about 1.6. The reason is that the resampling procedure in SEF v1 omits noise peaks and produces a slightly smoothed LC. In Fig. 9c, the ratios of the vertical asymmetry $R(v2)$ and $R(v1)$ for basic QPs (1) correlate faintly. Simultaneously, these ratios for $2p$ counterparts show no correlation. The reason is probably the physical and photometrical noise in the LC.

In this study, the P_2 profiles show positive skewness (Figs. 3f–8f). Similar positive skewness poses wholly different phenomena: LCs of RR Lyr, Delta Cep, and Mira Ceti, even the sale of the solar Wolf cycle. Therefore, we can speculate that P_2 is a display of some flashing, while P_1 may be a display of obscuration. Similar suspects hint at the QPs of Eta Car, P_1 , and P_2 , respectively (G+25). Note also that the shapes of the odd and even components of the pairs of periods of $2p$ QPs (Figs. 3gh, 4gh, 5ghj–8ghj) are somewhat different. Such particularities of $2p$ are present in G+25. The reasons may be the noise in the LC.

4. Supplementary illustrations

Fig. 10 shows by large dots signal profiles a_j and by error bars noise profiles d_j . There p , A and D are the QP and AVs of the signal and noise, respectively. Small dots represent the used pair of raw profiles – from direct and reverse RLC processing (for 2 SEFs build). In (a), the small dots fall just on the positions of the resampled input LC. In (b) and (c), the small dot points have arbitrary positions, where the profile sampling causes additional profile smoothing. Depending on the beginning of the input LC, the pair of profiles has an arbitrary phase shift. The profiles in the bottom panels of Figs. 3–8 averaged (after phase shift) and drawn twice.

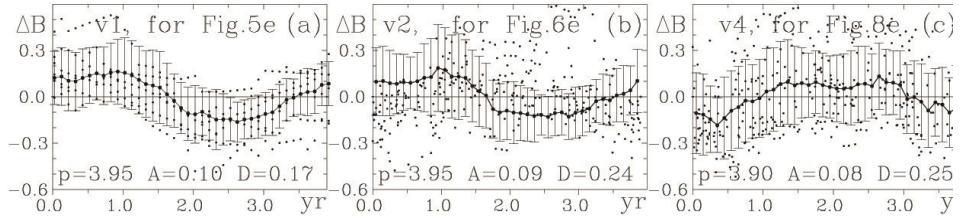


Fig. 10. Basic types of SEF profiles, corresponding to the SEF versions v1 (a), v3 (b), and v4 (c). See the text.

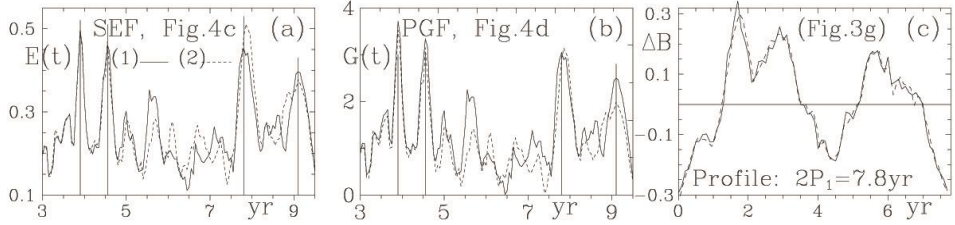


Fig. 11. Results from direct (1) or reverse (2) processing of RLCs: (a) – SEFs; (b) – PGFs; (c) – profiles. See the text.

Fig. 11 juxtaposes the PGFs from direct ((1), solid curves) or reverse ((2), dashed curves) processing of RLC. The differences between the curves are small. In all cases, the average SEFs, PGFs, and profiles are used, though.

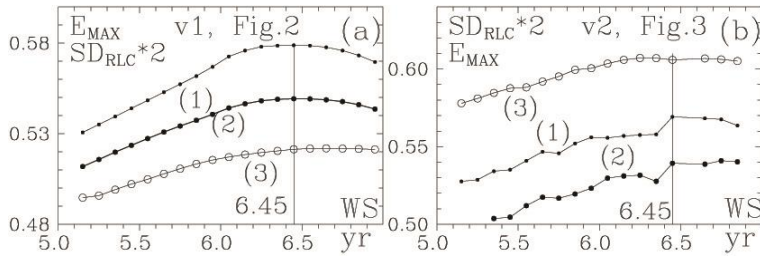


Fig. 12. Choice of optimal detrending WS = 6.45 yr for resampled (a) and completed (b) input LCs. See the text.

Fig. 12 shows the choice of WS according to the height of the PGF peak P_2 (1), AV of the three neighbouring points of the peak (2), and SD of the RLC after resampling (3) (v1, a) or completion (v2, b). The chosen WS of 6.45 yr corresponds to the beginning of the plateau of RLC SD (3).

5. Summary

We described and applied 4 variants of our SEF method for revealing quasi-periods in LCs. The method includes preliminary resampling or completing of the LC (if needed), as well as local or global flattening of the LC. Completing and global flattening seem preferable. The results are very close.

In the full LC of AF And we found a QP pair of 3.90 and 4.55 yr, similar to the QP pair of Eta Car (4.9 and 5.6–5.7 yr) (G+25). Here, the QP 4.55 yr profile poses positive skewness, similar to the QP of 5.6–5.7 yr of Eta Car. AF And is known as a single LBV star, but the found QPs hint that it may be a binary LBV, as maintained by Gallagher et al. (1981). The orbital period should be about 4.5 yr.

In the LC before 1972, we found a QP of 3.10 yr, strongly pronounced in 1940–1960. The QP of 3.1 yr seems unexplainable.

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КВАЗИ-ПЕРИОДИ В КРИВАТА НА БЛЯСЪКА НА LBV ЗВЕЗДАТА AF ANDROMEDAE ИЗЯВЕНИ ЧРЕЗ МЕТОДА SEF

Ц. Георгиев, П. Недялков

Резюме

Ние анализираме историческа В-крива на блясъка на AF And (1918–1990) тествайки нашия метод на функцията на структурна изявеност (ФСИ, Structure Eminence Function, SEF). Методът извлича и характеризира повтарящи се структури (патерни), отговорни за квази-периоди (КПи) в редове от данни. ФСИ е зависимостта на размаха (амплитудата) на структурата от дължината на структурата. Позициите на максимумите на ФСИ индикират КПи. Предимство на метода е, че той представя профила на КП (формата на повтарящата се структура). Асиметрията на профила може да подсказва природата на КП, напр. “затъмняване” или “просветване”. В това изследване ние описваме и прилагаме 4 варианта на метода. Ние изтъкваме 2 КПи, от 3.90 и 4.55 год (± 0.05 год). Профилът на КП от 4.55 год има положителна асиметрия. В сравнение с Eta Car, у която в наша скорошна работа намерихме 2 видни КПи, максимумите на ФСИ у AF And са около 1.5 пъти по ниски. За сега ние не можем да свържем някой намерените КПи с установено периодично явление у AF And. Обаче, подобие на двойките КПи на Eta и Car AF And подсказва, че е възможно AF And е двойна система.

PREDICTION VERIFICATION OF SOLAR CYCLE 25 BASED ON THE PRECURSOR METHODS

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Key words: 11-year solar cycle, Prediction, Precursor, Extrapolation

Abstract

Prediction of the level of solar activity is vital for all space programs, planning of space missions, weather variability, and climatic changes. Various approaches are used to predict the forthcoming solar cycle. In this paper, spotless days (SLDs) around the preceding minimum and the geomagnetic index aamin are used as precursors to re-predict the maximum of the 25th cycle from observed data sets. This method shows results that are quite acceptable, which gives the maximum amplitude of solar cycle 25 using SLDs to be equal to $R_{25SLD} = 108.58$ and the time of rise $T_{25SLD} = 4.2$ years. Using aamin, $R_{25aamin} = 111.6$ and $T_{25aamin} = 3.98 \sim 4$ years. Finally, the predicted maximum for the upcoming cycle 26th is found to be $R_{26SLD} = 96.6$.

Introduction

The periodic variations of solar activity cycles are considered a puzzle in solar physics, since we are far from understanding all processes of the solar dynamo. Deliberating on solar activity is a very important part of solar physics because of its significant impact on Earth's technological systems, which induces both violent short-term space weather and gradual long-term climatic changes. This emphasis is motivated by the present surge of interest in precisely this area, prompted by an unusually long and deep solar minimum and by sharply conflicting forecasts for the maximum of the incipient cycle. Solar cycle prediction is an extremely extensive topic of research, covering a wide variety of mathematical and physical forecasting schemes that are designed to improve the forecast [1, 2] and references therein. Many attempts have already been made in the past to predict the future strength of upcoming cycles, [3] traditionally based on forecasting physical models, e.g., Precursor, which include polar magnetic field, geomagnetic indices, and spotless days SLDs, and statistical forecasting, e.g., auto regression moving average [4, 5]. It should be noted that regression techniques, which provide short-term exploration, suffer from low performance during the transition from one cycle to another. An

extrapolation model without considering the prediction starting point was utilised by [6]. Nevertheless, some extrapolation methods may still be worth future study. Model-based forecasts are quickly coming into their own, and despite not having long proven records, their predictions are accepted with increasing confidence by the community [7]. Geomagnetic variations during solar minima are caused by the solar polar field in connection with the solar open flux [8]. According to dynamo theory, the measurement of the Sun's axial dipole gives more accurate results than the polar field for the forecasting needed to carry out the prediction of the previous cycles [9]. The polar field precursor yielded predictions in the right range during the past few solar cycles [7]. The historical measurements of geomagnetic records are used for driving the interplanetary field [10, 11]. This makes aa-index such a good predictor for the amplitude of the following cycle. Kane [12], Brown [13], Wilson [14], and Leighton [15] have used this aspect for decades. Precursor indices give an estimate of the amplitude of the next cycle one or two years before the previous cycle has ended [16]. However, the geomagnetic aa index at its minimum is a good predictor for the amplitude of the following cycle. The spotless days (SLDs) are noted along different phases of solar cycles, including the maximum phase. The highest number of SLDs has been used to define the minimum phase and the count of the events around the preceding minimum for forecasting the strength of the forthcoming solar cycle [17–19]. So, precursor method forecasting is the leading indicator of solar activity through solar minimum and is the most common category of prediction. It is already superior to extrapolation methods.

In this paper, we discuss verification of our early prediction of cycle 25th using the observed geomagnetic indices aamin and SLDs around the preceding minimum (deep minimum) of the 25th solar cycle as a precursor to re-predict the maximum level of the present cycle 25. Also, using the spotless events (SLDs_s) around the preceding minimum to predict the upcoming cycle on the 26th.

Source of data sets

Here we consider two precursors – solar variables, which are: the observed spotless days (SLDs) over two years around the preceding minimum (deep minimum) between two consecutive cycles. The source of data comes from the website: www.sidc.be/silso/datafiles

Secondly, the geomagnetic variable aa-index at minimum is taken from the website: www.geomg.bgs.ac.uk/data_service/data/magnetic_indices/aaindex [last accessed 19 July 2026].

Analysis and Results

In the present work, we are only concerned with the issue of re-predicting the amplitude of early forecasting of solar cycle 25th [12] using two indices of sun activities: spotless days SLDs and aa index as precursors.

Prediction according to spotless days SLDs:

We first used the least squares method to find the empirical equation for the ratio R_M/R_m against S_{om}/S_{omn} :

$$(1) \quad \ln\left(\frac{R_M}{R_m}\right) = a + b\left(\frac{S_{om}}{S_{omn}}\right)$$

The correlation coefficient of the above relation is $cc = 0.65$

Where cc is the correlation coefficient, R_M and R_m are the maximum and minimum Wolf numbers of solar cycles, S_{om} is the count of SLDs at about two years around the preceding minimum, and S_{omn} is the count around the upcoming solar cycle under test.

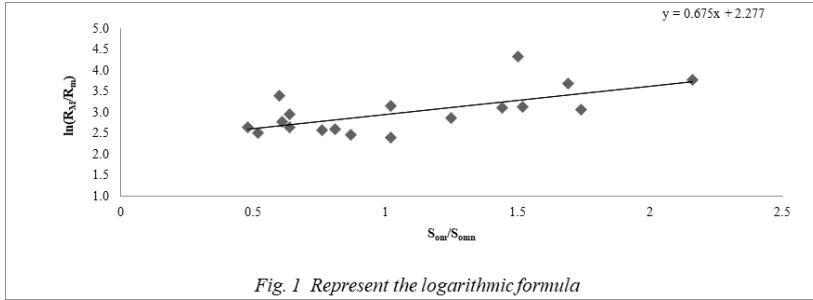


Fig. 1. Depicts visually Eq. (1) for solar cycles 7–24

Evaluation of the peak of the 25th cycle, depending on the observed SLDs, can be given by Eq. (2)

$$(2) \quad R_{25\text{ Somnt}} = 182.7 - 0.174S_{omn} = 108.6$$

Where S_{omnt} is the total predicted spotless days near the minimum, and the correlation coefficient $cc=0.68$

The corresponding time of rise Tr

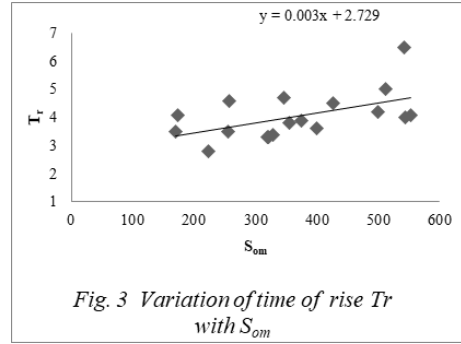
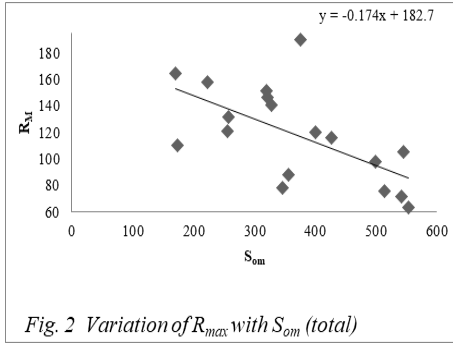
$$(3) \quad T_{25\text{ Somnt}} = 2.729 + 0.003S_{omn} = 4.3 \text{ years}$$

Fig. 2 and Fig. 3 are the linear regression relationships on implicit information.

For an odd cycle 7–23

Prediction of the strength of odd cycles between cycles 7–23 gives:

$$R_{25\text{ odd}} = 114.99 \text{ and } T_{25\text{ odd}} = 4.27 \text{ years}$$



Predictions according to aa_{min} index

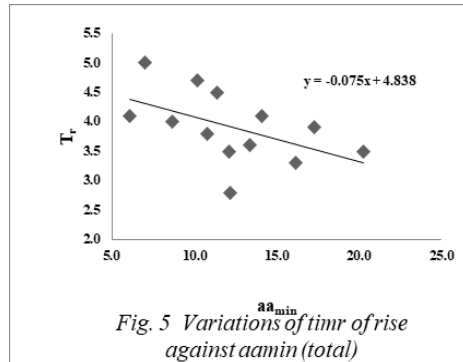
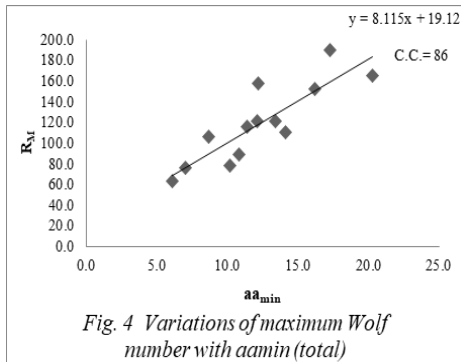
The observed aa -index data is available from cycle 12 onward. Our forecasts were dedicated to the estimation of the strength and timing for both total and odd cycles, written as:

For total cycles 12–24:

- (4) $R_{25aat} = 19.12 + 8.115 \times 11.4 = 111.6$ where $cc = 0.86$
- (5) $T_{25aat} = 4.838 - 0.075 \times 11.4 = 4.25$ years

Fig. 4 exhibits linear fit variations of maximum Wolf number as a function of aa_{min} .

Fig. 5 is the relation between the total time of rise T_{25} and aa_{min}



For odd cycles 13-23

Also, the results between aa_{minodd} and both $R_{max25odd}$ and $T_{25aaodd}$ are given by:

$$R_{25aaodd} = 99.5 \quad T_{25aaodd} = 4.1 \text{ Years}$$

The results show that cycle 25 will reach its maximum in late 2024.

An early prediction of the upcoming 26th solar cycle

We employ the modern era of sunspot cycles starting from cycle 10 onward to forecast cycle 26 using the empirical formula of Eq. (1) as follows:

$$(6) \quad \ln\left(\frac{R_M}{R_m}\right) = 2.380 + 0.611\left(\frac{S_{omn}}{S_{omn+1}}\right) \quad \text{where } cc = 0.63$$

Fig. 6 exhibits this relation.

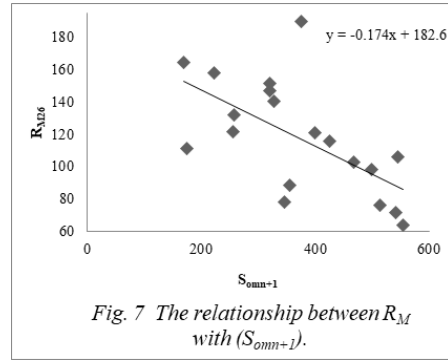
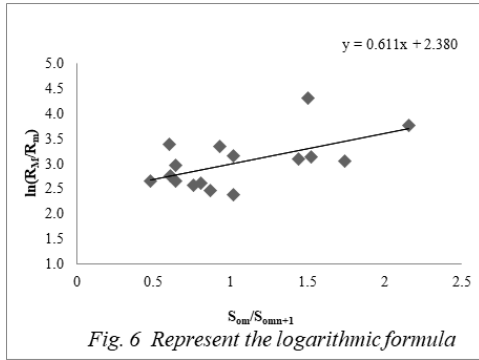
However, we get:

$$(7) \quad R_{26t} = 177.60 - 0.160 \times 457 = 96.6 \quad \text{where } cc = 0.60$$

We notice that cycle 26 will attain less strength than the previous cycles.

Our results are comparable with NOAA and NASA (recent level) of 115 in 2025.

Fig. 7 shows the variation of the maximum Wolf number (RM) as a function of spotless events around the following minimum. The linear fit is represented by the corresponding equations.



Comparison with the results of other authors

A number of forecasts, applying various techniques, have been published recently for the peak of the 25th solar cycle. Table 1 represents the results for cycle 25; our results are in the lower tier of the table. It is clear that our results concur with most other investigators in the sense that cycle 25 has lower amplitude than cycle 24. On the other hand, there are a few authors who claim that cycle 25 may be of similar or higher amplitude than 24.

Table 1. Predictions of Solar cycle 25

Author & year	Method	Maximum amplitude
Javaraiah (2017)	Cosine function + linear fit	30–40
Covas et al. (2019)	Neural networks Spatiotemporal	57 ± 17
Kakad et al. (2017)	Shannon entropy model	63 ± 11.3
Labonville et al. (2019)	Solar dynamo models	89 (+/- 29/14)
Attia et al. (2013)	Neural networks Neuro-fuzzy	90.7 ± 8
Gopalswamy et al. (2018)	Microwave imaging observations	89 and 59
Recent work	precursor technique of spotless total	108.6
	odd	114.99
	aa _{min} total	111.6
	aa _{min} odd	99.5
	precursor technique of SLDs (26 th)	96.6
NOAA and NASA	Recent	115
Recent work	precursor technique of SLDs (26 th)	96.6

Conclusion

In the present study, we have used two major solar indices - spotless events and aa_{min}. That has a better understanding of the variation of solar activity. The data sets of both parameters are used to estimate and forecast the level of activity for solar cycles 25th and the upcoming cycle 26th. Our work illustrates that cycle 25 will achieve a low amplitude in comparison to cycle 24.

Precursor techniques are major contributors to the consensus prediction of the solar maximum phase, and they are the most successful ones dealing with such a problem.

Large-scale discrepancy in the results is attributed to the large-scale variety of methods of analysis and data sets.

It seems that the distribution of SLDs across the successive solar cycles is responsible for the variety of their strength.

The more frequently and longer the record of SLDs, the smaller the values of the maximum Wolf number.

The simultaneous results show the effectiveness of our proposed method of analysis, which confirms our early prediction.

We can conclude with a sufficient degree of confidence that solar activity 22–26 will systematically decrease because of the increasing phase shift between SLDs and the strength of the solar cycle, possibly leading to a noticeable reverse relationship between SLDs and the maximum level.

Our results fall within the uncertainty of NOAA/NASA consensus predictions (December, 2019).

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ПРОВЕРКА НА ПРОГНОЗАТА НА 25-ия СЛЪНЧЕВ ЦИКЪЛ ВЪЗ ОСНОВА НА МЕТОДИ НА ПРЕДВЕСТНИЦИТЕ

Р. Хелал, М. Семейда, А. Абулуфа

Резюме

Прогнозирането на нивото на слънчева активност е жизненоважно за всички космически програми, планирането на космически мисии, промени във времето и климатични изменения. Използват се различни подходи за прогнозиране на предстоящия слънчев цикъл. В тази статия дните без слънчеви петна (**SLD**) около предходния минимум и геомагнитният индекс **aamin** се използват като предвестник за повторно прогнозиране на максимума на 25-ия слънчев цикъл от набор от наблюдателни данни. Този метод показва доста приемлив резултат, който дава максималната амплитуда на 25-ия слънчев цикъл, използвайки SLD, равна на $R_{25SLD} = 108.58$, а времето на покачване $T_{25SLD} = 4.2$ години. Използвайки aamin, $R_{25aamin} = 111.6$ и $T_{25aamin} = 3.98 \sim 4$ години, накрая се установява, че прогнозираният максимум за предстоящия 26-ти цикъл е $R_{26SLD} = 96.6$.

STATISTICAL STUDY OF EJECTIVE FILAMENT/PROMINENCE ERUPTIONS DURING SOLAR CYCLE 23

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Key words: CMEs, flare, filament, ejective eruption, Solar Cycle 23

Abstract

Filament/prominence eruptions in the solar atmosphere are one of the most important solar events that drastically affect space weather. The formation, evolution, and eruption of filaments are directly linked to the Sun's magnetic activity. Herein, 159 filament eruptions that occurred during 1998–2011 have been statistically analysed to distinguish between the different types of filament eruptions – confined or ejective. This is performed using the List of interplanetary (IP) Shocks Observed during Solar Cycle 23 (May 1996 – January 2008) and their Source Information Environmental Satellites (GOES) X-ray plots [1]. We have found that 69% of filament eruptions are confined, while 31% are ejective. We have examined confined filament eruptions (110 events) during the 23rd solar cycle (1996–2008) in Khaled et al. [2] and found that 21% are due to active filaments and 48% to disappearing filaments. Here we present a statistical investigation of the ejective filament/prominence eruptions. The relationships among filament eruptions, flares, and CMEs (coronal mass ejections) for each type have been studied separately. We have found a significant probability of CME occurrence in M and X flare classes. It has also been observed that the predominant X-ray energy of ejective eruptions is M-class. We have found that the CME velocity associated with active filaments ranges from 775 to 975 km/s, whereas that associated with disappearing filaments is much higher (up to 1800 km/s). Finally, our study shows that 40% of the events have an angular width of 360 degrees (Halo CME), indicating they can significantly impact Earth's upper atmosphere and cause changes in space weather.

Introduction

Filaments are gigantic arcs of hot plasma that extend above the photosphere of the Sun [3]. They are a collection of many threads that form an apparent loop. In the solar disk, they appear as stretched, dark features, which extend up to halfway across the solar disk. Because this plasma is slightly cooler than the solar surface below, they appear dark against the hotter background. When it is seen at the solar limb, it appears as a light, bright loop against the dark outer

space behind hence it is called a prominence. So the filaments and the prominences are two words that describe different perspectives of the same thing.

Decades of study have shown that it is very difficult to characterise filament properties. Filaments show differences in morphology, lifetime, position on the solar disk, complexity of their magnetic field environments, etc. The formation of a filament is quite a slow process. It takes a few days, especially when it is located far from an active region. Understanding the origin of such variety and attaining better knowledge of these structures and their environment during the different phases of their life can provide valuable information on the physics of the solar atmosphere [4].

Many studies in the literature have shown that flares and filament eruptions are the two main solar phenomena that may be associated with CMEs. Some of these studies address the relationship between prominences, which could be easily detected, observed, and measured against the dark sky background and CMEs. Moreover, CMEs associated with prominences are not difficult to detect. Gilbert et al. [5] examined 54 H α events to identify characteristics of active prominences (APs), eruptive prominences (EPs), and disappearing filaments (DFs) to study the relationship between prominence activity and CMEs. They found that 94% (17 of 18) of the EPs have an associated CME compared to only 46% (12 of 26) for APs. Also, they found that 70% of the events (seven of 10) are DFs.

Mouradian et al. [6] showed that the sudden disappearance (SD) of the filaments can be either dynamic (DSD) or thermal (THD). They showed that only DSDs are associated with CMEs, while THDs are only local disturbances in the lower corona.

We aim to investigate Filament/Prominence eruptions and their close relation with CMEs and flares, and to study whether a clear signature X-ray flare class could be associated with either confined or ejective eruptions. We classified the Filament/Prominence list (for 159 complete observations of the filament eruptions for the period 1998–2011) into two main categories: (1) confined eruption and (2) ejective eruption. This period is in the frames of the 23rd Solar cycle, which lasts 12.6 years, beginning in August 1996 and ending in December 2008. The maximum smoothed sunspot number observed during the cycle is 180.3. During the minimum transit from 23rd to 24th, there were a total of 817 days with no sunspots [7]. 23rd Solar cycle is medium in activity, but it is interesting that it is the last cycle before the deep minimum after it. We have conducted a statistical study of eruptions to identify precursors for each type of eruption. The data set and method of research are described in detail in Khaled et al. [2], where we consider only confined eruptions (69.2% of 159 filament eruptions).

In this paper, we investigate the signature X-ray flare class associated with ejective eruptions and some properties of CMEs (speed and angular width).

Relationship between X-ray flares and CMEs associated with ejective eruptions

Some properties of the X-ray flares and CMEs associated with ejective eruptions are analysed and displayed in this section. Table 1 summarises the X-ray flare classes associated with active and disappearing ejective filaments. It was found that the dominant X-ray flare energy of ejective eruptions is that of M class (15 events), or 30.6% from 49 data points selected. In addition, the number of X-ray flares in class B, C, and M associated with disappearing filaments is always higher than that associated with active filaments. On the other hand, A-class does not produce any associated filaments [8], while the energetic X-class only produces disappearing filaments. It was noticed that the percentage of M class in ejective eruption (30.6%) is higher than the percentage of M class in the confined eruption (18.2%) [2]. Additionally, disappearing filaments need more X-ray energy than active filament activations: namely, M, X, and EP (defined as eruptive prominence).

Table 1. Summary of the number of X-ray flares associated with active and disappearing ejective filaments

X-ray Flare class	Active filament type	Disappearing filament type
A	0	0
B	2	3
C	2	11
M	4	11
X	0	5
EP	1	10

Fig. 1 shows the number of ejective eruptions associated with different classes of X-ray flares, the distribution of ejective eruption events compared to filament extent, and the distribution of ejective eruption events compared to flare duration.

We have obtained that most of the ejective eruptions have a filament field extent between 5 and 20 degrees. And in some cases, only one event has an extent of more than 40 degrees, which represents about 4% of all the events. We have noticed that as the filament length increases on the solar disk, the probability of ejective eruption is higher (Fig. 1b)

Finally, we have also found that the most common X-ray flare durations for ejective eruptions are between 33 min and 1 hour 40 min. About 73.3% of all the ejective eruption events have a duration ranging between 33 min and 2 hours. And there is a duration of more than 3 hours, which represents about 11.8% of all data (Fig. 1c).

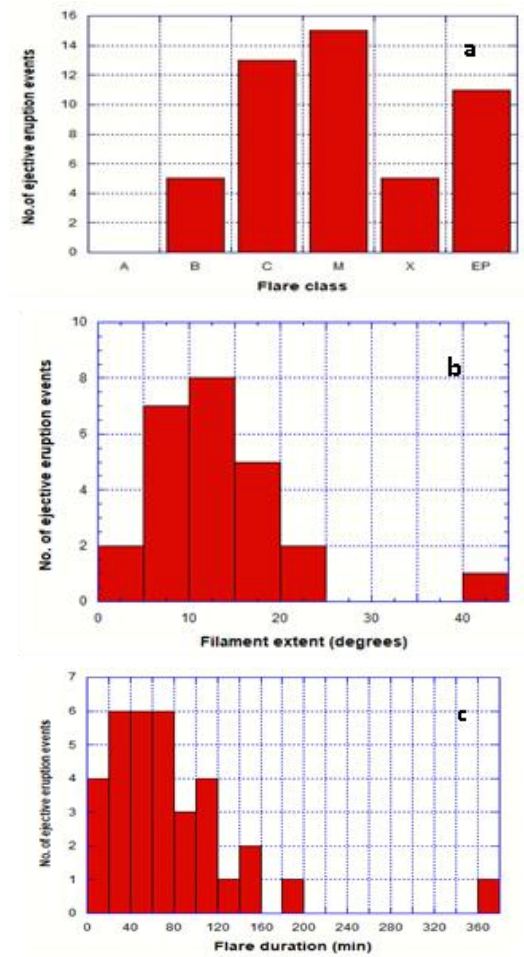


Fig. 1. a) Number of ejective eruptions associated with different classes of X-ray of flare; b) Distribution of ejective eruptions compared to filament extent, and c) Distribution of ejective eruptions compared to flare duration that result from ejective eruptions

CMEs properties (speed and angular width) resulting from ejective eruptions from active and disappearing filaments

Fig. 2 shows the histogram plot of CMEs speed resulting from ejective eruptions and the histogram plot of the angular width of CMEs associated with ejective filaments (Disappearing and Active filament eruptions).

Fig. 2a displays the distribution of CMEs speed of all ejective filaments used. It was found that the maximum speed reached 1800 km/s, while the minimum speed detected was about 300 km/s. This difference in speeds may be due to the amount of energy that the CME gained to be ejected.

From Fig. 2b one can see that CMEs speeds, which are associated with ejective eruptions, are in the range from 200 to 1800 km/s. Maximum speed with a value of 1600 km/sec is recorded for 3 events out of a total of 40 events, which represents 7.5%. Another 7.5% have a speed of 1200 km/s. This means that about 15% of the disappearing eruptive filaments have high speeds.

For eruptions resulting from active filaments, as shown in Fig. 2c, we see that each event (only 5 events found) in the data has its own distinct velocity. Speed ranges from 775 to 975 km/sec. It should be noted that CMEs with higher speeds are more likely to be formed due to disappearing filaments, not active filaments.

A histogram plot of the angular width of CMEs associated with ejective filaments (Disappearing and Active filament eruptions) is shown in Fig. 2d. One can see that the angular width of the CMEs associated with ejective filaments lies in the range of 60–360 degrees. About 40% of the events have an angular width of 360 degrees (Halo CME), which indicates that most CMEs resulting from ejective filaments have a high probability of reaching the Earth (they are geoeffective).

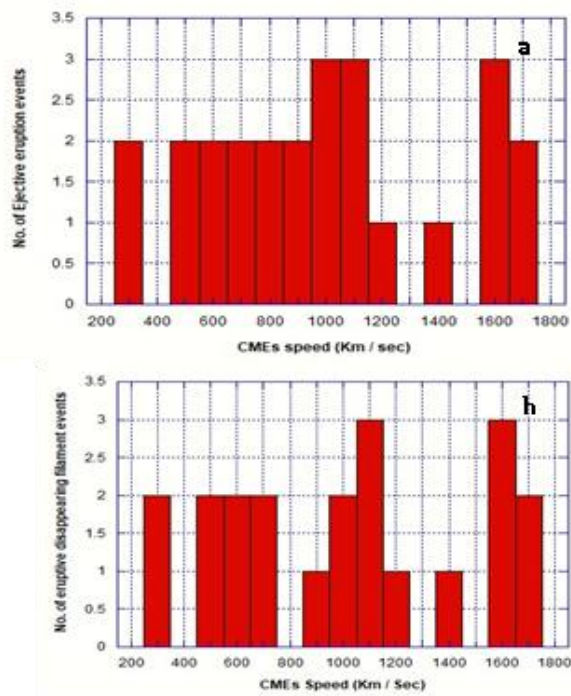
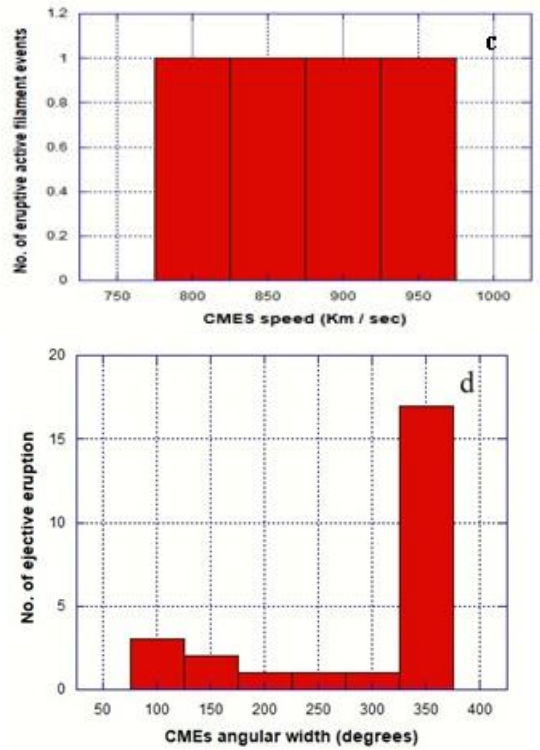


Fig. 2. a) Distribution of CMEs speed resulting from ejective eruptions;
b) The Distribution of CMEs speed of ejective eruptions in the case of disappearing



*Fig. 2. c) For active filament eruptions;
d) Distribution of CMEs' angular width that results from ejective filaments*

Regression analysis

Using regression analysis/curve fitting, we tried to find any relationships between the different parameters of confined and ejecting eruptions to use in forecasting.

Fig. 3 shows the weakness of the pairwise relationship among the considered variables (flare duration vs filament extent, eruption duration vs filament extent, and eruption duration vs flare duration). The maximum Correlation coefficient between any pair is always less than 0.4. So, we rely on the previous analysis to predict the behaviour of flares and CMEs ejections based on filament/prominence eruptions.

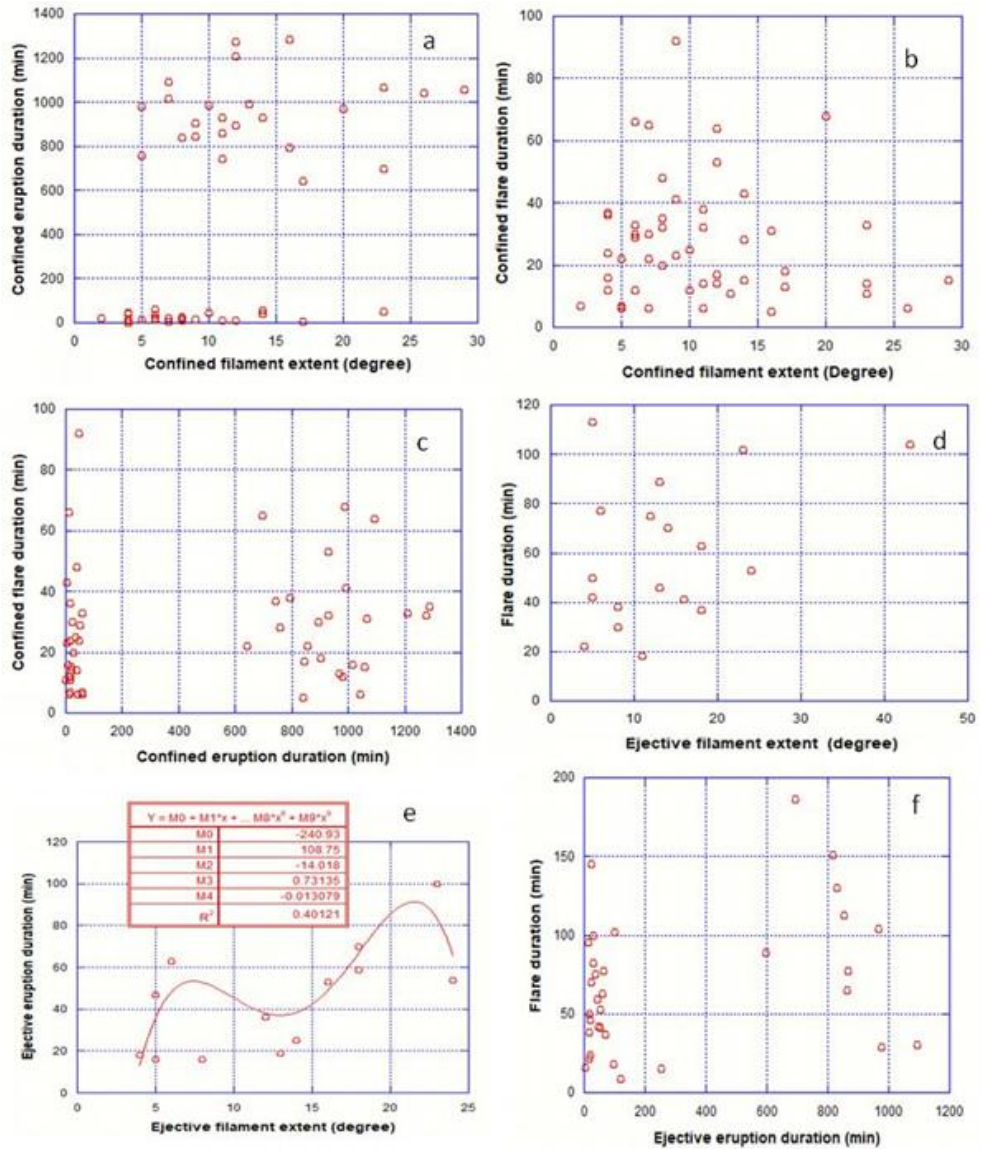


Fig. 3. Relationship between filament extent and flare duration and eruption duration for both confined and ejective eruptions (a, b) for confined eruption and (d, e) for ejective eruption. The relation between the eruption duration and flare duration in minutes for confined and ejective eruptions (c, f, respectively) is also shown.

Conclusion

In this work, we statistically examine ejective eruptions during the 23rd Solar cycle (1996–2008). They are 31% (49 events) of 159 filament eruptions that occurred in the period 1998–2011. Nine events (6%) are active filaments, and the other 40 (25%) are disappearing filaments.

The dominant X-ray flare energy of ejective eruptions is that of M class (15 events) or 30.6% from 49 data points selected. It is higher than the percentage of M class in the confined eruption (18.2% or 20 from 110 selected events). Additionally, disappearing filaments need more X-ray energy to be activated than active filaments: namely, M, X, and EP classes. This means that the M and X flare classes are highly likely to have CME ejection.

The distribution shows that the most common filament field extent is located between 5 and 20 degrees. We can use filament length as a good Predictor parameter. The shorter the filament length on the solar disk, the higher the probability of confined eruption [2], while the longer the filament length on the solar disk, the higher the probability of ejective eruption.

The most common flare duration is between 33 minutes and 2 hours for ejective eruption. It should be noted that besides filament/prominence eruptions, high-energy (relativistic) particles of solar and galactic origin, i.e., protons and heavier nuclei of galactic and solar cosmic rays, are important for space weather and space climate [9–11]. They cause complex nuclear-electromagnetic-lepton cascades in the Earth's atmosphere, which lead to ionisation of the surrounding air and the entire environment. Cosmic ray-induced ionisation is associated with effects on atmospheric chemistry and physics and is principal for radiation safety in spaceflight [12–15].

Studying properties of the CMEs (speed and angular width) resulting from ejective (active and disappearing) filament eruptions, we have found that:

- 1) CMEs speeds detected from the selected data range from 200 to a maximum of 1800 km/s.
- 2) About 15% of the disappearing eruptive filaments have high speeds – from 1200 km/sec to 1600 km/sec.
- 3) We have obtained that the CME velocity associated with active filaments varies between 775 and 975 km/s, and the CME velocity associated with disappearing filaments is much higher (up to 1800 km/s).
- 4) Finally, our study shows that 40% of the events have an angular width of 360 degrees (Halo CME), which indicates that they are geoeffective and can influence space weather.

The results of this work are essential for the analysis and prediction of processes in solar-terrestrial relations and space physics [16–20].

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СТАТИСТИЧЕСКО ИЗСЛЕДВАНЕ НА ИЗХВЪРЛЯЩИ ИЗРИГВАНИЯ НА НИШКИ/ПРОТУБЕРАНСИ ПО ВРЕМЕ НА 23-ИЯ СЛЪНЧЕВ ЦИКЪЛ

С. Халед, А. Шимеис, М. Хюсеин, М. Семейда, П. Стоева, А. Стоев

Резюме

Изригванията на нишки/протуберанси (filament/prominence) в слънчевата атмосфера са едни от най-важните слънчеви събития, които драстично влияят на космическото време. Формирането, еволюцията и изригването на нишките са пряко свързани с магнитната активност на Слънцето. В настоящата работа са статистически проучени 159 изригвания на нишки, случили се в периода 1998–2011 г., за да се разграничат различните видове изригвания на нишки – ограничени или изхвърлящи. Това е извършено с помощта на Списъка с междупланетни (interplanetary IP) шокове, наблюдавани по време на 23-ия слънчев цикъл (май 1996 г. – януари 2008 г.) и техните рентгенови диаграми от изходната информация за околната среда (GOES) [1]. Установихме, че 69% от изригванията на нишки са ограничени изригвания, докато 31% са изхвърлящи изригвания. Изследвахме ограничени изригвания на нишки (110 събития) по време на 23-ия слънчев цикъл (1996–2008 г.) в Khaled et al. [2] и установихме, че 21% от тях се дължат на активни нишки, а 48% – на изчезващи нишки. Тук представяме статистическо изследване на изригванията на изхвърлящи нишки/протуберанси. Връзката между изригванията на нишки, изригванията и свойствата на изхвърляния на маса от короната (CME) за всеки тип е изследвана поотделно. Установихме, че има значителна вероятност за CME с класове на изригвания M и X. Също така е наблюдавано, че преобладаващата рентгенова енергия на изхвърлените изригвания е от клас M. Получихме, че скоростта на CME, свързана с активните нишки, варира между 775 и 975 km/s, а скоростта на CME, свързана с изчезващи нишки, е много по-висока (до 1800 km/s). Накрая, нашето проучване показва, че 40% от събитията имат ъглова ширина от 360 градуса (Halo CME), което показва, че те могат да окажат значително въздействие върху горните слоеве на земната атмосфера и да причинят промени в космическото време.

Z-HELIOS SOLAR OPTICAL TELESCOPE FOR SPECTROHELIOGRAPH APPLICATION

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Keywords: *Spectroheliograph, Solar optical telescope*

Abstract

The current article focuses on the Z-Helios refractor solar optical telescope as a critical component within a novel, automated spectroheliograph system developed at the Space Research and Technology Institute – Bulgarian Academy of Sciences. The telescope is specifically engineered to provide a stable, high-resolution solar image to the spectrographic apparatus. This paper details the telescope's optical, mechanical, and electronic specifications, its integration into the spectroheliograph system, and the specific features and design that enable high-resolution, narrowband solar observations over the wavelength range of 360 nm to 830 nm.

The benefits of the proposed instrument are evident in system mobility, low hardware acquisition and maintenance costs, and ease of use – the telescope and the whole optical system require minimal operator involvement during observation, data acquisition, and data processing.

Introduction

Detailed observations of the solar disk in narrowband light across the visible, near-infrared, and ultraviolet spectrum are essential for scientific studies of the Sun. The aim is to observe, research, and analyse the processes taking place in the solar atmosphere. The latter extends from the end of the convection zone to the inner boundary of the heliosphere. The solar atmosphere consists of three layers: the solar photosphere, the solar chromosphere, and the corona. The photosphere is made of convection cells called granules and is slightly less opaque than air on Earth. The layer below the photosphere is opaque to visible light. The higher region of the photosphere is not as hot as its lower part. Hence, an image of the Sun disk becomes visually brighter moving from the limb to the centre. This phenomenon is known as limb darkening. The photosphere is only partially ionised – about 3%, thus having most of the hydrogen in atomic form. Extending to about 500 km above the photosphere, there is found the coolest layer of the Sun – a temperature minimum region at about 4100 K. In this layer, the low temperature allows for the existence of carbon monoxide, water, and other simple molecules.

Above the temperature minimum layer, we find the chromosphere – a layer about 2000 km thick having inherent spectrum emission and absorption lines. Its name is derived from the Greek ‘chroma’, meaning colour, due to its visible colored flash at the beginning and end of total solar eclipses. The temperature of the chromosphere increases with altitude and reaches 20000 K near its top. In the highest region of the chromosphere, helium gets partially ionised [1].

At the end of the chromosphere, just before the corona, there is a thin layer (200 km thick). This layer is a transition characterised by a pronounced temperature gradient – temperature rises from 20000 K in the top chromosphere to 1000000 K at the beginning of the corona. At the start of the corona, we observe full ionisation of helium that significantly decreases radiative plasma cooling. The transition region is not smooth, but acts as a nimbus around chromospheric irregularities such as spicules and filaments, thus being in continuous chaotic motion [2].

The solar magnetic field bears various effects collectively called solar activity. For example, solar flares and coronal mass ejections often occur at sunspot groups. High-speed streams of solar wind are slowly changing. They are emitted at the surface of the photosphere from coronal holes. Both high-speed streams and coronal mass ejections of the solar wind carry plasma outward into the Solar System. The solar activity affects Earth, invoking auroras at moderate to high latitudes, and stronger activity may induce disruption of radio communications and electric power [3, 4].

Solar activity changes according to the 11-year solar cycle. The sunspot number is correlated to the solar cycle [5]. In history, there were periods during which the solar cycle stopped completely for a few decades (during the 17th century). This period is known as the Maunder minimum. It is characterised by an era known as the Little Ice Age. Then, Europe lived through abnormally cold temperatures.

The first technology to offer capabilities for observing the solar atmosphere was the spectroheliograph instrument (SHG), developed concurrently and independently in 1892 by two scientists: the prominent French astronomer Jules Janssen's colleague Henri Deslandres at the Meudon Observatory and George Hale in Kenwood, USA [6, 7]. Deslandres later became the Director of the Meudon Observatory from 1907 to 1909. He developed two primary types of spectrographs: the *spectrohéliographe des formes*, a narrow-bandpass instrument which revealed structures in the chromosphere such as filaments and active regions, and the *spectrohéliographe des vitesses*, used to record line profiles of cross sections of the Sun to measure Doppler shifts of dynamic features. Deslandres finished his large quadruple spectroheliograph in 1908, initiating systematic observations of the Ca II K line that continues to this day, with H α observations following in 1909. This continuous data collection has accumulated over 100 000 observations

spanning more than 10 solar cycles. Optical and mechanical redesigns were carried out in 1989, and digital technology was implemented in 2002 [8].

The spectroheliograph system is primarily utilised today to observe the Fraunhofer lines in the solar spectrum. These absorption lines appear as dark spectral lines within the Sun's continuous spectrum (Fig. 1) and were first observed in 1814 by the German physicist Joseph von Fraunhofer [9, 10]. The lines are formed when specific elements in the cooler solar atmosphere absorb light emitted by the hotter underlying photosphere. The SHG delivers super-high contrast with an ultra-narrow bandpass. While a top-notch etalon filter may achieve around 0.5 Å (Angstrom) per-pixel spectral resolution, SHG easily reaches 0.06 to 0.1 Å. Etalons with 0.3 Å have prohibitive cost in most scenarios. SHG delivers exceptionally high contrast images without parasitic light leaks originating from the photosphere innate to single stack etalons.

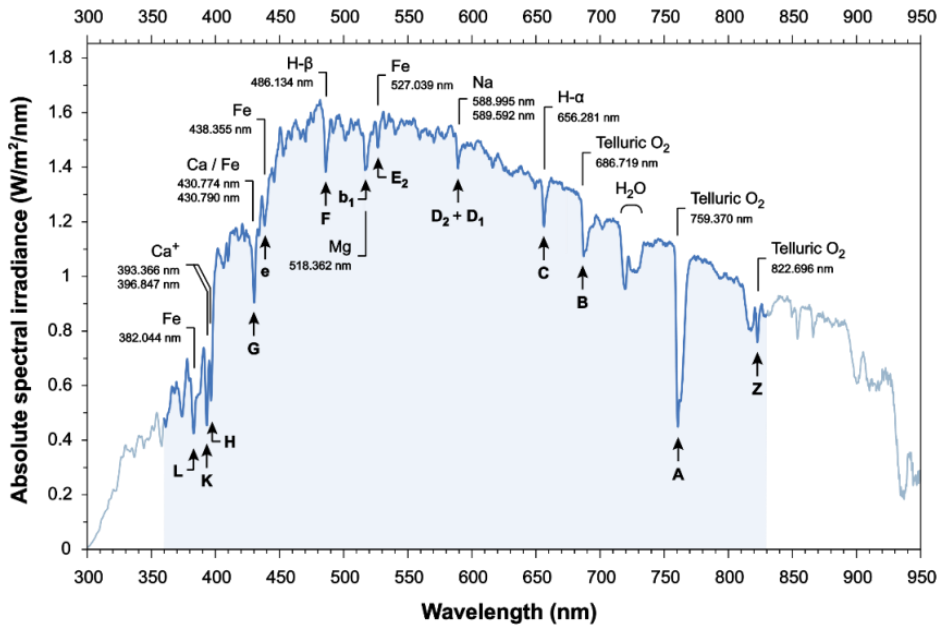


Fig. 1. Sun spectral irradiance measured with a calibrated spectrometer (Flame S-XR1-ES, Ocean Insight). The measurement was made on a sunny day on the 13th of June 2022 at noon from Hauterive, Switzerland (47°01'N 6°58'E). For photometry and colourimetry, standard measurements are usually carried out in the range 360–830 nm (highlighted area). Correlated colour temperature (CCT): 5470 K. Image Author: Cyamahat (on wikipedia.org) licensed under the Creative Commons Attribution-Share Alike 4.0, CC BY-SA 4.0 (<https://creativecommons.org/licenses/by-sa/4.0/deed.en>).

The Spectroheliograph

The spectroheliograph is an optical instrument that comprises an optical telescope (refractor or reflector), a narrow slit located on the telescope focal plane, a collimator lens, a prism or diffraction grating, an imaging lens (camera lens), and an imaging screen, photographic plate, photographic film, or camera.

The whole instrument is mounted on an astronomical telescope mount in order to be directed towards the Sun [11]. Another approach with large and heavy spectroheliograph devices is to utilise a mirror system that directs the solar beam towards the instrument instead of rotating the latter. The telescope focuses the solar image onto the focal plane, where the slit is placed. The circular image of the Sun covers the slit, and only a single line (a stripe) passes through the slit at a time. By scanning the solar disk stripe by stripe, the device is later capable of reconstructing, either on a photographic plate or digitally using a camera and a computer, the whole solar disk image.

After passing through the slit, the light enters a collimator lens. The purpose of the latter is to make the light rays parallel. These parallel light rays reach the prism or diffraction grating and are dispersed in relation to their wavelength. The dispersed light is focused by means of a camera lens onto a photographic plate or digital camera sensor. When a camera is used, the image of a single stripe of the solar disk is digitised and recorded by the computer controlling the camera. Then the next stripe is stored, and so on. The final image is reconstructed from the stored stripes. Due to the light dispersion, only a narrowband light is recorded at the desired wavelength. General optical lenses and telescopes are used for the light spectrum between near-infrared light and low-frequency ultraviolet light. For wavelengths outside this region, special optics are needed.

Innovative Spectroheliograph

The described telescope within the current paper is part of an innovative spectroheliograph being under development at the Space Research and Technology Institute – Bulgarian Academy of Sciences. It is expected to be tested soon. The SHG component and functional diagram are shown in Fig. 2. The instrument relies on a refractor optical telescope with an absolute aperture in the range of 80 mm to 125 mm. A telescope with a smaller aperture would yield low angular resolution, while a larger aperture beyond 125 mm would render the telescope too heavy and cumbersome for portable applications, while yielding unnoticeable improvement in resolution. Larger telescopes are useful in situations with low atmospheric distortions – not the general case when observing from low to medium altitudes. The slit is within 7 to 10 microns of width – either made of quartz glass or stainless steel to be able to resist the significant heat dissipated in it from the projected sunlight. Suitable slits may be readily purchased from optics vendors. The employed collimator lens is a photographic objective lens. This approach delivers much better resolutions and minimises aberrations in comparison with simple achromatic doublets. The

spectroheliograph employs a reflecting diffraction grating – those are available from optics manufacturers. The camera lens used is a high-quality photographic lens, either the standard component for the implemented camera or a general-purpose photographic lens. The requirements for the camera are lower in comparison with tasks in astrophotography – there is enough light and the resolution is significantly restricted by the seeing conditions to a few megapixels (2 megapixels in most scenarios). The apparatus also comprises a filter wheel installed in front of the camera lens. Its goal is to eliminate the dispersion of other wavelengths from higher diffraction orders. The innovative SHG is computer-controlled.

Telescope Specifications and Optical Design of Z-Helios

Refractor telescopes have a long history, dating back to Galileo's first astronomical uses in the 17th century. A refractor uses a primary objective lens at the front of the tube to collect light and bring it to a point of focus. A second lens system then magnifies this image for observation or projection onto a sensor. This design is robust and seldom requires collimation, in contrast to reflector telescopes. Key parameters of refractor telescopes are aperture, focal length, number of optical elements, focusing mechanism, etc.

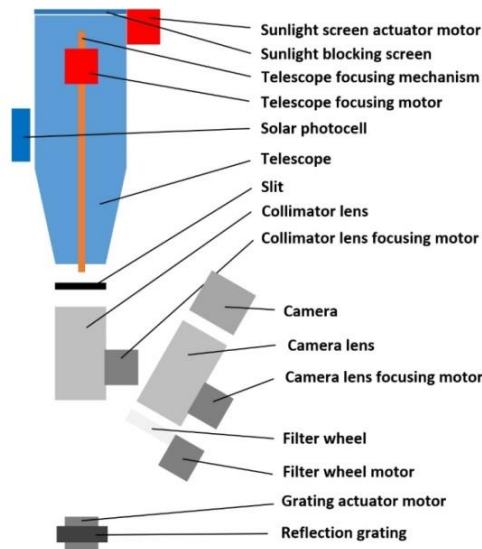


Fig. 2. Innovative computer-controlled refractor optical telescope Z-Helios as part of a spectroheliograph system. The components of the system not part of the telescope are shown in grey shades.

The Z-Helios telescope was specifically developed to be implemented in the innovative spectroheliograph. As mentioned above, the absolute apertures suitable for

portable spectroheliograph systems range from 80 to 125 mm in diameter. Z-Helios was chosen from these numbers with a 100 mm aperture. Thus, a compromise between portability, cost, weight, and resolution was achieved. Because the spectroheliograph instrument performs monochromatic, very narrowband imaging (less than 0.3 Å bandwidth), the telescope does not require the complex multi-element apochromatic design typically used in broadband imaging telescopes. The Z-Helios telescope is based on an objective lens, achromatic, doubled with maximum diffraction-limited resolution in the centre of the image and minimal corrections near the end of the image circle for aberrations due to the high magnification required. The instrument involves solar protection – a motorised sunscreen actuator motor. The sunscreen is automatically opened only when direct sunlight is registered by an external optical sensor, thus preventing damage to internal parts from angled solar rays (Fig. 2). The telescope focusing mechanism and the sunscreen function are controlled by the main computer of the spectroheliograph system. In Fig. 2, the reader may observe the components of the whole spectroheliograph system and the telescope in particular. The parts belonging to the telescope are shown in colour while all other components of the spectroheliograph are visualised in grey shades. The solar photocell is also part of the telescope and is directly connected to the computer governing the functions of the spectroheliograph system.

Conclusion

The Z-Helios telescope is part of an automated spectroheliograph system controlled by a computer module. The computer component controls all actuator motors, receives data from all sensors, and carries out the data acquisition process, then processes the data and creates the images. The Z-Helios telescope provides the necessary optical stability and resolution for the innovative spectroheliograph developed at the Bulgarian Academy of Sciences. Its robust design, suitable aperture, and automated focusing mechanisms make it an ideal front-end for a small-scale, mobile, and highly versatile solar observation system. The system design ensures minimal operator involvement in the acquisition process, freeing its users to engage with different scientific tasks.

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Z-HELIOS СЛЪНЧЕВ ОПТИЧЕСКИ ТЕЛЕСКОП ЗА ИЗПОЛЗВАНЕ В СПЕКТРОХЕЛИОГРАФ

С. Забунов, Г. Мардиросян

Резюме

Настоящата статия разкрива детайли относно иновативния слънчев оптически рефракторен телескоп Z-Helios. Последният се явява важен компонент от автоматизиран спектрохелиограф, разработен в Института за космически изследвания и технологии при Българска академия на науките. Телескопът е конструиран за да осигури стабилно и ясно изображение на слънчевия диск. В статията са показани детайлите относно оптичните, механичните и електронните особености на телескопа. Също така се разкрива общата функционалност и схема на спектрохелиографа, от който телескопът е неразделна част. Описани са характеристиките на телескопа, които са определящи за успешното функциониране на спектрохелиографа в честотния диапазон на електромагнитните вълни с дължини от 360 nm до 830 nm.

Предимствата на предложения телескоп са разкрити по отношение на стабилност на системата, цена на хардуера за придобиване и поддръжка, ниска сложност на експлоатация и намалена ангажираност на персонала с функциите на системата по наблюдение на Слънцето, събиране на данни и тяхната обработка.

VARIOGRAM-BASED FRACTAL ANALYSIS OF SLOPE MORPHOMETRY ON MERCURY

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Key words: *Mercury, fractal dimension, variogram, MESSENGER, slope, topography, hemispherical asymmetry*

Abstract

This study presents a quantitative assessment of the fractal characteristics of the spatial distribution of surface slopes within Mercury using a variogram-based fractal dimension (FD) approach applied to the global MESSENGER DEM. The obtained results reveal a clear fractal pattern of Mercury's slope distribution, with mean FD values of 2.127 in the Northern Hemisphere and 2.107 in the Southern Hemisphere, supported by very high coefficients of determination ($R^2 > 0.99$). A statistically consistent, though moderate, hemispherical asymmetry is observed, with higher fractal dimensions and greater spatial heterogeneity in the Northern Hemisphere, particularly in regions dominated by large impact basins and limited volcanic smoothing. In contrast, the Southern Hemisphere exhibits more homogeneous fractal properties, consistent with spatial differences in surface roughness and morphological complexity. These findings provide new insights into the geological evolution of Mercury's hemispheres and highlight the applicability of variogram-based fractal analysis as a methodological tool for comparative studies of planetary topography.

Introduction

Prior to the Mariner 10 spacecraft mission, the scientific community had very limited knowledge of the topographical features of Mercury, the planet closest to the Sun. In 1975, [1] produced the first geologic map of Mercury's surface, identifying various geological features. Mercury's surface is densely covered by impact craters. More than 30,000 craters with diameters exceeding 5 km have been catalogued from spacecraft imagery. The largest of these structures is the Caloris basin, approximately 3.9 billion years old and about 1,550 km in diameter. Owing to Mercury's proximity to the Sun, impactors typically strike the planet at significantly higher velocities than those affecting other terrestrial planets. These high-impact velocities enhance ejecta production and contribute to the formation of an unusually large number of secondary craters across Mercury's surface [2]. In addition to impact craters, Mercury's surface comprises a variety of other geological features, including heavily cratered plains, smooth plains, as well as hilly and mountainous regions (Fig. 1).

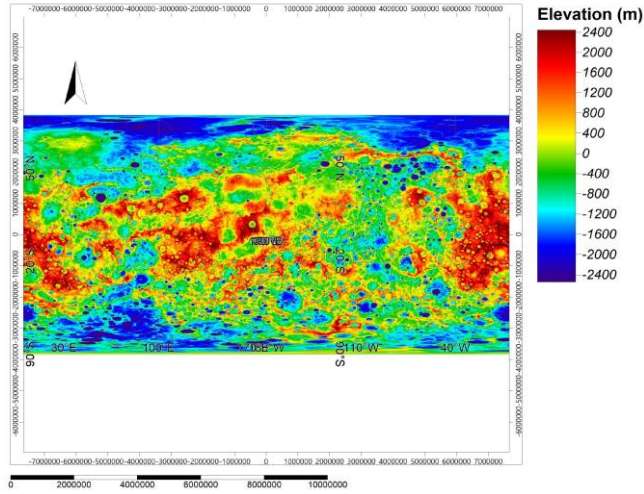


Fig. 1. Digital Elevation Model (DEM) of Mercury showing the main characteristics of its terrain. The surface is dominated by impact craters and elevated regions. Notably, the polar areas are largely characterised by negative elevations, whereas the equatorial regions predominantly exhibit positive elevations.

Subsequent missions, particularly MESSENGER [3], have significantly advanced our understanding of Mercury's surface. The global topography of Mercury varies from approximately -5365 m to 4457 m (Fig. 2). About 60% of the surface corresponds to negative elevations, while positive elevations account for roughly 40%. In the northern hemisphere, negative landforms dominate, whereas in the southern hemisphere, positive elevations are more prevalent.

In recent decades, the continuous acquisition of new data on planetary bodies within the Solar System has facilitated the development and application of innovative analytical and interpretative methods. Among them, fractal analysis occupies an important place. Fractal geometry provides a scientific framework for describing complex shapes and surfaces [4], making it a suitable methodological tool for investigating planetary topography.

Regarding Mercury, the application of fractal analysis remains limited. Only a few studies addressing this topic can be found in the literature. [5] applied fractal methods to analyse asteroid craters on the planet. [6] explored spatial variations of Mercury's terrain and gravity field based on fractal dimension. In a conference paper, [7] demonstrated that Mercury's topography exhibits scaling fractal properties, transitioning from monofractal behaviour at scales below 10 km to a multifractal regime at larger scales.

This scarcity of such studies highlights one of the main objectives of the present work. Unlike previous studies focusing on elevation and gravity field, the present work applies variogram-based fractal analysis to slope gradients, which

represent first-order derivatives of topography. By applying the variogram-based fractal dimension approach, the current study aims to comprehensively characterise the spatial patterns of slope distribution across Mercury's surface, providing new insights into its geological evolution.

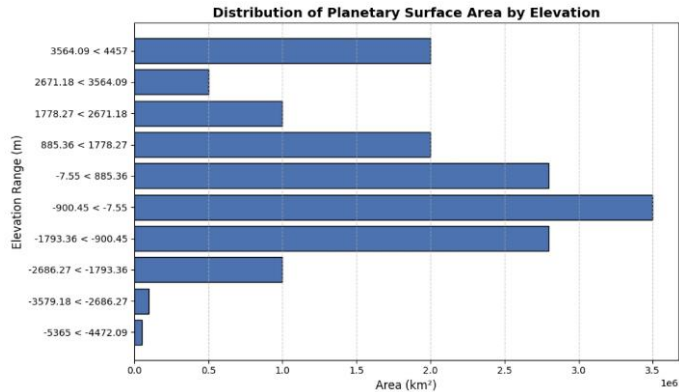


Fig. 2. The bimodal distribution of Mercury's topographic elevations. Negative elevations are more extensive than positive ones, reflecting the dominant influence of impact events that have shaped the planet's present-day surface morphology. The highest peaks are another characteristic dominating the positive elevations.

Methods and Data

Preprocessing, Noise Reduction, and Slope Calculation of the Mercury DEM

The global Mercury Digital Elevation Model (DEM), derived from MESSENGER/USGS data at 665 m spatial resolution, was pre-processed to mitigate high-frequency orbital noise and striping artefacts prior to morphometric analyses. The original DEM values were provided with a scale factor of 0.5; all raster values were multiplied by this factor to convert digital numbers into metric elevations (meters). This step ensured that subsequent slope calculations were physically meaningful.

To suppress high-frequency noise while preserving primary geological features, the scaled DEM was subjected to Gaussian smoothing with a standard deviation (σ) of 1 pixel (~ 665 m). This approach attenuates small-scale striping and random measurement noise without significantly altering surface morphology. The Gaussian-filtered DEM retained the original georeferencing and projection and served as the input for slope computation and subsequent variogram-based fractal analysis. This preprocessing strategy ensures that the derived slope values reflect genuine geomorphic variability rather than instrumental or orbital noise.

Slope (Table 1) was calculated using the Terrain Analysis $\rightarrow$ Morphometry $\rightarrow$ Slope module in SAGA GIS, which implements the algorithm of [8, 9] for estimating slope derivatives. The method employs a 3×3 moving window to

approximate the partial derivatives of elevation in the x- and y-directions (dz/dx and dz/dy) and computes slope as the magnitude of the local gradient vector. The slope angle theta (θ) is calculated as:

$$(1) \quad \theta = \arctan(\sqrt{(dz/dx)^2 + (dz/dy)^2})$$

where dz/dx and dz/dy represent the first derivatives of elevation along the x and y directions, respectively. In this study, slope values are expressed in degrees.

Although the classical variogram-based formulation of FD is defined for topographic surfaces, its application to slope fields is justified here as a measure of spatial roughness of gradient magnitudes rather than true geometric fractal dimension.

Table 1. Global slope distribution of Mercury's surface. The results indicate that nearly 97% of the total surface area has slope values lower than 1.5°.

Class	Slope Interval (Degrees)	Distribution (%)
1	$0^\circ < 0.72^\circ$	57.06%
2	$0.72^\circ < 1.44^\circ$	39.88%
3	$1.44^\circ < 2.16^\circ$	2.03%
4	$2.16^\circ < 2.88^\circ$	1.09%
5	$2.88^\circ < 3.60^\circ$	0.63%
6	$3.60^\circ < 4.32^\circ$	0.40%
7	$4.32^\circ < 5.04^\circ$	0.28%
8	$5.04^\circ < 5.76^\circ$	0.20%
9	$5.76^\circ < 6.48^\circ$	0.14%
10	$> 6.48^\circ$	0.29%

Fractal Analysis of Mercury's Topography Using a Variogram-Based Method

To investigate the fractal nature of Mercury's surface, a local fractal analysis was conducted on the global Mercury DEM at 665 m spatial resolution. Given the large size of the dataset (11520×23040 pixels), the DEM was divided into two hemispherical tiles (Northern and Southern ones) to reduce computational load and facilitate memory-efficient processing within the Python environment of QGIS.

Local fractal dimensions were computed using a variogram approach [10, 11] implemented in a Python script executed within the QGIS environment. A moving window of 64×64 pixels with a 32-pixel step was applied to each tile. Within each window, the semi-variance was estimated for a limited number of lag distances (up to five pixels), using horizontal and vertical offsets only, rather than a fully isotropic variogram:

$$(1) \quad \gamma(h) = 1/2 * \text{mean} [(z(x) - z(x+h))^2]$$

where $z(x)$ represents the elevation at position x , and h is the lag distance.

The slope of the log-log relationship between semi-variance and lag distance was then used to derive the local fractal dimension:

$$(2) \quad FD = 3 - (m / 2), \quad 2 < FD < 3$$

where m denotes the regression slope. The coefficient of determination (R^2) from the linear regression in log-log space was also recorded for each window as a measure of fit quality.

The computed FD and R^2 values were assigned to the corresponding pixels within each moving window and written to separate GeoTIFF files. Prior to analysis, elevation values were normalised to zero mean and unit variance to ensure numerical stability and comparability across windows. Each hemispherical tile was processed independently, after which the outputs were merged to obtain global maps of local fractal dimensions and R^2 . This tiling strategy ensured memory-efficient processing without compromising the spatial consistency of the DEM and, at the same time, constituted a prerequisite for a comparative analysis between the two planetary hemispheres.

Data and software

The analysis of Mercury's topography was performed using digital elevation data from the Mercury Global Digital Elevation Model (DEM) v2 [12], derived from observations by the MESSENGER spacecraft mission [3]. The DEM provides global coverage of Mercury's surface at a spatial resolution of 665×665 m per pixel, representing topographic variations across the entire planet. Elevation values are expressed in meters and were scaled according to the original data specifications.

Raster data processing and analysis were conducted using open-source geographic information systems (GIS). The primary platforms employed in this study were SAGA-GIS (System for Automated Geoscientific Analyses; [13]) and QGIS. This software environment enabled the extraction of slope values, the implementation of variogram-based fractal dimension analysis, and the spatial visualisation necessary to support the objectives of the study.

Results and Discussion

The results of this research are quantitatively summarised in Table 2 and graphically illustrated in Fig. 3 and Fig. 4. The interpretations are presented below.

Table 2. Fractal Analysis of Slope in the Mercurian Hemispheres

	Northern hemisphere	Southern hemisphere
FD min	2.005	2.000
FD max	2.773	2.876
FD mean	2.127	2.107
FD StdDev	0.0639	0.0527
R^2 min	0.805	0.589
R^2 max	0.999	0.999
R^2 mean	0.997	0.998
R^2 StdDev	0.0034	0.0071

The results presented in Table 2 clearly demonstrate that Mercury's slope distribution exhibits a pronounced fractal behaviour. The mean fractal dimension (FD) is 2.127 for the Northern Hemisphere (NH) and 2.107 for the Southern Hemisphere (SH). The high coefficients of determination further confirm the variogram-based fractal model, with mean R^2 values of 0.997 for the NH and 0.998 for the SH.

The visual analysis of Fig. 3 and Fig. 4 reveals that the highest latitudes, particularly the polar and peripolar regions ($> 50^\circ$ N and S), are characterised by the largest spatial variability in FD values. This pattern indicates a more complex and heterogeneous terrain marked by sharper topographic transitions. Several factors may contribute to this behaviour. On the one hand, Mercury's equatorial regions experience extreme diurnal temperature variations (approximately -170°C to $+430^\circ\text{C}$) and may contribute to differences in slope smoothing. In contrast, temperature contrasts at higher latitudes are less pronounced, favouring the preservation of steeper relief elements.

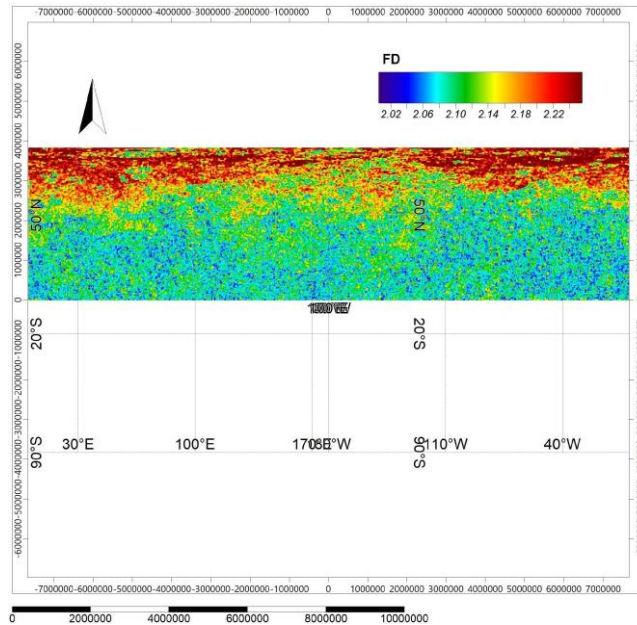


Fig. 3. Spatial distribution of slope fractal dimension (FD) within Mercury's Northern Hemisphere (NH)

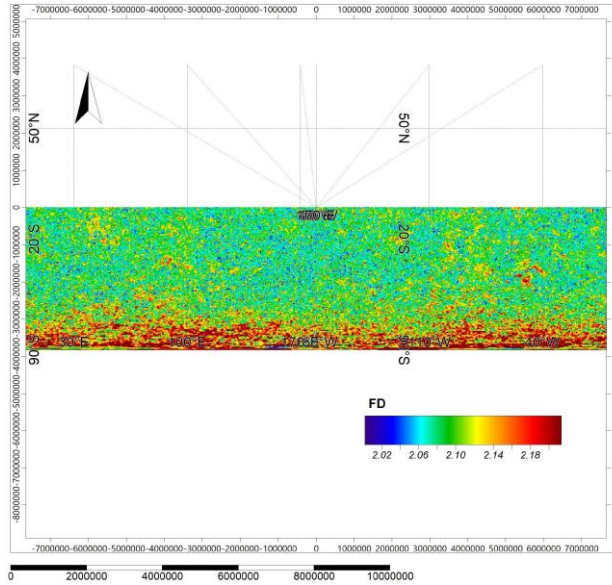


Fig. 4. Spatial distribution of slope fractal dimension (FD) within Mercury's Southern Hemisphere (SH)

Additional explanations are rooted in Mercury's geological evolution. As shown in Fig. 3, the highest FD values in the Northern Hemisphere are concentrated around deep impact structures in the polar regions. In the Southern Hemisphere, at comparable latitudes, FD variations are generally weaker and spatially more restricted. This hemispherical asymmetry likely reflects differences in volcanic resurfacing intensity. During Mercury's early history, extensive volcanic activity in equatorial regions resulted in partial infilling and flattening of pre-existing impact craters. Consequently, although large craters are present, their present-day depths are reduced. The Caloris Basin represents a prominent example, having likely been significantly deeper prior to volcanic resurfacing.

Volcanic processes also affected the polar regions, but to a lesser extent. As a result, a subtle hemispherical dichotomy is observed. The Northern Hemisphere exhibits sharper topographic contrasts and higher FD values compared to the Southern Hemisphere (Fig. 3 and Fig. 4). Craters in the north tend to be steeper, consistent with differences in impact preservation state. In contrast, craters near the south pole generally display gentler slopes, implying earlier cessation of volcanic and tectonic activity.

The results indicate that Mercury's two hemispheres experienced distinct geological histories and fractal characteristics of slope distribution in the Northern Hemisphere relative to the Southern Hemisphere. This provides a comparative framework for assessing hemispherical differences in topography complexity rather than direct constraints on absolute geological age.

Conclusion

This study demonstrates that the slope distribution of Mercury's surface exhibits a well-defined fractal nature, quantified using a variogram-based fractal dimension approach. The obtained fractal dimension values (mean FD = 2.127 for the Northern Hemisphere and 2.107 for the Southern Hemisphere), supported by very high coefficients of determination (mean $R^2 = 0.997$ for the Northern Hemisphere and 0.998 for the Southern Hemisphere), indicate that Mercury's slopes are organised in a scale-invariant manner. This spatial organisation reflects the cumulative influence of long-term geological processes acting on the planet's surface.

Comparative hemispherical analysis reveals a clear, though moderate, asymmetry. The Northern Hemisphere exhibits a slightly higher mean fractal dimension and greater spatial variability, characteristics that are spatially associated with large impact structures and regions that experienced limited volcanic smoothing, particularly at high latitudes. In contrast, the Southern Hemisphere displays more homogeneous fractal properties, suggesting earlier or more extensive surface modification.

The spatial patterns of fractal dimension further indicate that higher FD values correspond to areas with pronounced topographic gradients, such as deep basins and relatively well-preserved cratered terrains, whereas lower FD values dominate smoother plains affected by volcanic resurfacing. This confirms that slope-based fractal metrics are sensitive to variations in morphological complexity and the degree of surface modification.

The results support the interpretation that Mercury's hemispheres underwent distinct geological histories, marked by differences in impact preservation and volcanic resurfacing intensity. The variogram-based fractal analysis of Mercury's slope provides new opportunities for future comparative studies of Mercury in particular and other terrestrial planetary bodies more broadly.

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ФРАКТАЛЕН АНАЛИЗ НА МОРФОМЕТРИЯТА НА НАКЛОНИТЕ НА МЕРКУРИЙ НА БАЗАТА НА ВАРИОГРАМА

Р. Илиев, Б. Рангелов

Резюме

Изследването прилага вариограмен подход за определяне на фракталната дименсия (ФД) на разпределението на наклоните на повърхността на Меркурий въз основа на глобалния ЦМР (DEM) от мисията MESSENGER. Резултатите показват ясно фрактално поведение с високи коефициенти на детерминираност ($R^2 > 0.99$). Средните стойности на ФД са 2.127 за Северното полукуълбо и 2.107 за Южното, като Северното полукуълбо демонстрира по-голяма пространствена хетерогенност и по-висока сложност, особено в райони с големи импактни басейни и ограничено вулканично изглаждане. Южното полукуълбо показва по-хомогенни фрактални характеристики, което отразява разлики в интензивността на вулканично преоформяне и заравняване на релефа. Тези умерени, но статистически значими разлики подкрепят идеята за различна геоложка еволюция на двете полукуълба на Меркурий и потвърждават полезността на вариограмния фрактален анализ за сравнителни планетарни изследвания.

SPECTRAL MAPPING OF WASTE DISPOSAL SITES NEAR IHTIMAN

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Keywords: *satellite data, open data, unregulated landfill, climate change, LST, TCT*

Abstract

The presented study provides a spatial-temporal analysis of the development of a municipal waste landfill located near the town of Ihtiman, focusing on the processes and factors that led to the emergence and expansion of an unregulated landfill after the recultivation of the main landfill. This article is a continuation of a 2020 study that analyzed the main municipal waste landfill. At this stage, the focus is broadened to track the subsequent processes and changes that occurred after recultivation, including the emergence and development of illegal landfills.

Introduction

At the beginning of the 21st century, waste management remains one of the most serious challenges to sustainable development. Despite scientific and technological progress and the existence of regulatory mechanisms, there is a global trend towards increased waste generation, which puts pressure on both the environment and the institutional capacity to manage it effectively. The organization and management of municipal waste is the direct responsibility of local authorities, which should provide the necessary infrastructure for the collection, transport, treatment, and final disposal of household waste. However, a number of developed and developing countries are experiencing serious difficulties in maintaining landfills in a sustainable condition. The main challenges stem from inefficient management, often due to social, institutional, and technical constraints, including a lack of coordination between the responsible authorities, insufficient financial support, and outdated technological solutions. According to global estimates, the amount of waste generated has doubled over the last decade, and forecasts indicate that it will reach 2.5 billion tons per year by 2025. This negative trend is the result of the combined impact of accelerated urban development and increased consumption by the population [1].

The growing availability of open and spatial data sets has significantly improved opportunities for timely and informed decision-making, not only in the

business sector and decentralized administrations, but also in municipalities and local communities. This trend is particularly important in the context of the pronounced shortage of highly qualified specialists.

Financial constraints and limited institutional capacity in smaller settlements have necessitated the adoption of research approaches that could be implemented by a relatively small number of well-trained professionals. Given the wide availability of valuable administrative data, such as open and spatial data sets, satellite information from the Copernicus and Landsat programs, and data from continuous environmental monitoring provided by the Ministry of Environment and Water, it is imperative that these resources be used systematically to generate significant economic benefits and added value [2].

Unregulated landfills for household and construction waste pose a significant environmental and social challenge. Illegal waste accumulation is increasingly observed in various spatial contexts, including peripheral neighborhoods, suburban areas, and even central public spaces. Although population growth and urban expansion contribute to this phenomenon, the main factors for the formation and persistence of such illegal waste dumps remain inadequate monitoring and enforcement mechanisms [3].

Study area

The landfill for municipal waste in Ihtiman is a former municipal facility located in the area of “Swamp”, near the road to the village of Muhovo and the “Trakia” highway. The facility ceased operations in October 2016 due to non-compliance with the current waste management regulations [4, 5].

In the period prior to its final closure, a number of problems were reported, including the occurrence of combustion processes and the risk of contamination of environmental components, which necessitated control activities and the implementation of preventive measures to limit unauthorized activities. In 2018, the Regional Inspectorate for Environment and Water – Sofia carried out an inspection, which did not find any exceedances of the permissible standards for air pollution, but additional instructions were issued for enhanced monitoring and control [4, 6].

The process of closing and recultivating the landfill was carried out in stages, with the municipality of Ihtiman conducting public procurement procedures and market consultations. The technical recultivation of the site was finally completed in 2020 [6].

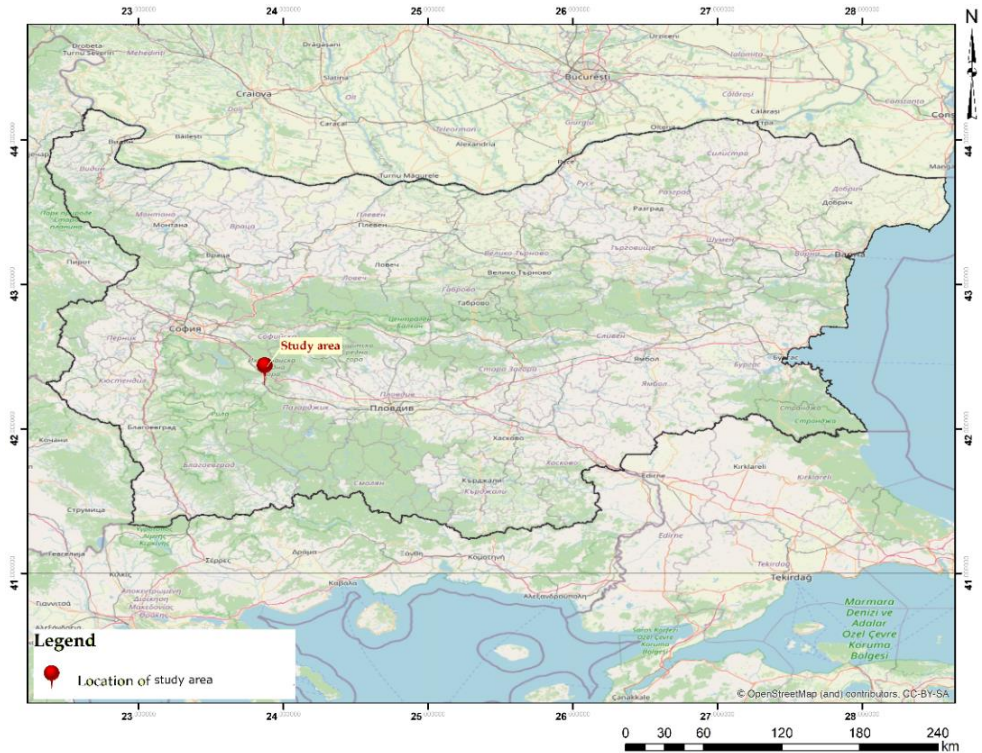


Fig. 1. Map of the area of interest

Materials and Methods

The satellite data used in this study were obtained from the European Space Agency (ESA) Sentinel-2B and Sentinel-3B missions and from the Landsat 8 and 9 OLI/TIRS sensors operated by the National Aeronautics and Space Administration (NASA) (Table 1). Sentinel satellite images are freely available through the Copernicus Data Space Ecosystem, and all Landsat 8 and 9 products are available free of charge through the Earth Resources Observation and Science (EROS) Center of the US Geological Survey (USGS) [7–10].

The selection of images was limited to scenes captured during cloudless weather over the study area to ensure data quality and reliability of the analysis. The capture dates of the satellite images used to monitor the study sites, along with the corresponding sensors, are presented in Table 1.

Table 1. Satellite data

Satellite	Date
Sentinel-2B	30.08.2020
Sentinel-2B	10.08.2025
Sentinel-3B LST	23.07.2023
Sentinel-3B LST	08.11.2023
Sentinel-3B LST	30.12.2023
Sentinel-3B LST	27.09.2024
Sentinel-3B LST	13.08.2025
Landsat 8 OLI / TIR	11.07.2016
Landsat 9 OLI / TIR	04.07.2022
Landsat 9 OLI / TIR	27.07.2022
Landsat 9 OLI / TIR	23.07.2023
Landsat 9 OLI / TIR	08.11.2023
Landsat 9 OLI / TIR	27.09.2024
Landsat 9 OLI / TIR	13.08.2025

Two optical indices were used in this study: Normalized Difference Greenness Index (NDGI) and Modified Soil-Adjusted Vegetation Index (MSAVI2).

MSAVI2 is an adapted version of the soil-adjusted vegetation index (SAVI). It was developed to reduce NDVI inaccuracies in areas with exposed soil surfaces [11]:

$$(1) \quad \text{MSAVI2} = \frac{\left(2 \cdot \text{NIR} + 1 - \sqrt{(2 \cdot \text{NIR} + 1)^2 - 8 \cdot (\text{NIR} - \text{RED})}\right)}{2}$$

The quasi-synchronous assessment using LST data from two satellite platforms, combined with vegetation and greenness indicators, provided a more comprehensive characterization of surface conditions and improved spatiotemporal stability. Verification and validation of the satellite images were performed using the Tessellated Cap Transformation (TCT) model in combination with the Normalized Difference Greenness Index (NDGI). The analyses focused on pre-selected test areas covering waste disposal sites outlined by high-resolution optical images.

All Sentinel-2 MSI bands are used for TCT calculation, Kauth and Thomas (1976) [12], Crist and Cicone (1984) [13]:

Brightness (Br), Greenness (Gr), Wetness(W)

$$(2) \quad nW = (W - E\{W\})/St.Dev(W)$$

$$(3) \quad nBR = (BR - E\{BR\})/St.Dev(BR)$$

$$(4) \quad (nGR=(GR-E\{GR\}))(St.Dev(GR))$$

Derived from the Greenness component of TCT-applied Sentinel-2 imagery, NDGI quantifies vegetation state variations over time. With values ranging from +1 to -1, it serves as an indicator of vegetation development [14]:

$$(5) \quad NDGI = \frac{GR_n(t_2) - GR_n(t_1)}{|GR_n(t_2)| + |GR_n(t_1)|}$$

To achieve the main objective of the study, temperature changes associated with thermal emissions from landfills were monitored over different time periods. For this purpose, satellite data from Landsat missions 8 – 9 were used, calculated from thermal infrared data by applying the following formula:

$$(6) \quad T_{[K]} = a * \ln^{-1} \left(\frac{b}{c * Q + d} + 1 \right)$$

where **a, b, c, d** are the constants for the different types of Landsat images;

T is the pixel temperature (K);

Q is the spectral brightness coefficient of the surface in the thermal bands of Landsat (4–9). After the georeferencing procedure of the thermal images, rectangular sections are cut out in each image, covering the area around the geographic coordinates. The time series {Q1, Q2, . . . , Qn} of the images in the thermal channel of each waste disposal site is extracted. The data from the image is converted into the surface temperature {T1, T2, . . . , Tn} using the transformation:

$$(7) \quad T_{[°C]} = a * \ln^{-1} \left(\frac{b}{c * Q + d} + 1 \right) - 273.15,$$

where

a is the K_2 = Thermal conversion constant for the band (K2_CONSTANT_BAND_n from the metadata);

b is K_1 = Thermal conversion constant for the band (K1_CONSTANT_BAND_n from the metadata);

c is M_l = Radiance multiplicative scaling factor for the band (RADIANCE_MULT_BAND_n from the metadata);

d is L_λ = Spectral radiance ($W/(m^2 * sr * \mu m)$);

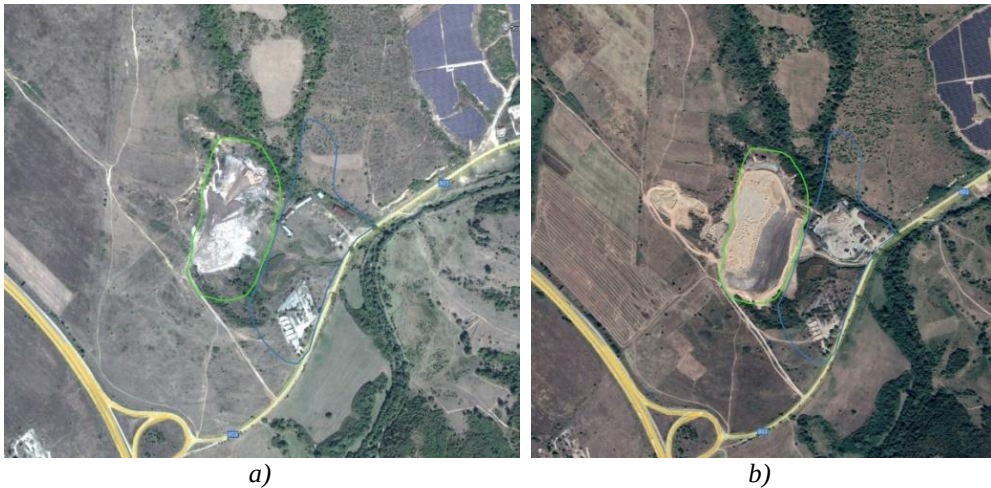
Q = L1 pixel value in DN;

T = TOA (Top of Atmosphere) Brightness Temperature [10].

The other data used are from Sentinel-3A and Sentinel-3B (Table 1), and the SLSTR thermal bands used to extract SST (the three infrared channels S7, S8, and S9 at 3.74 μm , 10.85 μm , and 12 μm) are also used to extract LST in SLSTR Level 2 products. The algorithms for extracting LST using split-window radiation are sufficiently sophisticated to achieve an accuracy of 1 K, especially at night when there is no differential heating of the surface [15].

Results and Discussions

Fig. 2 shows images from Google Earth, where the old landfill is marked with a green polygon and the new landfill with a blue polygon. Fig. 2a shows an image from September 23, 2020, and Fig. 2b shows an image from 2021, when the recultivation process began, according to data from the municipality of Ihtiman.



*Fig. 2. a) Image from Google Earth from 23.09.2012;
b) Image from Google Earth from 20.09.2020*

With regard to surface temperature (LST), data from Landsat 8 for 08.11.2013 were found (Fig. 3a). The figure shows an increase in surface temperature from the old municipal waste landfill (outlined in green), with a temperature of 17° C within the boundaries of the landfill, which is higher than the rest of the surface (+12°C – +14°C). In the northeastern part of the landfill, there is also a photovoltaic park, which further affects the surface temperature in the area. Several heat islands can be observed north of the landfill and the photovoltaic park.

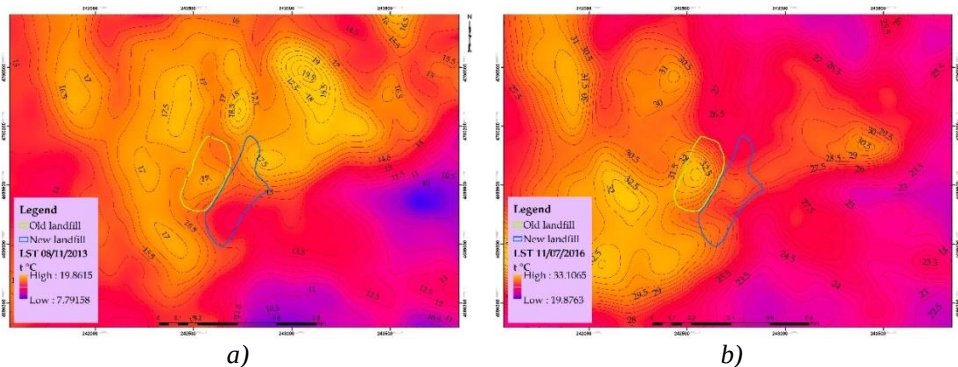


Fig. 3. a) LST Landsat 8 from 08.11.2013;
b) LST Landsat 8 from 11.07.2016

South of the landfill (newly formed after 2020), no increase in surface temperature is observed. Fig. 3b shows the LST from July 11, 2016, where a heat island is located, again within the boundaries of the old landfill. The maximum temperature in the center of the landfill is $+32^{\circ}\text{C}$, and several additional heat islands are observed to the west of the landfill itself.



Fig. 4. a) Image from Google Earth from 13.03.2023;
b) Image from Google Earth from 11.01.2025

Fig. 4 again shows images from Google Earth for a clearer visualization of the studied area in the visible spectrum. Fig. 4a shows an image from March 13, 2023, which shows that the old household waste landfill has been reclaimed. However, a new unregulated landfill is forming within the boundaries of the blue polygon. Fig. 4b shows an image from January 11, 2025, which reveals that the waste has already spread throughout the newly formed unregulated landfill.

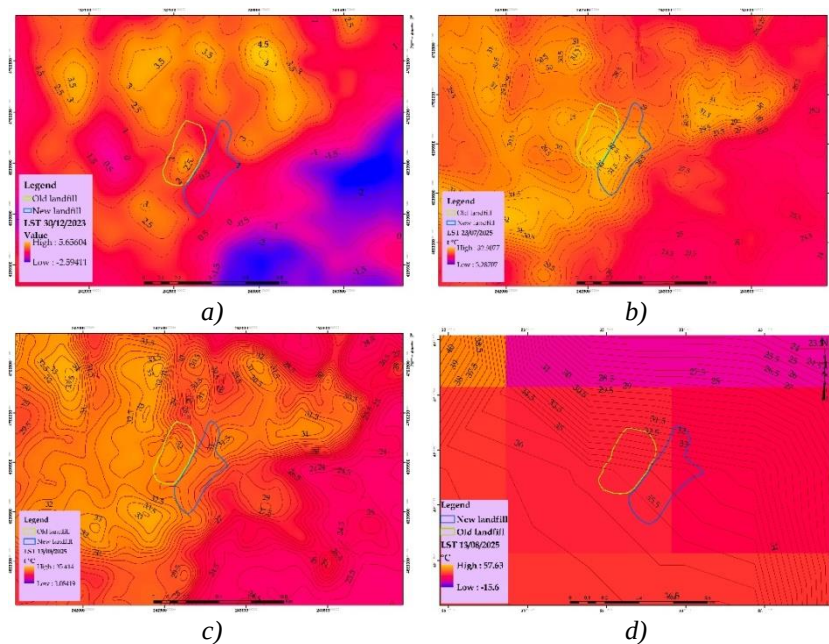


Fig. 5. a) LST Landsat 9 from 30.12.2023; b) LST from 23.07.2025, c) LST Landsat 9 from 13.08.2025; d) LST from Sentinel-3 from 13.08.2025

Fig. 5a–c shows surface temperature data from Landsat 9. To verify the results, LST from Sentinel was also used, with a spatial resolution of 1 km, while Landsat has a spatial resolution of 30 m. Fig. 5a shows data from December 30, 2025, where the local island that has formed again is within the boundaries of the old (already recultivated) landfill. The temperature reaches $+3^{\circ}\text{C}$, while for comparison, within the boundaries of the new island, it is $+0.5^{\circ}\text{C}$. For the rest of the surface, it varies from -1.5°C to $+0.5^{\circ}\text{C}$. Fig. 5b shows the LST values for July 23, 2025. Here, a large heat island has formed, which is within the boundaries of both the old (reclaimed landfill) and the unregulated landfill. The surface temperature reaches $+32.5^{\circ}\text{C}$, exerting a strong influence on the northwest. The formation of local heat islands is the result of the combined effect of the deposited waste and the photovoltaic panels, which change the albedo and heat balance of the surface located east of the landfill. The same can be observed in Fig. 5c and Fig. 5d, which are from the same date – 13.08.2025, but from different satellite platforms. The data from Landsat 9 again show the spread of local islands due to the combination of the nearby photovoltaic park and the reclaimed landfill, in combination with the unregulated one. Based on the data obtained from Landsat and Sentinel-3, it can be clearly concluded that the studied objects have a strong impact on the surrounding area, which is located to the northwest.

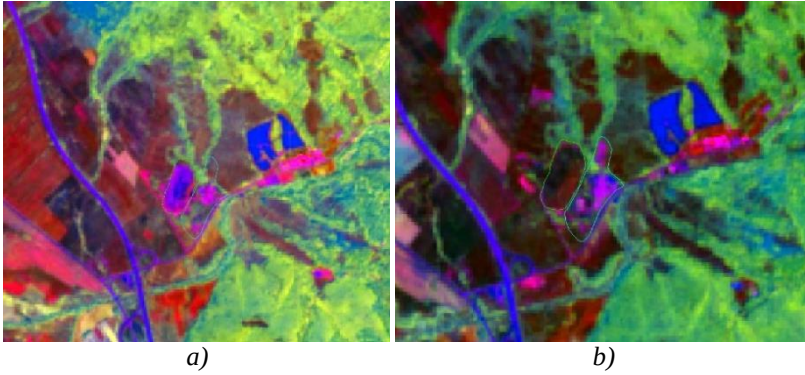


Fig. 6. a) TCT from 30.08.2020; b) TCT from 30.08.2025

TCT is the surest method of identifying municipal landfills, as they are colored in a color that is out of character for the other components – soil, vegetation, moisture. Fig. 6a shows the TCT model as of August 30, 2020, which shows purple coloration entirely within the old municipal landfill and purple coloration in the northeastern portion of the unregulated landfill. For 2025, the model indicates that the waste that is again colored purple is entirely within the boundaries of the unregulated landfill (Fig. 6b).

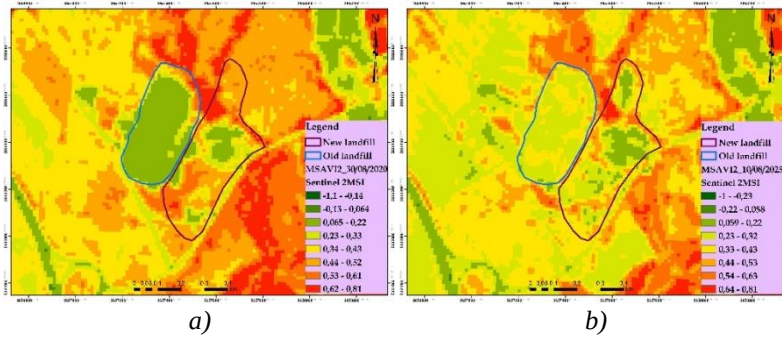


Fig. 7. a) MSAVI2 from 30.08.2020; b) MSAVI2 from 10.08.2025

The Modified Soil-Adjusted Vegetation Index (MSAVI2) is an enhanced version of the Soil-Adjusted Vegetation Index (SAVI), designed to account for soil brightness effects more effectively. The index is calculated using reflectance values from the near-infrared and red spectral bands, which are commonly available in satellite imagery. MSAVI2 is particularly sensitive to variations in vegetation density and provides a more accurate representation of green vegetation cover compared to other widely used indices, such as the Normalized Difference Vegetation Index (NDVI) [16].

MSAVI2 is widely applied in agricultural, forestry, and ecological studies, as well as in land cover mapping and classification. It is commonly derived from

satellite imagery acquired by sensors such as Landsat, MODIS, and Sentinel-2. In this study, MSAVI2 was calculated using Sentinel-2 data. The index provides valuable information on vegetation distribution and density [17], which can be used to monitor land cover dynamics, assess the impacts of land-use change, and support informed decision-making in land and natural resource management [18].

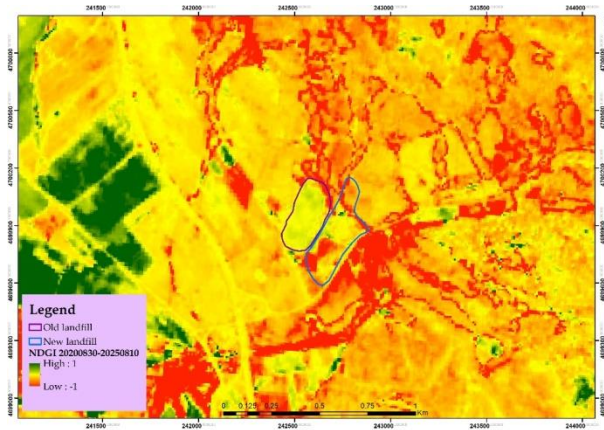


Fig. 8. NDGI 30.08.2020–10.08.2025

In general, the NDGI index shows insignificant changes in vegetation cover in the area of the waste disposal site during the period 2020–2025. The observed patterns indicate localized but clearly pronounced changes in vegetation dynamics, probably related to surface disturbances and waste disposal processes.

Furthermore, images from the Tasseled Cap Transformation (TCT) (Fig. 6b) reveal significant variations in surface moisture, represented by light blue tones, which may be associated with the presence of infiltrate and altered soil conditions characteristic of waste disposal sites.

Conclusion

Some of the key reasons for the need for regular and interim monitoring of municipal waste landfills are as follows:

- Monitoring the spread of harmful substances – hazardous materials such as heavy metals, chemicals, and electronic waste are increasingly finding their way into landfills, posing a danger if not controlled in time.
- Preventing soil and water pollution – improper waste treatment can lead to the release of toxic substances that can seep into the soil. Over time, these toxins contaminate groundwater and surface water, which are sources of drinking water, agricultural needs, and ecosystems. Regular monitoring of landfills can prevent such contamination.

- Control over the spread of heat islands and biochemical processes that can cause long-term damage to soil and surrounding water sources – Biochemical processes occurring within landfills generate methane and carbon dioxide, which are greenhouse gases and contribute to climate change. A local microclimate often forms around landfills, which differs from the rest of the surface. Methane, for example, is the main cause of spontaneous combustion in landfills. Monitoring these emissions is necessary in order to control air pollution.

- Improving waste management through informed and timely decisions based on up-to-date remote and field data.

It has been proven that land surface temperature (LST) is an important climate indicator and provides valuable information about the processes of thermal radiation from municipal waste landfills. It is these processes that contribute to the formation of localized microclimatic zones, which can lead to a number of adverse environmental and climatic consequences both in the immediate vicinity of landfills and over wider areas. Such changes may include an increase in local temperatures, changes in soil and air moisture, and a negative impact on biodiversity and agricultural productivity in neighboring areas.

Acknowledgements

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СПЕКТРАЛНО КАРТИРАНЕ НА ДЕПА ЗА БИТОВИ ОТПАДЪЦИ В БЛИЗОСТ ДО ИХТИМАН

А. Данчева, Т. Спасова, А. Стоянов

Резюме

В представеното изследване е извършен пространствено-времеви анализ на развитието на депо за битови отпадъци, разположено в близост до град Ихтиман, като акцентът е поставен върху процесите и факторите, обусловили възникването и разрастването на нерегламентирано сметище след рекултивацията на основното депо. Настоящата статия представлява продължение на изследване, проведено през 2020 г., в рамките на което е анализирано основното депо за битови отпадъци. В настоящия етап фокусът се разширява с цел проследяване на последващите процеси и промени, настъпили след рекултивацията, включително появата и развитието на нерегламентирани депонирания.

MAPPING AND DATA VISUALIZATION OF LAND COVER SURFACE HEAT DYNAMICS IN SOFIA, BULGARIA

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Key words: ECOSTRESS; urban heat; land surface temperature; heatwaves

Abstract

Heatwaves represent an increasingly critical challenge for European cities, particularly in regions with ageing populations and complex urban structures. This study examines the spatial variability of surface temperatures in Sofia, Bulgaria, using a combination of high-resolution ECOSTRESS thermal imagery and detailed land-cover data from Urban Atlas 2018. Two contrasting ECOSTRESS acquisitions were analysed: an evening scene from 14 July 2024, captured during an intense heatwave, and a morning scene from 2 July 2025, representing the baseline thermal state after nocturnal cooling. Zonal statistics were used to extract Land Surface Temperature (LST) metrics for each Urban Atlas polygon, allowing a detailed comparison of thermal behaviour across functional land-cover types. Results show strong diurnal contrasts, with evening mean LST exceeding morning values by approximately 9–10° C, and the highest thermal loads occurring in compact urban fabric, industrial zones, and transportation infrastructure. Natural and semi-natural areas, as well as mountainous terrain, consistently exhibited lower temperatures, confirming their cooling function within the urban environment.

Introduction

Under more frequent and longer heat waves, the urban environment responds in a particularly sensitive way. Different data sources consistently show that the spatial distribution of surface temperatures mirrors the structure, density, and functional characteristics of underlying land cover. Sofia is a city located in an intermontane basin with a highly heterogeneous urban fabric, in which different surface types accumulate, retain, and release heat in different ways, leading to significant intra-urban temperature contrasts. These processes are particularly pronounced on days with increased heat stress, when night cooling is incomplete, and the day begins on already heated urban surfaces.

Classical meteorological observations in-situ provide valuable information on air temperature, but do not capture the direct contact of humans with the urban surface and do not reveal the spatial logic of thermal anomalies across different urban zones. Satellite observations in the thermal infrared range, which allow for the

measurement of Land Surface Temperature (LST) at high spatial resolution, are particularly useful for providing insights. In this context, the ECOSTRESS instrument located at the International Space Station provides daily imaging with a resolution of 70 m, which makes it possible to map urban heat and its distribution at the level of neighbourhoods and even individual functional areas.

Research on heatwaves and their consequences for the human population has emerged only in the past few decades. Today, the availability of freely accessible satellite products, such as MODIS, Landsat & Sentinel-3 LST products, or the International Space Station's ECOSTRESS data, has accelerated the growth of studies dedicated to this topic. Over the last five years, analyses based on these datasets have been conducted across diverse regions of the world [1–3]. There are also a variety of studies [4, 5] using satellite data in the country consistently demonstrating the substantial impact of extreme heat on urban environments. There is also a noticeable increase in publications focused on population structure, urban ecology, and extreme events in Bulgaria. A portion of these works is directly or indirectly linked to the challenges posed by climate change in urban settings [6–9].

According to the National Institute of Meteorology and Hydrology's monthly bulletins [10, 11] in the summer of 2025 during the periods of 30 June 2025 and 09 July 2025, and between 19 July 2025 and 29 July 2025, the country was experiencing a heat wave, which meets the criteria defined for the presence of more than 5 consecutive days with a maximum air temperature above 32°C. In 2024, an intense heatwave affected the country between 06 July 2024 and 24 July 2024. Monthly temperatures exceeded climatological norms by +1.4°C to +3.9°C, and July 2024 was nearly as warm as July 2012, which was the warmest July since 1930. The highest temperatures in urban areas, ranging from 32°C to 42°C were registered between 14 and 18 July.

Bulgaria is among the fastest-ageing countries in Europe, with a steadily increasing share of the population over the age of 65 and a significant decline in the working-age segment. This demographic structure elevates the country's vulnerability to extreme heat because older adults are physiologically more sensitive to extreme temperatures and often have limited adaptive capacity. In this context, studying heat exposure and thermal risks becomes particularly important, as it supports urban planning interventions and public health measures that aim to protect the most vulnerable segments of society.

This paper aims to examine the spatial variability of surface temperatures in Sofia by combining ECOSTRESS morning and evening thermal observations with Urban Atlas land cover data. Through a comparative analysis of morning and evening ECOSTRESS acquisitions during a heatwave, the study assesses the thermal load of different functional urban areas and identifies the land cover types that contribute most strongly to heat accumulation and retention during periods of elevated thermal stress.

Methods and Data

Data sources

ECOSTRESS (Ecosystem Spaceborne Thermal Radiometer Experiment on Space Station) is a multispectral thermal infrared (TIR) instrument mounted on the International Space Station (ISS) [12]. It was designed to measure the temperature of the Earth's surface with high spatial and temporal detail. ECOSTRESS provides one of the most precise satellite-based Land Surface Temperature (LST) datasets currently available for environmental and urban studies. Because ECOSTRESS is hosted on the ISS, it does not follow a sun-synchronous orbit like other satellites used for urban studies & Earth observation. As a result, its overpass times are variable, allowing acquisition of surface temperature data at different moments of the diurnal cycle, for example, early in the morning, mid-day, or nighttime scenes. This characteristic of the data is highly advantageous for studying surface heat dynamics as it captures temperature states that are often missed by conventional sensors.

The research is based on two ECOSTRESS Land Surface Temperature (LST) scenes acquired over Sofia City Province during periods of elevated summer heat (Fig. 1). The first dataset represents an evening observation captured on 14 July 2024 at 20:53 local time, and the second corresponds to a morning observation taken on 2 July 2025 at 07:13 local time. Both scenes were selected as the only cloud-free or minimally impacted acquisitions available for the region during the respective summer seasons and captured during officially recognised heatwave periods by the National Institute of Meteorology and Hydrology's meteo bulletins.

Each ECOSTRESS scene provides surface temperature at a spatial resolution of 70 m. Prior to the analysis, both datasets were inspected for cloud-related pixels. In the 2024 scene, pixels affected by clouds were excluded entirely to ensure the reliability of the temperature statistics. They were located outside the city centre, which allowed further analysis without extracting important parts of the studied territory. The 2025 morning scene did not contain cloud-contaminated areas within the study extent.

To characterise the functional structure of Sofia's urban landscape, the study uses the dataset of Copernicus Land's product Urban Atlas 2018 V1 [13], a Copernicus dataset offering harmonised, high-resolution land-cover and land-use information for European cities. Urban Atlas polygons provide detailed classification of artificial surfaces, green urban areas, industrial zones, transportation infrastructure, agricultural land, forests, and water bodies. This spatial framework allows for a fine-grained assessment of thermal patterns across functionally distinct urban zones and is widely used in many studies and urban planning activities.

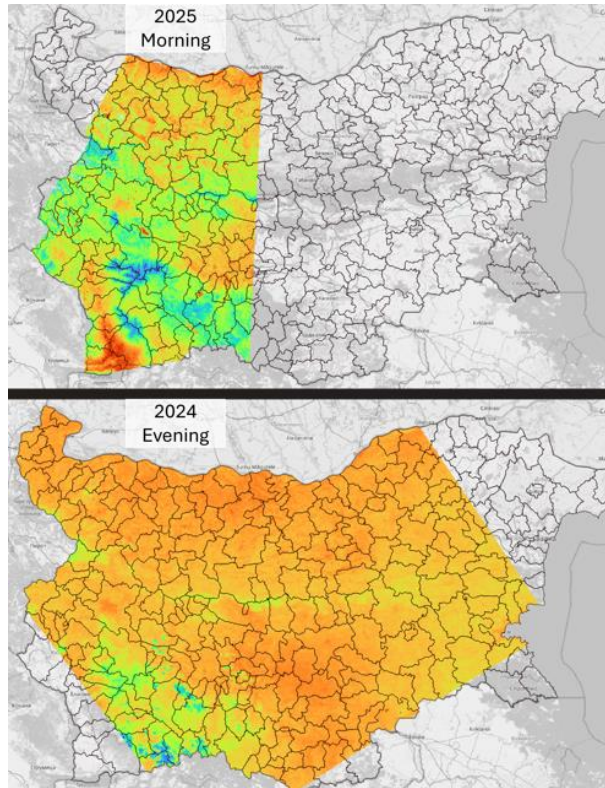


Fig. 1. ECOSTRESS data captured during heatwave periods used in the study

The combination of ECOSTRESS LST data with Urban Atlas polygons allows for a robust assessment of thermal load across different urban surfaces and supports a more nuanced interpretation of observed temperature patterns, particularly in complex and heterogeneous cities such as Sofia.

Zonal Statistics and Data Harmonisation

The surface temperature statistics of the rasters were converted from Kelvin to Celsius and then were derived using the Zonal Statistics tool in QGIS. For every Urban Atlas polygon, key descriptive indicators of the LST distribution were computed – minimum, maximum, mean, and median temperature values. These statistics were calculated separately for the 2024 evening and 2025 morning scenes. All statistics were harmonised to a unified naming scheme to enable consistent comparison between the two datasets. Polygons with zero pixel coverage were removed. To support comparative analyses, an additional “broad land cover group” attribute was created based on the hierarchical structure of Urban Atlas

codes, grouping polygons into categories such as Artificial surfaces, Agricultural areas, Natural and semi-natural areas, Wetlands, and Water bodies.

The harmonised datasets were merged into a single analytical table, preserving for each polygon its land-cover classification, area, and population (sourced from the layer Urban Atlas 2018), and LST statistics for both time periods. The comparison focuses on the overall temperature distributions in morning vs evening conditions, the differences in thermal load across broad Urban Atlas groups, detailed contrasts between specific land-cover classes, and the magnitude of evening–morning temperature differences for each class (Fig. 2).

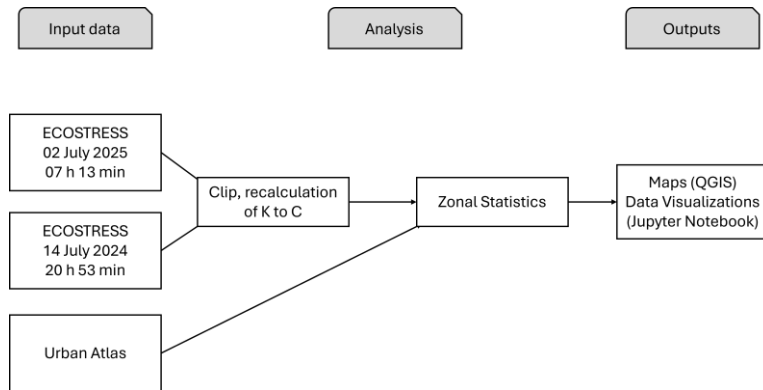


Fig. 2. Data processing steps & outputs of the study

Data exploration, descriptive statistics, and visualisations were performed in a dedicated Jupyter Notebook using Python libraries like pandas, matplotlib, and seaborn. The notebook and data analysis are publicly available on GitHub.

Results

Comparative Surface Temperature Patterns – Morning 2025 vs Evening 2024

The two ECOSTRESS acquisitions shown in Fig. 3 reveal distinct thermal patterns that reflect the different stages of the diurnal heating cycle during periods of elevated summer temperatures. The evening scene from 14 July 2024 on the right shows a persistent retention of daytime heat across Sofia’s built-up areas. Median LST values remain elevated, with artificial surfaces displaying the highest thermal load and forming a pronounced warm core within the urbanised territory. Natural and semi-natural areas appear noticeably cooler, though the thermal gradient between land cover types is still moderate, indicating that the urban fabric has not yet undergone significant nocturnal cooling.

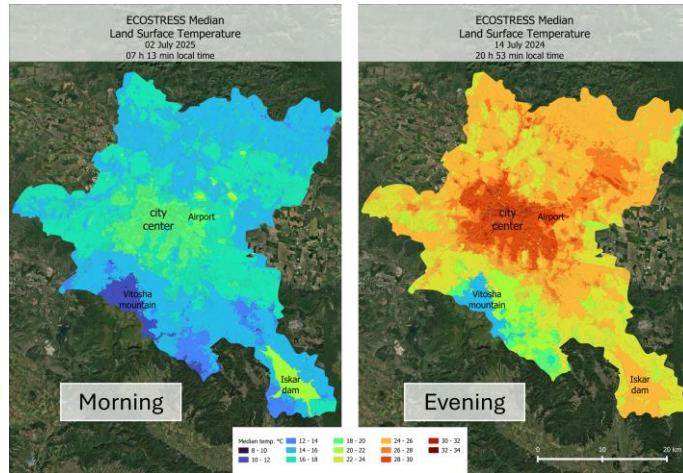


Fig. 3. Median LST of Urban Atlas polygons for the morning and evening ECOSTRESS data

The morning scene from 2 July 2025, acquired at 07:13 local time, depicts the city at the start of a new heating cycle. Surface temperatures are substantially lower across all land cover groups, and the overall distribution is narrower and shifted toward cooler values. Vegetated and mountainous areas exhibit the lowest LST, while artificial surfaces remain comparatively warmer, but with a considerably reduced thermal contrast relative to the evening dataset. This suggests that built-up areas retain higher residual heat overnight, yet early-morning conditions still allow clearer differentiation between surface types before solar heating intensifies.

In both scenes, the city centre forms the warmest and most spatially extensive hot spot, with the highest median surface temperatures in the evening and still clearly elevated values in the morning compared to the rest of the municipality. The area around Sofia Airport shows intermediate conditions that are warmer than the vegetated western and southern parts of the city, yet generally cooler than the compact central districts, reflecting a mixture of paved surfaces, runways, and open grassland.

Iskar Dam appears noticeably warmer than the surrounding mountainous terrain in the morning scene, forming a local warm patch within an otherwise cool landscape. In the evening scene, however, the dam becomes hotter, but not as much as in the morning, relative to its surroundings.

A Jupyter Notebook & Python libraries such as matplotlib, seaborn, and numpy were used for further statistical analysis of the data. Fig. 4 shows the density distributions of mean LST for the two ECOSTRESS acquisitions. It reveals a pronounced thermal contrast between morning and evening conditions. The morning scene (2 July 2025) is characterised by a compact, unimodal distribution centred around 14–18°C, reflecting the cooler state of the urban surface at the start of the day after partial nocturnal cooling.

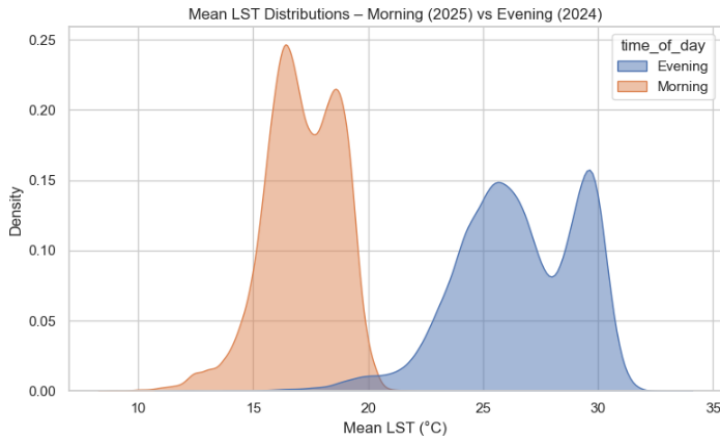


Fig. 4. Mean LST distributions in the evening and morning data capture

The evening scene (14 July 2024) exhibits a distinctly warmer and broader distribution, with values concentrated between 24°C and 30°C, indicating substantial heat storage throughout the day during a period of intense heat. The evening curve shows a slight bimodality, likely reflecting different thermal behaviours of dense built-up areas versus more vegetated or open surfaces. The two distributions show no overlap, illustrating that even the coolest evening surfaces remain significantly warmer than the warmest morning surfaces. This strong separation confirms the magnitude of diurnal temperature variability in Sofia during summer heat events and highlights the persistent thermal load in the city’s built-up areas.

Fig. 5 is a data visualisation of a boxplot comparison of mean LST across broad Urban Atlas land-cover groups. It highlights consistent thermal differences between morning and evening conditions, as well as clear contrasts among surface types. In all categories, evening temperatures are significantly higher and exhibit wider variability, reflecting the accumulated daytime heat during the July 2024 heatwave. Artificial surfaces show the highest evening medians, surpassing 28–30°C, and display the broadest spread, indicating strong intra-group heterogeneity typical of dense urban fabric. Agricultural areas and natural & semi-natural surfaces form intermediate evening ranges, while wetlands and water bodies remain relatively cooler but still elevated compared to morning values.

The morning scene from July 2025 presents a more compressed temperature range across all land-cover groups, with medians clustering around 14–18°C. Although absolute temperatures are lower, the relative ranking of land-cover types remains similar, with artificial surfaces consistently warmer than vegetated categories, indicating persistent residual heat in built-up zones even after nocturnal cooling. Water bodies show a distinct pattern: cooler than surrounding areas in the evening but comparatively warmer in the morning, reflecting their slower diurnal response compared to land surfaces.

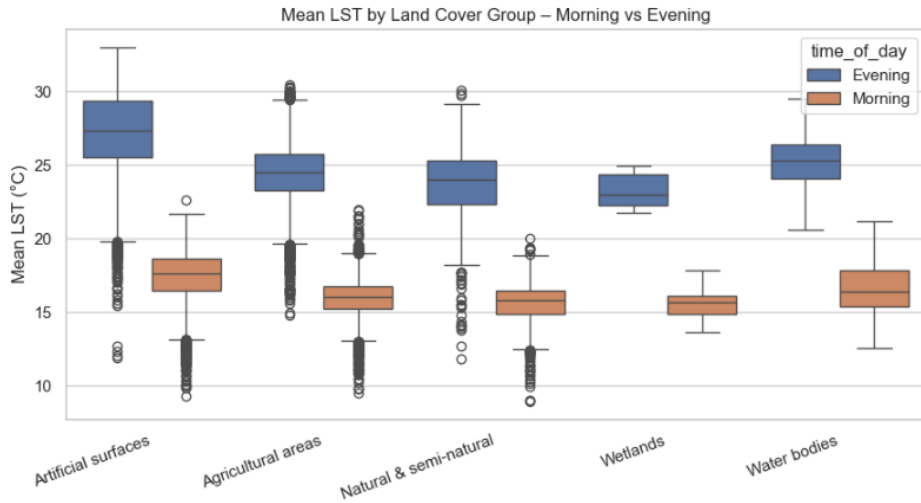


Fig. 5. Mean LST by land cover groups – a comparison between evening and morning data capture

The ranking of Urban Atlas classes by evening–morning LST difference reveals the land-use categories that retain the most heat during the day and release it the slowest overnight (Fig. 6). Continuous urban fabric (S.L. > 80%) exhibits the highest thermal contrast, with evening temperatures exceeding morning values by nearly 10°C, highlighting the strong heat storage capacity of dense, highly impervious surfaces.

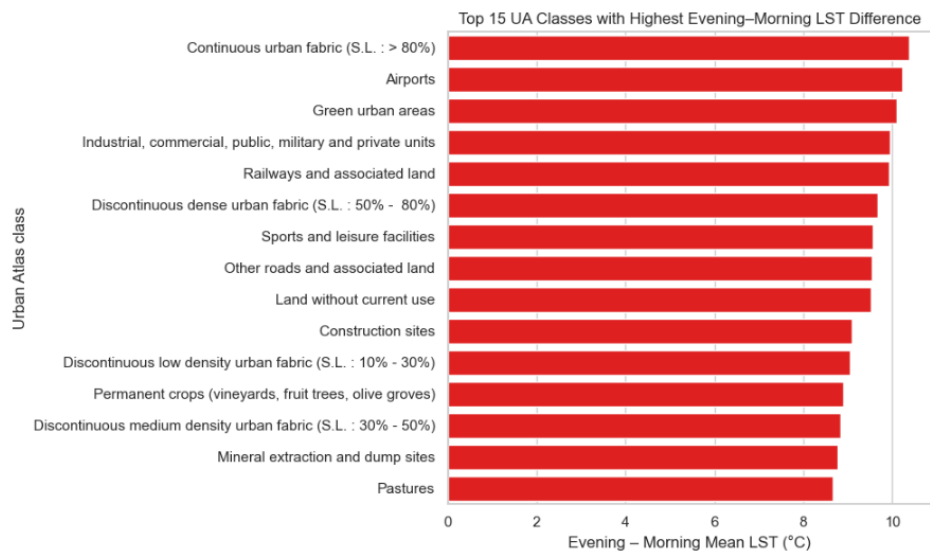


Fig. 6. Top 15 Urban Atlas Classes that have the highest evening-morning LST differences

Airports and green urban areas also demonstrate substantial differences, reflecting extensive paved infrastructure in the former and complex vegetation–soil interactions in the latter. Industrial and commercial units, along with transportation-related categories such as railways and associated land and other roads, show similarly large evening-morning temperature gaps, indicative of large asphalted and concrete surfaces with high thermal inertia. Among residential categories, discontinuous dense urban fabric (50–80% sealing) stands out with a substantial thermal range, suggesting that areas combining built-up patches with limited vegetation also accumulate considerable heat.

Lower-density settlement types, construction sites, and permanent crops (e.g., vineyards and fruit trees) appear in the lower portion of the top 15 but still exhibit differences of 7–8°C, reflecting moderate but significant heat retention. Even natural and semi-natural categories such as pastures appear in the list, although these show the smallest contrast among the top-ranked classes.

The summary statistics in Table 1 highlight the substantial diurnal contrast in surface temperatures captured by the two ECOSTRESS acquisitions. The evening scene registers a mean LST of 26.51°C, with maximum values approaching 33°C, reflecting the strong heat accumulation characteristic of late-afternoon and early-evening conditions during a summer heat event. The morning scene shows lower temperatures, with a mean of 17.09°C and a maximum of 22.59°C, indicating that overnight cooling significantly reduces surface heat, although residual warmth remains in certain areas.

Table 1. Summary table for pixel statistics in °C

Time of day	Mean LST	Median LST	Min LST	Max LST
Evening	26.51	26.453	11.827	32.977
Morning	17.09	17.090	8.938	22.588

Minimum temperatures also differ notably, with the evening recording 11.83°C compared to 8.94°C in the morning.

The magnitude of evening-morning differences varies substantially across land use types, with the highest thermal amplitudes occurring in compact residential fabric, transportation infrastructure, and industrial zones. Natural and semi-natural surfaces exhibit more moderate fluctuations. These findings confirm that during summer heat events, Sofia’s urban core functions as a persistent heat reservoir, whereas peripheral vegetated areas and higher altitudes show significantly lower thermal loads. The combined use of ECOSTRESS and Urban Atlas thus provides a detailed and coherent view of the spatial structure of urban heat, forming a solid basis for interpreting the drivers of these patterns.

Discussion

The results of this study demonstrate the clear potential of combining ECOSTRESS thermal data with detailed urban land cover classifications to gain meaningful insights into the spatial structure of urban heat in Sofia. Despite the contrasting acquisition times and seasonal conditions, both datasets consistently capture the strong influence of land cover on surface temperature, revealing coherent and interpretable thermal patterns across the city. The observed alignment between Urban Atlas classes and LST behaviour, such as the systematically higher temperatures in compact built-up areas and the pronounced cooling signature of natural and higher-elevation zones, shows that even a single high-quality morning or evening scene can provide valuable information about the functioning of the urban thermal environment. These findings confirm that open satellite data, when integrated with harmonised urban classifications, offer a robust and accessible foundation for understanding heat dynamics in complex metropolitan settings.

A key limitation of the present analysis arises from the spatial resolution of the ECOSTRESS data. Although the nominal pixel size of approximately 70 m is well suited for regional assessments of surface temperature, it restricts the level of detail achievable in dense urban environments. Fine-scale features such as individual streets, narrow green corridors, small parks, or internal temperature variability within residential blocks cannot be fully resolved. As a result, thermal contrasts may be smoothed, and the heterogeneity of urban microclimates, especially in compact and mixed-use areas, can be partially obscured. Despite this, the integration with Urban Atlas polygons helps mitigate some of these limitations by aggregating pixel values within meaningful urban units, allowing broader functional patterns to emerge even when fine-grained details remain beyond the sensor's capability.

The study also underscores the essential role of open geospatial data in advancing urban heat research. Both ECOSTRESS surface temperature datasets and the Urban Atlas land-cover layers are freely accessible, enabling high-quality, reproducible analyses without financial or institutional barriers. The ability to combine remote sensing products with harmonised European land-use classifications significantly enhances the interpretability of thermal patterns and supports robust cross-city comparisons across the EU. Open data availability thus not only democratizes access to advanced analytical tools but also strengthens policy-oriented research, allowing municipalities, planners, and researchers to collaboratively evaluate the thermal behaviour of cities in a consistent and comparable manner.

The findings further highlight the urgent need to deepen the understanding and communication of heatwave impacts on public health, especially in rapidly warming urban environments. Bulgaria's ageing population, combined with increasing frequency and intensity of heat extremes, positions heat-related risks as a growing public health concern. The observed strong thermal load in densely built-up areas suggests that large segments of the urban population may be exposed to

sustained heat stress, particularly during evenings when cooling is limited. Strengthening early-warning systems, improving public outreach, and conducting interdisciplinary research that links surface temperature patterns with demographic vulnerability, morbidity, and mortality data will be essential for developing effective adaptation strategies. In this context, remote sensing products such as ECOSTRESS can play an important role in informing targeted interventions and communicating risk in an accessible and spatially explicit manner.

Funding & Data Sharing

The repository is located at <https://github.com/eugeniasarafova/mapping-dataviz-ecostress-sofia/tree/main>, and the Jupyter Notebook at <https://github.com/eugeniasarafova/mapping-dataviz-ecostress-sofia/blob/main/Paper.ipynb>

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КАРТОГРАФИРАНЕ И ВИЗУАЛИЗАЦИЯ НА ДАННИ ЗА ДИНАМИКАТА НА ПОВЪРХНОСТНАТА ТОПЛИНА НА ЗЕМНОТО ПОКРИТИЕ В СОФИЯ, БЪЛГАРИЯ

Е. Сарафова, К. Найденов

Резюме

В настоящата статия пространственото разпределение на повърхностните температури в София е анализирано чрез комбиниране на данни от сензора ECOSTRESS и класификацията на градските функционални зони Urban Atlas 2018. За целите на изследването са използвани две термални сцени от различни етапи на денонощието – вечерно заснемане от 14 юли 2024 г. и сутрешно заснемане от 2 юли 2025 г. На базата на тези данни за всеки полигон от Urban Atlas са изчислени статистически показатели (минимум, максимум, медиана и средна стойност) посредством инструмента Zonal Statistics в QGIS. За да бъде осъществена сравнима оценка, данните са хармонизирани в единна структура и анализирани и визуализирани в Jupyter Notebook с помощта на езика Python. Резултатите показват ясно изразени разлики между сутрешното и вечерното термично състояние на градската среда, както и отчетлива зависимост на температурните стойности от вида на земното покритие. Най-високи термични натоварвания се установяват в зоните с плътна урбанизация, индустриални територии и транспортна инфраструктура, докато естествените и полуприродните площи запазват значително по-ниски температури. Представените резултати демонстрират потенциала на отворените сателитни данни за оценка на топлинните процеси в градска среда и подчертават необходимостта от по-задълбочени изследвания върху влиянието на горещите вълни върху общественото здраве.

FOREST FIRE DATABASE ON THE TERRITORY OF BULGARIA FOR THE PERIOD 2020–2024 BASED ON SATELLITE DATA

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Keywords: *Remote sensing, Forest fire database, MODIS, Bulgaria*

Abstract

This study presents the development and analysis of a geospatial database of forest fire events across the territory of Bulgaria for the period 2020–2024. The database was compiled from satellite-derived active fire detections, incorporating geographic coordinates, acquisition date and time, signal intensity, and satellite platform of origin (Terra or Aqua). Organised in shapefile format, it enables direct integration into Geographic Information Systems (GIS) for spatial analysis, visualisation, and correlation with other geospatial datasets. The results include both spatial and temporal assessments, with statistical summaries revealing interannual variability and a notable increase in recorded events in 2024. Kernel Density estimation was applied to identify high-density clusters of fire occurrences, providing insights into spatial patterns and potential hotspots. The dataset offers a robust foundation for risk assessment, supports targeted forest fire prevention and mitigation strategies, and contributes to data-driven decision-making for sustainable forest management in Bulgaria.

Introduction

Forest fires represent a significant global challenge with profound implications for the sustainable management of forest resources. This issue is of particular relevance to Bulgaria, where approximately one-third of the national territory is covered by forests, making the integrity of forest ecosystems a matter of strategic environmental concern.

In recent years, the wildfire situation in Bulgaria has become increasingly severe, particularly during the summer months of July and August. A substantial portion of these fires occur in agricultural landscapes and are often caused by the accidental or deliberate burning of stubble. Such practices are a major driver of forest fires, accounting for an estimated 40% to 60% of cases and frequently leading to the spread of fire into adjacent areas, including pastures, meadows, firebreaks, and field margins. Beyond vegetation loss, these fires often result in the destruction of entire habitats and their associated biodiversity, many of which fall within the Natura 2000 ecological network [1].

Over the past 15 years (2010–2024), more than 7,000 forest fires have been recorded in Bulgaria, according to data from the Executive Forest Agency and the Ministry of Interior [2], covering over 110,000 ha (over 1.1 million decares) of territory. The year 2024 marked a particularly critical point, with Bulgaria ranking second among European countries in terms of the number of forest fires, with the regions of the Rhodopes, Strandzha, Pirin, and Sakar being among the most severely affected. These incidents are not only increasing in frequency and intensity, but the ecological damage they cause is becoming more severe and widespread, posing a growing threat to biodiversity and forest sustainability at the national and European level.

Given the increasing frequency and severity of forest fires, there is a growing need for accurate, timely, and spatially comprehensive monitoring tools. Aerospace remote sensing methods represent an advanced technological approach for monitoring natural disasters [3–7], including forest fires [8, 9]. These methods provide the foundation for building a reliable and large-scale forest fire database, which supports the effective tracking of post-fire recovery processes in forest ecosystems [10].

Several studies have demonstrated the effectiveness of satellite-based approaches in compiling large-scale forest fire datasets, such as the MODIS burned area product [11] and the Landsat-derived global burn severity dataset [12], which have significantly contributed to fire monitoring and post-fire assessment at regional and global scales. While global forest fire datasets based on MODIS [11] and Landsat imagery [12] provide valuable insights, there remains a need for high-resolution, country-specific databases that reflect local fire dynamics and landscape characteristics.

In response to this need, the present research aimed to develop a comprehensive forest fire database for the territory of Bulgaria, covering a five-year period from 2020 to 2024. The database is based on satellite data and is intended to serve as a reliable tool for analysing fire dynamics, identifying high-risk areas, and supporting forest management and conservation efforts. Its development contributes to the implementation of data-driven strategies for mitigating the impact of forest fires and enhancing the resilience of forest ecosystems in Bulgaria.

Data and methods

For the purpose of developing the database, the following steps were undertaken: thermal anomaly data were selected for the entire territory of Bulgaria over a five-year period; areas covered by forest vegetation were filtered in order to exclude agricultural and grassland fires from the dataset; and all thermal anomalies were systematically verified (Fig. 1).

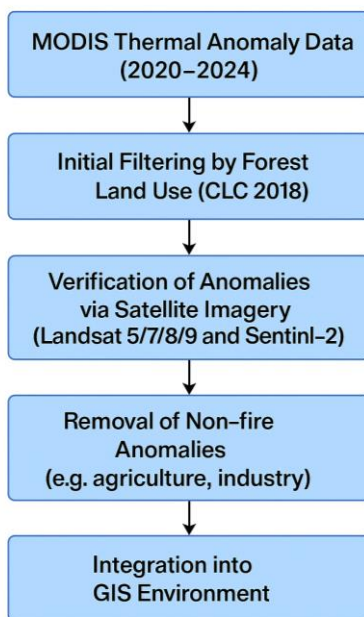


Fig. 1. Workflow diagram of the methodological framework for Forest Fire Database development (2020–2024)

Thermal anomaly data selection

Thermal anomaly data were selected for the entire territory of Bulgaria over a five-year period (2020–2024). For this purpose, data were extracted from the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor [13], mounted on the Terra and Aqua satellites, which provide regular observations with moderate spatial resolution and a broad spectral range. These characteristics make MODIS highly suitable for the detection and monitoring of thermal anomalies associated with forest and field fires.

In the first stage of database development, thermal anomalies were retrieved from the official archive of NASA's Fire Information for Resource Management System (FIRMS) [14], which offers access to pre-processed, geospatially referenced fire hotspots detected by MODIS. FIRMS automatically aggregates, filters, and publishes high-temporal-resolution data, enabling near real-time fire activity monitoring with high detection reliability.

The extracted data were structured and adapted to meet the requirements of the forest fire database being developed for the territory of Bulgaria for the period 2020–2024. Key attributes included the geographic coordinates of the thermal anomaly, date and time of detection, signal intensity, and the satellite platform of origin (Terra or Aqua). The downloaded data were integrated into a Geographic Information System (GIS) environment for further processing and analysis.

Filtering the forest vegetation

Areas covered by forest vegetation were filtered in order to exclude agricultural and grassland fires from the database. To further refine the dataset and eliminate irrelevant thermal anomalies such as those caused by field fires or industrial heat sources, the Corine Land Cover 2018 (CLC 2018) classification [15] was applied. CLC 2018 is a homogeneous pan-European land cover database developed under a unified methodology by the European Environment Agency (EEA). The classification includes more than 40 land cover categories and provides a reliable geospatial framework for ecological and territorial analysis at both national and regional levels.

At the time of the analysis, CLC 2018 represented the most recent officially available land cover classification for Bulgaria, offering standardised and comparable data for the entire national territory. Through spatial overlay of thermal anomalies with the updated land cover layers, areas classified as forest, namely broadleaved, coniferous, and mixed forests, were extracted. This step enabled the analysis to focus exclusively on forest ecosystems, in alignment with the research objectives.

Following this filtering and verification process, the resulting data were incorporated into the Forest Fire Database for Bulgaria (2020–2024) under development.

Verification of the thermal anomalies

Each thermal anomaly was individually examined to determine whether it was caused by a forest fire or by another source. The selected MODIS-detected hotspots may originate from active fires, fire-related smoke plumes, agricultural activity, or other heat sources. To verify the nature of each anomaly, optical satellite imageries were utilized from the following sources: Landsat 5 TM, Landsat 7 ETM+, Landsat 8 OLI, and Landsat 9 OLI-2 sensors, obtained via the USGS Earth Resources Observation and Science Center (USGS-EROS) [16], as well as data from the European Space Agency's Sentinel missions (ESA) [17], made available through Bulgaria's status as a cooperating state since 2015.

The satellite images from Landsat and Sentinel were used to visually inspect each hotspot and validate whether it was the result of a forest fire. If no evidence of fire was present in the corresponding Landsat or Sentinel-2 imagery, the thermal anomaly was excluded from the database. This verification process effectively filtered out false positives, thermal anomalies not associated with wildfires.

Although labour-intensive, this approach significantly enhanced the accuracy of the forest fire database by ensuring a high level of reliability in identifying true fire events. The combined use of high-resolution multispectral satellite imagery and thermal anomaly data from MODIS enabled an efficient mechanism for filtering out false detections. As a result, a consistent and reliable

geospatial dataset was created, suitable for spatial analysis, risk assessment, and the formulation of forest fire management policies.

Upon completion of the thermal anomaly verification process, the forest fire database has been finalised and is ready for further analysis and application.

Results and discussion

In the following section, the results derived from the database are presented, including its visualisation within a GIS environment (Fig. 2), the structure of the attribute table (Fig. 3), and the key spatial and descriptive parameters associated with each recorded forest fire event.

The database is organised in a shapefile format (Fig. 2), which enables its direct use and visualisation within GIS, facilitating spatial analysis and integration with other geospatial datasets. This format ensures broad compatibility across GIS platforms and allows for efficient querying, layer integration, and spatial analysis, making it a practical tool for researchers, policymakers, and forest management authorities.

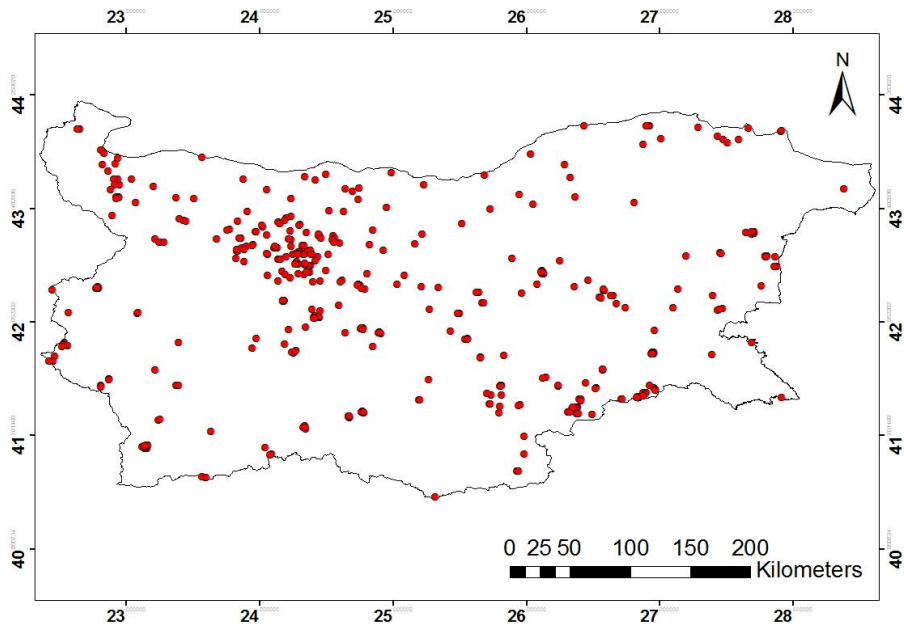


Fig. 2. Forest Fire Database in Bulgaria (2020–2024) organised as a shapefile format

FID	LATITUDE	LONGITUDE	BRIGHTNESS	ACQ DATE	ACQ TIME	SATELLITE
0	42.7166	24.1776	300.5	4.1.2020 r.	0920	Terra
1	43.5883	22.9505	301.4	23.1.2020 r.	1133	Aqua
2	43.6425	26.3309	304.6	25.1.2020 r.	0939	Terra
3	41.877	25.7948	303.4	1.2.2020 r.	1126	Aqua
4	42.3056	25.8349	303.4	1.2.2020 r.	1126	Aqua
5	43.2189	25.2204	316.2	1.2.2020 r.	1127	Aqua
6	43.6591	25.6878	300.8	1.2.2020 r.	1127	Aqua
7	43.6883	22.865	308.5	1.2.2020 r.	1127	Aqua
8	42.6823	24.5977	302.6	3.2.2020 r.	1114	Aqua
9	43.0481	24.4408	309.7	3.2.2020 r.	1114	Aqua
10	43.0817	24.33	312.5	18.2.2020 r.	1210	Aqua
11	43.4971	22.9269	300.7	18.2.2020 r.	1210	Aqua
12	43.4955	22.9441	311.3	24.2.2020 r.	1133	Aqua
13	42.9758	27.8753	307.1	11.3.2020 r.	1133	Aqua
14	42.9741	27.8584	308.2	11.3.2020 r.	1133	Aqua
15	42.7178	24.1786	306.7	12.3.2020 r.	0857	Terra
16	43.6313	22.9399	317.9	13.3.2020 r.	1121	Aqua
17	42.7173	24.1801	308	17.3.2020 r.	0915	Terra
18	42.9414	24.5003	308	20.3.2020 r.	1127	Aqua
19	42.9296	24.3786	304.1	21.3.2020 r.	0850	Terra
20	42.8391	24.7386	306	21.3.2020 r.	0850	Terra
21	42.8343	24.7538	307.1	21.3.2020 r.	0850	Terra

Fig. 3. The attribute data: geographic coordinates, acquisition date, acquisition time, signal intensity, and the satellite platform of origin (Terra or Aqua) for the Forest Fire Database in Bulgaria (2020–2024)

In addition to the spatial representation of the data, the database enables the extraction of statistical summaries that provide insights into the temporal distribution of forest fire events. Such analyses help identify interannual variability and potential trends within the study period. Fig. 4 presents the total number of recorded forest fires for each year from 2020 to 2024, providing a quantitative overview of the temporal dynamics in the dataset.

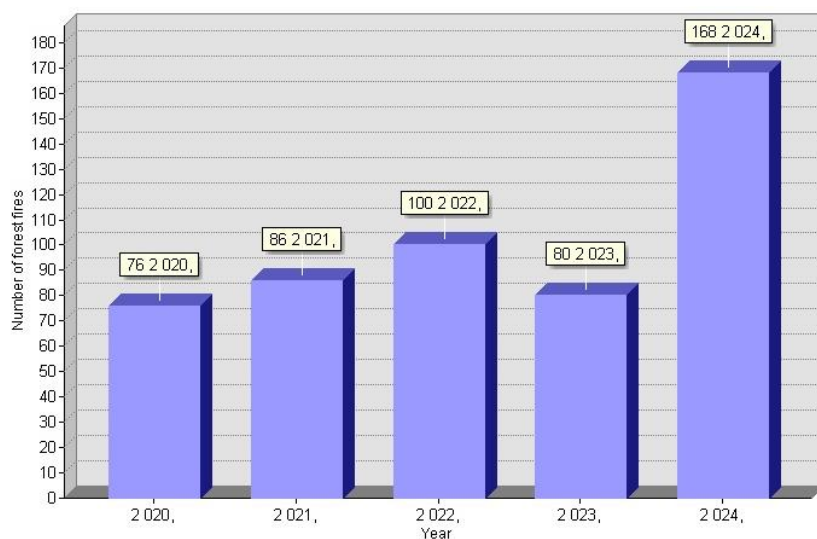


Fig. 4. The total number of recorded forest fire events in Bulgaria for the period 2020–2024

The temporal dynamics of recorded forest fire events across the study period indicate distinct fluctuations that merit detailed examination. In 2020, a total of 76 events were documented, representing the baseline for subsequent comparisons. The following year, 2021, shows a moderate increase to 86 events, which may be associated with variations in meteorological conditions or shifts in land use and vegetation patterns. In 2022, the number of forest fires rose further to 100, marking the highest value observed up to that point in the study period, and possibly reflecting a combination of prolonged dry spells and elevated summer temperatures.

A decline is registered in 2023, with 80 events, suggesting either more favourable climatic conditions for fire prevention, the effectiveness of fire management strategies, or natural variability in ignition sources. However, 2024 exhibits an exceptional surge to 168 events – more than double the previous year’s figure – which may be indicative of extreme weather phenomena, such as heatwaves and droughts, compounded by human activities. This substantial increase underscores the necessity for targeted investigation into the underlying drivers and for the implementation of adaptive management measures to mitigate future risks.

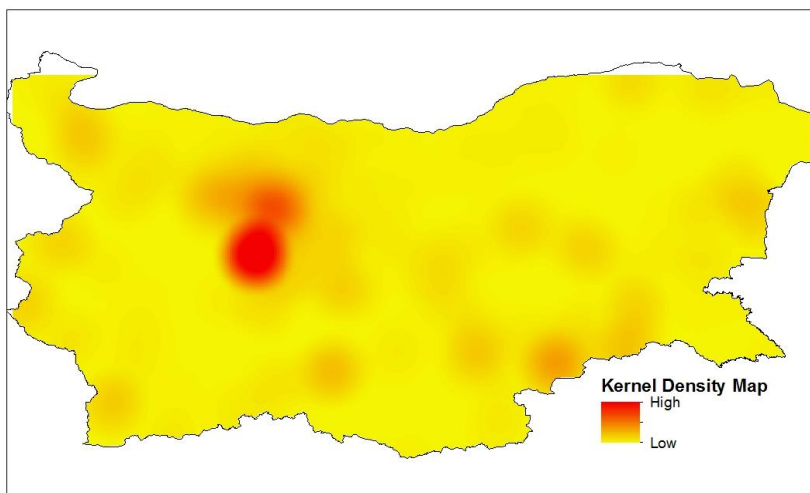


Fig. 5. Kernel Density estimation of forest fire events for the period 2020–2024, displayed using a stretched yellow-to-red colour ramp to indicate a continuous increase in density values (events/km²)

To further explore the spatial distribution patterns of the recorded forest fire events, a Kernel Density estimation was applied to the dataset. This method generates a continuous surface representing the concentration of events per unit area, allowing for the identification of high-density clusters and spatial trends that may not be evident from raw point data alone. The Kernel Density map (Fig. 5),

visualised using a stretched colour ramp from low to high density values, highlights several distinct hotspots of fire occurrence. These spatial clusters provide a valuable basis for examining potential correlations with environmental variables, land cover characteristics, and proximity to anthropogenic features, thereby supporting more targeted prevention and mitigation strategies.

The finalised database provides a consistent, high-confidence dataset of forest fire events across Bulgaria for the period 2020–2024. This structured geospatial resource serves as a solid foundation for subsequent spatial analyses, risk assessments, and the development of data-driven forest fire management strategies.

By integrating both spatial and temporal dimensions, the dataset facilitates the identification of patterns, trends, and high-risk zones, thereby supporting more targeted and effective prevention measures. The methodological framework applied in this study ensures broad compatibility of the database with other geospatial resources, enabling its use in multidisciplinary research and operational contexts. Ultimately, the presented resource has the potential to contribute significantly to evidence-based policy-making, enhance preparedness, and strengthen adaptive management in the face of evolving forest fire dynamics.

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БАЗА ДАННИ ГОРСКИ ПОЖАРИ НА ТЕРИТОРИЯТА НА БЪЛГАРИЯ ЗА ПЕРИОДА 2020–2024 Г. ПО СПЪТНИКОВИ ДАННИ

Н. Станкова, Д. Аветисян

Резюме

Настоящото изследване представя разработването и анализа на геопространствена база данни за горски пожари на територията на България за периода 2020–2024 г. Базата данни е съставена от спътникови наблюдения за активни огнища, като включва географски координати, дата и час на регистриране, интензитет на сигнала и изходна спътникова платформа (Terra или Aqua). Организирана във формат Shapefile, тя позволява директна интеграция в Географски Информационни Системи (ГИС) за пространствен анализ, визуализация и корелация с други геопространствени набори от данни. Резултатите включват пространствени и времеви оценки, като статистическите обобщения показват междугодишна изменчивост и значително увеличение на регистрираните събития през 2024 г. За идентифициране на зони с висока плътност на пожарите е приложен методът Kernel Density, което позволява откриването на пространствени модели и потенциални горещи точки. Базата данни предоставя надеждна основа за оценка на риска, подпомага целенасочените стратегии за превенция и ограничаване на горските пожари и допринася за вземането на решения, основани на данни, в подкрепа на устойчивото управление на горите в България.

ASSESSMENT OF FIRE-PRONE AREAS USING MULTISPECTRAL SATELLITE DATA: A CASE STUDY FROM BREZNIK MUNICIPALITY (WESTERN BULGARIA)

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Key words: vegetation index, land cover, natural hazard

Abstract

The present study deals with the application of the Vegetation Condition Index (VCI). The main aim is to calculate it to distinguish fire-prone areas. The object of research is Breznik Municipality, located in the western parts of the country. Landsat 8 images were derived, and Corine Land Cover classes were used as a basic territorial unit for the analysis. The main focus was the month of June for the years of 1990, 1994, 1996, 2000, 2007, 2011 and 2021. The results of the study varied with VCI across the different years. Non-irrigated arable land stood out as the land cover type most under threat.

Introduction

Climate change is altering the environment. Drought and rising temperatures are among the consequences of it. This leads to the emergence of more susceptible areas to natural hazards. Fires are one of the types that are expected to have an increased occurrence. Nowadays, we possess more sophisticated technology that allows us to make better predictions. Landsat 8 and Landsat 9 possess the Operational Land Imager (OLI) optical sensor and Thermal Infrared Sensor (TIRS) [1–3]. An advantage of satellite images is that they contain a combination of bands with different wavelengths that can be used for imagery analysis, including ones on vegetation [4, 5]. The most notable among them is the Normalised Difference Vegetation Index (NDVI), which has its pros and cons. By studying its flaws, Kogan [6] created a modified NDVI, which he called the Vegetation Condition Index (VCI). The author offered a concept and technique for

the elimination of NDVI's imperfections, using Advanced Very High Resolution Radiometer (AVHRR) data for the 1984–1987 seasons in Sudan. He began by studying the climate impact on different areas with non-homogeneous vegetation. The author noted that a problem stands out when it comes to considering differences between vegetation and other geographical features, such as climate, soil, topography, etc. So VCI offers better dynamics in terms of precipitation compared to NDVI and allows not only the description of vegetation, but also the assessment of spatial and temporal changes in it.

The Vegetation Condition Index compares the current NDVI to the range of values observed in the same period in previous years. The VCI is expressed in % and offers an idea of where the observed value is situated between the extreme values (minimum and maximum) in the previous years. Lower and higher values indicate bad and good vegetation state conditions, respectively. VCI varies from 0 for extremely unfavourable conditions to 100 for optimal.

Several scientific works have favoured the application of VCI since its introduction. They can be applied both to natural environments and to agricultural areas for studying drought, which can have different implications on the two given examples. Liu & Kogan [7] monitored soya bean production in Brazil (1985–1998). Domenikiotis et al. [8] applied the VCI for studying cotton crops in Greece. Quiring & Ganesh [9] conducted research in Texas, USA. The authors focused on the period between March and August (1982–1999) and concluded that VCI has to be used cautiously due to the presence of a number of ecological factors that affect it. Dutta et al. [10] evaluated droughts in the northern Indian state of Rajasthan. Jiao et al. [11] applied the VCI for drought monitoring in the continental areas of the United States of America. Zambrano et al. [12] studied a 16-year period of the BioBio region, Chile. Qian et al. [13] studied agricultural areas in China between 1982 and 2010. Kamble et al. [14] evaluated the impact of drought on rice crops for the period of 1985–2015.

The analysis of the cited literature shows that VCI may be used in different geographical areas and for a prolonged period, and this is one of the aims of the present research, among others, which will focus on the investigation of fire hazard in Breznik Municipality, Western Bulgaria.

The VCI may successfully be adopted as a tool for the determination of fire-prone areas in Bulgaria, as proved by Avetisyan & Nedkov [15], who applied it for the assessment of hazard zones in forest landscapes in Simitli Municipality (Bulgaria). Avetisyan et al. [16] built upon the research idea using the index in the Lom River Upper Valley. VCI has also been applied in the country for satellite monitoring of winter crop status [17] and wheat yields [18] when it comes to agriculture. Other studies [19] and [20] have also made scientific contributions.

The object of the present research is Breznik Municipality. The authors chose a municipality as a territorial unit because it allows authorities to account for environmental management and territorial planning with its related decision-making.

Materials and methods

The study area – Breznik Municipality is situated in the western part of Bulgaria in the region of Kraishte (Fig. 1). The study area is located mainly within 600–1000 m a.s.l. It covers an area of over 400 km². It has ample natural diversity. The mountains of Zavalska, Lyubash, Viskyar, Erulska and Cherna Gora are situated here, as well as the Breznik Valley. The lithology includes conglomerates, sandstones, clays, marls, limestones, dolomitic limestones, dolomites, marls, shales and volcanics – hornblende andesites, trachyandesites, and andesitobasalts according to Zagorchev et al. [21]. Koynov et al. [22] studied the soils, which are mainly represented by Luvisols, Leptosols, and Fluvisols. Only a restricted part of the study area falls within the NATURA 2000 sites Lyubash BG0000624 and Rebro BG0000314 [23].

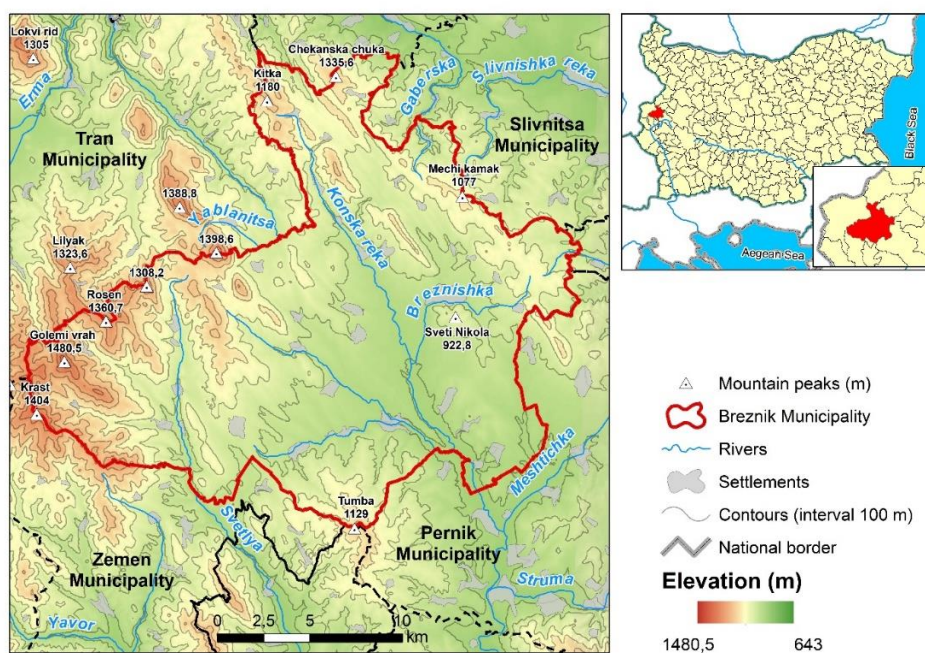


Fig. 1. Location of the study area

Images from Landsat 8 (Landsat Collection 2 Level-2, Landsat 8–9 OLI/TIRS C2 L2) were used for the calculation of VCI. Composite bands were created to get the VCI by using the Image analysis tool in ArcGIS 10.6.1. We used images only from the month of June, as follows: 25.06.1990, 20.06.1994, 09.06.1996, 04.06.2000, 24.06.2007, 19.06.2011, 30.06.2021 (Table 1). The month was chosen due to the fact that vegetation may be regarded as fully developed, still fresh and is expected to be in the same phenophase. Data regarding one month is easy to replicate, as well.

Table 1. List of used Landsat scenes

Landsat Scene Identifier	Date acquired (dd-mm-yy)	Path x Row	Cloud cover (%)
LT51840301990176FUI00	25.06.1990	184 x 30	7,00
LT51840301994171FUI00	20.06.1994	184 x 30	7,00
LT51840301996161FUI01	09.06.1996	184 x 30	0,00
LT51840302000156FUI00	04.06.2000	184 x 30	1,00
LT51840302007175MOR00	24.06.2007	184 x 30	3,00
LT51840302011170MOR01	19.06.2011	184 x 30	2,00
LC81840302021181LGN00	30.06.2021	184 x 30	0,02

VCI was calculated after the following steps:

Step 1: Maximum and minimum NDVIs were calculated (Spatial Analyst Tools – Local – Cell Statistics).

Step 2: VCI was calculated using maximum and minimum NDVI values (Spatial Analyst Tools – Map Algebra – Raster Calculator).

Step 3: The following formula was applied:

$$VCI = 100 * (NDVI - NDVI \min) / (NDVI \max - NDVI \min) [6, 24].$$

NDVI max and NDVI min are the multiple-year maximum NDVI and minimum NDVI for a pixel with reference to a specific climatology.

Step 4: The calculated VCI was reclassified to 5 classes (using Spatial Analyst Tools – Reclass – Reclassify). The following Break Values (%) were inserted: 10, 20, 35, 50, 100 (Table 2).

Table 2. Classification of VCI values

Value	Drought_Severity
< 10%	Extreme drought
10%–20%	Severe drought
20%–35%	Moderate drought
35%–50%	No drought
50%–100%	Wet

Corine Land Cover (CLC) [25] classes were applied to the territory of Breznik Municipality. They were the units upon which VCI analysis was applied.

Results and Discussion

The results are showing certain interconnections. The territories near the extreme drought category are more prone to fires than the ones in the wet category. CLC 2018 classes (Table 3, Fig. 2) were consistent with those of previous years, so this database was enough to get the outcomes.

Table 3. Corine Land Cover codes and nomenclature

CLC code	Level 1 nomenclature	Level 3 nomenclature	% of total area
112	Artificial surfaces	Discontinuous urban fabric	2,96
121		Industrial or commercial units	0,22
142		Sport and leisure facilities	0,08
211	Agricultural areas	Non-irrigated arable land	28,67
231		Pastures	3,17
242		Complex cultivation patterns	2,71
243		Land principally occupied by agriculture, with significant areas of natural vegetation	16,73
311	Forest and semi-natural areas	Broad-leaved forest	11,29
312		Coniferous forest	4,11
313		Mixed forest	6,92
321		Natural grasslands	10,27
324		Transitional woodland-shrub	12,46
333		Beaches, dunes, sands	0,23
512	Wetlands	Water bodies	0,17

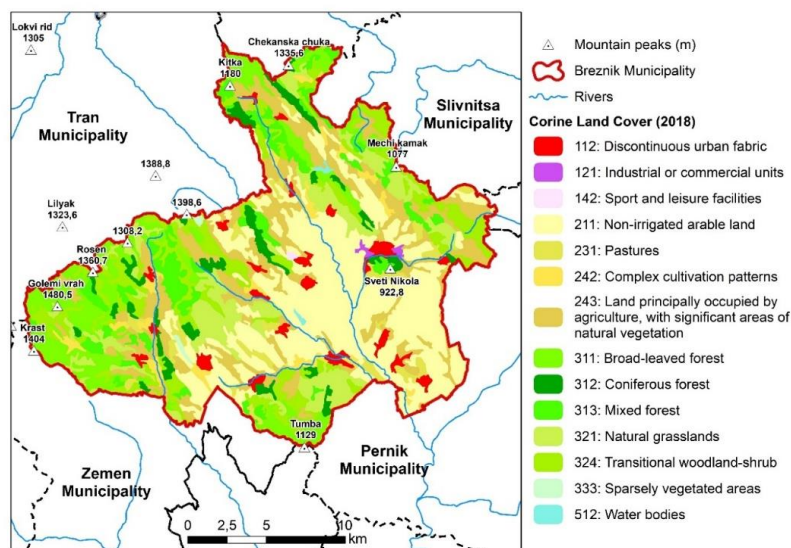


Fig. 2. Spatial distribution of Corine land cover classes within the area of interest

More than half of Breznik Municipality (51,28%) is occupied by arable land, while deciduous, coniferous and mixed forests cover about 22,32% of the administrative area. Grasslands, shrubs and areas with sparse vegetation canopy cover about 22,97% of the municipal area. Several small dams used for agricultural purposes (mainly irrigation) occupy an insignificant portion of the study area – less than 1%.

The spatial analysis will follow the presented data in Fig. 3. The first impression is that each year had its typical features. First in line will be 1990. Territories falling within the extreme drought category (red colour) this year are distributed mainly in the mountains of Zaval'ska and Viskyar to the north, as well as along the riverbed of Konska River. The territories with moderate drought are unevenly dispersed throughout the municipality. The areas falling within the wet category (green colour) may be discovered in Breznik Valley, but not to the full extent.

Next is the year 1994. Areas with extreme drought have moved from the north to the west and can be located in the mountains of Erul'ska and Lyubash. Such territories can still be discovered in Viskyar. Moderate drought locations are again unequally dispersed. Areas falling within the wet category are mainly situated in the central, southern and eastern parts of Breznik Municipality.

The year 1996 is the one with the least number of territories in the extreme drought category. They can be viewed mainly along the Konska River. Moderate drought areas are situated in the central and western parts predominantly, while the majority of the municipality's area falls within the wet category.

The situation changed in 2000. Extreme drought areas appear in the central parts and the mountains of Cherna gora to the south. More extensive moderate drought territories are located to the east. The mountains of Zaval'ska and Erul'ska may be given as examples of locations with territories falling within the wet category.

The extreme drought in 2007 was observed in the Cherna gora mountain and the Breznik Valley. There is unequal dispersal of moderate drought areas around the municipality. The mountains of Lyubash and Erul'ska may be given as examples of territories included in the wet category.

The year 2011 had extreme drought areas mainly in the Breznik Valley. They were accompanied by areas with moderate drought. Cherna gora mountain is in the wet category alongside the mountains of Erul'ska, Viskyar and Zaval'ska.

The last year that was in our scientific focus was 2021. The extreme drought areas were restricted back then mainly to the Breznik Valley. Moderate drought areas were mainly in the central and eastern areas of the municipality, while the territories in the wet category were prevailing, and the riverbeds of Konska and Breznishka Rivers stood out.

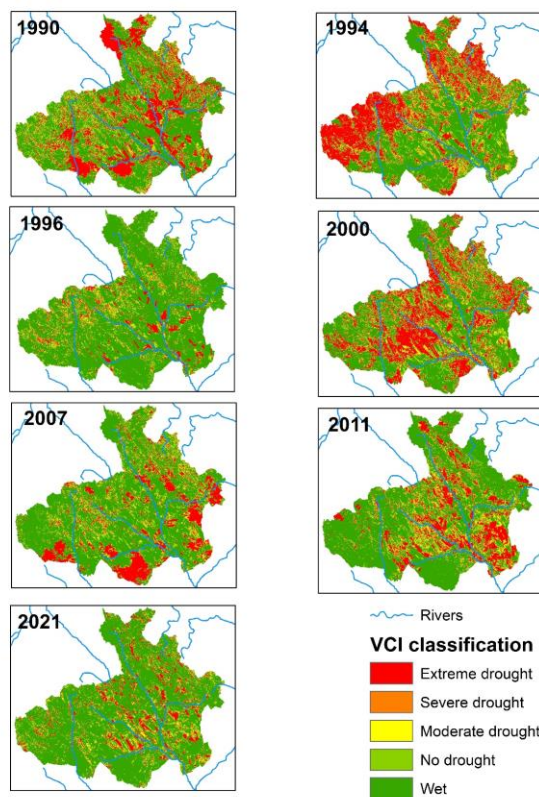


Fig. 3. Temporal changes in VCI of Breznik Municipality

The next lines consist of data regarding the drought severity, assigned to certain CLC classes. Territories that were more prone to fires will be in the focus. Forests, complex cultivation patterns, land principally occupied by agriculture with significant areas of natural vegetation, non-irrigated arable land and transitional woodland and shrub were the classes that were under threat in 1990. Forest and semi-natural areas were under the greatest threat in 1994, with a focus on broad-leaved and mixed forests and transitional woodland and scrub. Non-irrigated arable land was the most fire-prone area in 1996. Natural grasslands, non-irrigated arable land, land principally occupied by agriculture with significant areas of natural vegetation and complex cultivation patterns were among those classes that were in greatest threat in 2000. The year 2007 had its own features. The most fire-prone areas were territories with transitional woodland-scrub, natural grasslands, non-irrigated arable land, pastures and broad-leaved forests. The non-irrigated arable land class was the most prone to fires in 2011, followed by broad-leaved forests and land principally occupied by agriculture with significant areas of natural vegetation and pastures to some extent. Non-irrigated arable land was the

class that was under the biggest threat (extreme drought category) for the year 2021, followed by broadleaved forests, while the largest proportion of the other CLC classes was within the “wet” zone.

Overall, the class of the non-irrigated arable land has to be under special attention in the following years, because it is the one that was under the greatest threat according to the VCI. It is followed by broad-leaved forests, transitional woodland-scrub, land principally occupied by agriculture with significant areas of natural vegetation, complex cultivation patterns, natural grasslands and pastures. These results are consistent to some extent with those of Avetisyan & Nedkov [15] who point out that the riskiest areas are the ones that are in poor vegetation condition, represented by grasslands, shrublands and forests with *Pinus nigra* sp.

Conclusion

The present study dealt with the application of the Vegetation Condition Index (VCI). It was calculated on the basis of Landsat 8 (Landsat Collection 2 Level-2, Landsat 8–9 OLI/TIRS C2 L2) images. The VCI was calculated for the month of June, as a representative month for the years of 1990, 1994, 1996, 2000, 2007, 2011 and 2021. Territories that were under threat of fire were distinguished by the use of the Corine Land Cover classification. The analysis showed that among them are Breznik Valley and the mountains of Viskyar and Cherna gora Mountains. Non-irrigated arable land was the class that stood out the most, so it has to be a main focus of policymakers when it comes to this type of natural hazard. The results of the study showed promise and may serve as a basis for extending this type of research to neighbouring administrative units and adjacent territories.

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ОЦЕНКА НА ПОДАТЛИВИ КЪМ ПОЖАРИ РАЙОНИ ЧРЕЗ ИЗПОЛЗВАНЕ НА САТЕЛИТНИ ДАННИ: ОБЩИНА БРЕЗНИК (ЗАПАДНА БЪЛГАРИЯ)

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Резюме

Настоящото изследване е насочено към прилагането на вегетационния индекс VCI. Целта е да бъдат открити райони, податливи на пожари. Обектът на изследване е община Брезник. Използвани са данни от Landsat 8, като са приложени и класове Corine Land Cover с цел анализ. Основен фокус е месец юни през годините: 1990, 1994, 1996, 2000, 2007, 2011 и 2021. Резултатите варират за различните години. Ненапоояваните обработваеми земи излизат на преден план, като класът, който е най-застрашен.

SNOW MELT-OUT DATE IN THE TREELESS ZONE OF THE HIGHEST MOUNTAINS IN THE EASTERN BALKAN PENINSULA FROM SENTINEL-2 OBSERVATIONS

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Abstract

Measurements of Snow melt-out date (SMOD), the day of the year when seasonal snow disappears, from a limited number of climatological stations are unable to characterise the complex pattern of snow melting in mountain areas. Satellite remote sensing can help fill this knowledge gap. This study mapped the SMOD in the treeless zones of six mountainous regions in the eastern Balkans. Sentinel-2 Level-2A surface reflectance data in Google Earth Engine were used to implement a multiyear aggregation method, which previous studies have proven highly efficient with Landsat data. First, we analysed a set of Normalised Difference Snow Index (NDSI) images using Otsu's method to determine an optimal threshold to separate snow-free and snow-covered pixels. The optimal thresholds for the individual images varied, but were tightly clustered around the median value of 0.181. Then, we used this threshold and all Sentinel-2 data from 2017–2025 to estimate SMOD. The results were realistic in terms of both spatial and temporal patterns. We found that in the relatively low Osogovo Mountains, almost all snow cover (90%) disappeared by May 2, while in Pirin, this occurred on June 8. We also analysed the effect of the NDSI threshold on the SMOD estimates, showing that it is generally small in magnitude and spatially limited. The threshold of 0.40, often used in the literature, resulted in SMOD deviations of less than 10 days for 90% of pixels, compared with the optimal value of 0.181.

Introduction

Seasonal snow cover is a key characteristic of the climate of temperate mountains. In Bulgaria, situated in the eastern part of the Balkan peninsula, a persistent snow cover (i.e. a snow cover with continuous duration of over 30 days) is observed annually in mountainous areas at an altitude of over 1100–1400 m [1]. The number of days with snow cover increases with increasing elevation and reaches an average of 190–200 days per year on the highest peaks [1]. The Snow

melt-out date (SMOD), i.e., the day of the year when the snow cover disappears, is one of the primary seasonal snow cover characteristics. The timing of snowmelt plays a significant role in ecosystem functioning. Later SMODs are usually associated with a delayed and potentially shorter growing season. Sites with prolonged snow cover are characterised by poorly developed soil and vegetation [2], lower plant diversity, and dominance of a few, well-adapted species [3, 4]. Studies in alpine and Arctic tundra environments [5, 6] indicate that flowering and other phenological events in some species are affected by snowmelt timing. Snow is also an important water reservoir that stores winter precipitation and contributes to runoff in spring and early summer [7]. Potential runoff production in these seasons is governed by the snowmelt timing and rate, among other factors [8]. However, despite the ecological, hydrological, and climatic importance [9–11] of snowmelt timing, spatially detailed information on SMOD is still lacking for the high mountains of Bulgaria and the eastern Balkan Peninsula. As a result, the strong local variability of snowmelt across alpine terrain remains poorly characterised in this region.

Different sources of information have been used to analyse temporal patterns in snowmelt at national to continental scales, including weather station measurements [10, 12, 13], spatial climatic datasets [11], and low-resolution satellite sensors [14–17]. However, these types of data are too coarse to provide an accurate spatial picture of snowmelt timing in the alpine zone of mountains where variations in SMOD of one or more weeks can be observed within just a few tens of meters. These irregularities are closely related to topography. Wind redistributes the snow, blowing it away from the ridge tops and exposed slopes and accumulating it in the protected bases of the slopes [18]. Gravitational snow transport processes, such as avalanches [19], lead to the removal of snow from higher elevation regions and deposition in regions of lower elevations. They are responsible for extreme snow depths at the base of steep slopes [20]. These processes contribute to snow depth variability and thus to the uneven melting across mountain terrain. The attempts to map snowmelt patterns at fine detail in mountain areas are relatively few and recent, although the Landsat satellites have allowed significant progress to be made in this area.

The practice of satellite remote sensing mapping of the extent of snow cover has a long history dating back to the first Landsat and Advanced Very High Resolution Radiometer (AVHRR) satellite missions [21]. While visual interpretation is usually considered the most accurate method to delineate snow-covered areas in a satellite image, automated approaches that minimise human intervention may be needed in some cases [22]. A common semi-automated approach is the one based on spectral indices. Such indices are designed to distinguish snow from other land cover types based on its spectral reflectance pattern. Pure snow cover is characterised by high reflectance in the visible and near-infrared part of the electromagnetic spectrum, followed by a sharp decrease toward the shortwave infrared part, where two well-

expressed minimums at 1500 nm and 2000 nm are observed [23]. This is in contrast to vegetation and soil, which usually have much lower reflectance in the visible range [24] and to clouds, which have much higher reflectance in the shortwave infrared range [25]. Based on the Landsat Thematic Mapper (TM) bands, Dozier [21] suggested the normalised difference of Band 2 (520–600 nm) and Band 5 (1550–1750 nm), an index later known as Normalised Difference Snow Index (NDSI), as an indicator of the presence of snow. NDSI is now widely used, including for operational snow cover mapping [26].

The NDSI-based snow mapping approach relies on the selection of an appropriate threshold value. NDSI values greater than about 0.4 were found to represent snow cover well [21, 27]. However, it was recognised that an exact NDSI threshold for snow does not exist [22, 27, 28] and that the optimal threshold can vary within a certain range, depending on the image and the atmospheric corrections applied to the data. One can either find a credible value to apply to the analysis of several images [29] or select a threshold for each image [30–32], the choice depending on the specific task. The effect of the chosen threshold on SMOD mapping is a research topic that has received little attention to date.

While a single clear-sky image from platforms like Landsat and Sentinel-2 can be used to map snow cover over large areas with fine spatial resolution thanks to the NDSI, SMOD mapping remains challenging because it requires frequent observations. The number of clear sky observations depends on the revisit time of the satellite and the meteorological conditions, and it is generally insufficient to detect the SMOD on a yearly basis with those satellites. Recent studies have proposed utilising (aggregating) all observations within a period of several years, which enables a reliable estimation of the SMOD [29, 33, 34]. Such SMOD practically characterises the “average” snow-melting condition of the period. The method was tested with Landsat data for two 12-year periods by Bayle et al. [29] and Choler et al. [34]. However, further experimenting with this method, utilising the higher temporal and spatial resolution Sentinel-2 data and over other regions, is desirable.

To address the lack of fine-scale information on snowmelt timing in the high mountains of the eastern Balkans, this study applies a multiyear SMOD mapping approach to Sentinel-2 imagery for selected mountain regions in Bulgaria and adjacent areas. Building on the framework proposed by Bayle et al. [29] and Choler et al. [34], we aimed not only to map SMOD but also to determine an appropriate NDSI threshold for our study area and to assess the sensitivity of SMOD estimates to threshold choice and to the length of the aggregation period.

Study area

In this study we analyzed the SMOD in six mountainous regions from the eastern Balkan peninsula, including (Fig. 1): the western part of Stara planina Mountains at the border of Bulgaria and Serbia (SPW, 2168 m a.s.l.); the central part of Stara planina Mountains in Bulgaria (SPC, 2376 m a.s.l.); the Osogovo

Mountains at the border of Bulgaria and North Macedonia (OSO, 2251 m a.s.l.); the Vitosha Mountains in Bulgaria (VIT, 2290 m a.s.l.); the Pirin Mountains in Bulgaria including the Slavyanka/Orvilos mountain on the border with Greece (PSO, 2914 m a.s.l.); and Rila Mountains in Bulgaria (RIL, 2925 m a.s.l.). This study focuses on the high-altitude treeless zone characterised by alpine and subalpine grass and low shrub vegetation. The study area is formally defined as the area above 1600 m a.s.l., which is not covered by forest and dwarf mountain pine (*Pinus mugo* Turra) communities. The water bodies were also excluded.

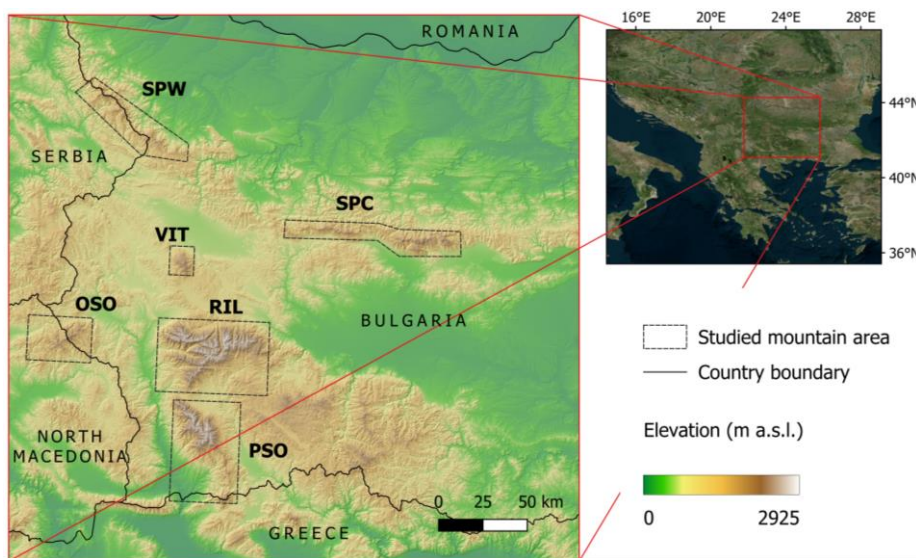


Fig. 1. Location of the six study areas in the eastern Balkan peninsula

Methods

SMOD mapping

A detailed description of the SMOD method used in this study can be found in Bayle et al. [29] and Choler et al. [34]. Here we briefly report the procedure, the data, and the settings used. All Sentinel-2 surface reflectance (Level 2A) images available in Google Earth Engine (GEE; [35]) between 2017 and 2025 (referred to as a data aggregation period) with less than 50% cloud cover which intersected the study areas were selected. Cloudy pixels were masked using the GEE Cloud Score+ dataset [36]. This dataset includes a quality assessment band (band “cs”) which grades the usability of individual pixels with respect to surface visibility on a continuous scale between 0 and 1, where 0 represents “not clear”, while 1 represents “clear” observations. We masked out pixels with values of the “cs” band lower than 0.60. For each image, we calculated the NDSI using

bands B3 and B11, namely $NDSI = (B3 - B11) / (B3 + B11)$ and converted it to a binary image representing the snow extent where snow-covered pixels have value 1 and snow-free pixels have value 0. A pixel was labelled as snow-covered if its NDSI value was larger than a specified optimal threshold (see below). Each image was assigned the day of the year (DOY) corresponding to its acquisition date. Sorting the images by DOY enabled a densified annual time series to be obtained, where all acquisitions ranged between DOY 1 (January 1) and DOY 365 (December 31). The time series of binary images was smoothed using a centred moving median filter with a window size of 51 DOYs. It calculates, for each existing observation, the median of the observations which are within 25 DOYs from that observation. This procedure does not interpolate between observations but just smooths them. As a result, a time series of a “probability of snow” index [29], ranging between 0 and 1, was obtained. The observations before DOY 51 (February 20) were removed from the time series. The first observation in this shortened time series with a probability below 0.5 was identified as the SMOD. Pixels with “permanent snow”, i.e. with probability always above 0.5, were assigned the value 365. Observations before DOY 51 were discarded to avoid detecting earlier DOYs due to snow onset after January 1 [29]. Finally, the SMOD image was masked to exclude forest/dwarf mountain pine, water, and areas below 1600 m. a.s.l. and exported from GEE at 20 m pixel size. We used Copernicus DEM to exclude low-altitude areas below 1600 m a.s.l. The water bodies were excluded using the European Space Agency’s WorldCover 10 m 2021 product [37]. Finally, we used the CORINE Land Cover plus (CLCplus) Backbone 2023 [38] to exclude forest and dwarf mountain pine pixels. Forest was defined as the union of classes 2, 3, and 4. Dwarf mountain pine was excluded only in the study areas RIL and PSO, where it occupies a significant area. For that purpose, we excluded pixels belonging to the CLCplus Backbone class 5 (Low-growing woody plants). Note that in this way we excluded not only dwarf mountain pine communities but also areas covered by *Juniperus sibirica* or other shrubs that fall into this class. This was not the goal, so for the remaining study areas, where the risk of including dwarf mountain pine is minimal due to its limited distribution, we treated class 5 pixels as valid. For the SMOD mapping, we adapted the GEE script provided in Bayle et al. [29].

Optimal NDSI threshold

The optimal NDSI threshold for distinguishing between snow-covered and snow-free pixels in Sentinel-2 data was determined using the partially snow-covered images approach described in Bayle et al. [29]. Snow-covered surfaces are characterised by high NDSI values close to unity. In contrast, snow-free surfaces show lower, including negative, NDSI values. Therefore, when both types of surfaces appear on an image, the NDSI experiences a bimodal distribution. The thresholding method of Otsu [39] can be used to find a theoretical “optimal”

threshold separating the two groups of pixels in the bimodal distribution of NDSI [22, 29, 40]. It is an unsupervised method of automatic threshold selection from a grey-level histogram [39]. We followed this approach by analysing Sentinel-2 surface reflectance images (Level 2A) for each study area. All images from April, May, June, and November with less than 5% cloud cover available in GEE were initially selected. Cloudy pixels were masked using the Cloud Score+ dataset as described in the previous section. Images from adjacent Sentinel-2 tiles having the same acquisition date were mosaicked. NDSI images were computed and masked to exclude forest/dwarf mountain pine, water, and areas below 1600 m a.s.l., as described above, and finally exported from GEE at 20 m pixel size. The terra package [41] in R [42] was used to generate a histogram of each image. The histograms were evaluated visually, and the images with bimodal histograms were selected. The R's package *autothreshdr* [43] was used to apply Otsu's threshold selection method on the selected images. We examined the difference in the thresholds between study areas using ANOVA and calculated the median of the thresholds to use as a generally applicable (for our study areas) "optimal" threshold.

SMOD dependence on the NDSI threshold and the length of the data aggregation period

The effect of the NDSI threshold and the length of the data aggregation period on the SMOD estimates was investigated for part of the RIL study area. To this aim, an image subset (1.6 km × 2.82 km, 11 280 pixels) was selected representing different geomorphologic features and slope expositions as well as a wide range of SMODs. The SMOD was calculated using thresholds from 0.0 to 0.4 in increments of 0.05, and the estimates were compared with those obtained by utilising the optimal threshold. Furthermore, we calculated SMOD for progressively shorter periods (excluding one year from the start of the initial nine-year period 2017–2025) to visually assess the effect of the reduction in the number of clear-sky observations on the quality of the SMOD map.

Results

A total of 414 NDSI images were exported from GEE for the six study areas. Most of them were not suitable for applying Otsu's method because one of the two pixel types, snow-covered or snow-free, dominated the scene, or because no valid pixels remained after applying the masks. A relatively balanced distribution of snow-covered and snow-free pixels was observed in the histograms of 67 of the images. These histograms showed a clear bimodal distribution, and the corresponding images were selected for further analysis. The number of suitable images varied depending on the size of the study area. Only 5 images were available for the smallest study area (VIT, Fig. 1), while 17 images could be used

for PSO. The optimal threshold differences between study areas (Fig. 2a) were relatively small and not statistically significant according to the one-way ANOVA ($F(5, 61) = 0.942$, $p = 0.46$). The small sample size precludes further investigation of the possible specificity of the optimal threshold depending on the area studied. However, Fig. 2a suggests that the variation within a single study area surpasses the difference between study areas. The distribution of the optimal threshold for all study areas is shown in Fig. 2b. It shows a bimodal pattern with two closely located modes (~ 0.125 and ~ 0.195). Nevertheless, we decided to use a single optimal threshold determined as the median of the distribution, as this approach is objective and reproducible. The median optimal NDSI threshold was 0.181.

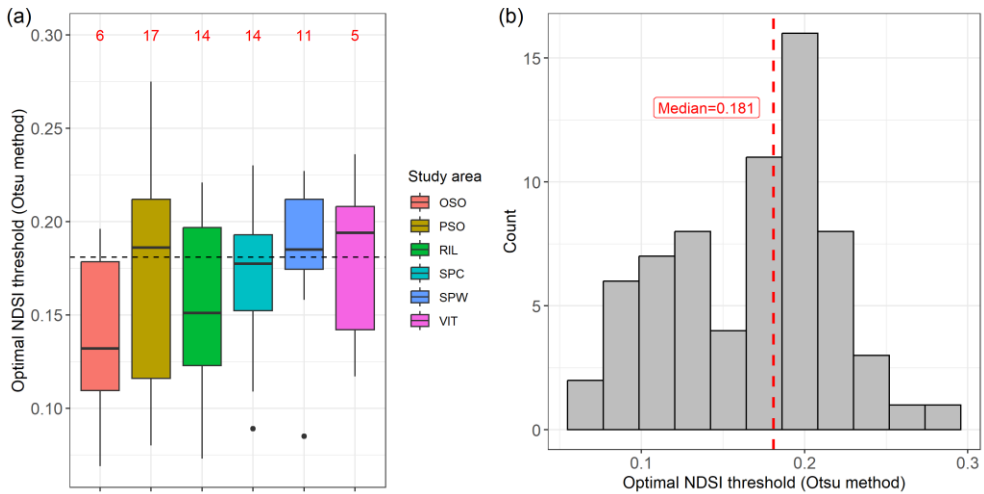


Fig. 2. Results of the optimal NDSI threshold analysis. (a) Boxplots of the optimal NDSI threshold for the study areas (Center line, median; box, interquartile range; upper/lower whisker, the largest/smallest value no further than $1.5 \times$ interquartile range from the box; dots, outliers). For the location of the study areas, see Figure 1. The red numbers at the top represent the sample size. (b) Distribution of the optimal NDSI threshold for all study areas. The median optimal NDSI threshold for all study areas is indicated by the horizontal line in (a) and the vertical line in (b).

Fig. 3 illustrates the estimated SMOD in the six study areas. The maps show credible patterns both within individual study areas and between them. The highest mountains, Rila and Pirin (study areas RIL and PSO, respectively), have later SMODs than the other study areas. A tendency for SMOD to increase with elevation is observed in each individual mountain area. The effect of exposition is clearly presented. For instance, the small subset image in Fig. 3f shows a ridge with an east-west direction in the Rila Mountains. The northerly exposed slopes, the upper half of the image, have later SMOD than those with south exposition, the

bottom half of the image. The area marked with the red rectangle shows side ridges to the south of the main ridge with alternating late and early SMODs corresponding to slopes with northwest and southeast exposition, respectively. Finer patterns are also observed, such as localised late SMODs at the base of cirque walls in Rila and Pirin, and earlier SMODs at the wind-exposed ridge tops (as shown by the red ellipse in the subset in Fig. 3f) and on steep slopes with rock outcrops. Fig. 4 shows the cumulative distribution of pixels in each study area with respect to the SMOD. It can be used to find what percent of the pixels (respectively the area) has an earlier or later SMOD than a certain DOY. For instance, in SPC, about 40% of pixels have SMOD of DOY 100 (April 10) or earlier and in PSO, about 20% of pixels have SMOD later than DOY 150 (May 30). At PSO, the latest estimated SMOD is DOY 269 (September 26), and 90% of the pixels have SMOD not later than DOY 159 (June 8). At RIL, SPC, VIT, OSO, and SPW these figures are, respectively, DOY 234 (August 22) and DOY 146 (May 26), DOY 204 (July 23) and DOY 128 (May 8), DOY 179 (June 28) and DOY 133 (May 13), DOY 162 (June 11) and DOY 122 (May 2), DOY 159 (June 8) and DOY 126 (May 6). The SMOD algorithm identified 24 pixels (0.96 ha) in PSO as “permanent snow” (value 365 in Fig. 3). These were concentrated in the Golemia Kazan cirque (the subset image in Fig. 3e), Banski suhodol cirque, and Bayuvi dupki cirque. Two glacierets (1.68 ha) and several sustainable snow patches are indeed formed under present-day climatic conditions in Golemia Kazan and Banski suhodol, but not in Bayuvi dupki cirque [44, 45]. Fig. 4 also shows differences in the dynamics of snowmelt between study areas. In the lower mountains (OSO, SPC, and SPW), snowmelt starts rapidly and early, around mid-March (~DOY 75) and takes place at a constant rate. For the highest mountains (PSO and RIL), snow-melt in the beginning of spring is slower and accelerates in May (approximately after DOY 125, May 5).

The effect of the NDSI threshold on the SMOD estimates in the selected part of the RIL study area is shown in Fig. 5. The usage of thresholds lower than 0.181 resulted in later SMOD estimates, therefore positive difference (e.g. Fig. 5c) and the opposite, the thresholds larger than 0.181, which are stricter with respect to the snow-covered area detection, resulted in earlier SMOD estimates, thus, negative differences (e.g. Fig. 5d). The maximal differences exceeded 30 days but such deviations were more of an exception even with the extreme thresholds of 0.0 and 0.4. Using the 0.4 threshold, about 35% of the pixels had the same SMOD and another 40% had one to five days earlier SMOD compared to the optimal threshold (Fig. 5f). For thresholds between 0.10 and 0.25 the pixels with deviation of 10 or more days were about one percent and their share reached about 10% for threshold of 0.40 (Fig. 5g). In general, the differences are greatest in regions where SMOD change rapidly over short distance. In areas which are more homogeneous in terms of SMOD, the effect of the threshold is smaller.

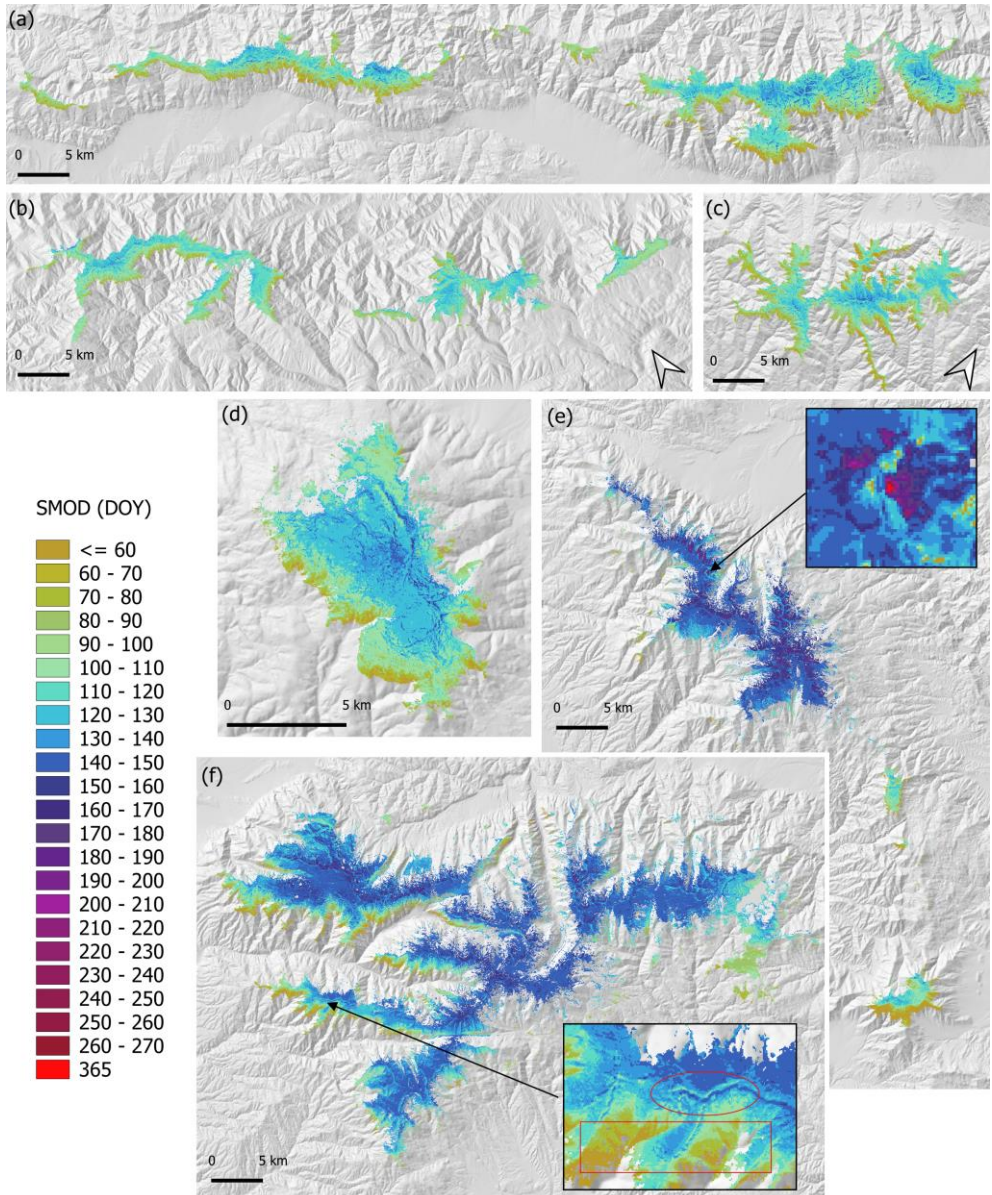


Fig. 3. SMOD in the six study areas estimated using Sentinel-2 observations from 2017 to 2025.
 (a) SPC, (b) SPW, (c) OSO, (d) VIT, (e) PSO, and (f) RIL.
 See the text for explanations of the image subsets in (e) and (f).

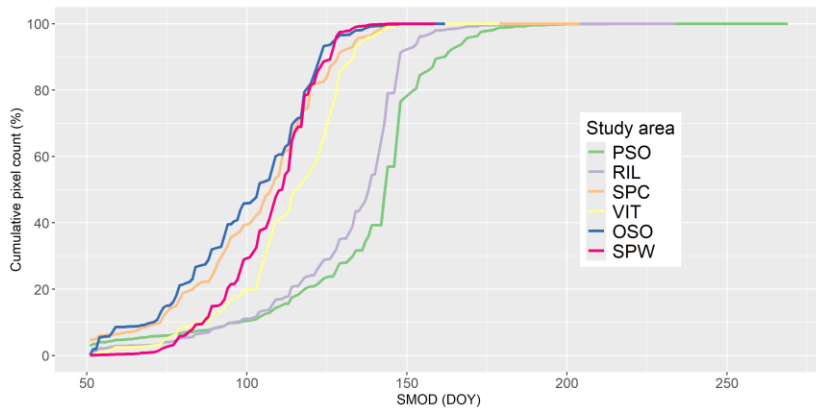


Fig. 4. Cumulative distribution of the SMOD estimates for the six study areas

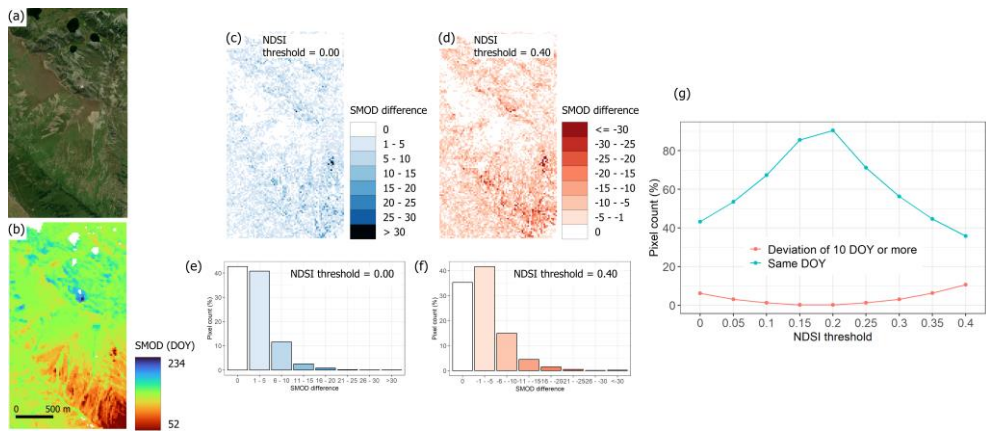


Fig. 5. Effect of the optimal NDSI threshold on the estimated SMOD in part of the RIL study area. (a) Satellite image (Microsoft Bing) of the analysed area. (b) SMOD was estimated using the optimal NDSI threshold from this study (0.181). (c) and (d) Difference in SMOD estimated using thresholds 0.0 and 0.4, respectively, and the SMOD estimated using the optimal threshold (calculated as $SMOD_{0.0} - SMOD_{0.181}$ and $SMOD_{0.4} - SMOD_{0.181}$, respectively). (e) and (f) Percentage distribution of the pixels among SMOD difference classes in images (c) and (d), respectively. (g) Percent of the pixels with no change in the estimated SMOD and with deviation of 10 days or more compared to the optimal threshold (0.181) for different NDSI thresholds.

The results from the experiment with different lengths of the aggregation period are shown in Fig. 6. The map created with one year of data failed to depict fine-scale patterns in the SMOD. The estimated SMOD was unstable in maps based on one to four years, and stabilised at five or more years. Little difference was observed between maps created with five and nine years of data.

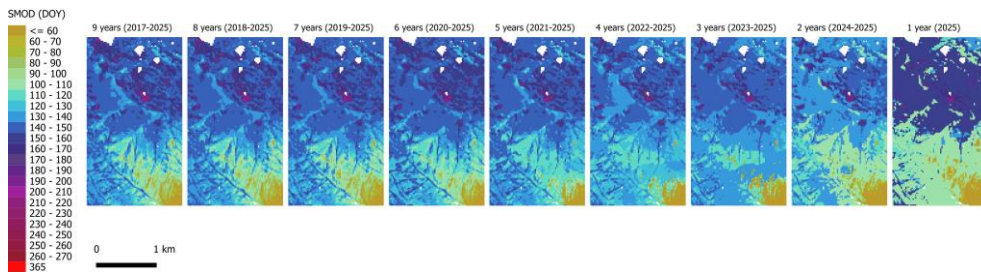


Fig. 6. SMOD estimated using Sentinel-2 data collected for periods of one to nine years in part of the RIL study area

Discussion

In this study, we presented the first detailed remote sensing-based maps of snowmelt timing for high-mountain areas in Bulgaria and adjacent regions. Only two climatological stations in the studied mountains, Cherni Vrah (Vitosha Mountain) and Vrah Botev (Stara Planina Mountains), are currently collecting snow depth data from which snowmelt date can be determined (<https://hydro.bg/>). Therefore, the presented approach can contribute significantly to spatial characterization and monitoring of snow cover melting patterns in this region.

Furthermore, we investigated the possibility of identifying an optimal NDSI threshold for Sentinel-2 data in this region. To this end, a statistical method based on the image histogram [39] was used, which has been shown by Yin et al. [22] to yield results very similar to those of an expert-derived threshold. Since the threshold value determined using Otsu's method [39] depends on the NDSI frequency distribution in the analysed image, which is determined by the land cover (e.g. vegetation and rock types [40]) and the proportion of the image covered by snow, it is necessary to analyse a large number of images. Studies by Bayle et al. [29] and Härer et al. [40] show that despite some variation, Otsu thresholds are highly concentrated around a certain value, and the mean (or median) can be used as a reasonable approximation. Using 67 images, we obtained a median threshold (0.181), which was very close to that of Bayle et al. [29], who analysed 121 Landsat images over the Pyrenees, the European Alps and the Greater Caucasus covering the period 1984–2023, and found the average optimal NDSI threshold to be 0.1543. Furthermore, both our study and that of Bayle et al. [29] used atmospherically corrected data, suggesting that compatible results can be obtained between Landsat and Sentinel-2 on the same processing level. Our optimal threshold is also close to the value of 0.2 used by Dimitrov [46] for a study area in the Rila Mountains and Landsat data. The results also comply with Poussin et al. [28], who found that the standard value of 0.4 underestimated the snow cover extent in their study area. On the other hand, Härer et al. [40] analysed Landsat images between 2010 and 2015 and found that, for two study areas in the European

Alps, the thresholds predicted by Otsu's method were clustered around 0.4. It is noteworthy that the data used in their study had a different processing level—top-of-atmosphere reflectance. Stoyanov [30, 31] determined the NDSI threshold for Sentinel-2 based on visual interpretation and also found it to be higher than our study – between 0.21 and 0.58 for the central part of the Stara Planina and between 0.34 and 0.69 for the Pirin Mountains. This may be due to different processing of the images [30, 31]. While the optimal threshold value determined in this study may not be perfect for each image, it is a convenient choice in scenarios when a large number of images are to be analysed, and a dynamic threshold selection method is not available or feasible.

Compared to the widely used value of 0.4 in the literature, our optimal threshold of 0.181 resulted in later SMOD estimates (Fig. 5). We do not have validation data to assess the accuracy of the two thresholds. However, for a small test area, we evaluated the relative effect of changing the threshold on SMOD and found that when our optimal threshold was used instead of the standard value of 0.4, only 10% of the pixels had SMOD that was 10 days or more later. Such small differences are supported by Fig. 7 illustrating that the snow cover extent determined using the two thresholds is very similar. The threshold of 0.181 includes more pixels that can be interpreted as “intermediate” between “typical” snow-covered and snow-free pixels on the false-colour composite image. Such “intermediate” pixels may have patchy and/or thin snow cover, occupying a different proportion of the pixel [28]. We conclude that Bayle et al.'s SMOD estimation method [29] is not very sensitive to the NDSI threshold used and provides reliable results with a range of values.

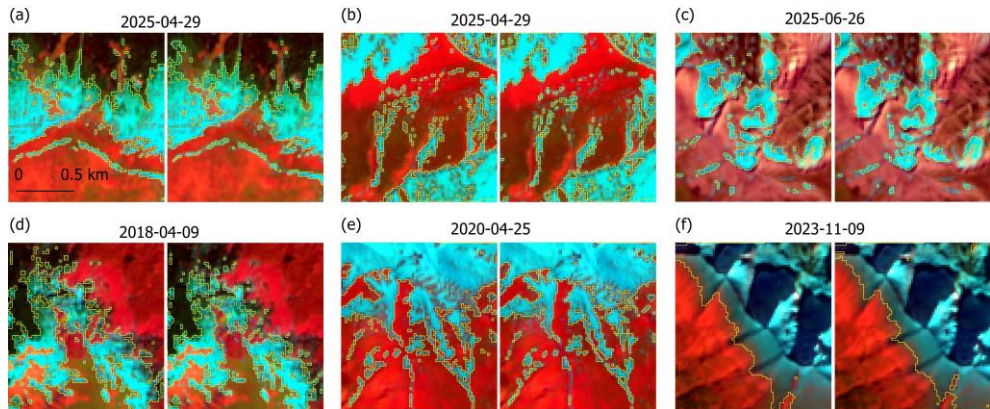


Fig. 7. Illustration of snow cover extent detected using two NDSI thresholds. Six image subsets, (a) to (f), are presented where the boundary (yellow line) superimposed on the left image is for a threshold of 0.181, and that on the right image is for a threshold of 0.4. Background images, false-colour composite images from Sentinel-2 (B11/B8A/B3). The date of the image is indicated for each subplot.

Bayle et al. [29] assessed the impact of the number of available Landsat clear-sky observations on SMOD estimates with their method and found that at least 15 observations were required for accurate results. Reducing the number of observations below 15 led to a rapid deterioration in the quality of the estimate. Therefore, a sufficiently long aggregation period is needed to ensure that an adequate number of observations are available for the entire or at least most of the area. This study used 9 years of Sentinel-2 data. Due to the high revisit frequency (5 days with two satellites, two to three days in the overlap areas of the swaths; [47]), Sentinel-2 satellites provide more cloud-free observations than Landsat satellites. Fig. 8 shows the number of clear-sky observations between March 1 and August 31 in the RIL study area for one year (2025) and for the entire period (2017–2025). The number of clear-sky observations for 2025 was between 10 and 20 for most of the area, and this was not enough for an accurate SMOD estimate, as seen from Fig. 6. For the period 2017–2025, clear-sky observations were between 80 and 130. In the eastern part of the study area, where there is an overlap of the swaths, the number of observations is approximately double. The ability to obtain good SMOD estimates with only five years, as suggested by Fig. 6, has important implications for the studies of SMOD change. However, our analysis was performed over a small area, and future change studies should determine the length of the aggregation period that is appropriate for their study area, as cloud frequency may differ.

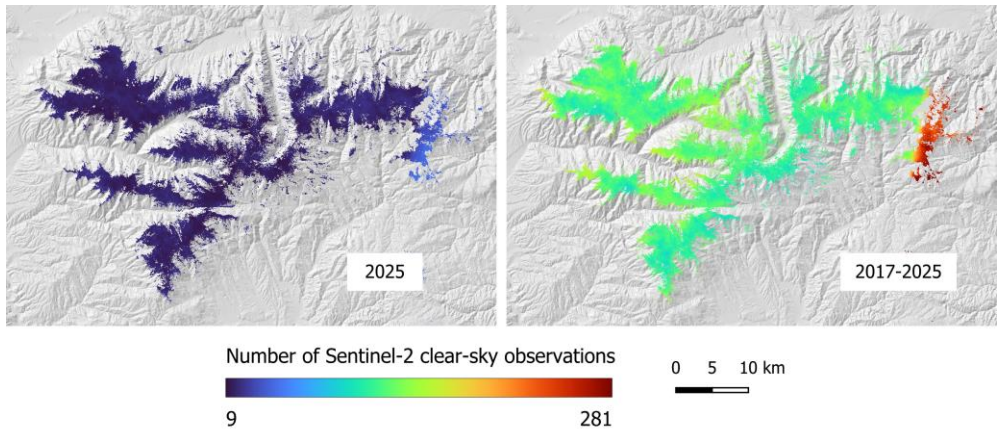


Fig. 8. Number of clear-sky observations in the RIL study area. The number of clear-sky observations between March 1 and August 31 are shown for 2025 (left-hand map) and for the entire period 2017–2025 (right-hand map).

Conclusion

This study created SMOD raster layers at 20 m resolution across six high-mountain areas in the eastern Balkan Peninsula following the methods in Bayle et al. [29] and Choler et al. [34], which represent the first fine-scale, spatially explicit snowmelt timing dataset in this region. The estimated SMODs showed credible spatial patterns related to altitude, exposition and topography. Melting of seasonal snow cover in the lower study areas, Osogovo Mountains and Stara Planina Mountains, occurs in the second half of March and in April. In these mountains, 90% of the open areas above 1600 m a.s.l are snow-free in early May. In the two highest surveyed areas, Pirin and Rila, this occurs in late May and early June. Vitosha Mountains occupy an intermediate position with respect to SMOD. Further studies should focus on validation of these results with data from climatological stations or other methods such as phenocameras. In addition, we determined an optimal NDSI threshold for 67 Sentinel-2 Level 2A images between 2017 and 2025 using Otsu's histogram method. The median optimal threshold value of 0.181 was close to a threshold reported in the literature for other temperate mountains and Landsat data [29]. An experiment carried out in part of one of the study areas showed that the effect of the NDSI threshold value on the SMOD estimates is relatively small and mostly expressed as isolated pixels in areas experiencing a large difference in SMOD over a small distance. Using the typical threshold of 0.40 resulted in only 10% of pixels having SMOD estimates deviating by 10 days or more, compared with the optimal value of 0.181. Our SMOD estimates were based on the full length of the Sentinel-2 L2A dataset available in GEE, i.e. nine years. However, a shorter aggregation period may be sufficient for a reliable estimate of SMOD, as suggested by the analysis of the number of available cloud-free Sentinel-2 observations and the "stabilisation" of the mapped SMOD pattern from five years onwards. The generated raster layers of SMOD, which are freely available on Zenodo [48], may find different applications, including in the distribution modelling of alpine plant species and communities and in hydrological studies.

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ДАТА НА СТОПЯВАНЕ НА СНЕЖНАТА ПОКРИВКА В БЕЗЛЕСНАТА ЗОНА НА НАЙ-ВИСОКИТЕ ПЛАНИНИ В ИЗТОЧНИТЕ БАЛКАНИ ПО НАБЛЮДЕНИЯ ОТ SENTINEL-2

П. Димитров, А. Бел

Резюме

Измерванията на снежната покривка в планинските райони обикновено се извършват в ограничен брой климатични станции, което не позволява да се оценят съществени пространствени различия в датата на стопяването и, които са характерни за тези райони. Спътниковите дистанционни наблюдения предоставят данни способни да запълнят тази празнина. Това проучване картографира датата на стопяване на снежната покривка (ДССП) във високопланинската безлесна зона на шест планински региона в източната част на Балканския полуостров използвайки данни от Sentinel-2 Level-2A и многогодишен метод за агрегиране, който е бил вече успешно тестван с данни от Landsat. Първоначално анализирахме хистограмите на набор от изображения на спектралния индекс Normalized Difference Snow Index (NDSI), използвайки метода на Otsu, за да определим оптимален праг за разделяне на пикселите със и без сняг. Оптималните прагове за отделните изображения варираха, но бяха добре концентрирани около медианата от 0,181. Тази прагова стойност беше впоследствие използвана за картографиране на ДССП на базата на всички данни от Sentinel-2 за периода 2017–2025 г. Получените карти представят реалистично както относителните пространствените различия, така и момента на стопяване на снежната покривка във времето. Оценките показват, че в относително ниската Осоговска планина почти цялата снежна покривка (90%) се стопява до 2 май, докато в Пирин това се става на 8 юни. Анализирахме също така ефекта на праговата стойност на NDSI върху оценките на ДССП, показвайки, че като цяло той е малък по величина и ограничен в пространството. Прагът от 0,40, често използван в литературата, доведе до отклонения на ДССП по-малки от 10 дни за 90% от пикселите, в сравнение с оптималната стойност от 0,181.

SEASONAL AND TEMPORAL BEHAVIOR OF AIR POLLUTION OVER SOFIA CITY FOR THE PERIOD FROM 2007 TO 2025 BASED ON SATELLITE AND GROUND DATA

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Key words: *air pollution, remote sensing, satellite data*

Abstract

In the paper, we study seasonal and temporal air pollution trends over the city of Sofia for the period from the beginning of 2007 to the end of 2025. We use data from all Automatic Ground Measurement Stations and satellite data from the MetOp A and B satellites. We investigated all pollutants, such as SO₂, NO_x, CO, O₃, and others. The only pollutants that show significant values, close to or above the limits here, are dust particles and NO_x, so we present results only for these pollutants. We also use ground temperature data and present the results of its seasonal and temporal trends.

Introduction

Cities are often hotspots for poor air quality. As rapid urbanisation increases the number of people breathing dangerously polluted air, city-level data can help inform targeted efforts to curb urban air pollution and improve public health. Outdoor air pollution is a major environmental health problem affecting everyone in low-, middle-, and high-income countries.

Air pollution in both cities and rural areas was estimated to cause 4.2 million premature deaths worldwide per year in 2019; this mortality is due to exposure to fine particulate matter, which causes cardiovascular and respiratory disease, and cancers [1].

Air pollutants can be of natural (biogenic), anthropogenic or mixed origin, depending on their sources or the sources of their precursors [1]. They are categorised as primary or secondary. Primary pollutants are emitted directly into the atmosphere, while secondary pollutants are formed by interaction with other substances (precursors) through chemical reactions and microphysical processes. Primary air pollutants are fine particulate matter (PM), black carbon (BC), sulphur oxides (SO_x), nitrogen oxides (NO_x) (including both nitric oxide (NO) and nitrogen dioxide (NO₂)), ammonia (NH₃), carbon monoxide (CO), methane (CH₄), non-

methane volatile organic compounds (NMVOCs), including benzene (C₆H₆), some metals and polycyclic aromatic hydrocarbons (PAHs), including benzo[a]pyrene (BAP). Secondary air pollutants are PM (formed in the atmosphere from SO₂, NO_x, NH₃ and VOCs), ozone (O₃), NO₂ and several volatile organic compounds (VOCs).

Particulate matter, nitrogen dioxide and ground-level ozone are now generally recognised as the three pollutants that have the greatest impact on human health. Long-term exposure to high levels of these pollutants ranges in severity from respiratory damage to premature death. Around 90% of European city dwellers are exposed to concentrations above levels considered harmful to health [2].

Sofia, the capital city of Bulgaria, is unfortunately exposed to high levels of particulate matter (PM), despite extensive efforts by the government and the municipality in recent decades, and some authors have tried modelling air quality there [3, 4].

Air quality monitoring is mainly carried out using three methods – satellite data, ground-based measurements and unmanned aerial vehicles. Satellite data show the presence of individual pollutants in the column of atmospheric air from the ground surface to the measuring device, but with relatively low spatial and temporal resolution. Ground-based measurements (mainly from AIS) provide accurate quantitative measurements with good temporal resolution, but only for a small area around their location. Unmanned aerial vehicles provide the intermediate between the two, namely – the possibility of dynamic measurements at different heights and locations. Then, present satellites measure only Aerosol indexes, but not PM_x concentration and NO₂ only [5]. Automatic Ground Measure Stations (AGMS) in Sofia provide data for NO, NO₂, NO_x, PM2.5 and PM10 [5].

In this paper, we use both satellite and ground measurement data to inspect temporal and seasonal trends of main air pollutants in Sofia.

Data and Method

In this work, we use monthly values of the Absorption Aerosol Index and NO₂ from MetOp A and B satellites [5] for the period November 2007 to the end of 2025. Data from MetOp A is available till the end of 2020, while data from MetOp B starts at the beginning of 2013. We use data from all AGMS in Sofia, including Mobile station and two new stations – those in Busmanci and Trebich [6] for the period from the beginning of 2007 till the end of 2025. In Fig. 1, we show their locations. In Fig. 2, we show a working time diagram. We use data from the mobile station only for these periods, when it stays in the parking zone at Paris 5 Str.

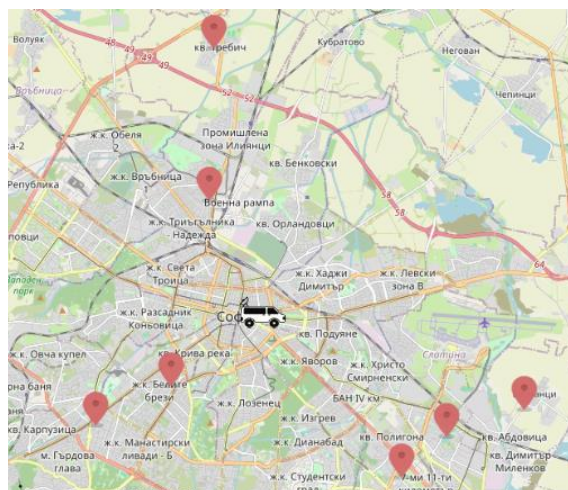


Fig. 1. AGMS positions in Sofia

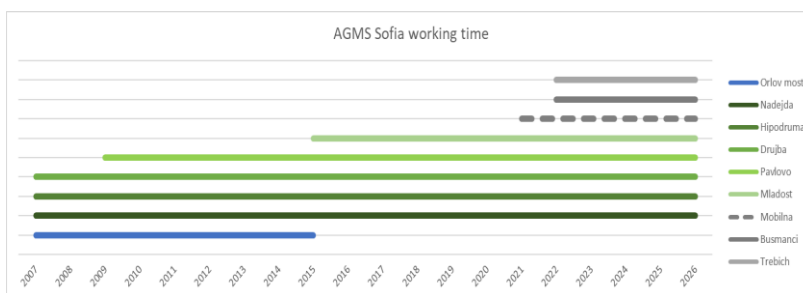


Fig. 2. AGMS in Sofia – working time diagram

Data from AGMS is provided in daily base and here we average it over every month.

We build seasonal and temporal trends for AAI and NO_2 from satellite data and seasonal and temporal trends for all pollutants from AGMS – $\text{PM}_{2.5}$, PM_{10} , NO , NO_2 , NO_x , SO_2 , CO and O_3 . Temporal trends are obtained by averaging monthly data for each year and seasonal averaging monthly values for each month over years [7].

We build seasonal and temporal trends for averaged daily temperature only to show its significant increase over the last few years.

In Sofia, only PM_x and NO_x data show values close to or above the obtained maximal limits, so we study them in more detail.

Monthly values for AAI are with spatial resolution 1×1 degree, while NO_2 are with resolution 15×15 minutes (or $1/4$ degree). In both cases, Sofia is placed in only one pixel. In Fig. 3, we illustrate pixel sizes for the AAI and NO_2 columns, respectively.

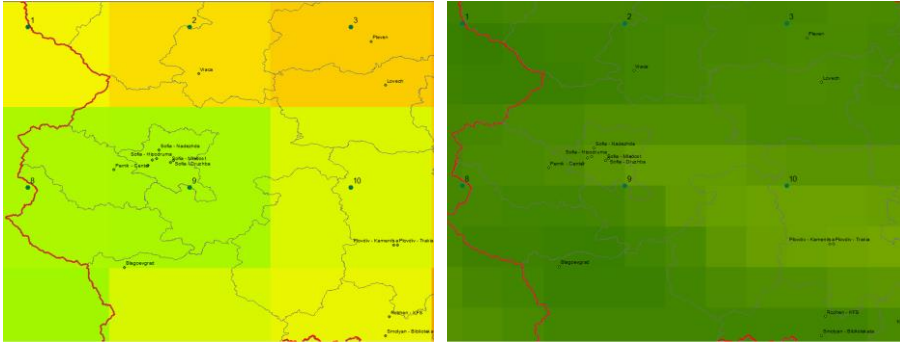


Fig. 3. Spatial resolution of MetOp A and B for AAI and NO₂

Results

In Fig. 4 and Fig. 5, we show temporal and seasonal AAI behaviour, respectively.

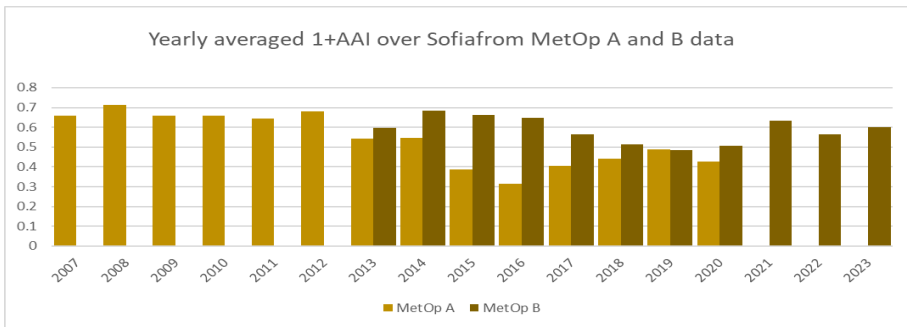


Fig. 4. Temporal AAI trend in Sofia

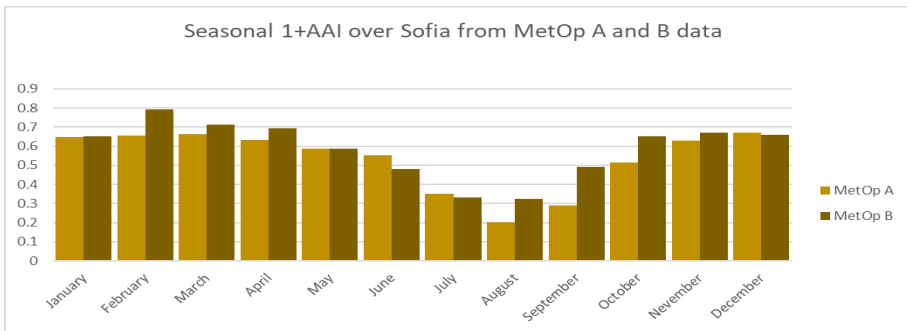


Fig. 5. Seasonal AAI trend in Sofia

In Fig. 6 and Fig. 7, we show the same trends for MP10, obtained from AGMS.

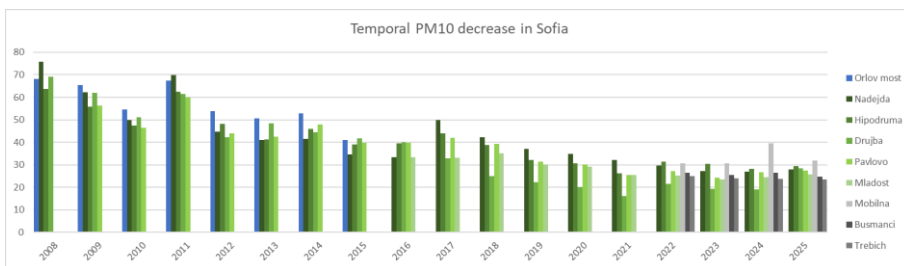


Fig. 6. Temporal PM10 trend in Sofia

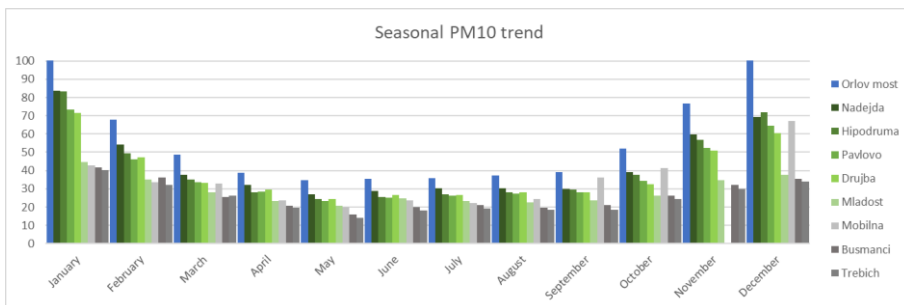


Fig. 7. Seasonal PM10 trend in Sofia

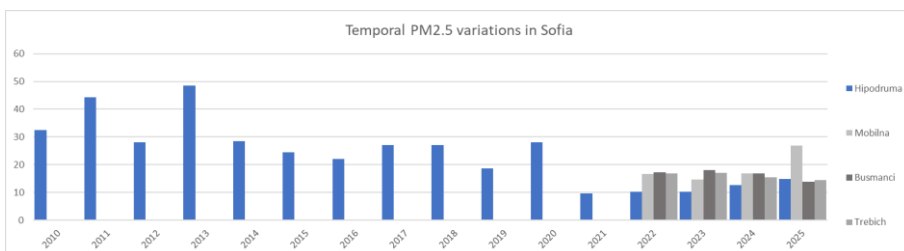


Fig. 8. Temporal PM2.5 trend in Sofia

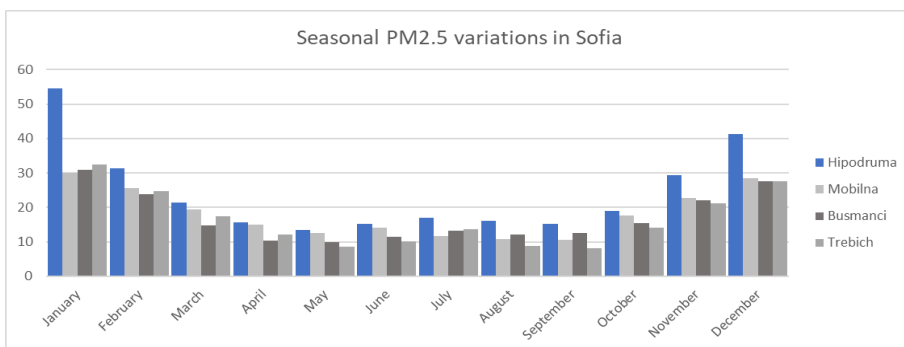


Fig. 9. Seasonal PM2.5 trend in Sofia

In Fig. 8 and Fig. 9, we show temporal and seasonal trends for PM2.5.

In all figures from AGMS, we use the same colours for all measurement stations for easier comparison.

In Fig. 10 and Fig. 11, we show temporal and seasonal NO₂ behaviour obtained from MetOp A and B data, respectively.

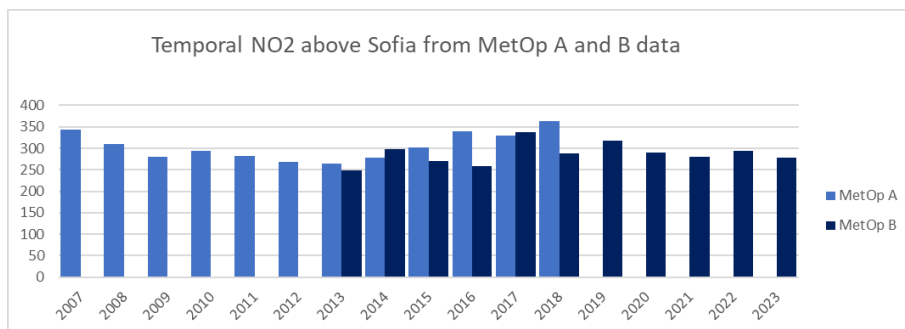


Fig. 10. Temporal NO₂ trend above Sofia

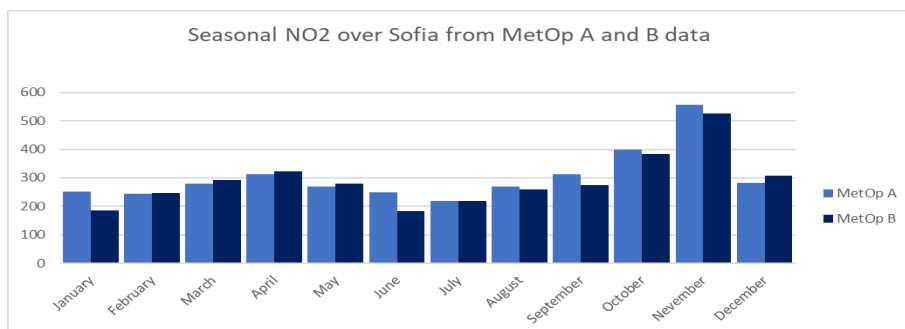


Fig. 11. Seasonal NO₂ trend above Sofia

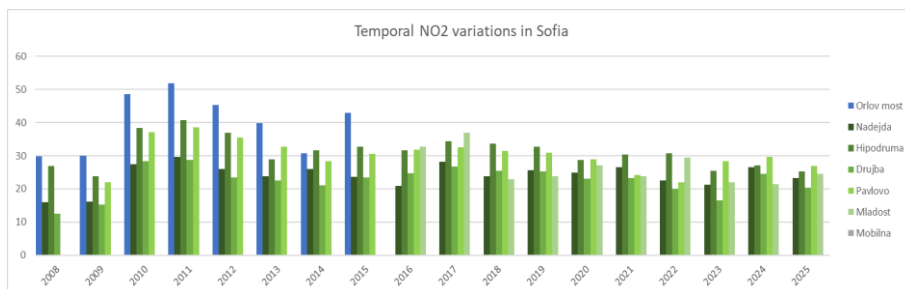


Fig. 12. Temporal NO₂ trend in Sofia

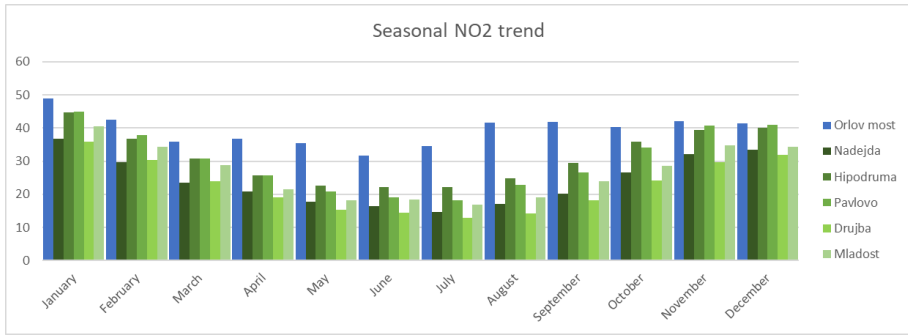


Fig. 13. Seasonal NO₂ trend in Sofia

In Fig. 12 and Fig. 13, we show temporal and seasonal NO₂ behaviour obtained from AGMS in Sofia.

Seasonal and temporal trends of NO and NO_x are similar to those of NO₂.

In Fig. 14, we show temporal and seasonal trends for total NO_x, SO₂, CO, and O₃ at the Hipodruma station.

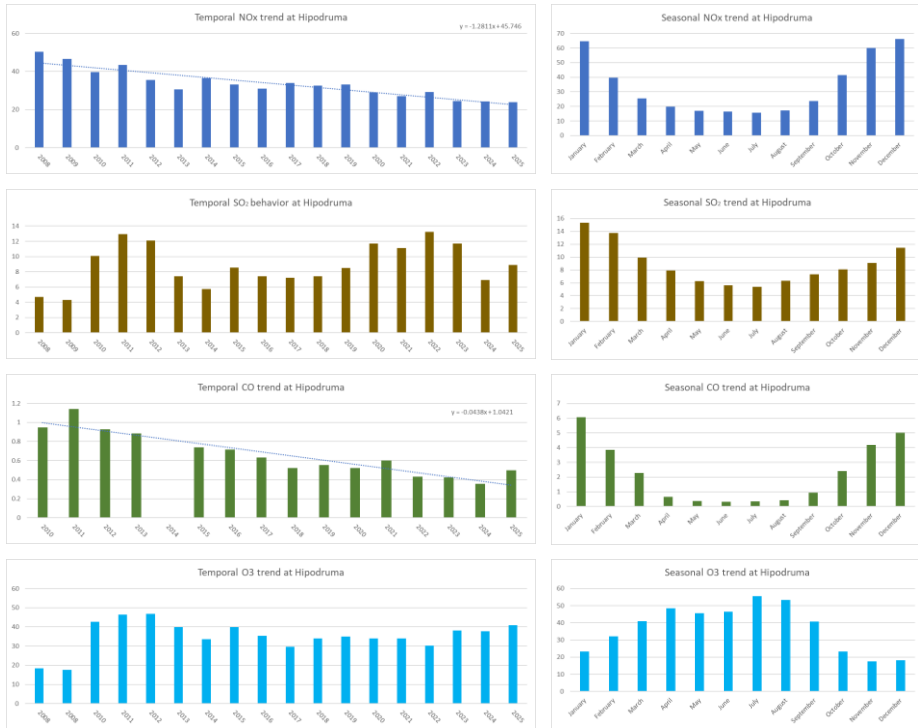


Fig. 14. Temporal and seasonal SO₂ CO and O₃ trend in Sofia

In Fig. 15 and Fig. 16, we show temporal and seasonal temperature increases obtained from AGMS in Sofia.

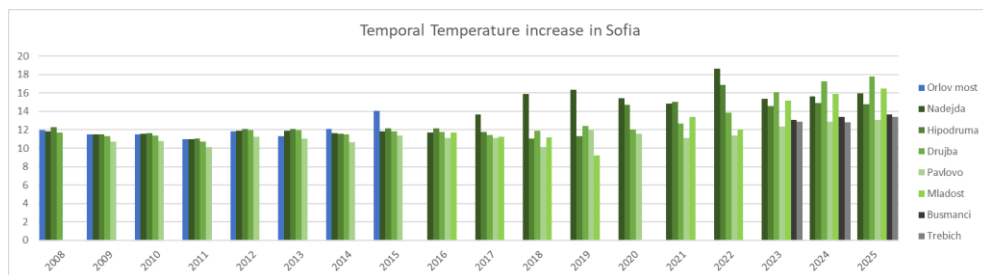


Fig. 15. Temporal temperature trend in Sofia

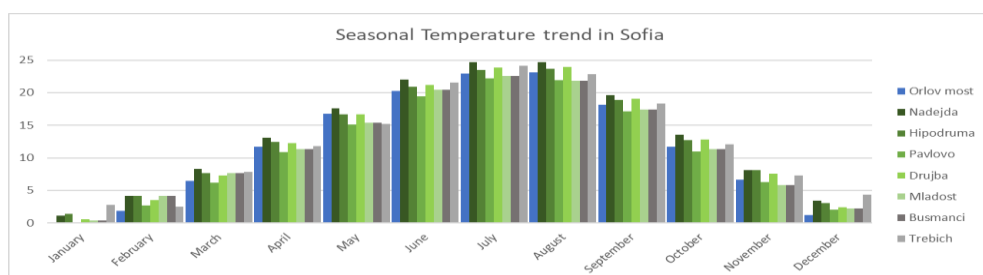


Fig. 16. Seasonal temperature trend in Sofia

Discussion and conclusions

As we see from Fig. 4 and Fig. 6, seasonal trends of AAI and PM show similar behaviour. The same is seen for NO₂, NO_x, SO₂, and CO from AGMS. All NO, NO₂ and NO_x show nearly equal trends. All these pollutants have their maximum in January, February and December. NO₂, measured from satellite data, shows a different seasonal trend – it has a maximum in November.

Near-ground O₃ shows a different seasonal trend, too. Its monthly values are higher in summer and show a maximum in July and August.

While AAI and NO₂ from satellite data show no temporal trend, PM₁₀ and NO₂ at the ground show a significant decrease over the years. A significant decrease trend shows CO too. SO₂ and O₃ show no temporal trend.

Yearly averaged air temperature, measured from AGMS, shows an increase of about 40–50% during the last five years.

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СЕЗОННО И ВРЕМЕННО ПОВЕДЕНИЕ НА ЗАМЪРСЯВАНЕТО НА ВЪЗДУХА НАД ГРАД СОФИЯ ЗА ПЕРИОДА ОТ 2007 ДО 2025 Г. ВЪЗ ОСНОВА НА СПЪТНИКОВИ И НАЗЕМНИ ДАННИ

М. Димитрова

Резюме

В настоящата статията изследваме сезонните и времеви тенденции на замърсяване на въздуха над град София за периода от началото на 2007 г. до края на 2025 г. Използваме данни от всички автоматични наземни измервателни станции (АИС) и сателитни данни от спътниците MetOp A и B. Всички замърсители като SO₂, NO_x, CO, O₃ и други са разгледани. Единствените такива, които показват значителни стойности, близки или над пределно допустимите норми тук са праховите частици и NO_x, така че представяме резултати само за тези замърсители. Използваме и наземни данни за температурата и представяме резултатите за тяхното времево и сезонно поведение.

QUASI-SYNCHRONOUS AEROSPACE MONITORING OF CRITICAL INFRASTRUCTURE OBJECTS USING UNMANNED AERIAL VEHICLES AND RADAR SATELLITES

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Key words: remote sensing, aerospace monitoring levels, critical infrastructure, unmanned aerial vehicles for surveillance, video imaging, thermal imaging, radar surveillance satellites, synthetic aperture radars

Abstract

The conditions for conducting quasi-synchronous aerospace monitoring are revealed. The advantages of using unmanned aerial vehicles to monitor critical infrastructure objects using video and thermal cameras are outlined. The advantages and disadvantages of monitoring with SAR satellites are defined, and an analysis of radar images of critical infrastructure objects is performed. Conclusions from the quasi-synchronous aerospace monitoring conducted in the field are formulated, and directions for improving its effectiveness are indicated.

Introduction

Quasi-synchronous aerospace monitoring of various objects located on the Earth's (sea) surface uses the conceptual apparatus of the complex synchronous aerospace experiment for remote sensing (RS) of the Earth [2]. This experiment is aimed at obtaining additional information about the observed objects and processes from various sensors located in space, the atmosphere, and on Earth, and at processing and interpreting this information.

The complex synchronous aerospace experiment for RS of the Earth is most effective when conducted on three levels (floors) – through space vehicles (SV) for RSE, through aerodynamic observation vehicles – mainly aircraft, helicopters, and drones, and through ground-based measuring complexes. In this case, the spacecraft for remote sensing operate in low orbits (up to 1,000 km), and the aerodynamic observation aircraft – at altitudes from 100 m to 10,000 m.

In a number of cases, synchronous aerospace experiments are conducted at two levels, for example, corresponding to the CLA for DI and the aerodynamic observation aircraft. In this case, if aerospace monitoring of objects is carried out at the same time interval, the aerospace experiment is synchronous [2]. Otherwise, but under unchanged monitoring conditions, the aerospace experiment is quasi-synchronous.

In this article, when considering quasi-synchronous aerospace monitoring, taking into account the results of a flight experiment conducted in October 2025, listed below, we first analyse the aeromonitoring of critical infrastructure (CI) objects and then space monitoring.

Aerial monitoring of sites and processes from critical infrastructure

Aerodynamic surveillance aircraft are essentially means of aerial monitoring, and the common feature that unites them is the ability to obtain images of the objects and processes being observed. Among this class of surveillance aircraft, unmanned aerial vehicles (UAVs) are emerging as particularly effective and promising in the 21st century. Their main advantages over manned aircraft are their significantly lower cost and weight, longer flight duration, significantly lower fuel consumption, reduced flight operating costs, the ability to take off without a runway for takeoff and landing, etc.

Unmanned aerial vehicles appeared during World War I, with their use beginning in 1917. The development of these technologies includes key moments from World War I and World War II, the Cold War, and the technological boom of the 21st century. In addition to military purposes, UAVs have found diverse applications in civilian areas [5]. UAV technology is widely used in agriculture for monitoring yields, crop fertilisation needs, disease and pest control, irrigation, etc. [6]. Another application is in urban planning, where UAV data is used to build various types of infrastructure to improve the quality of life [7, 8]. UAVs are also used to monitor damage from various types of natural disasters such as floods, forest fires, and earthquakes [9].

To implement the first level of quasi-synchronous aerospace monitoring and taking into account the significant role of UAVs at the present stage, on October 28, 2025, a team of specialists from the Institute for Space Research-BAS (ISR-BAS), the G. S. Rakovski Military Academy (G. S. Rakovski MA), the N. Y. Vaptsarov Naval Academy and the Institute of Chemical Engineering – BAS conducted a flight experiment in the area of Varna, related to task 1.1.6 of the National Scientific Program "Security and Defence," using UAVs for aerial monitoring and specialised measurements of CI objects. Through expert assessment for conducting the flight experiment, the industrial zone of the city of Devnya and the area of Asparuhov Bridge with the adjacent island in the city of Varna were selected [1].

A wing-type UAV manufactured by the Bulgarian company Fraga X was prepared for the flight experiment, with a corresponding payload (PT) – Fig. 1, operated by a team from the G. S. Rakovski Air Force Academy. This UAV, with a maximum speed of 200 km/h, was equipped with three types of payloads: a TV camera, an IR camera, and a gas analyser, with a resolution of 1920/1080 pixels per frame for the video camera (TV camera), was 640/480 pixels per frame, and the gas analyser was designed to detect nitrogen oxides.



Fig. 1. Integrated payload of the UAV

Given that there are numerous CI facilities located in the industrial zone of the town of Devnya and in the area of Asparuhov Bridge in the city of Varna, in accordance with the capabilities of the UAV's target equipment, several CI facilities were selected for analysis of the results of the flight experiment [1]. The UAV flew over the two above-mentioned areas at an altitude of 300 m. When interpreting the images obtained, it should be noted that the angle of view of the video camera is greater than that of the infrared camera.

As a result of the flight experiment shown in Fig. 2, a video image and a thermal image of the Asparuhov Bridge in Varna are presented. The bridge connects the Asparuhovo and Galata neighbourhoods with the central part of the city, separated by navigation channel No. 1, which connects Lake Varna and Lake Beloslav with the Black Sea.

In the middle and upper left corners of the thermal image (Fig. 2 on the right), operating enterprises can be seen, and in the lower corner, moving cars. South and north of the Asparuhov Bridge, one and four ships, respectively, can be seen sailing along the canal.

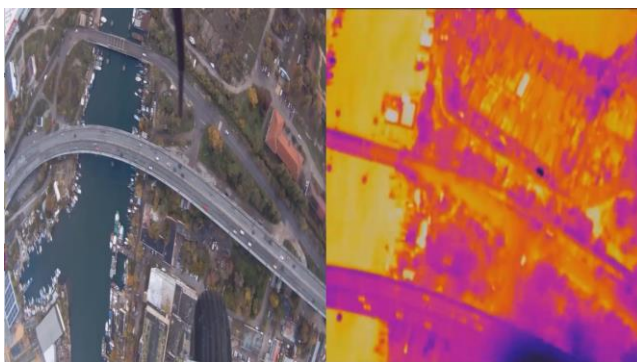


Fig. 2. Video image and thermal image of Asparuhov Bridge

Moving cars are much clearer in the video image (Fig. 2, left). The results of the aerial monitoring allow us to conclude [1] that when comparing video images and thermal images of CI objects captured using UAVs, multispectral infrastructure (tanks, working machines, etc.) and its condition, as well as the perimeter of the objects, can be observed. In addition, in a number of cases, the thermal images obtained from UAV observations of various CI objects are more informative than the corresponding video images.

Space-based monitoring of critical infrastructure objects and processes

After the completion of the UAV flight experiment at approximately 11:00 on 28 October 2025, later the same day at around 16:09, the Earth observation radar satellite Sentinel-1 (Fig. 3), part of the European Copernicus Earth Observation Programme, overpassed the area of the city of Varna.

As is well known, the Copernicus programme includes operational optical and radar satellites from the Sentinel-1, -2, -3, -4, -5, and -6 missions. However, on the day of the UAV flight experiment over the Varna region, only the Sentinel-1 radar satellite passed over the same area. This satellite is equipped with a Synthetic Aperture Radar (SAR). This type of Earth observation spacecraft offers several advantages over comparable optical or infrared observation systems.

Specifically, the main advantages of SAR satellite systems include the capability to perform SAR measurements under cloudy conditions and during nighttime. Important is the ability to detect radar-contrasting objects concealed beneath forest canopies, vegetation, or snow cover that are invisible in the optical or infrared portions of the electromagnetic spectrum. Other advantages of some advanced SAR systems also include: the capability to detect and estimate motion parameters of moving targets; multi-mode operation and flexible control of the onboard SAR sensor, enabling rapid changes in swath position and size, spatial resolution, and data representation; the capability for three-dimensional object “imaging”; terrain mapping by means of SAR interferometry.



Fig. 3. General view of a Sentinel-1 series Earth observation radar satellite

On the other hand, the main disadvantages of satellite-based SAR Earth observation systems include geometric distortions in SAR imagery and the presence of inherent speckle noise resulting from the coherent nature of SAR systems. Another limitation is the relatively lower spatial resolution of freely available SAR data compared to optical satellite systems (e.g., Sentinel-2 and Landsat-8). In addition, SAR systems are generally associated with significantly higher costs than comparable optical–electronic satellite systems.

The Sentinel-1 satellite flies in a sun-synchronous orbit (SSO) at an altitude of approximately 693 km. On the day of the UAV flight experiment, the satellite overpassed the Varna region on an ascending orbit, with right-looking geometry in the direction of motion, from south to north along the SSO. The spacecraft operates in the C-band of the microwave portion of the electromagnetic spectrum and supports two linear polarisation states of the transmitted and received electromagnetic pulses, as follows:

- 1) Co-polarised – VV,
- 2) Cross-polarised – VH.

In addition to the advantages outlined above, SAR-equipped satellites are characterised by high radiometric resolution, also referred to as contrast or brightness sensitivity, which defines the ability to discriminate objects with different radar backscattering properties.

Sentinel-1 SAR imagery is acquired in four acquisition modes, with spatial resolutions ranging from 10 to 100 m. Depending on the acquisition mode, the swath width is 80, 100, 250, or 400 km, respectively.

The primary type of SAR measurements from Sentinel-1 is in the **Interferometric Wide Swath (IWS)** mode, represented in radar geometry, where the recorded signal is expressed as complex numbers (*Slant Range Complex – SLC*). The scene dimensions are approximately 250 km in swath width and 180 km

along-track. However, for the purposes of the present analysis, the utilised image product is **Ground Range Detected (GRD)**, in which only the amplitude of the complex signal is represented, projected onto the ellipsoid and multilooked. This product includes the amplitudes of both polarisations – VV and VH.

The available Sentinel-1 image acquired on 28 October 2025 was processed using the cloud-based platform **Sentinel Hub (SH)** [4]. For the purposes of this analysis, three types of images were generated, as follows:

- Pseudo-colour image (RGB composite) – SAR Urban – proposed by Sentinel Hub for urban environment analysis. Backscatter intensity values above – 5 dB are associated with urban objects and engineering infrastructure, appearing as bright green, pink, and white tones in the composite image. All types of metallic macro-objects, such as ships, silos, and similar structures, are also recognisable in these bright tones. The colour variation (pink or green) depends on the orientation of the backscatter vector relative to the radar line of sight (RLOS), which is perpendicular to the satellite motion vector. In flat areas outside mountainous regions, the tones are dark (dark blue), corresponding to backscatter from natural objects such as forests, agricultural land, and water bodies. Calm sea surfaces appear dark.
- VV polarisation – representing the backscattering coefficient (Sigma-Nought – σ^0) in co-polarized waves (σ^0 VV), which provides the highest contribution for detecting urban targets and metallic objects from engineering and military infrastructure.
- VH polarisation – representing the backscattering coefficient in Cross-polarised waves (σ^0 VH), which are primarily sensitive to natural objects such as forests and agricultural areas.

Fig. 4 presents a radar image in VV polarisation (σ^0 VV) of Navigation Channel No. 2, connecting Varna Lake and Beloslav Lake, along with the approaches from both lakes. The water surface of the navigation channel and the lake basins appear black due to weak backscattering toward the radar antenna. A clearly distinguishable fairway is visible along the channel as a sequence of bright white points, outlined with red circles and labelled 9, 10, and 11, indicating strong backscattering toward the radar.

Along the length of the navigation channel, a sequence of paired white points is clearly observed, representing navigation buoys. These structures are metallic constructions with diameters smaller than 1 m and edges positioned approximately 1.5 m above the water surface, equipped with corner reflectors. This results in strong backscattering of the signals emitted by the onboard radar of Sentinel-1. Consequently, these buoys appear in the radar image as a sequence of paired white points delineating the navigational fairway of vessels along the channel (points 9, 10, and 11).

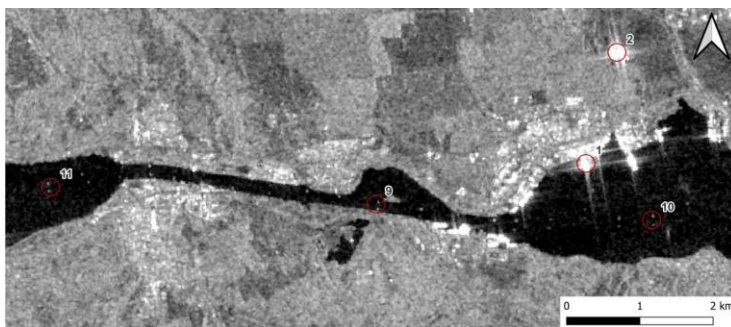


Fig. 4. Sentinel-1 radar image of Varna Lake in VV polarisation (σ_{0VV})

These buoys define safe navigation routes used by vessels (ferries, ships, etc.) travelling from the Black Sea to Beloslav Lake and vice versa.

Fig. 5 presents a three-channel radar image with assigned colours of the entire navigation channel connecting Varna Lake and Beloslav Lake with the Black Sea, including the Asparuhov Bridge and all points relevant to the present analysis.

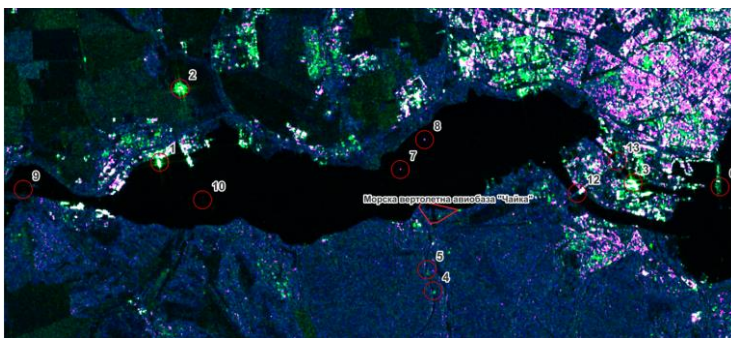


Fig. 5. The “SAR Urban” RGB composite (SH) of Sentinel-1 SAR image along the channel area of the city of Varna

North of the delineated fairway in Varna Lake, approximately opposite the “Chaika” Naval Air Base, two pink points are observed in the radar image, located toward the northeast (points 7 and 8, Fig. 5). These most likely represent restriction buoys or light vessels, such as large fishing boats, associated with the adjacent fishing settlement.

On the left side of the radar image in Fig. 5, at the northwestern end of Varna Lake, the port of the thermal power plant (TPP) “TPP-Varna” is observed, indicated by two light-green patches against the water background (also known as TPP “Ezerovo” Port JSC; point 1, Fig. 5). Both breakwaters of the port are visible in the same colour, although no docked vessels are observed.

North of the “TPP-Varna” port in Fig. 5 and Fig. 6, a bright green patch is observed, indicating the municipal waste processing plant “Eco-Invest Assets” (point 2). It is known that one of the buildings of this facility has a metal roof, which explains the strong backscattered signal response toward the radar.

In Fig. 5, south of the breakwater of Varna-East Port, depicted in green (point 6), two points of the same colour are observed in the sea. These most likely represent two vessels floating or anchored in Varna Bay. Two similar points are also observed in Fig. 4 along the “Black Sea” highway, south of the “Chaika” air base (points 4 and 5). These likely correspond to two large tanker trucks, which produce significant backscattering of electromagnetic waves while travelling along the Burgas–Sofia highway.

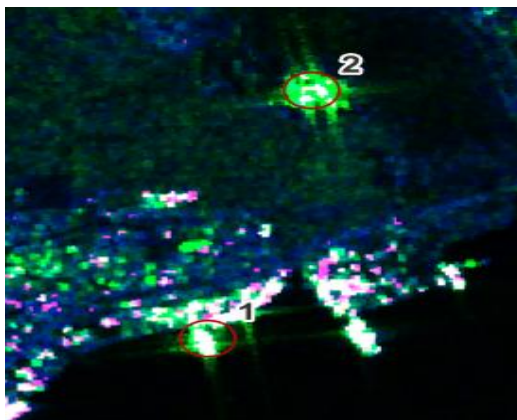


Fig. 6. Detail from “SAR-Urban” RGB composite from Sentinel-1 SAR image

In Fig. 5 and Fig. 6 of the “SAR Urban” pseudo-colour RGB composite imagery generated in Sentinel Hub, white patches are observed east of the port of the shipbuilding company MTG “Delfin” (point 1) at the northern end of Varna Lake. These patches extend into the channel waters east of the port of STF JSC (“Construction Technical Fleet”). These correspond to two floating cranes' metallic structures with large reflective surfaces (point 0).

Due to the metallic nature of the objects and the dense presence of structures, a strong backscattered electromagnetic response toward the Sentinel-1 radar antenna is observed. Consequently, the tones are predominantly white and bright green.

In Fig. 7 (left and right), the “Asparuhov Bridge” is clearly distinguished, crossing the northern and southern branches of the navigation channel (points 12 and 13). The total length of the bridge is 2050 m, its width is 21 m, and its height is 52 m, and its main span is 160 m.

To the right of the “Asparuhov Bridge” (Fig. 7), a bright white patch is observed in the centre of the island, indicating strong backscattering of

electromagnetic waves in green tones (point 3, Fig. 7 left), corresponding to the location of the “Odesos” shipyard. To the right of this white patch (point 3, Fig. 7 (right): the shipyard dock is visible, and the boundaries of the patch allow the facility area to be delineated. In the southeastern lower part of the island, two white and green patches are observed, likely indicating oil storage tanks.

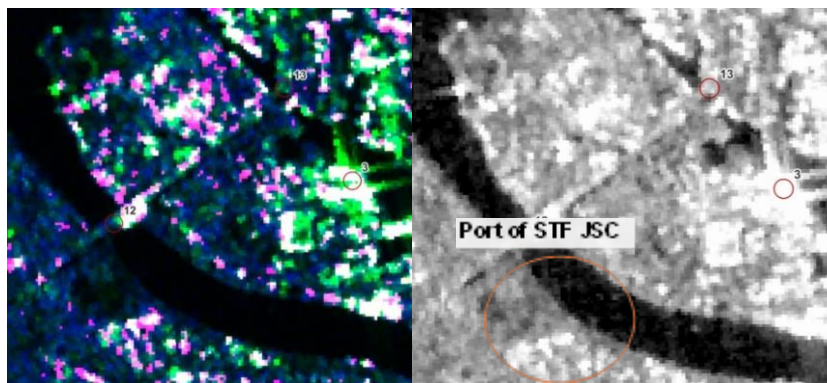


Fig. 7. Left: “SAR Urban” RGB composite image by Sentinel Hub; Right: VV-polarized radar image in the area of the “Asparuhov Bridge” over the channel of Varna

Analysis of the results of quasi-synchronous aerospace monitoring of critical infrastructure objects using UAVs and radar satellites

When analysing the results obtained, the different information capabilities of UAVs for surveillance and radar satellites for DI should be taken into account.

The resolution of the images obtained by the TV and IR cameras of the surveillance UAV (mentioned above) is high, enabling observation of moving vehicles (Fig. 2).

According to official classifications, the spatial resolution of radar images obtained by satellites from the Sentinel-1 series is average, i.e. no higher than 10 m. This allows for the observation of images of objects with similar linear dimensions, such as breakwaters, floating docks, oil tanks, large cisterns, and highways. This is how the radiometric resolution of these images (i.e., contrast-brightness sensitivity) manifests itself, characterising the ability to distinguish objects with different reflectivity.

The observation on the radar image of the fairway of vessels in the channel, as a sequence of pairs of white dots (Fig. 4), is due to the navigational buoys marking it being of metal construction with edges and equipped with corner reflectors for better radar visibility. This artificially increases the radar contrast of the radar image of the channel fairway.

Based on the above, it can be concluded that satellite radar images, even with medium spatial resolution (e.g., from Sentinel-1), when conducting quasi-

synchronous aerospace monitoring, are more comprehensive than high-resolution video and thermal images obtained by the respective cameras of the surveillance UAV. The aforementioned satellite radar images can be used to monitor the country's territorial waters, linear and area objects of critical infrastructure, large oil spills at sea and other large-scale pollution, wake trails from moving large ships, etc.

At the present stage, the possibilities for improving the informative value of space monitoring using SAR satellites are closely linked to the activities of the best-known commercial operators of high-precision radar images, such as the American companies Capella Space (Fig. 8) and Umbra Lab [3].



Fig. 8. General view of the Capella 2 radar observation satellite

For example, if the radar image of an object from the CI is obtained from a commercial radar observation satellite from the Capella series (Fig. 8), operating in the X-band and characterized by a spatial resolution in spotlight mode of 0.3-0.5 m (i.e., with ultra-high resolution), the characteristics of the CI objects observed within the framework of quasi-synchronous aerospace monitoring will be more detailed, accurate, and complete.

The advantages of the Capella series satellites mentioned above are not the only ones. According to the manufacturer, Capella Space, in addition to the high and ultra-high resolution of radar images in different observation modes, a full orbital configuration of 36 Capella satellites provides high observation frequency (within hours) and operational delivery of the relevant radar images to users. The ability to quickly redirect the SAR satellite from one object to another, as well as the availability of an interferometric imaging mode, should also be taken into account. These advantages significantly increase the information content of the images obtained from the Capella series satellites and similar ones, and on this basis, the effectiveness of aerospace monitoring, both synchronous and quasi-synchronous.

Conclusion

The results obtained from quasi-synchronous aerospace monitoring of CI objects using UAVs and radar satellites can be updated and even changed if synchronous aerospace monitoring is implemented in the future, provided that the relevant information is available and the necessary organisation is in place. In addition to radar satellites, it is advisable to use modern optical satellites with high information capabilities. For example, the private space companies Maxar Technologies Inc. and Planet Labs produce, use, and market information from satellites of the same name for optical-electronic observation with a spatial resolution of 0.3–0.5 m in panchromatic mode and 1.2–1.3 m in multispectral mode.

Broad prospects for aerospace monitoring of CI objects are also opening up with the use of hyperspectral imaging equipment for the Earth's surface on board satellites, providing multidimensional spatial spectral images.

After conducting and analysing the experimental part of the problem, we can move on to the systematic implementation of aerospace monitoring of CI objects in our country, with the results being reported to the authorised state authorities.

In conclusion, the listed engineering infrastructure objects, such as Asparuhov Bridge, metal tanks, ships, and buildings in the area of STF AD, the Odessos shipyard, and the Delfin group, are characterised by strong backscattering in the direction of the antenna, with values above 0 dB of the backscattering coefficient σ_{0VV} in co-polarised waves (VV). The reason is that metal structures, as well as buildings, form more than one reflection with high intensity of backscattered electromagnetic flux in the direction of the satellite antenna.

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КВАЗИСИНХРОНЕН АЕРОКОСМИЧЕСКИ МОНИТОРИНГ НА ОБЕКТИ ОТ КРИТИЧНАТА ИНФРАСТРУКТУРА ЧРЕЗ ИЗПОЛЗВАНЕ НА БЕЗПИЛОТНИ ЛЕТАТЕЛНИ АПАРАТИ И РАДАРНИ СПЪТНИЦИ

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Резюме

Разкрити са условията за провеждане на квазисинхронен аерокосмически мониторинг. Формулирани са предимствата на използване на безпилотни летателни апарати за наблюдение на обекти от критичната инфраструктура с помощта на видео и термокамера. Дефинирани са достоинства и недостатъците на наблюдението със сателити със SAR и е извършен анализ на радарни изображения на обекти от критичната инфраструктура. Формулирани са изводи от проведения на терен квазисинхронен аерокосмически мониторинг и е посочено направление за повишаване на неговата ефективност.

AEROSPACE SYSTEM FOR MONITORING MAN-MADE AND NATURAL DISASTERS

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Key words: *monitoring; unmanned aerial vehicles; critical infrastructure*

Abstract

Monitoring natural and man-made disasters and phenomena is an important element of national security and aims to help address key challenges in detecting and preventing regional crises. This implies the use of a national monitoring system that enables analysis of the stability of the functional structure of natural and man-made systems, and the implementation of short- and long-term ecological forecasts and the operational solution of tasks related to actions during crises and the prevention of their consequences. In this monitoring process, a complex use of information from satellite, aircraft, and ground levels is necessary, which is also the subject of research in this article.

Introduction

Based on the analysis and existing experience, the concept of monitoring is proposed, which consists of a complex use of space-, aviation-, and ground-based methods and means of observation, to be implemented by an aerospace monitoring.

Tasks of system: To define the essence of environmental disasters and critical infrastructures as an object for monitoring and research; Based on the system analysis, to determine the methods, structure and composition of the complex monitoring system; To justify the expediency of using UAVs as an element of the national monitoring system; To determine the type, orbit and duration of the flight over the object of the microsatellites in the monitoring system; To determine the composition and structure of the Center for Receiving Aerospace Information and the possibilities for pre-processing the received information and its thematic suitability.

The main sources of information about the Earth's surface are electromagnetic radiation, reflected solar radiation, intrinsic radiothermal radiation and reflected artificial radiation. The registration of these radiations is carried out by various means. Analysing the characteristics of remote sensing equipment (dimensions, mass and power consumption), conclusions can be drawn about the

possibilities for placing on board instruments that are mounted on aeroplanes and artificial Earth satellites (ESAs), possibilities for pre-processing the received information and its thematic suitability. Images and data obtained from satellite and aviation systems are subjected to pre-processing, including analysis and linking to a specific coordinate grid, and then offered to individual users. Linking images to geographic coordinates and developing geographic information systems helps to accumulate a database of data necessary for various industries and application areas.

The database includes the following layers with their respective attributive information: State border, Administrative (district and municipal) borders; River network, Artificial and natural water areas; Road, Railway network; Potentially dangerous objects; Electricity transmission network; Gas transmission network; Settlements; Forests. To solve the tasks of operational monitoring in real or near real time, it is advisable to use the MODIS and VIIRS satellites, since the images received from them have good repeatability of their flight over the same territory. A major drawback in this case is the small spatial resolution. However, this can be overcome if the range up to 250 m is supplemented by the use of a national or regional satellite, providing images with a spatial resolution of 40 to 80 m transmission network; Settlements; Forests. Archival satellite images with medium spatial resolution [1].

Considering the increasing penetration of UAVs, an on-board video system operating in the visible and near-infrared range with a spatial resolution of less than 50 cm can be used.

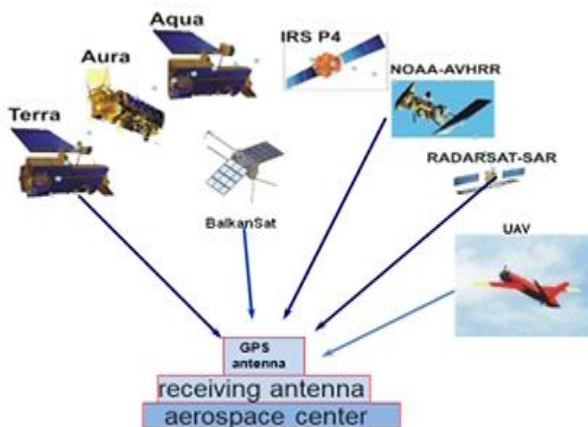


Fig. 1

Based on the analysis and existing experience, a monitoring concept has been proposed, consisting of the complex use of space, aviation and ground-based observation methods, to be implemented by an aerospace monitoring system (Fig. 1) [2, 3].

The proposed concept and centre fully comply with the requirements for monitoring national and regional critical infrastructures set by the European Critical Infrastructure Protection Program [3–6].

To assess the qualities of a UAV in operation, the so-called “formula for its ability to conduct aerial reconnaissance and surveillance” is proposed. It reflects the degree of influence of various factors (mainly the capabilities of the UAV) in forming the tactics of action in the presence of a certain payload.

According to this “formula”, the ability of a UAV to conduct aerial surveillance depends on the following factors: thrust, armament; stability and controllability; payload characteristics/electronics factor; autonomy and multifunctionality; small number of personnel for service; mobile and transportable ground equipment [2].

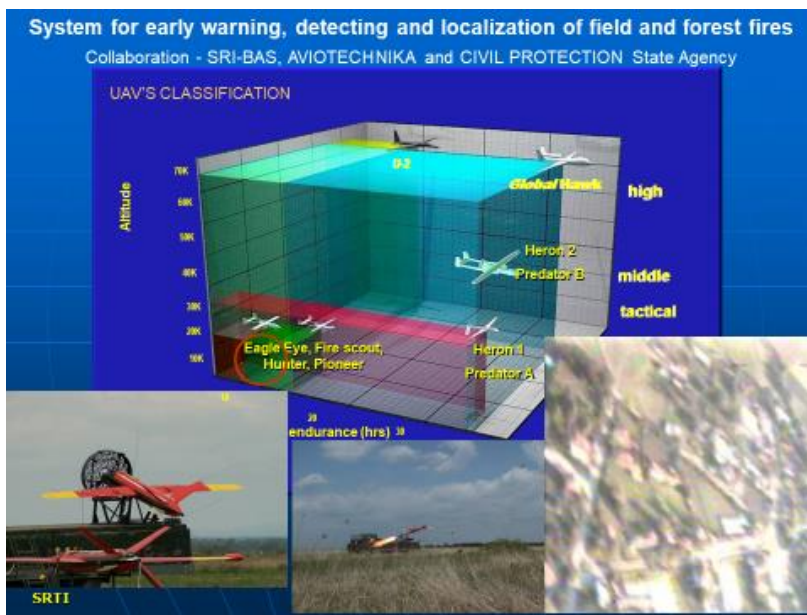


Fig. 2

The design of the UAV should allow for future modernisation to meet additional requirements dictated by the constantly changing environmental and logistical situation. Unmanned aerial systems for reconnaissance, surveillance and control of the earth's surface are currently widespread and are used in a variety of tactical tasks, and UAVs have been analysed, and data for various flight missions have been presented. Key elements of these systems are unmanned aerial vehicles (UAVs) and aerial surveillance systems, including airborne and ground parts. World experience in using UAVs for these purposes shows that they are most suitable where operating conditions are particularly extreme, and there is an

unacceptable risk for manned aviation operations. Such is the monitoring of strictly protected sites and areas, as well as areas with large-scale fires and floods. In these conditions, the use of people is associated with a real threat to their lives, and practically, UAVs as a means of collecting and processing information are indispensable. To assess the current state and development trends of UAV types (Fig. 2) [3].

The main criteria by which the analysis was carried out are: the general and aerodynamic scheme of the UAV; weight-mass characteristics; characteristics of the power plant; flight technical characteristics; take-off and landing system; control and navigation systems; and air surveillance systems [2, 6].

When determining the composition of the system for early detection, localisation, and notification of forest and field fires and floods that have occurred on the territory of the Republic of Bulgaria, the results of flight modelling and modern technical achievements, as well as regulatory documents for aviation systems of this class, were taken into account. The exemplary composition of the Unmanned Aviation Complex (UAC) should include: Unmanned aerial vehicle (UAV); Ground control station (GSC); Operational equipment (EO).

The choice to develop a microsatellite as an element of the monitoring system corresponds to the increasingly convincing trend in recent years to move from large and heavy satellites to small high-tech satellites, as well as to economic feasibility based on the tasks assigned to the microsatellite, its orbit should be sun-synchronous, circular with a period of revolution of 92 min and inclination of 97 [3].

From the calculations made, the time for actual use of data from the satellite in orbits between 800 and 900 km is limited to 5.5 years. This figure is justified by the time for the descent of the orbit between 900 and 800 km. Joint lunar and solar disturbances lead to long-term changes in the parameters of the satellite's orbit, with oscillation periods ranging from several months to 84 years. If this disturbing effect is not taken into account within a day, the error in calculating the MS trajectory will be several hundred meters. Therefore, the calculations must account for the first harmonics of the Earth's gravitational field and disturbances from the Moon and the Sun [10].

Currently, the most cost-effective means of launching small spacecraft (MS) into orbit is via conversion rockets, as is the case for launching payloads for space stations into space (Fig. 3).

MS can be financed at the expense of projects under national programs for the development of education and high technologies, as well as with investments from private and state companies. Proposals are also made under the programs of the Government and the EU [3, 6].

As already noted in the concept for complex monitoring for images with spatial resolution in the range of 30 to 50 m, a national or regional satellite can be very successfully used. Based on this, the Institute for Space Research – BAS is working on the topic of “Balkansat” [9, 10].

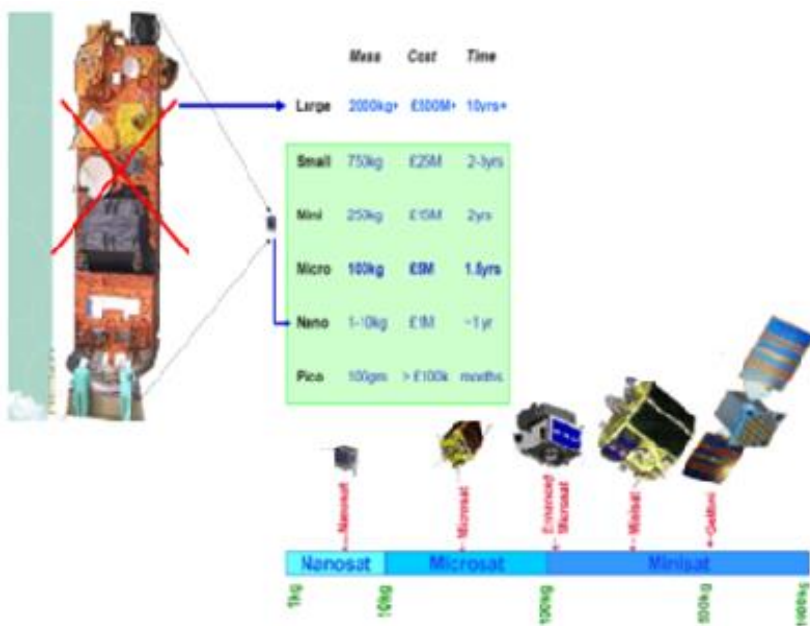


Fig. 3

This satellite should be in the weight range of 10 to 100 kg, i.e. a microsatellite or, as it is commonly called, a “small” satellite [3].

The use of the satellite is mainly aimed at monitoring the Earth's surface, but the possibility of studying the magnetosphere and ionosphere is not excluded.

For the successful solution of tasks related to the prevention of catastrophic phenomena, it is necessary to carry out: Monitoring of fires and other dangerous phenomena and objects on Earth; Monitoring of the atmosphere: control of the distribution and trends of greenhouse gases (CO₂), detection of large releases of hazardous substances into the atmosphere.

Space weather and monitoring of the state of the ionosphere, radiation belts and solar wind.

Based on the tasks listed above, the approximate composition of the specialised equipment of the small satellite “Balkansat” can be determined, including [2, 9]: Photometric equipment complex – KFA; Atmospheric research complex – KAI; Magnetic-wave complex – MVK.

On a circular orbit with an altitude of 800 km, $t_{seq} \approx 3042$ days. For a similar orbit of 900 km, $t_{seq} \approx 5085$ days.

The base orbit to which a satellite should be launched is selected from the type of circular quasi-geosynchronous orbits [10]. They ensure an approximate passage of the satellite's path on each subsequent day through the path of the previous day.

From the analysis we have made of existing small satellites and taking into account the Balkansat project, we have focused on the possibility of using, as a base platform, the microsatellite “Chibis” (a sketch of its appearance is shown in Fig. 4), which has already flown and is currently being launched into orbit with the cargo ship “Progress”, providing the International Space Station (ISS) [7, 9].

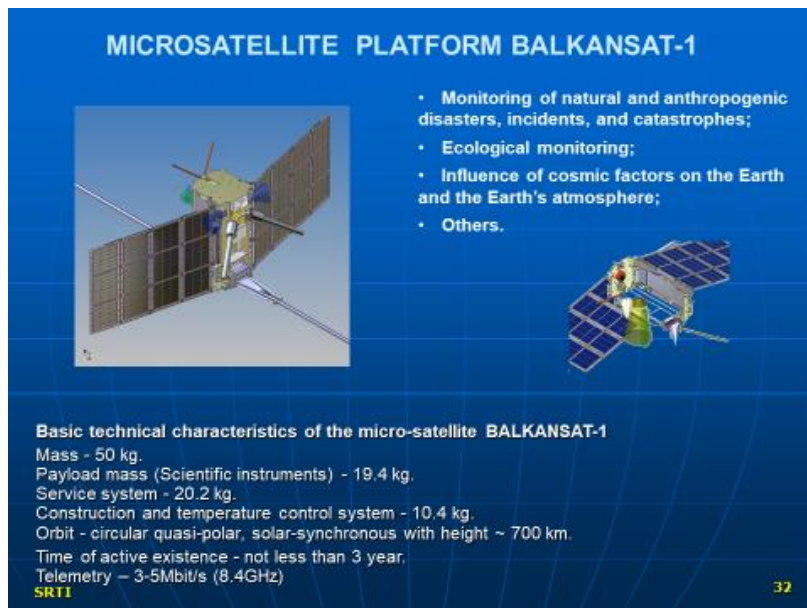


Fig. 4

The service systems of the MS in the most general case are the following: Power supply system (PSS); Three-axis orientation and stabilisation system (SOS); Thermoregulation system; Temperature measurement system; Command and telemetry radio lines; Information collection, processing and control system.

The specified inclination of the orbital plane to the plane of the equator indicates the need to create a universal PSS, which must provide the necessary power supply to the MS, constantly changing its orientation with respect to the Sun and must function in a circular orbit with an altitude of 800 km and an inclination of 97°.

To determine the bases for orientation, accurate knowledge of the coordinates of the MS in orbit around the Earth is necessary. The orbit of the MS can be determined on Earth by a number of observations at different points of the orbit. The calculation of the initial conditions for the construction of the MS orbit is published in the space monitoring centres and is specified in the MS control centre based on the data published on the initial conditions, data from radio control and orbits and data from the navigation equipment on board the MS.

Aerospace Information Centre

The creation of the national monitoring system can be carried out based on the implementation of the proposed concept, including the construction of a national aerospace monitoring centre (Fig. 5).

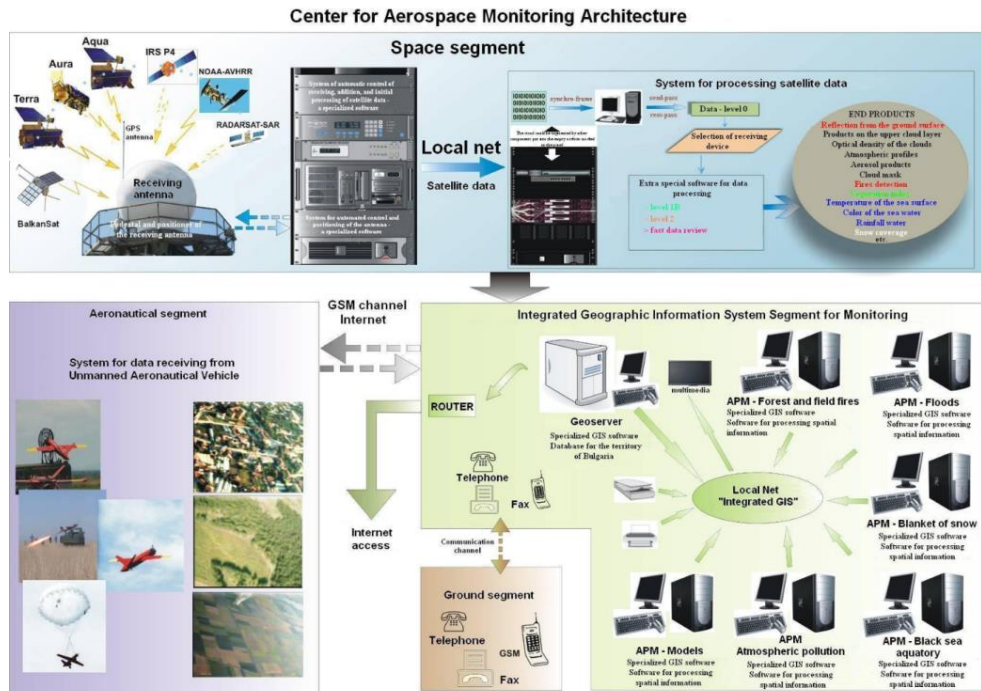


Fig. 5

For the receiving station of the centre, we focused on the Basic configuration of the UniScan™-24 complex, which allows the reception not only of data from the Terra and Aqua satellites, but also of data from other satellites for which, however, additional software and payment of the relevant license are required [3, 5, 11].

The strategy for forecasting and controlling natural and man-made disasters is based on the principle of minimising the time for detection, identification, and recognition of the event, in order to adopt an optimal solution to master and control the situation that has arisen. The implementation of this strategy is based on the use of a multiplicative type of spatial data in different time intervals and their correlation at specifically defined time points. Fig. 6 schematically shows the principle by which the proposed strategy is implemented.

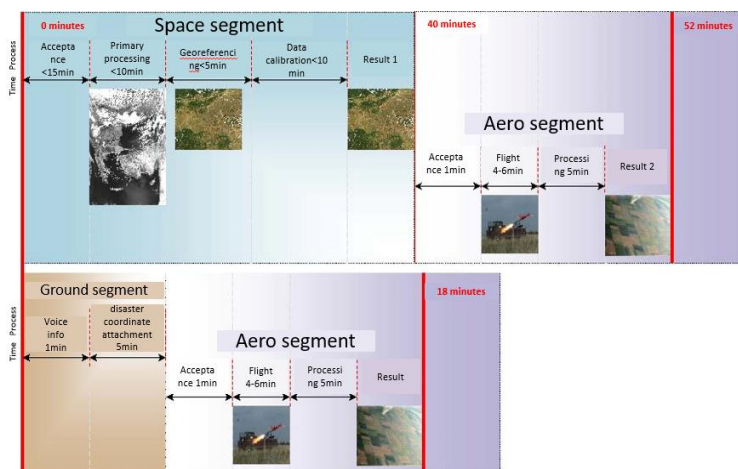


Fig. 6

Implementation of the strategy for using multi-spatial data in different time intervals. The proposed architecture allows for receiving data in real or near real time for the territory of the country and cross-border regions in the event of natural and man-made disasters. Information is received from three independent sources: space, aero and ground segment.

The Aqua and Terra satellites provide 4 images per 24 hours for fire monitoring. MODIS data can be used to monitor stubble burning, vegetation type and condition, smoke aerosols, water vapour, and clouds, providing comprehensive monitoring of the fire development process and its impact on ecosystems, the atmosphere, and climate. This includes the location of the fire, the rate of heat release from the fire, and a rough estimate of the smouldering-to-burning ratio [3].

The 7-2-1 channel combination of the MODIS multi-channel spectroradiometer “colours” objects in tones different from those seen by the human eye. It is suitable for visual identification of water bodies due to the inclusion of channel 7 (2.11–2.16 μm) of the infrared spectral range.

The snow cover product is used to estimate snowmelt during the spring months and thus has applications in water resources management.

Ocean and sea surface color files contain the products of measurements of normalized water surface radiance, aerosol optical density, aerosol epsilon correction, diffusion attenuation; biooptical and optical properties for water including chlorophyll-a, chlorophyll-a + phaeopigment, total pigment and total suspended solids concentration, phytoplankton and total absorption coefficients; pure water epsilon; instantaneous photosynthetic irradiance and phytoplankton absorbed irradiance; chlorophyll fluorescence line height, baseline and efficiency; isolated coccolith concentration, pigment concentration in coccolithophore colors, calcite concentration; phycoerythrin and phycourobilin concentration [12–15].

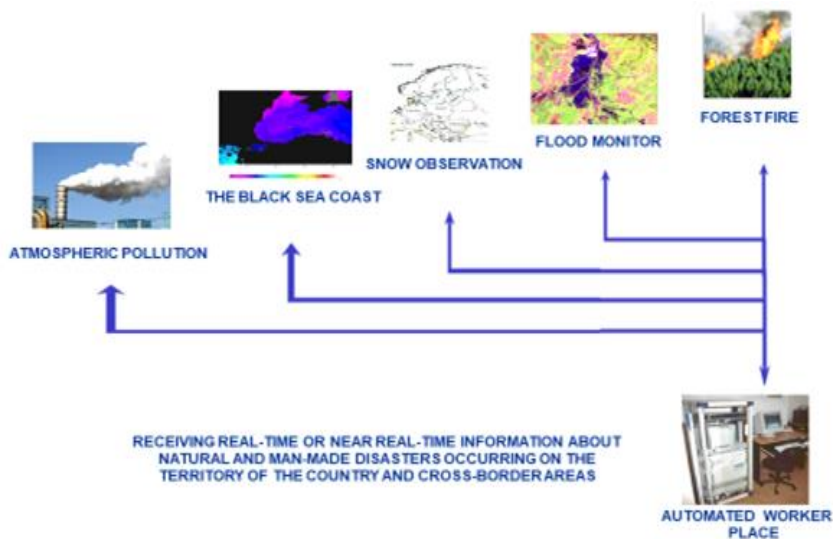


Fig. 7

Most MODIS atmospheric properties products are used to monitor atmospheric pollution.

Using infrared methods, cloud top temperature, height, effective radiance, phase (ice-water, opaque-clear), and cloud fraction are obtained, both during the day and at night. The MODIS cloud properties product includes cirrus reflectance in the visible part of the spectrum at 1 km-pixel resolution, which is necessary to eliminate the scattering effect of cirrus clouds from the land surface reflectance product.

Conclusions

1. Aerospace monitoring has no alternative in objectifying the state of the environment and security.
2. The development of an aerospace monitoring system is part of the general efforts to ensure an effective mechanism for the prevention and averting of crises of various natures. When this is not possible, it can help reduce their consequences and alleviate human suffering.
3. European institutions must provide the necessary prerequisites for the inclusion of the scientific and research community, private business and industry in major European and NATO projects related to global monitoring systems, which, however, should not be at the expense of the development of national and regional activities in this area.

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АЕРОКОСМИЧЕСКА СИСТЕМА ЗА МОНИТОРИНГ И ЗАЩИТА ОТ ТЕХНОГЕННИ И ПРИРОДНИ БЕДСТВИЯ

П. Гецов

Резюме

Мониторингът на природните и техногенните бедствия и явления се явява важен елемент от националната сигурност и има за цел да подпомага решаването на някои основни проблеми, свързани с откриването и предотвратяването на регионалните кризи. Това предполага използване на национална система за мониторинг, позволяваща анализиране на устойчивостта на функционалната структура на природните и техногенни системи и осъществяване на краткосрочни и дългосрочни екологически прогнози и оперативното решаване на задачите свързани с действията по време на кризите и предотвратяване на последствията от тях. В процеса на този мониторинг е необходимо комплексно използване на информация от спътниково, самолетно и наземно ниво, което се явява и предмет на изследване на настоящата статия.

SEASONAL CORRELATION BETWEEN ATMOSPHERIC POLLUTION AND COVID-19 INCIDENCE DERIVED FROM SATELLITE AND GROUND-BASED OBSERVATIONS: A CASE STUDY OF SOFIA AND BURGAS

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Key words: COVID-19, air pollution, particulate matter, NO₂, Absorbing Aerosol Index, Sentinel-5P, GOME-2, remote sensing, GIS, low-cost sensors

Abstract

The epidemiological footprint and clinical severity of COVID-19 are significantly modulated by atmospheric contaminants, notably nitrogen dioxide (NO₂) and fine particulates. This research focuses on the seasonal dynamics of air quality in relation to COVID-19 within Bulgaria. By leveraging satellite-based tropospheric Absorbing Aerosol Indices (AAI) from the GOME-2 instruments, we mapped aerosol loading from mid-2020 through July 2024. Case studies for the municipalities of Sofia and Burgas integrated these satellite retrievals with localised ground-based measurements. Our observations revealed distinct, synchronised seasonal patterns: pollution and case numbers both peak during late winter, decline significantly in summer, and re-emerge as autumn progresses. A central outcome of this work is a robust GIS database that serves as an adaptable spatial platform for investigating various respiratory conditions and environmental health indicators.

1. Introduction

The baseline environmental condition in Bulgaria is characterised by significant exposure to particulate matter and gaseous pollutants, largely driven by domestic heating with solid fuels, an ageing vehicle fleet, and heavy industrial activities concentrated in specific regions such as Stara Zagora [1–3]. Studies have demonstrated that long-term exposure to these pollutants not only increases the prevalence of pre-existing cardiovascular diseases (CVD) but also heightens the susceptibility of the population to respiratory infections [4, 5]. In major urban centres such as Sofia, Plovdiv, and Varna, the convergence of high population density and localised pollution hotspots creates an environment where respiratory pathogens can propagate more effectively [4].

Bulgaria faces a unique set of challenges regarding extreme weather events and persistent air pollution from fossil fuel burning and traffic congestion [4]. This is of growing concern, as air pollution was the second-leading risk factor for approximately 8.1 million cases of premature mortality globally in 2021. In the EU-27, a total of 327,000 deaths were attributable to exposure to PM_{2.5}, NO₂, and O₃ and concentrations above the 2021 WHO guideline levels [1]. Bulgaria, specifically, suffers from the highest CVD mortality rate in the EU, often exacerbated by the release of proinflammatory mediators in the lungs in response to inhaled pollutants. These mediators trigger oxidative stress and systemic inflammation, leading to endothelial dysfunction and atherosclerotic plaque formation [4].

Comparative Air Quality Standards and Bulgaria's Compliance

The regulatory landscape in Bulgaria is shaped by both European Union (EU) directives and World Health Organisation (WHO) guidelines. However, a stark disparity remains between these two frameworks, particularly following the 2021 update to WHO guidelines [1, 6]. While EU standards provide a legal threshold, the WHO guidelines reflect a stricter health-based ideal that highlights the ongoing risks even at concentrations currently deemed legal under regional law [1].

Table 1. Comparison of WHO 2021 annual air quality guidelines and EU limit values with observed typical ranges for major atmospheric pollutants in Bulgarian urban areas (2020–2022)

Pollutant	2021 WHO Annual Guideline (µg/m ³)	EU Annual Limit Value (µg/m ³)	Typical Bulgarian Urban Range (2020–2022)
PM _{2.5}	5	20	15.0 – 25.2 [7, 8]
PM ₁₀	15	40	25.0 – 45.0 [10, 11]
NO ₂	10	40	18.0 – 35.0 [9]
SO ₂	40 (24-hour)	125 (24-hour)	5.0 – 15.0 [3, 7]

The systematic failure to meet the lower WHO thresholds in Bulgarian cities has profound implications for the pandemic's impact. For instance, in Sofia, approximately one-fifth (20%) of all ischemic heart disease (IHD) hospitalisations are attributable to exposure [4, 9]. All Sofia residents live in neighbourhoods where levels exceed WHO guidelines, illustrating a significant baseline vulnerability of the respiratory and cardiovascular systems before any viral infection occurs [9].

Urban Microclimates and Topographical Influences

The topographical features of Bulgaria, especially the valley settings of Sofia and Plovdiv, exacerbate the accumulation of pollutants. In Sofia, the surrounding Balkan Mountains and Vitosha Massif contribute to frequent temperature inversions during the winter months [4, 10]. Under these conditions, the atmospheric boundary layer (ABL) remains stable, trapping emissions from

traffic and domestic heating near the surface. This "bowl effect" increases pollution in central urban areas through flow convergence at night, when atmospheric conditions lack vertical mixing, leading to the accumulation of emitted pollutants near the surface [4, 10].

Analysis of the urban heat island (UHI) effect in Sofia reveals an average summer increase of 2.5°C, which further complicates the dispersion of secondary pollutants [10]. The modification of urban landscapes has led to the formation of human-induced heat islands, affecting both air quality and disease burden. In Sofia, the risk of IHD increased primarily at cold temperatures, whereas in Plovdiv and Varna, both high and low temperatures were associated with IHD hospitalisations [4].

Mechanistic Linkages Between Air Pollutants and SARS-CoV-2

The biological and physical pathways through which atmospheric pollutants influence COVID-19 incidence are multifaceted, involving both the modulation of the host's immune response and the potential role of particles as viral carriers [5, 12].

Particulate Matter as Viral Vectors

Fine particulate matter, specifically, has been hypothesised to act as a "carrier" for the SARS-CoV-2 virus. These particles, characterised by a large surface area and high porosity, can adsorb viral droplets [5, 12]. The inhalation of these coronavirus-laden particles allows for deeper penetration into the respiratory system, potentially reaching the distal alveoli and subsequently entering the bloodstream [7, 12]. Studies utilising Aerosol Optical Depth (AOD) and the Absorption Aerosol Index (AAI) from satellite sensors have shown that regions with higher aerosol concentrations often correlate with increased clusters of respiratory distress cases [5]. Furthermore, the presence of can reduce the diffusion coefficient of viruses, effectively keeping them suspended in the breathing zone for longer periods [12].

Impairment of Immune Defence Mechanisms

Beyond acting as carriers, pollutants like and are known to induce systemic inflammation and oxidative stress within the lungs [4, 12]. Prolonged exposure impairs the function of alveolar macrophages and bronchial epithelial cells, which are the first line of defence against inhaled pathogens [4]. This inflammatory priming renders individuals more susceptible to severe manifestations of COVID-19, including pneumonia and prolonged recovery periods [5]. In Bulgaria, the spatial distribution of NO₂, mapped via the TROPOMI sensor, reveals that urban residents face a chronically elevated risk profile that likely contributed to the high COVID-19 case fatality rate [5, 13], NO₂-induced inflammation exacerbates immune responses, impairing the body's ability to combat infections effectively [5].

Remote Sensing and Ground-Based Data Integration

The assessment of seasonal correlations in Bulgaria relies on a hybrid monitoring approach, reconciling the high temporal frequency of ground stations with the comprehensive spatial coverage provided by satellite instruments [2, 14, 15]. The specific objectives of this study are:

1. To analyse the seasonal behaviour of Covid-19 and key pollutants (PM and NO₂) in two contrasting municipalities, Sofia and Burgas.
2. To develop a GIS database that integrates all relevant datasets and supports future applications to other respiratory diseases.

2. Materials and Methods

2.1. Study Area

Our research focuses on the territory of Bulgaria in Southeastern Europe, a region characterised by a complex administrative and demographic landscape. A critical factor in our modelling is the heterogeneous distribution of the population, which exhibits high-density clustering in major metropolitan hubs such as Sofia and Burgas, while remaining significantly sparse in rural and mountainous zones.

Furthermore, the operational structure of the Bulgarian healthcare system directly influences the granularity of our available data. Because comprehensive medical facilities and hospitals are primarily centralised in regional urban centres, patients from smaller, underserved settlements are forced to seek care in these hubs. Consequently, public health metrics and COVID-19 statistics are systematically aggregated and reported at the municipal level rather than at finer, more localised levels. This centralised reporting mechanism imposes an inherent limitation on the spatial resolution of our epidemiological analysis, precluding a more granular investigation into neighbourhood-level transmission dynamics.

2.2. Satellite Aerosol Products

GOME-2 Absorbing Aerosol Index

The Absorbing Aerosol Index (AAI) indicates the presence of elevated absorbing aerosols such as desert dust, biomass burning smoke and volcanic ash in the troposphere. AAI separates the spectral contrast at two UV wavelengths caused by absorbing aerosols from that due to Rayleigh scattering, surface reflection, gaseous absorption and scattering by non-absorbing particles. AAI is a unitless quantity; positive values are indicative of absorbing aerosols in the atmosphere, whereas near-zero or negative values generally correspond to weak or non-absorbing aerosol conditions [16].

In this study, we use monthly Level-3 AAI data derived from GOME-2 observations and distributed through the Tropospheric Emission Monitoring Internet Service (TEMIS) [17, 18]. The Level-3 product provides AAI values on a regular latitude-longitude grid with a spatial resolution of 1°. For the period

June 2020 – July 2024, we use data from the MetOp-B platform, which offers stable coverage over the study period. With 1° grid spacing, 17 grid cells fully cover the Bulgarian territory (Fig. 1).

Fig. 1. Administrative division of Bulgaria into 28 municipalities and locations of official ground-based monitoring stations (GMSs)

To investigate seasonal relationships between COVID-19 and air pollution, we focus on two municipalities: Sofia (the capital and largest city, with relatively uniform distribution of population, health services and monitoring stations within a single municipality) and Burgas (a large coastal municipality with distinct geographic characteristics and the largest municipal area among the 28).

The seasonal cycle of COVID-19 is represented by the monthly mean number of active cases in each municipality. To highlight recurrent patterns, we compute the multi-year mean seasonal cycle of active cases and of each pollutant by averaging the same month over the years 2020–2024.

The statistical analysis was designed to (i) characterise the spatial variability of air pollution and Covid-19 across the 28 Bulgarian municipalities, and (ii) examine the temporal (seasonal) co-variability between pollution indicators and COVID-19 in Sofia and Burgas.

2.4.1. Seasonal cycles and temporal co-variability

For Sofia and Burgas, we constructed monthly mean time series of:

- active Covid-19 cases,
- ground-based PM1, PM2.5, PM10 and NO₂ concentrations,
- satellite AAI (aggregated over the relevant municipality or over the national territory, as specified).

Given the limited length of the time series and the strong annual cycle of both pollution and Covid-19, we focused on the mean seasonal cycle. For each variable X and for each calendar month m (January–December), we averaged all available values for that month over the years 2020–2024:

$$(1) \quad \bar{X}(m) = \frac{1}{N_m} \sum_{k=1}^{N_m} X_k(m)$$

where N_m is the number of years with data for month m , and $X_k(m)$ is the monthly mean in year k . This averaging reduces the influence of inter-annual variability and highlights recurrent seasonal patterns.

To facilitate comparison of the shapes of the seasonal cycles across variables with different units and magnitudes, we also considered normalised seasonal cycles, obtained by dividing $\bar{X}(m)$ by the annual mean of X or by expressing monthly deviations from the annual mean as anomalies:

$$(2) \quad X'(m) = \bar{X}(m) - \frac{1}{12} \sum_{m'=1}^{12} \bar{X}(m').$$

The similarity between the seasonal cycles of Covid-19 and those of the pollutants was quantified using Pearson correlation coefficients computed across the 12 monthly mean values (or anomalies) for each pair of variables. These correlations were interpreted with caution, recognising that the 12 points are not independent over time and that both series are strongly influenced by common meteorological and behavioural drivers.

To explore potential time lags between pollution and Covid-19, we additionally examined lagged correlations between monthly pollution and Covid-19 series at lags of 0–2 months (pollution leading Covid-19). Given the short time series and the coarse monthly resolution, these lag analyses are purely exploratory.

Software and significance considerations

All statistical analyses and graphical representations were performed using standard scientific computing software and GIS tools for spatial aggregation and mapping. Throughout the paper, we report correlation coefficients and non-parametric test results primarily as descriptive measures of association. Given the observational nature of the data, the relatively small number of spatial units (28 municipalities) and the potential presence of unmeasured confounders, we do not attempt formal causal inference. Instead, statistical results are interpreted in

conjunction with physical reasoning and with consistency across multiple independent data sources (satellite, ground-based and low-cost sensors).

3. Results and Discussions

We investigated the seasonal relationship between atmospheric pollution and COVID-19 incidence across 28 Bulgarian administrative regions over four years (June 2020 – July 2024), employing an innovative multi-source data integration approach combining GOME-2 satellite observations with ground-based measurements from both official monitoring stations and low-cost sensor networks [5, 19]. The central finding demonstrates that neither the Absorbing Aerosol Index (AAI) nor nitrogen dioxide (NO₂) alone adequately reproduce the spatial pattern of COVID-19 cumulative incidence. In contrast, their combination in a defined Pollution Index exhibits substantially improved spatial correspondence with the distribution of COVID-19 cases across Bulgarian municipalities [5]. This multi-pollutant approach represents a significant methodological advancement over single-pollutant analyses [20, 21] and aligns with emerging evidence that COVID-19 outcomes are modulated by complex interactions among multiple environmental stressors rather than by isolated pollutants [20, 21].

The observed seasonal cycles characterised by winter maxima, summer minima, and renewed autumn increases were consistent across geographically distinct regions (Sofia and Burgas), reinforcing the hypothesis that COVID-19 transmission in temperate continental climates exhibits pronounced seasonality driven by synergistic interactions between meteorological conditions and pollution levels [20]. The parallel seasonal evolution of pollution and COVID-19 incidence provides indirect support for mechanistic pathways through which chronic and acute air pollution exposure may enhance viral susceptibility and disease severity [21].

3.1. Seasonal Behaviour of Covid-19 and PM in Sofia and Burgas

Fig. 2 and Fig. 3 show the seasonal distribution of COVID-19 active cases in Sofia and Burgas, together with the seasonal cycles of PM₁, PM_{2.5}, and PM₁₀ derived from IQAir sensors in both cities. The seasonal cycle of COVID-19 exhibits pronounced peaks during the first two to three months of the year, a clear minimum in summer and a renewed increase in the last two months of the year. The two municipalities display very similar seasonal patterns of Covid-19, despite their different geographical and climatic conditions.

The seasonal cycles of PM₁, PM_{2.5}, and PM₁₀ also show the highest concentrations during winter and early spring, consistent with increased emissions from domestic heating and reduced dispersion efficiency. Concentrations decrease in summer, when atmospheric mixing is stronger and heating-related emissions are reduced, and then increase again in late autumn. The overall seasonal patterns of PM are comparable in Sofia and Burgas, although absolute levels and the relative amplitudes of the peaks may differ.

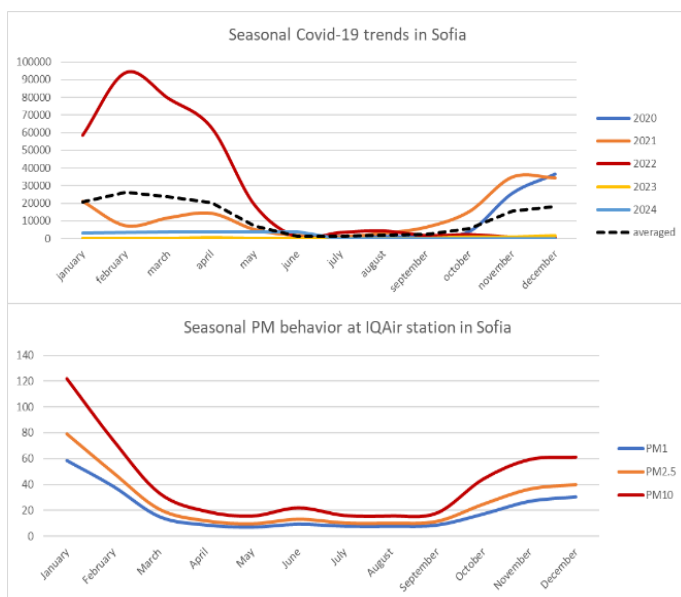


Fig. 2. Seasonal cycles of active COVID-19 cases and PM1, PM2.5 and PM10 concentrations in Sofia derived from IQAir sensors

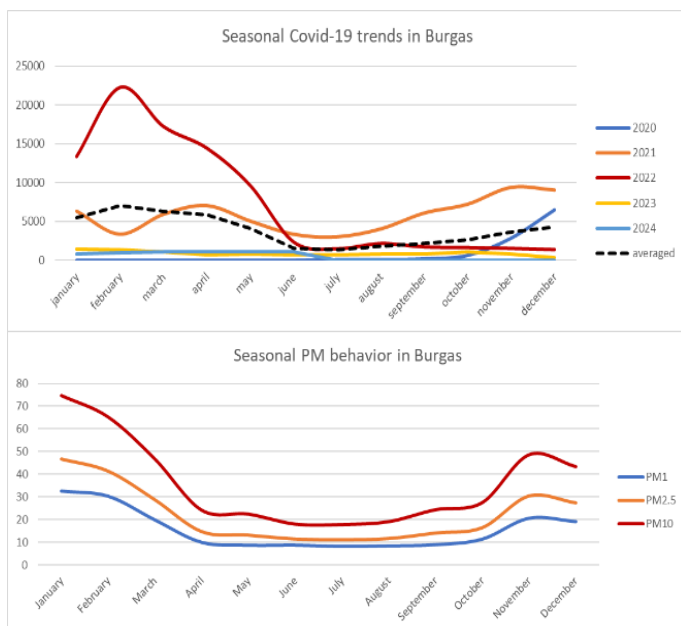


Fig. 3. Seasonal cycles of active COVID-19 cases and PM1, PM2.5 and PM10 concentrations in Burgas derived from IQAir sensors

The similarity between the seasonal cycles of COVID-19 in Sofia and Burgas is further illustrated in Fig. 4, which shows almost identical multi-year mean monthly profiles of active cases in the two municipalities.

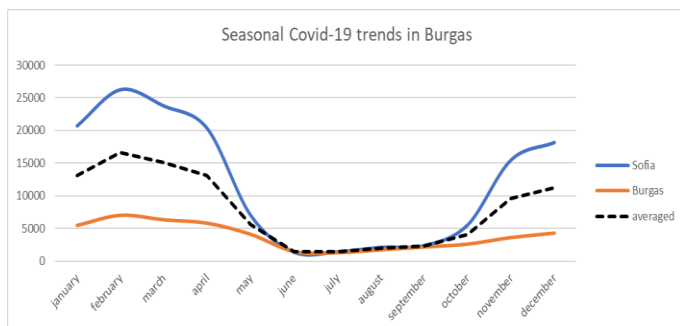


Fig. 4. Multi-year mean seasonal cycle of active COVID-19 cases in Sofia and Burgas

3.2. Seasonal Behaviour of AAI and Ground-Based Pollutants

Fig. 5 presents the seasonal behaviour of AAI over the entire Bulgarian territory, derived from GOME-2 MetOp-A and MetOp-B data, as well as the average from both satellites. The seasonal AAI curves exhibit a characteristic pattern, with enhanced absorbing aerosol loading during periods when Saharan dust intrusions and other aerosol episodes are more frequent, and lower AAI values during cleaner periods. The multi-year average provides a stable climatology of absorbing aerosols over Bulgaria.

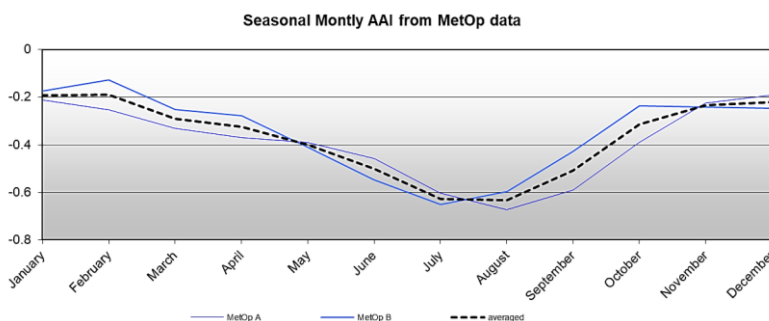


Fig. 5. Seasonal evolution of AAI from MetOp GOME-2 data averaged over the Bulgarian territory

Fig. 6 presents the seasonal trends of PM_{2.5}, PM₁₀ and NO₂ in Sofia, obtained from the Hipodruma GMS station. The seasonal cycles of ground-based PM and NO₂ closely resemble the patterns observed in the satellite-derived AAI climatology and in the low-cost sensor data. In particular, both satellite and ground measurements indicate higher aerosol and NO₂ pollution in winter, lower levels in summer and transitional behaviour in spring and autumn.

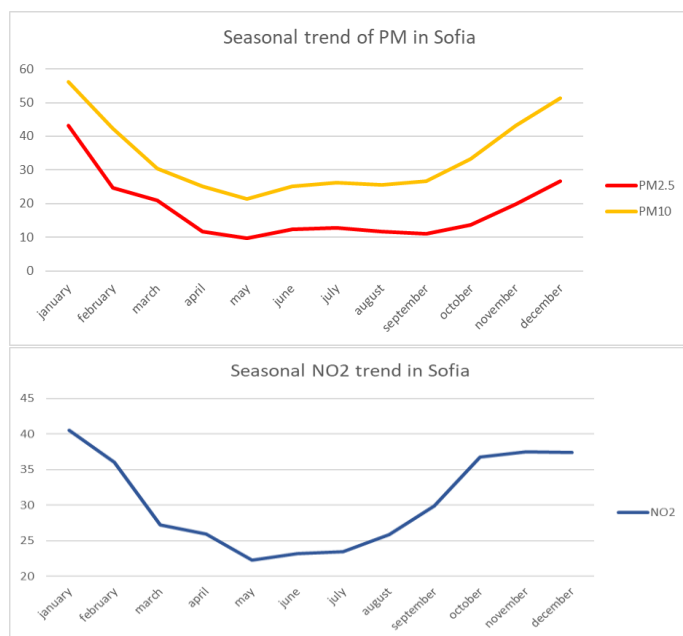


Fig. 6. Seasonal trends of PM_{2.5}, PM₁₀ and NO₂ concentrations in Sofia based on measurements from the Hipodruma GMS station

Overall, the seasonal trends in pollution derived from satellite and ground-based data are consistent with one another and with the seasonal pattern of Covid-19, particularly the winter maxima and summer minima. The main difference is that the spring increase of COVID-19 cases tends to persist somewhat longer than the corresponding increase in PM and NO₂ concentrations.

3.3. Comparison with National Studies in Bulgaria

Our study advances these local findings in several critical dimensions:

Temporal Extent: The current four-year observation period (June 2020 – July 2024) substantially exceeds shorter timeframes of prior studies, capturing additional COVID-19 waves and enabling more robust assessment of long-term pollution exposure effects on cumulative disease burden rather than short-term daily case fluctuations [5, 19].

Pollutant Characterisation: Whereas previous work examined PM₁₀, NO₂, and CO individually, the present study introduces AAI as a satellite-derived proxy for absorbing aerosol loading [22] and develops a novel combined Pollution Index that integrates AAI and NO₂ [5]. This composite metric explicitly recognises that respiratory health impacts arise from multi-pollutant exposures and that satellite-based AAI provides complementary information to trace gas retrievals, particularly for characterising elevated aerosol layers from dust transport and biomass burning that may not be captured by surface PM measurements [5, 22].

Data Integration: The current study integrates observations from three independent platforms: GOME-2 [23] and ground-based networks, including both official stations and low-cost sensors, providing cross-validation and enhanced spatiotemporal coverage [24]. The integration of satellite remote sensing with ground-based measurements has proven effective for overcoming spatial discontinuities in monitoring networks [24].

GIS Framework: A dedicated GIS database developed for this study provides a structured, scalable framework for spatial analyses of respiratory disease-environment relationships that can be extended to other health outcomes and pollutants [5, 19].

3.4. Comparison with Studies in Similar Climatic Zones (Temperate Continental Climate)

European Temperate Regions

The seasonal COVID-19 patterns observed in Bulgaria with pronounced winter peaks, summer minima, and autumn resurgence closely parallel findings from comprehensive multi-country European analyses [15]. Research has documented strong negative correlations between monthly average temperature and daily COVID-19 mortality across multiple temperate European countries, suggesting that colder temperatures may be associated with increased COVID-19 deaths [20].

Quantitative estimates of seasonal forcing magnitude indicate a 42.1% (95% CI: 24.7%–53.4%) reduction in the time-varying reproduction number (R_t) from peak winter to peak summer across 143 European temperate regions. This quantitative estimate of seasonal forcing magnitude aligns with the qualitative seasonal cycles observed in both Sofia and Burgas, reinforcing the interpretation that seasonality represents one of the dominant modulating factors of COVID-19 transmission in temperate climates, operating in concert with air pollution exposure [20].

Central and Eastern European Regional Studies

Research analysing air quality monitoring data and COVID-19 spread across Central and Eastern European and Balkan countries during the 2020–2021 winter period, with a particular focus on regions where residential heating from fossil fuel combustion drives elevated winter PM_{2.5} concentrations, revealed strong correlations between PM_{2.5} and COVID-19 outcomes [20]. These correlation coefficients indicate significant relationships, particularly in contexts with high winter pollution from domestic heating.

Our findings corroborate and extend this regional evidence in several ways:

First, Bulgaria's heating infrastructure and energy mix resemble those of neighbouring Central and Eastern European countries, with widespread use of solid-fuel heating (wood, coal) in both urban and rural areas, contributing to elevated winter PM levels and combustion-related pollutants. The seasonal pollution maxima observed

in Sofia and Burgas during late winter align temporally with peak heating demand and are consistent with the emission profile documented in regional analyses [20].

Second, the multi-pollutant approach employed, integrating satellite AAI (sensitive to absorbing aerosols, including black carbon from biomass/coal combustion) with NO₂ (a marker of combustion processes), provides a more mechanistically interpretable representation of the complex winter pollution mixture in Central and Eastern Europe [5, 22]. Absorbing aerosols have distinct toxicological properties and optical signatures, and their explicit characterisation via satellite AAI offers complementary insights to ground-based PM measurements [5, 22].

Third, the four-year study period extends beyond initial pandemic phases, enabling assessment of whether pollution-COVID-19 relationships persist across multiple viral variants and evolving population immunity landscapes [19]. The continued correspondence observed between pollution levels and COVID-19 incidence through July 2024 suggests that environmental modulation of respiratory disease transmission may be robust across different epidemiological contexts [5].

3.5. Satellite Remote Sensing: Advantages and Limitations

The dual-satellite approach leverages the complementary strengths of the GOME-2 instruments. GOME-2 on MetOp platforms provides a long-term data record (MetOp-A since 2006) with consistent AAI retrievals, enabling multi-year trend analysis [23, 25]. Recent algorithmic improvements for GOME-2 NO₂ retrievals, including extended spectral fitting windows, refined air mass factor calculations with explicit aerosol corrections, and improved treatment of instrumental degradation, have enhanced accuracy and consistency across the MetOp series [23, 25].

3.6. Seasonal Cycles and Meteorological Drivers

The parallel seasonal evolution of pollution and COVID-19 observed in Sofia and Burgas winter maxima, summer minima, and autumn resurgence reflects the complex interplay of meteorological, emission, and behavioural factors characteristic of temperate continental climates [19, 20, 26]. Research has demonstrated that COVID-19 transmission rates in temperate climates respond dynamically to daily average temperature, with colder temperatures correlating with higher infection rates. This aligns with the timing of COVID-19 peaks in Bulgaria (late winter), when average daily temperatures are consistently low [20]. Low temperatures enhance viral stability in respiratory droplets, increase indoor occupancy and crowding, and reduce ventilation rates, all favouring respiratory virus transmission [20, 26]. Winter pollution maxima in Bulgaria result from increased residential heating emissions (from wood and coal combustion, producing PM, black carbon, and gaseous pollutants), reduced atmospheric mixing heights that trap pollutants near the surface, and stagnant anticyclonic conditions common in southeastern Europe during winter [21]. These pollution peaks coincide

temporally with COVID-19 incidence peaks, creating synergistic exposure conditions where respiratory systems compromised by air pollution encounter peak viral circulation [21]. The renewed increase in both pollution and COVID-19 during late autumn likely reflects the onset of the heating season, transition to cooler temperatures and reduced absolute humidity, and increased indoor activities [20, 26]. This pattern is consistent with influenza seasonality in temperate regions and supports the hypothesis that COVID-19 exhibits endemic seasonal behaviour comparable to that of other respiratory viruses [20, 26].

3.7. Low-Cost Sensor Networks: Emerging Data Source

The integration of low-cost sensor (LCS) network data alongside official monitoring stations represents a significant methodological advancement [19, 24]. Recent guidance emphasises the strategic value of LCS networks when combined with satellite observations and air quality models for enhanced environmental monitoring [19, 24]. Key advantages include spatial density for capturing neighbourhood-scale pollution gradients, real-time data streams, and community engagement fostering public awareness [19, 24]. Individual LCS devices have inherent limitations in measurement accuracy compared to reference-grade monitors [24]. However, aggregation strategies can mitigate these limitations and yield data suitable for epidemiological exposure assessment [24].

3.8. GIS Database Framework: Scalability and Future Applications

The dedicated GIS database integrates satellite-derived pollution metrics (AAI, NO₂) aggregated to municipal boundaries, ground-based air quality measurements, COVID-19 epidemiological data by municipality, and administrative /sociodemographic variables [8]. This framework is scalable to other geographic regions, temporal periods, and health outcomes [19]. Beyond COVID-19, the GIS database can support spatial epidemiological analyses of seasonal influenza, respiratory syncytial virus (RSV), pneumonia, and chronic respiratory disease [5, 19].

4. Conclusions

This study demonstrates a clear and consistent seasonal relationship between COVID-19 incidence and atmospheric pollution across Bulgaria from June 2020 to July 2024. Both epidemiological and environmental indicators exhibit synchronised temporal dynamics, with pronounced peaks during late winter, declines in summer, and renewed increases in autumn. This alignment is particularly evident in major urban centres such as Sofia and Burgas, suggesting that common controlling factors, most notably meteorological conditions and human behavioural patterns, simultaneously influence pollutant accumulation and viral transmission. Wintertime conditions, characterised by increased residential heating emissions, temperature inversions, and prolonged indoor exposure, appear

to create an environment conducive to both elevated air pollution and intensified spread of respiratory infections.

The observed co-occurrence of pollution peaks and COVID-19 surges points to potentially compounded public health risks. While causality cannot be inferred, the findings are consistent with established evidence that chronic exposure to pollutants such as PM_{2.5} and NO₂ may weaken respiratory defences and increase vulnerability to infection and adverse outcomes. In this sense, air pollution should be understood not only as an environmental issue but also as a contributing factor within broader respiratory disease dynamics, particularly under high-exposure winter conditions.

A key contribution of the study lies in its integrative methodological framework. By combining satellite-derived indicators (AAI, tropospheric NO₂), ground-based monitoring data, and measurements from low-cost sensor networks, the analysis achieves improved spatial and temporal representativeness compared to reliance on official monitoring systems alone. This is especially important in Bulgaria, where the limited number of stations measuring fine particulate matter constrains exposure assessment. The inclusion of citizen-science and commercial sensor data significantly enhances the ability to capture intra-urban variability, although these data sources require careful calibration and validation to ensure reliability.

The development of a unified GIS-based platform further strengthens the analytical approach by enabling the integration of heterogeneous datasets—environmental, epidemiological, and demographic—into a coherent spatial framework. This allows for more nuanced exploration of spatial patterns and supports scalable applications in environmental health monitoring and urban planning. The approach is transferable and can be adapted to other regions or extended to additional respiratory conditions.

Importantly, the study shows that composite indicators provide added analytical value. The combined Pollution Index, derived from AAI and NO₂, demonstrates a stronger spatial correspondence with COVID-19 distribution than individual pollutants considered in isolation. This supports the notion that population exposure to air pollution is inherently multi-dimensional, reflecting the interaction of different emission sources and atmospheric processes. By integrating both anthropogenic and natural aerosol components, the composite index offers a more comprehensive proxy for environmental health risk.

At the same time, several methodological limitations must be taken into account. Satellite-derived indicators such as AAI provide indirect information on aerosol presence and are influenced by factors such as vertical distribution and surface reflectance, limiting their ability to represent near-surface particulate concentrations accurately. The use of temporally aggregated data (monthly averages) obscures short-term variability that may be relevant for infection dynamics. In addition, COVID-19 case data are subject to uncertainties related to

testing practices, reporting systems, and healthcare access, which may affect comparability over time and space.

Furthermore, the associations identified in this study are inherently correlational. Both air pollution levels and COVID-19 incidence are shaped by a complex set of confounding variables, including population density, socioeconomic conditions, mobility patterns, public health interventions, and weather variability. A more rigorous assessment of causal relationships would require advanced epidemiological modelling and higher-resolution datasets, which fall beyond the present scope.

Despite these limitations, the results provide robust evidence that integrating satellite observations, in situ measurements, and low-cost sensor data within a GIS framework offers valuable insight into the seasonal interplay between environmental quality and public health. The methodology is practical, scalable, and particularly relevant for regions with limited monitoring infrastructure. Future research should focus on refining the Pollution Index through the inclusion of additional pollutants (e.g., ozone), improving data harmonisation, and applying statistical models capable of disentangling causal pathways.

Overall, the study underscores the importance of coordinated environmental and public health strategies. Reducing air pollution, especially during winter, should be considered a key component of preparedness and prevention frameworks for respiratory diseases, including, but not limited to, COVID-19.

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Disclosure of Interests

The authors have no competing interests to declare that are relevant to the content of this article.

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СЕЗОННА КОРЕЛАЦИЯ МЕЖДУ АТМОСФЕРНО ЗАМЪРСЯВАНЕ И ЗАБОЛЕВАЕМОСТ ОТ COVID-19 ПО СПЪТНИКОВИ И НАЗЕМНИ НАБЛЮДЕНИЯ ЗА ТЕРИТОРИЯТА НА СОФИЯ И БУРГАС

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Резюме

Епидемиологичният отпечатък на COVID-19 се модерира значително от атмосферните замърсители, по-специално азотния диоксид (NO₂) и фините прахови частици. Настоящото изследване се фокусира върху сезонната динамика на качеството на въздуха във връзка с COVID-19 случаите в България. Чрез използване на спътникови данни за тропосферния индекс на поглъщащите аерозоли (AAI) от инструментите GOME-2, е картографирано аерозолното натоварване за периода от средата на 2020 г. до юли 2024 г. Изследваните общини София и Бургас са допълнени с данни от наземни измервания. Наблюденията разкриват отчетливи синхронизирани сезонни модели: както нивата на замърсяване, така и броят на случаите достигат пик в края на зимата, намаляват значително през лятото и отново нарастват с настъпването на есента. Основен резултат от това изследване е създаването на устойчива ГИС база данни, която служи като адаптивна пространствена платформа за изследване на различни респираторни заболявания и показатели за екологично здраве.

AN EFFICIENT METHODOLOGY FOR GENERATING A DETAILED THREE-DIMENSIONAL MODEL OF AN ARCH MONUMENT BY EMPLOYING AN OPTIMIZED UAV FLIGHT PLAN

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Key words: *unmanned aerial system (UAS), Smart 3D Capture, three-dimensional modelling, monument-arch, efficiency*

Abstract

Remote sensing methods enable the collection of information about objects from a distance, particularly where ground-based imaging is difficult or impossible. The rapid development of unmanned aerial systems has greatly expanded the potential to generate high-precision, three-dimensional photogrammetric models of cultural heritage monuments. These models not only facilitate spatial documentation and visualisation but also support efforts in reconstruction, restoration, conservation, adaptation, and the integration of such sites into the socio-cultural environment. The emergence of new close-range photogrammetric acquisition techniques and the ability to capture images from varying camera orientations, including capturing images with camera axes oriented perpendicularly to vertical surfaces, has led to an increase in model accuracy and the level of detail. This article presents a methodology for photogrammetric modelling of an arch monument using the new “Smart 3D Capture” flight-planning feature, implemented in modern flight-planning applications in 2025, and for automating the photogrammetric processing workflow. An accuracy assessment of the results was carried out by measuring a set of control distances. This study aims to present a methodology for capturing and generating detailed photogrammetric models of such objects, featuring similar characteristics and bas-reliefs, and to establish optimal workflow parameters. The results confirm the effectiveness of the proposed methodology, which allows not only for the generation of detailed models but also for monitoring the condition of monuments and similar objects, providing specialists from various fields with the means to perform such tasks at an affordable cost.

Introduction

In recent years, the development of unmanned aerial systems (UAS) has been very dynamic, with increasingly small aircraft offering ever more advanced capabilities. At the same time, new image capture methods are being integrated into applications used to create flight plans, also known as missions. This development necessitates research into these innovations – both to address various practical tasks and to assess the accuracy and effectiveness of the resulting data. Creating three-dimensional models of cultural monuments, buildings, or other objects that may be complex in shape and considerable in height is a challenging

task. To address it effectively, a practical, readily applicable methodology is required, one that ensures sufficient accuracy and detail in the final product while relying on relatively affordable equipment.

The established methods for capturing architectural monuments, such as the use of oblique or combined nadir and oblique images and/or free-flight missions [1–3], do not always guarantee high-quality three-dimensional models without errors or imperfections. These shortcomings often arise from factors such as distance to the object, the inability to capture vertical surfaces with a perpendicular camera axis, operator errors, and other limitations.

Other methods used for creating high-accuracy models rely on a combination of terrestrial laser scanning (TLS) and unmanned aerial systems (UAS) [4–6]; however, the current high cost of laser scanners limits the accessibility and efficiency of this methodology.

Developing optimised solutions that utilise a rough model of the object during the flight plan preparation offers an alternative approach capable of achieving higher model accuracy and detail compared to conventional oblique image acquisition [7].

The unmanned aerial systems introduced in 2025, such as the Matrice 4E and Matrice 4T, together with their associated flight-planning applications based on optimised solutions, enable image capture at closer distances and at varying camera-axis orientations relative to the surveyed object. The ability to design precise mapping routes adjusted for capturing buildings and irregularly shaped objects allows for higher spatial resolution of captured images and, consequently, greater detail in the resulting models. Such models can also be used for remarkably efficient structural inspection [8].

In addition to automatic image capturing, another factor influencing workflow efficiency is automating the process of establishing the photogrammetric processing parameters for UAS-generated three-dimensional models of cultural heritage monuments of specific shapes and sizes, for which ground-based image capturing cannot be achieved.

The present study aims to propose an efficient methodology based on automated image acquisition and established photogrammetric data processing parameters, accessible to a wide range of users across various fields at an affordable cost.

Materials and Methods

Object of Study

The “Arch of Freedom” monument is located in the Central Balkan Mountains, on Mount Goraltepe (1.595 m) in the area of the Trojan Pass, also known as Beklemeto. It lies 25 km from the town of Trojan and 100 km from Plovdiv (Fig. 1). The monument was designed by sculptor Prof. Velichko Minekov and architect Georgi Stoilov. It stands on a concrete platform and represents a

massive concrete structure, with a height of 35 m, shaped as an arch. The monument features bas-reliefs depicting Bulgarian haiduks, partisans, as well as Russian and Soviet soldiers. On the northern side of the arch can be seen bas-reliefs of women in traditional Bulgarian costumes welcoming them with bread and salt in 1878 and 1944 [9].



Fig. 1. Object of study: (a) geographic location; (b) photograph of the monument – author's archive

Equipment and Data Acquisition

The photogrammetric survey was carried out using a DJI Matrice 4E unmanned aerial system (UAS), designed for geodetic surveying, mapping, construction, and inspection tasks. The aircraft has a takeoff weight of 1,219 g and supports high-speed image acquisition, with a maximum flight speed of 21 m/s and a capture interval of 0.5 s, significantly improving operational efficiency. Its camera is equipped with a 24 mm wide-angle lens (f/2.8–f/11) featuring a mechanical shutter and a 4/3 CMOS sensor with a resolution of 20 MP. The UAS withstands wind speeds of up to 12 m/s, and its maximum flight time under calm conditions is 49 minutes. The UAS integrates a DJI RTK module supporting multi-frequency GNSS (GPS, Galileo, BeiDou, GLONASS) and the extended L5 frequency band. The module works in combination with a GNSS+Vision Fusion positioning and navigation system, guaranteeing high stability and reliability even under limited or weak satellite signal conditions. The RTK module provides positioning accuracy of $\pm 1 \text{ cm} + 1 \text{ ppm}$ horizontally and $\pm 1.5 \text{ cm} + 1 \text{ ppm}$ vertically [8, 10].

The flight plan (mission trajectory) was created using the DJI Pilot 2 application. The latest image acquisition feature introduced in 2025, called “Smart 3D Capture” mode, enables the generation of precise and detailed 3D models. The method is designed to apply intelligent image-capturing strategies that allow dynamic adaptation of the flight trajectory based on the morphology of the object.

This functionality simplifies the 3D modelling process by automating the mapping process based on a preliminary rough model of the object, thus increasing

efficiency by approximately 40% when compared to traditional oblique image acquisition [11]. In “Smart 3D Capture” mode, the Distance to Slope parameter defines the perpendicular distance the UAS maintains from the surface being captured and the object. The parameter value was chosen to ensure an optimal Ground Sample Distance (GSD) of precisely 0.22 cm. Similarly, a distance of precisely 8 m was selected in another study describing the generation of a three-dimensional photogrammetric model of the Ryhope Engines Museum building, which was achieved using the same “Smart 3D Capture” mode [12].

Another parameter influencing the vertical and horizontal accuracy is the image overlap ratio. Higher frontal and side overlap ratios increase the accuracy of the generated 3D point clouds by eliminating false matches and extending the reliability of the points in the vertical direction [13]. For the object of this study, the frontal overlap was set to 80%, and the side overlap to 70%. The flight parameters are shown in Table 1, and the flight plan is illustrated in Fig. 2.

Table 1. Flight plan parameters

Indicator	Value
Distance to Slope (m)	8
Ground sample distance (cm)	0.22
Along the track overlap (%)	80
Across the track overlap (%)	70

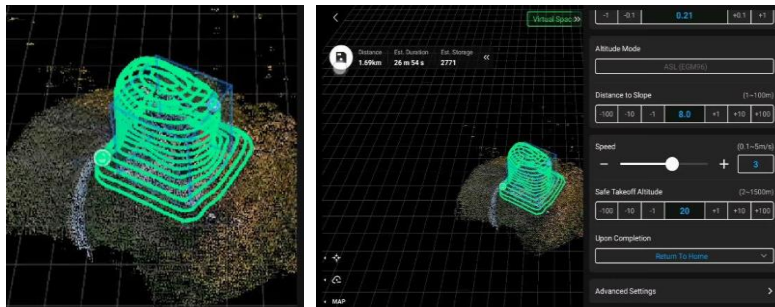


Fig. 2. UAS flight plan executed in the DJI Pilot 2 application, version 2.2.5

Due to the monument's location at the top of Mount Goraltepe, relatively strong wind gusts were observed for most of the day, even under calm, sunny conditions. Despite these conditions, the UAS successfully completed its flight mission within 26 minutes, capturing 2,276 images.

Apart from the flight parameters, the model's accuracy – especially vertical accuracy – is influenced by the available ground control points (GCPs). Previous studies have shown that using only RTK data for georeferencing may result in systematic errors in elevations [14, 15]. Therefore, in the present study, 7 reference points were used – 4 as control points and 3 as checkpoints (the marking on the

fourth checkpoint was destroyed). The points were evenly distributed around the monument on its concrete platform (foundation) and marked with black-and-white square targets (30×30 cm). The positions of the control points and checkpoints on the foundation are shown in Fig. 3. Additional checkpoints were placed on the monument's arches approximately 2 m above the ground, marked in the same manner but in a different colour and slightly smaller in size. These points were also used in the accuracy assessment of the model.

A local geodetic network consisting of seven polygonal points was established around the monument for model georeferencing. These points were measured using a CHCNAV CHS-A100 total station, with a direct angular measurement accuracy of $2''$ and a distance measurement accuracy of $\pm 2 \text{ mm} + 2 \text{ ppm}$ with a prism or $\pm 3 \text{ mm} + 2 \text{ ppm}$ without a prism (up to 300 m). This total station was also used to determine the positions of all ground control points and checkpoints, both on the foundation and on the monument itself, as well as to measure identical reference points on the object, which were later used for analysing the results.

The global positioning of the polygon was determined through GNSS observations in compliance with the existing Bulgarian national regulatory framework for determining geodetic points using GNSS [16]. The measurements were carried out in the WGS84 / UTM Zone 35N (EPSG: 32635) spatial reference system. To achieve high positioning accuracy in the present study, a CHCNAV i76 GNSS-RTK receiver with an inertial measurement unit (IMU) was used, operating with the LandStar 7 field software. The receiver provides a standard RMS accuracy of approximately 0.8 cm horizontally and 1.5 cm vertically under optimal conditions.

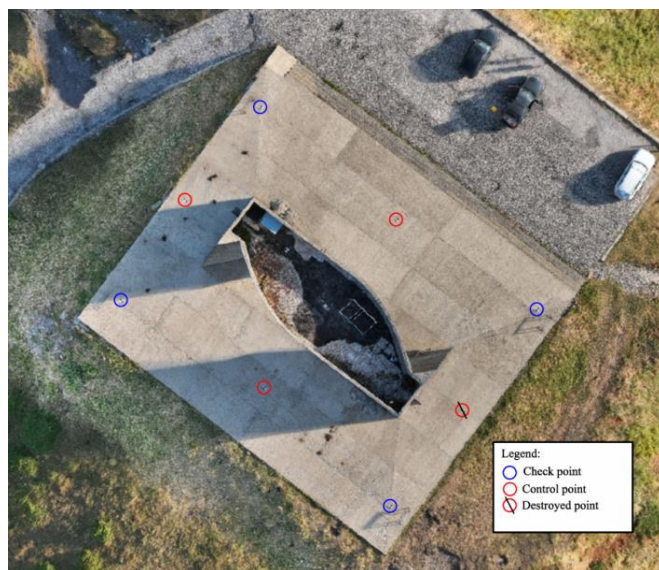


Fig. 3. Location of control and check points on the foundation

Photogrammetric Processing and Analysis of Results

Photogrammetric Processing

The processing of captured imagery data was carried out using Agisoft Metashape Professional, version 2.2.2. It is known that both the processing method and the selected parameters influence the model's accuracy. In this study, the Structure-from-Motion (SfM) algorithm was applied – a photogrammetric method that simultaneously reconstructs three-dimensional geometry and estimates the camera's internal and external orientation parameters based on multiple overlapping images captured from different spatial positions. The accuracy and reliability of the reconstructed model directly depend on the imaging geometry, image resolution, and the selected reconstruction parameters.

During the first stage (Align Photos), the processes of Aerial Triangulation (AT) and Bundle Block Adjustment (BBA) are carried out [17]. SfM employs the correlation of common feature points in the input images to determine the camera positions and the spatial configuration of the objects. Therefore, two key processing parameters in this study are the key point limit and the tie point limit. In studies aiming to extract the maximum number of image matches and achieve a stable geometric configuration, both parameters are commonly set to zero (i.e., key point limit = 0, tie point limit = 0) [18, 19]. The same parameter values were adopted and applied in the present study.

An important stage is the incorporation of ground control points and checkpoints and subsequent optimisation. A primary method for assessing the accuracy of the georeferenced three-dimensional model is the root-mean-square error. In the present study, the root mean square error for the ground control points was 0.002 cm, while for the checkpoints it was 0.012 cm

The next stage of processing involves cleaning the model from noise, also referred to as removing spurious or parasitic points. In this study, an automated filtering procedure was implemented using the Gradual Selection function. This filtering automatically removes unnecessary points from the model without operator intervention, thereby increasing the methodology's overall efficiency. The filtering parameters were analysed, and based on the obtained results, certain parameter values were specified, which are presented in Table 2. Fig. 4 illustrates the point cloud before and after the applied filtering. The same table also consecutively lists the parameters applied in the subsequent workflow stages of photogrammetric processing, including automatic generation of the textured three-dimensional model.



Fig. 4. Comparison of the generated point cloud before and after applying filtering

The next stage of processing involves generating a dense point cloud. This process is based on depth maps computed for overlapping image pairs, taking into account their relative external and internal orientation parameters as estimated through bundle adjustment. The resulting set of depth maps is then merged into a combined depth map, during which erroneous depth measurements are filtered out. These maps are subsequently converted into partial point clouds, which are later merged into a final unified point cloud. The Agisoft Metashape software typically produces point clouds with densities comparable to, or even exceeding, those of LIDAR clouds [17]. Evidence of this is the dense point cloud of the arch monument generated in this study, which contains 301,289,009 points.

Table 2. Parameters of the workflow applied in Agisoft Metashape Professional

Alignment Cameras	Accuracy: High Generic Preselection: Yes Reference Preselection: Yes Key Point Limit: 0 Tie Point Limit: 0
Gradual Selection	Reconstruction Uncertainty: 10 Projection Accuracy: 3 Reprojection Error: 0.3
Optimize Cameras	k3, k4, p3, p4: No
Build Point Cloud	Quality: High Depth Filtering: Mild
Build Model	Source data: Depth maps Quality: High Face count: High Interpolation: Enabled Depth filtering: Mild
Build Texture	Texture type: Diffuse map Source data: Images Mapping mode: Generic Blending mode: Mosaic Enable hole filling – yes Enable ghosting filter – yes

The final stages of processing involve the creation of the polygonal and textured model. The process of generating the polygonal model can be described as the reconstruction of the surface geometry by converting the dense point cloud into a continuous mesh of interconnected triangles. For this purpose, algorithms for spatial interpolation and topological optimisation are applied. A total of 37,795,937 triangles were generated for the object under study. The photogrammetric processing concludes with the creation of a photorealistic visualisation of the three-dimensional model - namely, the construction of the model's texture. A portion of the resulting three-dimensional textured model is shown in Fig. 5. On the right side of the figure, the fine detail of the bas-relief on this part of the arch can be seen, while on the left, part of the facade reinforcement is visible. This demonstrates that such models can also be effectively used for the inspection of cultural heritage monuments.

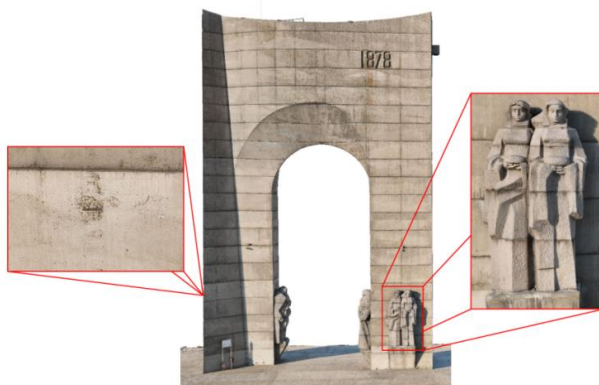


Fig.5. Portion of the three-dimensional textured model of the "Arch of Freedom" monument

Analysis of the Results

To assess the accuracy of the generated three-dimensional photogrammetric model, 46 distances were measured across the monument's surface at various heights. A statistical series of the errors between the control-measured distances and their corresponding model-derived distances was compiled. A gross error check was performed using the $\pm 3\sigma$ criterion. The calculated skewness and kurtosis values were smaller than their corresponding 3σ limits, indicating that the hypothesis of a normal distribution is consistent with the experimental data. The median and mode values were close to the mean, further supporting this hypothesis.

A check for the presence of systematic errors was conducted using Student's t-test at a significance level of $q = 0.05$. The results showed that the mean error did not differ statistically significantly from zero, indicating the absence of systematic deviations in the measurements.

In summary, one can say that the measurement errors are small (root mean square error = 0.011 m). Their distribution is symmetric and close to normal, without statistically significant shifts or extremes, confirming the accuracy and reliability of the measurements used in constructing the three-dimensional model.

Conclusion

The advantages of remote sensing methods are indisputable when creating models of objects that cannot be captured from the ground. The dynamic development of unmanned aerial systems and the emergence of new modes for automated flight execution have made it possible to model three-dimensional spatial representations of cultural and historical sites and to monitor them with remarkable accuracy and detail.

Both terrestrial laser scanning and aerial unmanned image acquisition [20], as well as their combination [4–6], have found broad application when solving problems while documenting immovable cultural heritage. However, in terms of efficiency and cost, the methodology based on optimised UAS image acquisition is preferable. It enables the capture of otherwise inaccessible objects and allows for process automation, thereby minimising the influence of human factors.

The results of the present study demonstrate that, given the specific type and shape of the studied object, the image acquisition method, image quality, and established data processing workflow, the proposed methodology ensures high accuracy in generating point clouds and three-dimensional models of architectural monuments. The model's high level of detail is a result of the fine spatial resolution of 0.22 cm, achieved through the optimised image acquisition of the object. This accessible methodology allows for efficient surveying of similar monuments even in urban environments, allowing not only their modelling but also regular monitoring.

A limitation of the methodology is its dependence on weather conditions and, to some extent, on processing time, which in this case amounted to 36 hours. It should be noted, however, that the processing was performed on a desktop computer with the following specifications: Windows 64-bit, AMD Ryzen 9 5950X 16-Core Processor, 64 GB RAM, NVIDIA GeForce RTX 3090. From a cost perspective, this can even be viewed as an advantage, since professional photogrammetric workstations are typically at least four times more expensive.

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ЕФЕКТИВНА МЕТОДОЛОГИЯ ЗА ГЕНЕРИРАНЕ НА ДЕТАЙЛЕН ТРИИЗМЕРЕН МОДЕЛ НА ПАМЕТНИК АРКА ПРИЛАГАЙКИ ОПТИМИЗИРАН ПЛАН НА ЛЕТЕНЕ

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Резюме

Дистанционните методи осигуряват набирането на информация от дистанция за обекти при които е невъзможно или затруднено заснемането от земната повърхност. Динамичното развитие на безпилотните летателни системи разкриват все по-големи възможности за създаване на триизмерни фотограметрични модели на паметници на културата не само за визуализация, но и за реконструкция, реставрация, консервация, адаптация и социализация на подобен тип обекти в социално – културната среда. Появата на нови начини за заснемане от все по-близка дистанция и възможността за заснемане с различно положение на снимачните оси включително и перпендикулярни на вертикалните повърхнини на обектите, водят до повишаване точността и детайлността на моделите. Статията представя методология за фотограметрично моделиране на паметник - арка, целящо използването на нов начин на заснемане „Smart 3D Capture“ внедрен в съвременните софтуери за планиране на полети през 2025 г. и автоматизиране на работния процес за фотограметрична обработка. Извършен е анализ на точността на получените резултати, като са измерени набор от разстояния. Целта на изследването е да представи методология за заснемане и генериране на детайлни фотограметрични модели на такъв тип обекти със сходни характеристики и барелефи върху тях, както и да се установят оптимални параметри на работния процес. Получените резултати доказват ефективността на предложената методология. Тя ще позволи не само създаването на модели, но и извършване на мониторинг на състоянието на паметници и други подобни обекти и ще даде възможност на различни специалисти да реализират такъв тип задачи на достъпна цена.

REMOVAL OF ARTIFACTS IN THE OSCILLOMETRIC CURVE DURING ARTERIAL BLOOD PRESSURE MEASUREMENT

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Keywords: *Non-invasive blood pressure measurement, blood pressure monitoring*

Abstract

Arterial blood pressure is one of the most important vital parameters of warm-blooded organisms, directly connected to their survival. This paper presents a method for measuring arterial blood pressure using the oscillometric technique. Algorithms for processing the oscillometric curve are discussed, with particular attention to the removal of parasitic signals recorded during measurement, such as noise and electrical and mechanical artefacts. The determination of systolic and diastolic arterial blood pressure is demonstrated. The proposed method applies to aerospace medical instrumentation for continuous monitoring of arterial blood pressure in pilots and astronauts under extreme operating conditions.

Introduction

Arterial blood pressure (BP) is one of the most important vital parameters of warm-blooded organisms, directly linked to their existence. This applies fully to humans as well. BP is the pressure exerted by blood on the walls of the arteries. Two types of pressure are measured: systolic (SP), the pressure during the contraction of the heart muscle chambers, and diastolic (DP), the constant pressure in the circulatory system during the relaxation of the heart muscle. Normal average statistical values are: 110 to 120 mm/Hg for SP, and 70 to 80 mm/Hg for DP.

Depending on the method used, BP is measured invasively or non-invasively. The invasive method is more accurate but is primarily used in cases of surgical intervention. This method is impractical in daily practice for several reasons, such as the presence of a highly qualified specialist, a sterile environment, or measurement modules often integrated into expensive operating monitors. Non-invasive methods are more widely used in practice. Some of them date back more than 3000 years. Such is the measurement of BP by "palpation" (feeling the pulse with fingers), where, depending on the heart rate and "distinctness of pulsations", 3 to 7 levels of blood pressure can be determined in

China and other Eastern countries. Centuries later, after the invention of the stethoscope, the Russian physician Korotkoff applied a simple and relatively accurate method, which remains one of the most widely used to this day. With the development of technology, a number of other non-invasive methods have been created, such as tonometric, ultrasonic, oscillometric, and temporal methods.

Each of the methods listed above has both advantages and numerous disadvantages, significantly affecting the quality and reliability of the measurements made. Of all the methods mentioned, the oscillometric method is the most widely used in modern practice. The measurement of BP using the oscillometric curve recording method has been described in numerous scientific articles [1, 2, 7].

The purpose of this paper is to demonstrate not only the implementation of an algorithm for processing the oscillometric curve but also the removal of parasitic signals recorded during the measurement, such as pathologies and artefacts of electrical and mechanical origin. These can seriously compromise the accuracy of the final results when determining systolic and diastolic blood pressure.

When measuring BP using the oscillometric method, two measurement approaches are known. Measuring BP after stopping blood flow with controlled release of pressure from the cuff, and measuring during the process of controlled increase of pressure in the cuff until blood flow stops. The second method is better due to the fact that there is no need to control the air release from the cuff, the measurement time is shorter, and the upper limit of the pressure value is accurately determined regardless of the current state of systolic pressure.

Exposition

The measurement process consists of four main phases:

- Increasing cuff pressure until blood flow stops.
- Recording and saving the oscillometric curve.
- Analysing the oscillometric curve and correcting for noise and artefacts.
- Determining the BP (Systolic and Diastolic).

The operating algorithm is shown (Fig. 1).

During the process of increasing cuff pressure (Fig. 2), shown by the red line, the maximum pulsation values caused by turbulence in the blood flow passing through the arteries narrowed by the cuff are recorded. The amplitudes of these pulsations in the cuff are very small, which necessitates the introduction of an AC amplifier with sufficiently high gain and a frequency band of 0.1–10 Hz. The oscillometric curve represents the envelope curve of the maximum values of the pulsations obtained at the output of the amplifier.

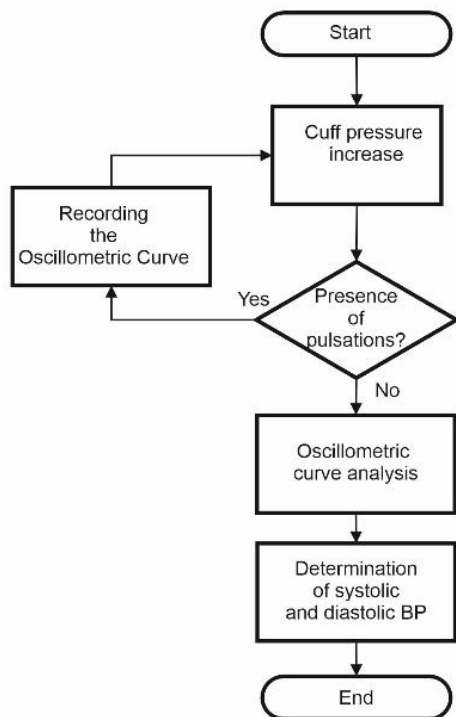


Fig. 1. Algorithm of operation for measuring NIBP using the oscillometric method

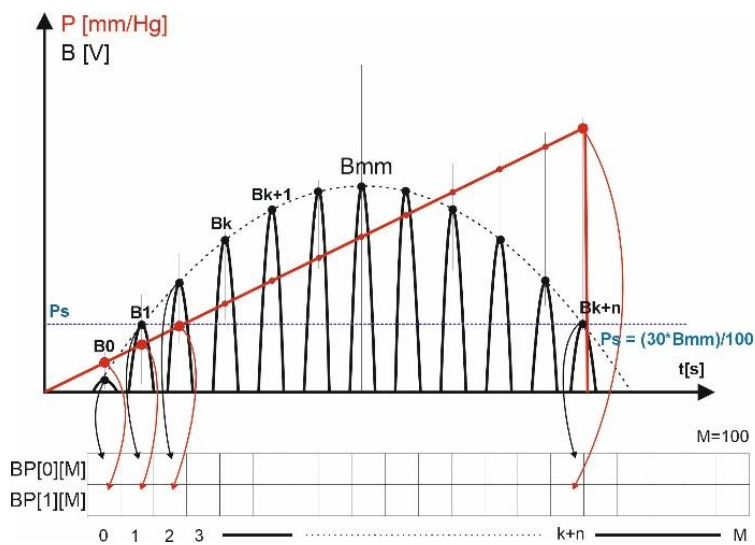


Fig. 2. Algorithm for recording the oscillometric curve

For each registered local maximum, the cuff pressure value is recorded. The data is stored in a two-dimensional array $BP[2][M]$, where M is taken as $M = 100$. The first row of the array $BP[0][M]$ stores the maximum amplitude values of the registered pulsations, B_0 to B_n , and the second row $BP[1][M]$ stores the instantaneous cuff pressure for each maximum. During the process of registering and recording each pulsation, B_k , B_{mm} (the pulsation with the largest amplitude among all registered pulsations) is determined. The instantaneous pressure associated with the maximum of this pulsation determines the mean blood pressure parameter. After B_{mm} is registered, the pulsation amplitudes decrease due to the increase in cuff pressure and the closure of the arterial lumen in the measurement area. When an amplitude B_{k+n} less than 30% of B_{mm} is reached, the pressure increase is stopped, the valve opens, and the cuff pressure becomes zero, which completes the recording of the oscillometric curve.

After the maximum values of the registered pulsations and their associated pressure are recorded, the pulse curve is analysed. In real conditions, the amplitude often does not increase/decrease smoothly (depending on whether the cuff pressure is below or above the mean arterial pressure, P_{mm}). This can be caused by ventricular extrasystoles, characterised by the generation of a large amplitude, as well as artefacts due to movement during the measurement. The presence of signals with amplitudes that disrupt the bell-shaped nature of the envelope curve can corrupt the measurement and lead to incorrect results. Fig. 3 shows such a disturbance for pulsation B_k in red and blue, which disrupts the nature of the envelope curve. To eliminate such parasitic signals, an amplitude analysis is applied to all recorded values in the array $BP[0][M]$.

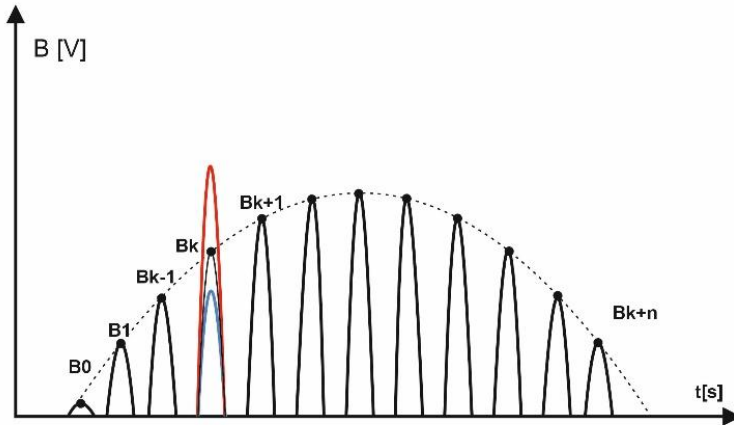


Fig. 3. Artefact and interference removal

Provided that:

$$(1) \quad B_k \geq B_{k+1} \cup B_k \leq B_{k-1}$$

The value of B_k is determined by the expression:

$$(2) \quad B_k = \frac{(B_{k+1} + B_{k-1})}{2}$$

After checking and correcting the amplitudes of the pulse curve, the systolic and diastolic pressure values are determined. The systolic pressure is taken as the pressure corresponding to a pulsation in the array with an amplitude of 0.5 of B_{mm} . The processing of the $BP[0][i]$ array is carried out in the region for $i_{B_{mm}} < i < 100$. The calculated systolic pressure must satisfy condition (3), where P_{sys} is equal to the associated pressure for a pulsation belonging to the right half of the oscillometric curve with pressure greater than P_{mm} and amplitude 0.5(B_{mm}).

$$(3) \quad P_{sys} = 0.5(BP[1][i_{B_{mm}}]) \text{ като } B_s = 0.5(BP[0][i_{B_{mm}}])$$

The determination of diastolic pressure is carried out after analysing the left half of the oscillometric curve, i.e. for all indices of the $BP[0][i]$ array, where $0 \leq i < i_{B_{mm}}$. Diastolic pressure must be less than P_{mm} and satisfy condition (4):

$$(4) \quad P_{dia} = 0.65(BP[1][i_{B_{mm}}]) \text{ като } B_s = 0.65(BP[0][i_{B_{mm}}])$$

Usually, the $BP[0][M]$ array does not contain amplitudes with the desired values. Assuming the closest values that satisfy condition (3) for systolic and (4) for diastolic pressure would lead to significant errors. For this reason, interpolation is necessary to determine both the desired amplitude for the respective pressure and the associated static cuff pressure.

Discussion of results

To simplify the task, it is assumed that the amplitude changes linearly between two adjacent pulsations of the oscillometric curve. The processing of the recorded data in the BP array starts from the index with the largest value, $i = M$, corresponding to the highest cuff pressure (Fig. 4). The most general case is considered, in which the desired amplitude B_s , corresponding to the systolic pressure, falls between the values of the amplitudes B_k and B_{k+1} . The section of the envelope curve to the left of B_{mm} .

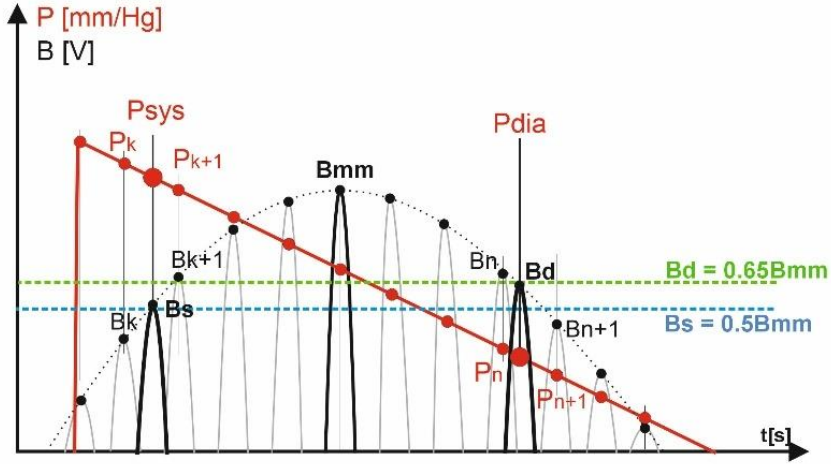


Fig. 4. Determination of systolic and diastolic BP

Then conditions (5) and (6) are valid for B_s and P_s , with processing carried out from the B_{mm} index to the end of the BP array.

$$(5) \quad B_k < B_s < B_{k+1}$$

$$(6) \quad P_k > P_s > P_{k+1}$$

An interpolation step Δ_b is adopted, which is determined by expression (7).

$$(7) \quad \Delta_b = \frac{(B_{k+1} - B_k)}{100}$$

For the desired pulsation with amplitude B_s , the number of increments N added to B_k is determined.

$$(8) \quad N = \frac{(0.5(B_{mm}) - B_k)}{\Delta_b}$$

where:

$$(9) \quad B_s = B_k + N\Delta_b$$

The same number N (8) of interpolation steps must be applied for the pressure in the range (P_k, P_{k+1}) . For this purpose, the interpolation step (10) in the pressure range is determined:

$$(10) \quad \Delta_p = \frac{(P_k - P_{k+1})}{100}$$

The systolic pressure is obtained from dependence (11).

$$(11) \quad P_{sys} = P_k - N\Delta_p$$

Diastolic pressure is determined similarly, but it should be noted that the analysis of the pulsation amplitudes recorded in the BP array is performed from index 0 to index B_{mm} , i.e. $0 \leq i < i_{Bmm}$.

For B_d and P_d , conditions (12) and (13) apply.

$$(12) \quad B_n > B_d > B_{n+1}$$

$$(13) \quad P_n > P_d > P_{n+1}$$

The interpolation step is accepted Δ_b , defined by the expression (14).

$$(14) \quad \Delta_b = \frac{(B_n - B_{n+1})}{100}$$

The desired pulsation with amplitude B_d is determined by the number of increments N added to B_{n+1}

$$(15) \quad N_{dia} = \frac{(0.65(B_{mm}) - B_{n+1})}{\Delta_b}$$

The same number N_{dia} (15) of increments must also be applied to the pressure in the range $P_n - P_{n+1}$. For this purpose, the interpolation step (16) in the pressure range is determined:

$$(16) \quad \Delta_p = \frac{(P_n - P_{n+1})}{100}$$

Diastolic pressure is determined by the dependence:

$$(17) \quad P_{dia} = P_{n+1} + N\Delta_p$$

Conclusion

During the reference measurements performed using the Korotkoff method (with a stethoscope and sphygmomanometer), as well as with a TRANSTEK device operating on the oscillometric method principle, measurement deviations of +5/-4 mmHg for systolic and +2/-3 mmHg for diastolic pressures were achieved, from which it can be concluded that the described measurement method allows for reliable and accurate determination of blood pressure. The reviewed algorithms have been applied in various devices and have shown good results. The described algorithm has been implemented at the OxyLife Sofia medical centre, on the BeOn1 psychophysiological research equipment, and in a bilateral stimulation system for treating post-traumatic stress.

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ОТСТРАНЯВАНЕ НА АРТЕФАКТИ В ОСЦИЛОМЕТРИЧНАТА КРИВА ПРИ ИЗМЕРВАНЕ НА АРТЕРИАЛНОТО КРЪВНО НАЛЯГАНЕ

С. Танев

Резюме

Артериалното кръвно налягане е един от най-важните жизнени параметри на топлокръвните организми, пряко свързан с тяхното оцеляване. Тази статия представя метод за измерване на артериално кръвно налягане с помощта на осцилометричен метод. Обсъждат се алгоритми за обработка на осцилометричната крива, като особено внимание се обръща на премахването на паразитните сигнали, записани по време на измерването, като шум и артефакти от електрически и механичен произход. Демонстрирано е определянето на систолното и диастолно артериално кръвно налягане. Предложеният метод е приложим в аерокосмическа медицинска апаратура за непрекъснат мониторинг на артериалното кръвно налягане при пилоти и космонавти изпълняващи дейности в екстремни условия на работа.

SIMULATION AND MODELS OF SECONDARY POWER SUPPLIES FOR AEROSPACE SYSTEMS

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Key words: *Secondary power sources, Simulation models, Micro-Cap, TINA-TI, MultiSim, SIMetrix*

Abstract:

The design and evaluation of secondary power sources and systems using simulation and models are discussed. Experiments with electronic circuits are performed. The models allow measurement and visualisation of various parameters as well as analysis of the results. Micro-Cap, TINA-TI, MultiSim, and Symetrix software products are used. The simulation helps to understand the basic characteristics, analyse and tune electronic circuits, and study processes in secondary power sources and systems.

Introduction

The power supply of aerospace equipment (AE) is carried out by two cooperative systems: the primary power supply system (PES) and the secondary power supply system (SES). The purpose of the PES is to convert non-electrical energy into electrical energy. In most cases, the PES, in terms of stability and voltage, is not suitable to power AE, which determines the use of secondary power sources (SPS) and PES designed according to the requirements of specific users and operating conditions. The main energy source of the spacecraft is usually the solar battery, which, together with the batteries, primary pulse converters, power automation, cables and connectors, forms the primary onboard network, which in some Russian spacecraft and aircraft has a constant voltage varying in the range from +24 V to +34 V. Voltages of positive and negative polarity are used in the power supply of AE. In the case of unmanned aerial vehicles, stable voltages with values of +3.3 V, +5 V, etc., are usually applied to digital electronics, and +6 V, +12 V, etc. for actuators.

The developed circuit and design solutions of the SES are tested for compliance with the normative documents and are checked during aerospace flights.

When designing specialised SPS and SES for AE, the following shall be taken into account:

- The characteristic features of the equipment and the specific scientific experiment;
- Operating conditions: outer space; artificial atmosphere in an airtight compartment; mechanical loads at launch; flight; maneuvering and transport; radiation conditions; thermal regimes, etc.;
- The electromagnetic compatibility on board the aerospacecraft.

With qualitatively performed design, research, adjustment, and optimisation of the SES, the main parameters of the SES are improved.

Micro-cap software product

With the Micro-cap software product [1, 5], the following analyses are possible:

- Transient analysis;
- Frequency analysis at a small signal: amplitude-frequency characteristic, phase-frequency characteristic, and Bode diagram (AC analysis);
- Direct voltage and current transmission function: transmission function; volt-ampere response and family of static transmission characteristics (DC analysis);
- Dynamic DC analysis;
- Dynamic AC analysis;
- Sensitivity analysis of the equivalent circuit for constant voltages and currents to changes in the parameters of the components (Sensitivity analysis);
- Transfer Function analysis;
- A series of calculations when changing one or more parameters (Stepping);
- Statistical processing (Monte Carlo);
- Fourier analysis;
- Graph calculation of the dependency of certain characteristics (Performance);
- Study of the temperature instability of the model.

The model of a transformer flyback SPS shown in Fig. 1 contains parameters of standard manufactured components, whereby the simulation of their joint operation is as close as possible to the real processes. Shown in a rectangular frame next to the corresponding element are the values of currents calculated by the software (blue colour) and dissipated power (red colour). Some of the parameters from Fig. 1 are observed in Fig. 2 sequentially from top to bottom: gate voltage V_{drv} on transistor $X13$; current sensor voltage V_{sense} ; drain voltage V_{drain} on transistor $X13$; secondary winding current I_{sec} ; secondary voltage V_{vsec} and output voltage V_{out} .

Software product TINA-TI

The TINA-TI software [9, 10] is free of charge and has been developed by Texas Instruments. Fig. 3 shows a model of a step-down SES, and Fig. 4 shows its start-up process and analytical dependencies for the capacitor C_{ss} and chokes L_{min} . Fig. 5 shows a model of a transformer flyback SES for three output voltages V_{out6} , V_{out7} , and V_{out8} . Due to the high output current at the relatively low output voltage $V_{out6} = 3.3$ V, a synchronous rectifier was implemented with the transistor Q2 and elements D4, D5, and R4 to increase the efficiency of the converter. Fig. 6 shows a model of a transformer flyback SES with a controller UCC2860. The time diagrams from Fig. 7 and Fig. 8 refer to the model in Fig. 6. From the first graph in Fig. 7 for the output voltage, the pulsations from peak to peak can be reported, and from Fig. 8 in green, three half-waves of the start-up readjustment process are visible for the time interval $\Delta t = 3 \div 8$ ms.

Multisim software product

The first versions of the software were called Electronics Workbench. The Multisim Education version is designed for educational institutions and contains prepared solutions and manuals. Fig. 9 demonstrates the capabilities of the Multisim program [3–5] for simulation of forward SPS with two key transistors X1 and X2. The Multisim element library contains more than 2000 SPICE models. The Convergence Assistant tool automatically corrects modelling errors. The disadvantage of Multisim is the high load on the processors and memory of Multisim when working with large circuit diagrams.

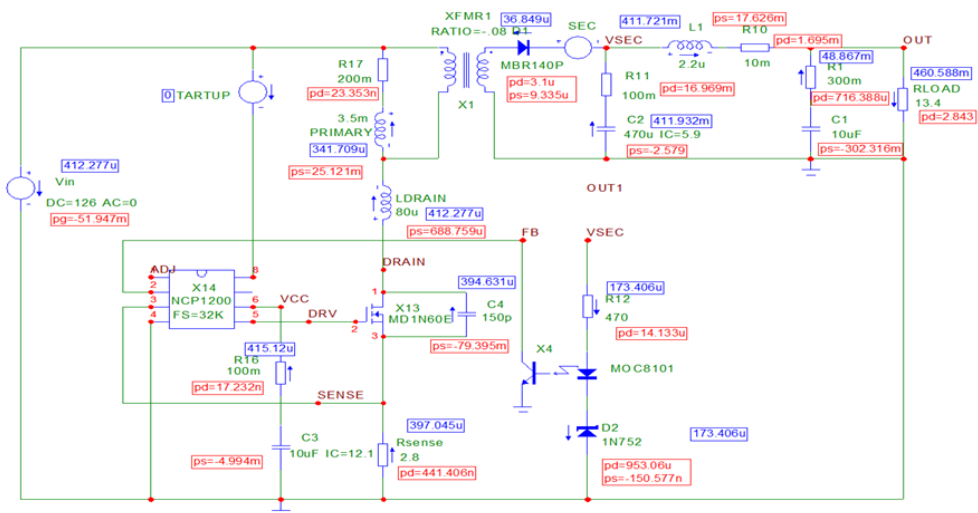


Fig. 1. Model of transformer flyback SPS with *Micro-cap*

SIMetrix software product

The SIMetrix software product [2, 6–8] uses two publicly available models (SPICE and XSPICE) and is characterised by high performance. There is an efficiency calculator and a Bode probe. In transformer models, not only can the hysteresis curve be set, but also the value of the air slit. Fig. 10 shows the model of the flyback SES, and Fig. 11 shows its starting process. In Fig. 12, the model of the step-up SPS is presented, and in Fig. 13 are its Bode diagrams (amplitude and phase characteristics of feedback).

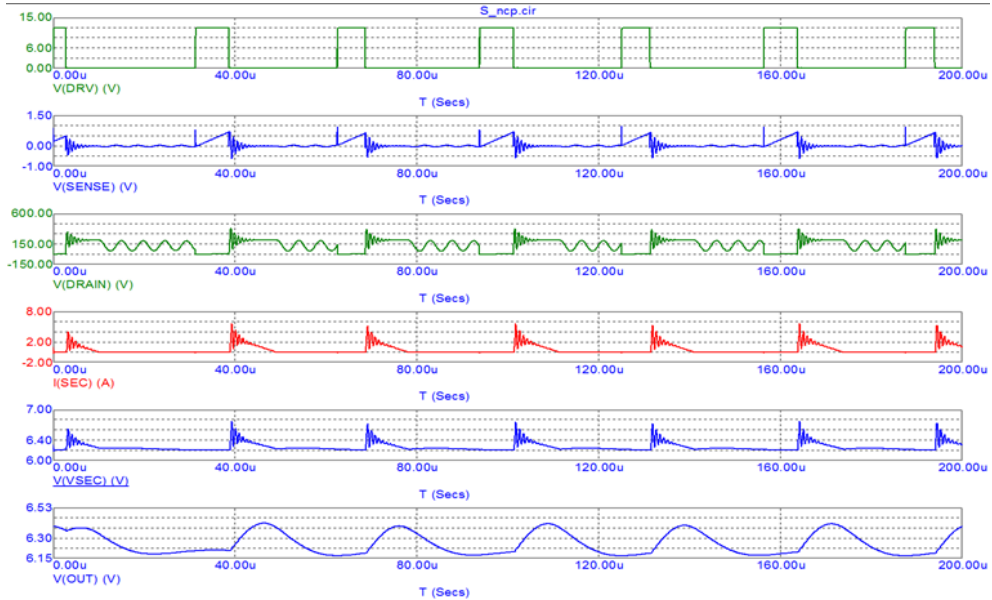


Fig. 2. Time diagrams with *Micro-cap* of transformer flyback SPS from Fig. 1

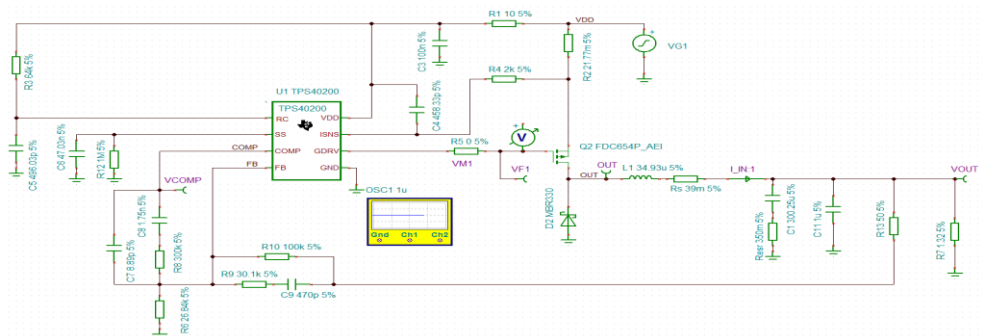
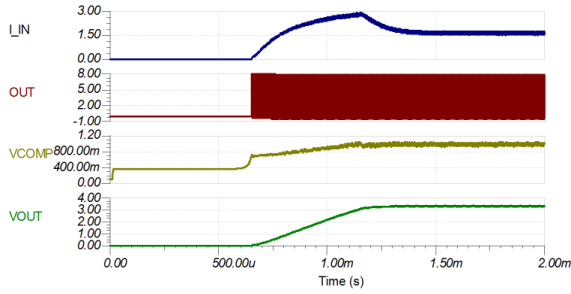


Fig. 3. TINA-TI model of a step-down SPS filled with a TPS40200 controller



$$C_{ss} = \frac{t_{ss}}{R \cdot \ln\left(\frac{V_{sst}}{V_{sst}-1,4}\right)}$$

$$L_{min} = \frac{V_{in} - V_{out}}{I_{peak}} \cdot t_{on}$$

Fig. 4. TINA-TI time diagrams and formulas of SPS from Fig. 3

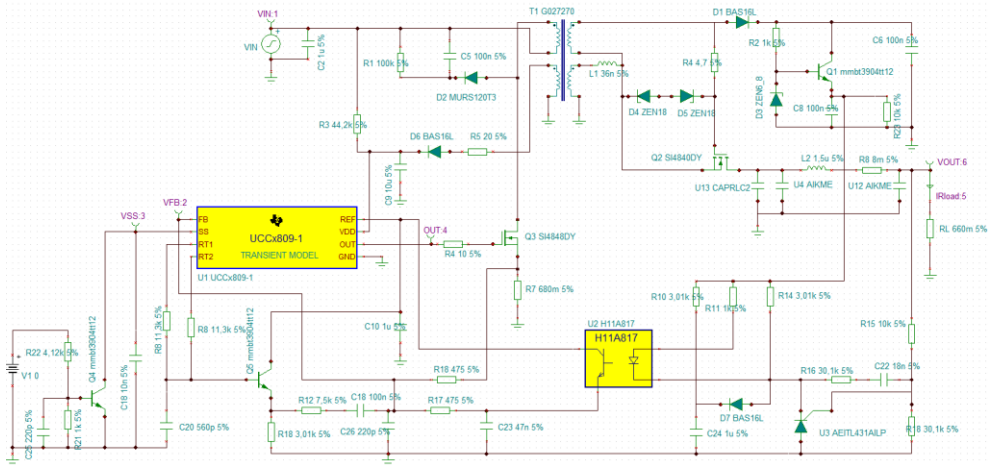


Fig. 5. TINA-TI model of a transformer flyback SES completed with a UCC2809-1 controller

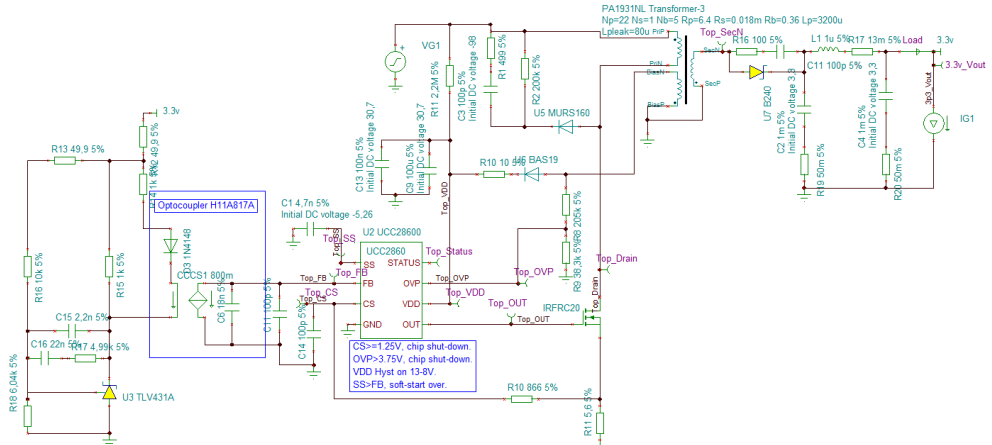


Fig. 6. TINA-TI model of a transformer flyback SES completed with a UCC2860 controller

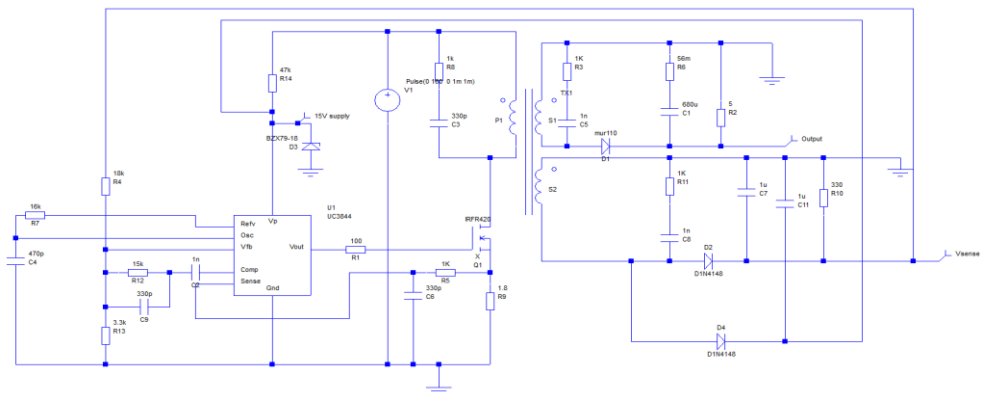
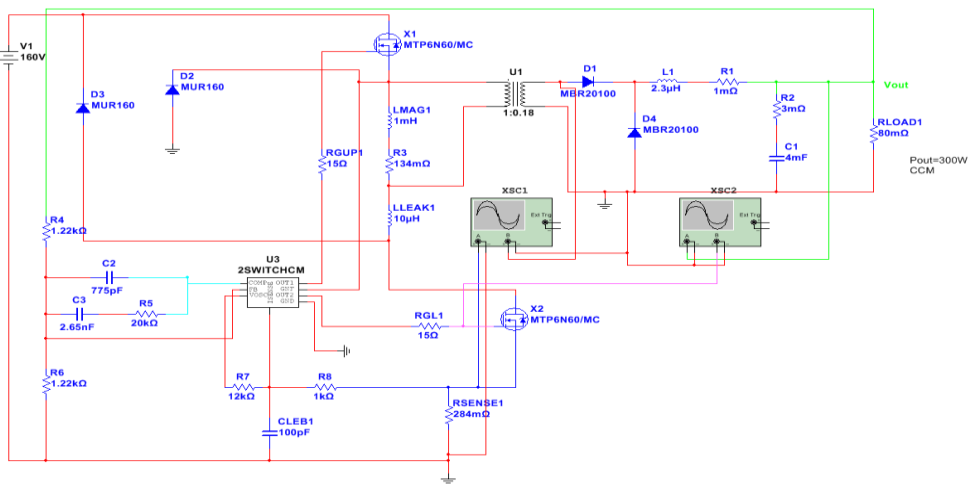
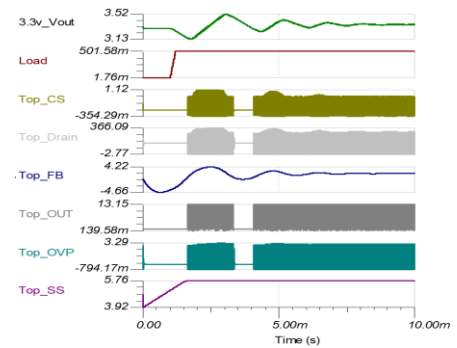
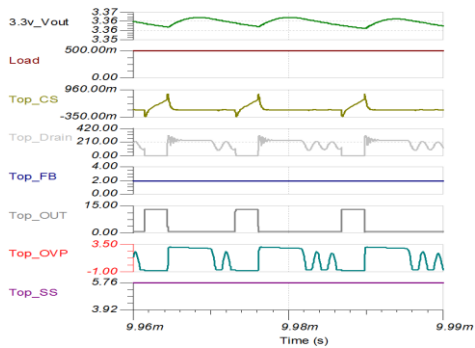




Fig. 11. Starting process of the SES from Fig. 10

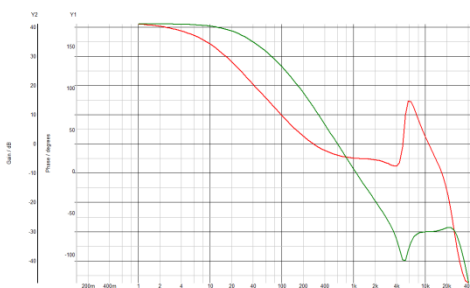
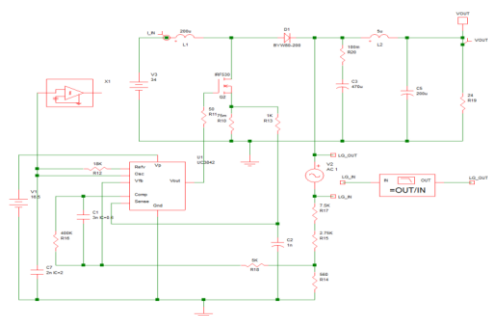


Fig. 12. *SIMetrix* Model of step-up SPS

Fig. 13. *SIMetrix* Bode diagrams from Fig. 12

Conclusion

Simulations and models of secondary power sources and systems have been implemented using four free software products. With the considered instruments, the following are analysed: frequency characteristics; start-up processes; switching pulse powers; virtual meters; transients; and static modes in terms of current, voltage, etc.

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СИМУЛАЦИЯ И МОДЕЛИ НА ВТОРИЧНИ ТОКОЗАХРАНВАЩИ ИЗТОЧНИЦИ ЗА АЕРОКОСМИЧЕСКИ СИСТЕМИ

Павлин Граматиков

Резюме

Разглеждат се проектирането и оценката на вторични токозахранващи източници и системи с помощта на симулация и модели. Извършени са експерименти с електронни схеми. Моделите позволяват измерване и визуализиране на различни параметри, както и анализ на резултатите. Използват се програмните продукти Micro-Cap, TINA-TI, MultiSim и SIMetrix. Симулацията помага да се разберат основните характеристики, анализът и настройката на електронните схеми, както и процесите във вторичните токозахранващи източници и системи

THE SINGLE SHOOTING METHOD APPLIED TO AN ORBIT COPLANAR TRANSFER

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Key words: *Astrodynamics, Two-body problem, J2 perturbation, Single shooting*

Abstract

In this paper, the Single-shooting method is applied to design a coplanar orbital transfer trajectory for an artificial Earth satellite. The satellite moves in a central force field, taking into account the central body (the Earth) oblateness (J2 zonal coefficient). During transfer trajectory computation, the state vector is propagated numerically, and a state transition matrix is used to determine how small disturbances in the initial velocity vector affect the final position vector. For this purpose, the so-called Hohmann coplanar transfer (altitude change) is used as a validation case. The numerical results are presented graphically and discussed thoroughly.

Introduction

The single shooting method is a numerical approach to solving boundary value problems (BVPs) for ordinary differential equations (ODEs). The method essentially reduces the boundary value problem to a system of ODEs with initial conditions (initial value problem – IVP) that is easier to solve.

The single shooting method is relatively easy to implement. The method works well with problems that are less sensitive to initial conditions, yet difficulties are expected in solving stiff problems, such as divergence or instability during iterations.

Coplanar manoeuvres such as Hohmann, bi-polar, and one-tangent burns have already been thoroughly investigated and formulae developed in many textbooks in Astrodynamics, such as Vallado [1], to name but a few. In particular, Hohmann orbit transfer analysis concerning national security issues has been carried out by Marinov in paper [2].

The current study presents a numerical implementation of the single-shooting method to perform a co-planar Hohmann orbital transfer. Rather than conducting theoretical research, the current study focuses on the numerical algorithm stages to bring the problem to successful completion.

Governing equations

A solution to the following IVP describes a satellite motion in a central gravitational field (two-body problem) expressed in Earth-centred inertial (ECI) reference frame:

$$(1) \quad \dot{\mathbf{x}} = \begin{bmatrix} \dot{\mathbf{r}} \\ \dot{\mathbf{v}} \end{bmatrix} = \begin{bmatrix} \mathbf{0}_{3 \times 3} & \mathbf{I}_{3 \times 3} \\ -(\nabla U + \nabla U_{J_2}) & \mathbf{0}_{3 \times 3} \end{bmatrix} \begin{bmatrix} \mathbf{r} \\ \mathbf{v} \end{bmatrix} \quad r = \|\mathbf{r}\|_2 = \sqrt{x^2 + y^2 + z^2}$$

$$\mathbf{r}(t_0) = \mathbf{r}_0 \quad \mathbf{v}(t_0) = \mathbf{v}_0$$

where two potential functions U and U_{J_2} , taking into account the second zonal harmonic coefficient $J_2 = 1.08262668\text{E-}3$, are defined as follows. The Earth is regarded as a potential well, hence the negative sign.

$$(2) \quad U = -\frac{\mu}{r} \quad U_{J_2} = -\frac{\mu}{r} J_2 \left(\frac{R_\oplus}{r} \right)^2 \left[\frac{3}{2} \left(\frac{z}{r} \right)^2 - \frac{1}{2} \right]$$

The inclusion of J_2 accounts for the Earth's deviation from perfect sphericity due to the equatorial bulge. The J_2 perturbation, in turn, affects the right ascension of the ascending node Ω (line of nodes precession) and the argument of perigee ω .

The gradient of the potential function ∇U_{J_2} was computed symbolically by the SymPy package implemented in GNU Octave. For example, the partial derivative $\partial U_{J_2} / \partial x$ was reported as shown in Fig. 1.

```

Command Window
>> pkg load symbolic
>> syms x y z r U J2 RE mu
>> r = sqrt(x^2 + y^2 + z^2);
>> U = -mu/r*J2*(RE/r)^2*(3/2*(z/r)^2 - 1/2);
>> dUdx = diff(U,x)
dUdx = (sym)

```

$$\frac{3J_2RE^2\mu x^2}{\sqrt{x^2+y^2+z^2}^{7/2}} + \frac{3J_2RE^2\mu x^2}{\sqrt{x^2+y^2+z^2}^{5/2}} \left(\frac{3z^2}{2\sqrt{x^2+y^2+z^2}} - \frac{1}{2} \right)$$

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>> |

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Command Window | Documentation | Variable Editor | Editor

Profiler

Fig. 1. SymPy exemplary session

After computing gradients ∇U and ∇U_{J_2} and replacing them in (1), the following formulae for acceleration vector $d\mathbf{v}/dt$ components are obtained:

$$(3) \quad \begin{aligned} a_x &= -\frac{\mu x}{r^3} \left[1 + \frac{3}{2} J_2 \left(\frac{R_\oplus}{r} \right)^2 \left[1 - 5 \left(\frac{z}{r} \right)^2 \right] \right] \\ a_y &= \frac{y}{x} a_x \\ a_z &= -\frac{\mu z}{r^3} \left[1 + \frac{3}{2} J_2 \left(\frac{R_\oplus}{r} \right)^2 \left[3 - 5 \left(\frac{z}{r} \right)^2 \right] \right] \end{aligned}$$

This constitutes a system of 6 first-order ODEs in terms of the state vector $\mathbf{x}$.

The state transition matrix $\Phi(t, t_0)$ is a fundamental term in a linearised celestial mechanics problem. It is used to propagate small deviations in the initial state (a.k.a. differential correction). In the case of non-linear equations

$$(4) \quad \dot{\mathbf{x}}(t) = f(\mathbf{x}, t)$$

the perturbed state $\delta\mathbf{x}(t)$ might be derived from initial deviation $\delta\mathbf{x}(t_0)$ as follows

$$(5) \quad \delta\mathbf{x}(t) = \Phi(t, t_0) \delta\mathbf{x}(t_0)$$

Equation (5) is required to compute small deviations $\delta\mathbf{v}_0$ necessary to diminish deviation from the desired position $\delta\mathbf{r}_1$

$$(6) \quad \begin{bmatrix} \delta\mathbf{r}_1 \\ \delta\mathbf{v}_1 \end{bmatrix} = \begin{bmatrix} \Phi_{rr}(t, t_0) & \Phi_{rv}(t, t_0) \\ \Phi_{vr}(t, t_0) & \Phi_{vv}(t, t_0) \end{bmatrix} \begin{bmatrix} \delta\mathbf{r}_0 \\ \delta\mathbf{v}_0 \end{bmatrix}$$

The immobility constraint implies $\delta\mathbf{r}_0 = 0$. If the final velocity deviation $\delta\mathbf{v}_1$ is left unconstrained, then the initial velocity is amended in accordance with the formula

$$(7) \quad \delta\mathbf{v}_0 = \Phi_{rv}(t, t_0)^{-1} \delta\mathbf{r}_1$$

Besides the state vector $\mathbf{x}$, the state transition matrix Φ is propagated too. The initial conditions $\mathbf{x}(t_0)$ can be adapted to obtain a numerical solution $\mathbf{x}_1(t_1)$ near the desired values $\mathbf{x}_d(t_1)$. Hence, a numerical solution to the following IVP of 36 first-order ODEs is sought in addition.

$$(8) \quad \dot{\Phi}(t, t_0) = \mathbf{A}(t) \Phi(t, t_0) \quad \Phi(t_0, t_0) = \mathbf{I}$$

where the block matrix $\mathbf{A}$ is

$$(9) \quad \mathbf{A}(t) = \begin{bmatrix} \mathbf{0}_{3 \times 3} & \mathbf{I}_{3 \times 3} \\ \frac{\partial \mathbf{a}(\mathbf{x}, t)}{\partial \mathbf{r}} & \mathbf{0}_{3 \times 3} \end{bmatrix} \quad \frac{\partial \mathbf{a}(\mathbf{x}, t)}{\partial \mathbf{r}} = \begin{bmatrix} \frac{\partial a_x}{\partial x} & \frac{\partial a_x}{\partial y} & \frac{\partial a_x}{\partial z} \\ \frac{\partial a_y}{\partial x} & \frac{\partial a_y}{\partial y} & \frac{\partial a_y}{\partial z} \\ \frac{\partial a_z}{\partial x} & \frac{\partial a_z}{\partial y} & \frac{\partial a_z}{\partial z} \end{bmatrix}$$

Partial derivatives $\partial \mathbf{a}(\mathbf{x}, t) / \partial \mathbf{r}$ are obtained as excessively large by SymPy even after applying simplification. This is the reason why the following formulae derived in thesis [3] have been adopted instead:

$$(10) \quad \begin{aligned} \frac{\partial a_x}{\partial x} &= \frac{\mu}{r^5} \left[3x^2 - r^2 - \frac{3}{2} J_2 R_\oplus^5 + \frac{15}{2} \frac{J_2 R_\oplus^2}{r^2} (x^2 + z^2) - \frac{105}{2} \frac{J_2 R_\oplus^2}{r^4} x^2 z^2 \right] \\ \frac{\partial a_x}{\partial y} &= \frac{3\mu xy}{r^5} \left(1 + \frac{5}{2} \frac{J_2 R_\oplus^2}{r^2} - \frac{35}{2} \frac{J_2 R_\oplus^2}{r^4} z^2 \right) \\ \frac{\partial a_x}{\partial z} &= \frac{3\mu xz}{r^5} \left(1 + \frac{15}{2} \frac{J_2 R_\oplus^2}{r^2} - \frac{35}{2} \frac{J_2 R_\oplus^2}{r^4} z^2 \right) \\ \frac{\partial a_y}{\partial x} &= \frac{\partial a_x}{\partial y}; \quad \frac{\partial a_y}{\partial y} = \frac{y}{x} \frac{\partial a_x}{\partial y} + \frac{a_x}{x}; \quad \frac{\partial a_y}{\partial z} = \frac{y}{x} \frac{\partial a_x}{\partial z} \\ \frac{\partial a_z}{\partial x} &= \frac{\partial a_x}{\partial z}; \quad \frac{\partial a_z}{\partial y} = \frac{\partial a_y}{\partial z} \\ \frac{\partial a_z}{\partial z} &= \frac{\mu}{r^5} \left[-r^2 + 3 \left(z^2 - \frac{3}{2} J_2 R_\oplus^5 + \frac{15}{2} \frac{J_2 R_\oplus^2}{r^2} z^2 - \frac{35}{2} \frac{J_2 R_\oplus^2}{r^4} z^4 \right) \right] \end{aligned}$$

The single-shooting method is depicted schematically in Fig. 2. Given certain initial conditions $\mathbf{x}(t_0)$, the propagated vector $\mathbf{x}(t_1)$ differs from the desired value $\mathbf{x}_d(t_1)$ by some error $\delta \mathbf{x}(t_1)$. The error is then backpropagated (6) to work out the initial vector value necessary for achieving the desired outcome. In most cases, it only takes a few iterations to succeed. The process is repeated until the Euclidean norm of the absolute error vector $\|\delta \mathbf{x}(t_1)\|_2$ becomes sufficiently small. Alternative definitions of residual are also acceptable.

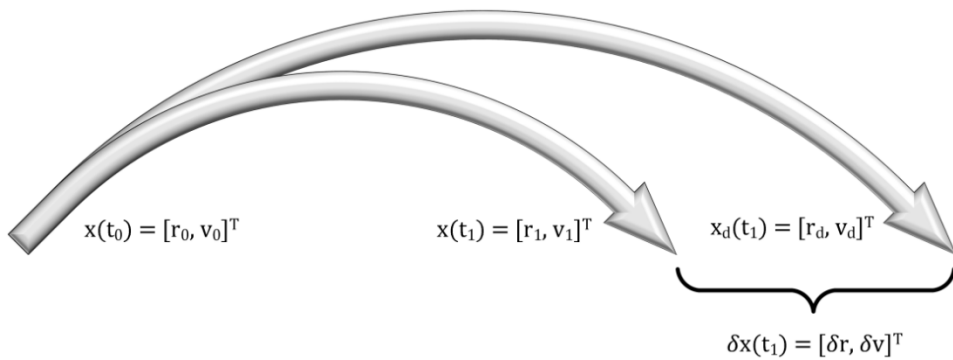


Fig. 2. The single shooting formalism

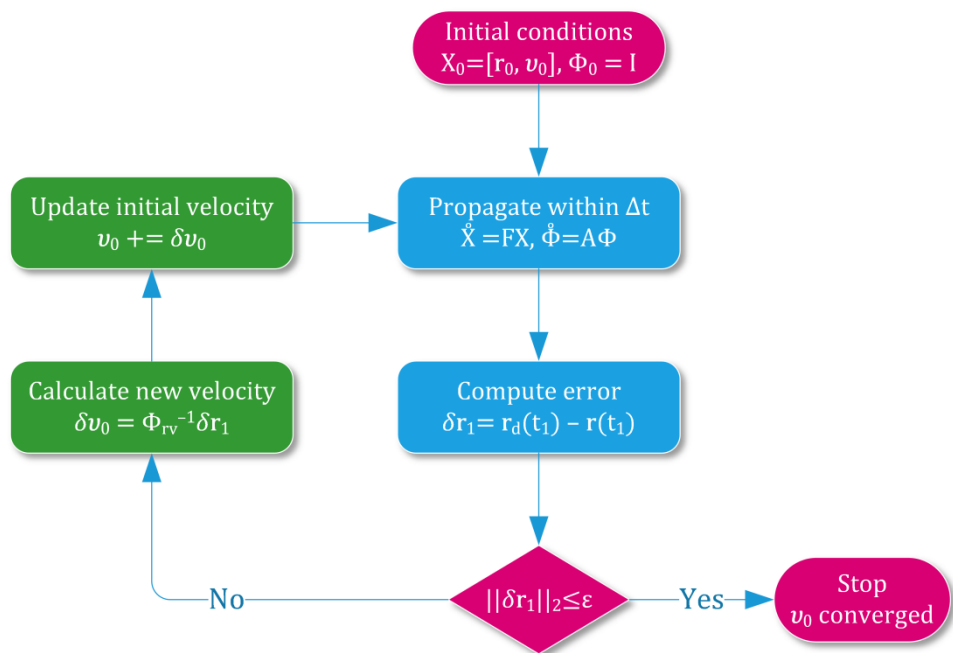


Fig. 3. Computational steps taken by the single shooting method, [4]

The single shooting algorithm is depicted in Fig. 3 as a flowchart adopted from Ref. [4]. To start with, initial values (ECI reference frame) are assigned to the state vector whilst the state transition matrix is initialised with identity one. Both the state vector and the state transition matrix are propagated, and the final position is compared to the desired one. In case of a large difference, the initial velocity is updated according to formula (7). The transfer trajectory is propagated until the error vector $\delta \mathbf{r}_1$ becomes sufficiently small.

The desired position is computed by altering the flight altitude, which is essentially a manoeuvre confined within the orbital plane. It suggests the position vector $\mathbf{r}(t_1)$ is simply enlarged, for example, by a factor $2R_\oplus$

$$(11) \quad \mathbf{r}_d(t_1) = \frac{\mathbf{r}(t_1)}{\|\mathbf{r}(t_1)\|_2} 2R_\oplus$$

Two transfer trajectories with two bursts are computed: the first burst deviates from the initial orbit, and the second burst fine-tunes what is expected to be a final orbit.

The GNU Octave function `ode45` is used in the current project to propagate both the state vector and the state transition matrix. The function implements the explicit Dormand-Prince method of order 4, [5]. It is only capable of solving (systems of non-stiff) first-order ODE(s), which is yet another reason why the governing equations (1) are written in vector form.

Results

Consider the following osculating Keplerian elements as initial conditions:

- | | |
|---|------------------------------|
| • Semi-major axis | $a = 8639 \text{ km}$ |
| • Eccentricity | $e = 0.1869$ |
| • Inclination | $i = 34.28 \text{ deg}$ |
| • Argument of perigee | $\omega = 331.9 \text{ deg}$ |
| • Right ascension of the ascending node | $\Omega = 348.7 \text{ deg}$ |
| • Mean anomaly | $M = 19.22 \text{ deg}$ |

Before commencing iterations, these elements must be converted to position and velocity vectors in the ECI reference frame. An excellent tutorial on conversions between $[\mathbf{r}, \mathbf{v}]^T$ ECI vector and Keplerian elements might be found in link [6]. The resulting initial ECI vector $\mathbf{x}_0 = [\mathbf{r}_0, \mathbf{v}_0]^T$ at epoch 0 is (units are km and km/s) $\mathbf{x}_0 = [7021, -1393, 5.459, 1.890, 6.409, 4.537]^T$

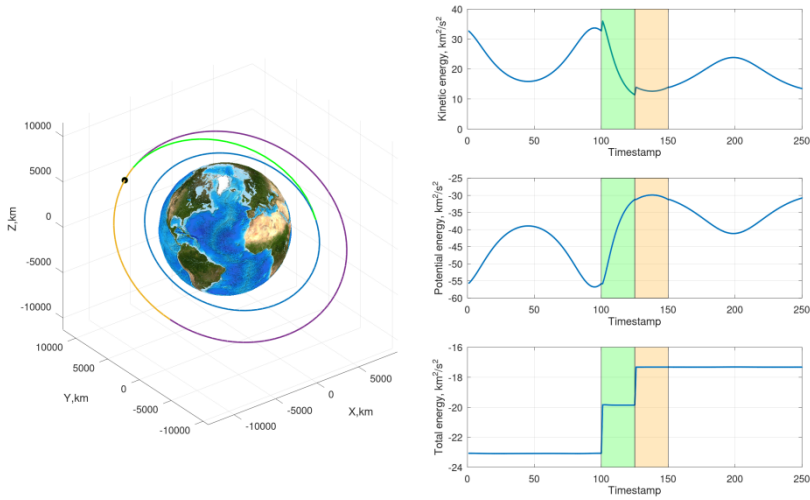


Fig. 4. Numerical results

In Fig. 4, the initial orbit, two transfer trajectories, and final orbit are depicted next to kinetic, potential, and total energy graphs. The total energy remains constant along each orbital segment as expected. Shaded regions (green and orange) make it easier for the reader to discern two consecutive transfer trajectories in the graphs. The potential energy is always negative, for the reference altitude has been chosen at infinity.

In the current case study, the norm 2 of the absolute error approaches zero rapidly. It takes the algorithm only five iterations to converge, as shown in Fig 5.

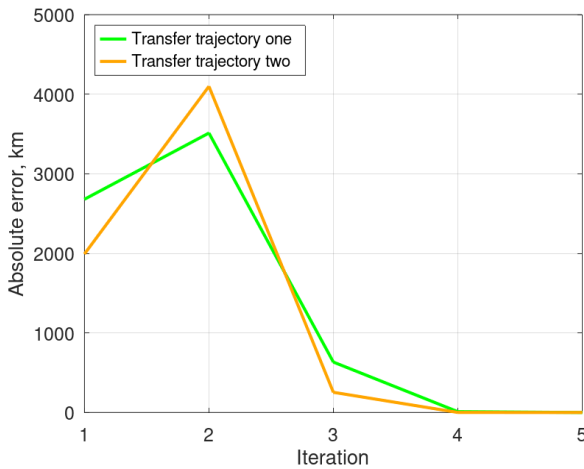


Fig. 5. Numerical solution convergence

Conclusion

The presented implementation of the Single Shooting Method is a prerequisite for performing more complex manoeuvres, including noncoplanar ones. In addition, the developed source code in GNU Octave might be used as a testbed for further project improvement. The **code** might be **downloaded** from link [7].

Multiple shooting and Finite differences are alternatives to the Single shooting method. These methods distribute nonlinearities and improve numerical stability.

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ОРБИТАЛЕН РАВНИНЕН ТРАНСФЕР КАТО ГРАНИЧНА ЗАДАЧА

К. Методиев

Резюме

В настоящата статия е демонстриран „Методът на стрелбата“ за проектиране на преходни равнинни траектории на движение на изкуствен спътник на Земята. Спътникът се движи в централно силово поле с отчитане на сплеснатостта на централното тяло (зонален коефициент J_2). По време на пресмятане на преходната траектория се изчисляват както вектора, така и преходната матрица на състоянието, за да се разбере как малки смущения в началната скорост отклоняват крайната точка на траекторията. За тази цел т. нар. „Трансфер на Хохман“ (промяна на височината) е използван за валидация. Числените резултати са представени графично и обсъдени изчерпателно.

ENSURING THE SAFETY OF A HELICOPTER WITH AN EXTERNAL FIRE EXTINGUISHING DEVICE FOR EXTINGUISHING FIRE IN EXTREME METEOROLOGICAL CONDITIONS IN FLIGHT

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Key words: *helicopter, external fire extinguishing device, flight, balance, fluctuations*

Abstract

Methods for stabilizing the external device have been investigated and proposed based on the study of the mechanism for the occurrence of oscillations of the external device and the mathematical description of the dynamics of movement of the "Helicopter–external fire extinguishing device" system, consisting of synchronizing the movement of the helicopter and the external device in flight and creating a rotational movement of the device around the vertical axis coinciding with the central cable for attachment to the helicopter.

Introduction

Over the past two decades, the role of aviation in combating forest fires has been increasing, as fires are becoming more numerous, threatening larger areas and settlements. Along with the use of specialised aircraft, the use of various types of helicopters and various types of external fire extinguishing devices of the “Bambi Bucket” type (“BB4453”, “BB5566”, “BBHL5000”, etc.), manufactured by SEI Industries LTD, Canada [1], is increasing. In the Republic of Bulgaria, one Mi-17 helicopter and several AS532AL Cougar helicopters [2] with an external fire extinguishing device “BB4453” with a capacity of 2,000 l are used in fire extinguishing operations. However, the prediction of the behaviour of the external fire extinguishing device during dynamic changes in helicopter flight parameters in the environment is carried out primarily based on the experience of individual flight crews. This is because the dynamics of the external fire-extinguishing device in the flight of a firefighting helicopter have not yet been studied in sufficient depth.

To increase the safety of helicopter firefighting with an external fire-extinguishing device, it is necessary to thoroughly study the characteristics of the external device's dynamic stability and their effect on helicopter behaviour in flight. Then, it is necessary to develop a set of methods, techniques, and modes of

using a helicopter with an external fire-extinguishing device for performing aviation activities in extreme conditions, such as extinguishing forest fires, especially fires located in mountainous areas with highly rugged terrain.

Main issues for the flight dynamics of a helicopter with an external fire-extinguishing device

One of the main problems is the identification of airflow disturbances taking into account the complex aerodynamics of the flow around the blades of the main propeller, fuselage, and tail rotor, as well as the identification of the characteristics of the aerodynamic flow around the external device. Another main problem is the determination of the boundaries of the dangerous zones for the deviation of the moving elements of the structure relative to the external fire-extinguishing device, for warning when approaching critical and emergency situations.

It is necessary to study the processes and develop effective methods for extinguishing the oscillations of the external device in flight. Methods for manoeuvring the helicopter with an external fire-extinguishing device must be developed and subsequently tested in aviation practice. It is necessary to study the process of "falling" of the helicopter in flight, in which the length of the central cable for attaching the external device to the helicopter changes almost instantly, which affects the oscillation period of the external fire-extinguishing device.

To study the dynamic motion of a helicopter with an external fire-extinguishing device, it is necessary to develop complex mathematical models. In the considered system "Helicopter-External Fire Extinguishing Device", in complex spatial motions, the degrees of freedom reach almost fifty. The Lagrange-2 method is not suitable for solving differential equations of motion of systems with many degrees of freedom and a set of non-potential forces, especially in the case of control systems with feedback-based regulation algorithms.

One of the most important issues for ensuring the safety of firefighting flights with helicopters and external devices is the creation of aviation simulators for training flight crews, in which the aerodynamics and flow dynamics of the helicopter and the external device can be reproduced as a dynamic system with many degrees of freedom, under non-potential forces and control effects.

Developing methods to dampen oscillations of an external device attached to a central cable on a helicopter in flight is very important because the helicopter has some of the most difficult and dangerous flight modes to control. These dangers associated with helicopter control in flight increase when the helicopter is considered as a single system with the fire-extinguishing device.

On the other hand, there are requirements in several international documents developed by international and national organisations [3–6] that require further research into the issues of formalising procedures for assessing aviation safety when performing helicopter flights with an external fire-extinguishing

device for extinguishing fires. The International Civil Aviation Organisation (ICAO) develops standards, regulations, procedures, and recommended practices on aviation safety, which are disseminated to aviation operators worldwide.

Aircraft flight safety assessment based on ICAO standards

ICAO Annex 19 contains comprehensive provisions applicable to safety management functions related to or in direct support of the safe operation of aircraft. It emphasises the importance of State safety management in several aviation areas [7]. The annex provides recommendations to complement the State (national) Safety Programme (SSP) and Safety Management System (SMS) frameworks. The annex also includes recommendations (provisions) for State monitoring and oversight of aviation safety (through specialised State bodies), as well as an obligation to collect, analyse, exchange and protect safety information.

Safety Management Standards and Recommended Practices are designed to assist States in managing aviation safety risks, in coordination with their service providers [8]. Given the increasing complexity of the global air transport system and its interconnected aviation activities required to ensure the safe operation of aircraft, safety management provisions support the continuous development of a proactive safety improvement strategy. The foundation of this proactive safety strategy is based on the development and implementation of a State Safety Programme (SSP) that systematically addresses safety risks, consistent with the implementation of safety management systems (SMS) by service providers.

ICAO guidance documents on the principles and concepts of safety management, the State Safety Programme (SSP) and the implementation of the safety management system are contained in the ICAO Safety Management Manual (SMM) (Doc 9859) [9]. To respond to the needs of the diverse aviation community implementing safety management and to new recommendations arising from the materials, discussions, and views expressed at the second High-Level Safety Conference held in 2015, a supplement to the 4th edition of the SMM has been developed.

The other related and applicable aviation safety document is the international standard ISO-8402:1994 [10]. It provides definitions and terms related to quality management and quality assurance, as well as tools and techniques for quality assurance and management.

The following definition is adopted in Doc 9858-AN/460: *“Flight safety is a state of the aviation system in which the risk of causing harm to property or personnel does not exceed an acceptable level”*.

From the analysis of the accepted concept of flight safety, it follows that *“risk is such a state with predictable (definable) possible harmful consequences for the elements of the system in the studied flight situations, provided that in the system under some threats a dangerous (or risky) random event R with negative*

consequences of the type of loss H_R may occur". The concept of risk assessment R is mathematically defined by the following formula [11]:

$$(1) \quad R = A_*(\omega_\xi | \mu_1, H_R, \Sigma_0),$$

where: A_* is an event with a criticality sign (*), separated from the set of possible events $A_* \in \{A_i\}$

ω_ξ is an elementary event with a randomness symbol;

μ_1 is an indicator of the randomness frequency, i.e. how often events of type A_* occur;

Σ_0 is a set of conditions that characterise the functioning of the aviation system, for example, "a helicopter with an external fire extinguishing device in flight to extinguish natural fires".

Research shows that formula (1) is universal for many types of air transport. It allows the level of aviation safety for the helicopter to be determined by the level of danger, which determines the significance (level) of the risk as the value of $\hat{R}$ - an integral function of the estimated amount of danger in the studied aviation system:

$$(2) \quad \hat{R} = \hat{f}(\mu_1, \bar{H}_R | \Sigma_0).$$

In this regard, it is important to establish the adequacy of aviation practice to the following recommendations:

- influence of the helicopter on the dynamics of swinging of the external fire extinguishing device as a pendulum [12]. It is known that if the complex aerodynamics of the flow around the external device are not taken into account, the influence of the helicopter is not significant, especially at small initial angles of deviation of the central cable of the device from the vertical position;

- the mutual influence of the dynamics of the two components of the connected system "Helicopter-external fire extinguishing device" without external critical disturbances is sufficiently reliably described as a conservative dynamic system without damping using the model of an ideal spherical joint [12];

- to assess the influence of the "failure" of the central cable attachment point of the external device on the magnitude of the device's oscillations, which will allow the crew to determine control modes when manoeuvring to extinguish the oscillations.

Of interest is the determination of the degree of influence of the movement of the point of attachment of the central cable to the helicopter on the studied system "Helicopter-external fire extinguishing device" and for assessing the possibilities for damping the oscillations of the external device.

Some practical methods and means for combating the longitudinal-transverse swing of the external device are known: reducing the flight speed; creating vertical and horizontal acceleration of the helicopter, i.e., changing the movement characteristics of the central cable attachment point. In this case, it is important to study and determine how the central cable attachment point of the external device should move to extinguish the oscillations of the external fire-extinguishing device as quickly as possible.

Damping of external fire extinguishing device oscillations in flight

Let us consider the dynamics of the behaviour of two absolutely rigid bodies connected by an ideal spherical joint (Fig. 1). In the diagram in Fig. 1, body No. 1 (m_1) is a supporting body, and body No. 2 (m_2) is located below body No. 1 (relative to the Earth), and we will call it a suspended body.

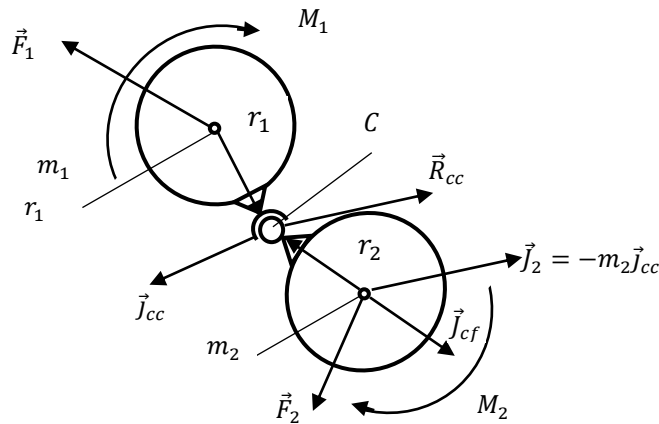


Fig. 1. Diagram of the interaction of two absolutely rigid bodies connected to each other by an ideal spherical joint

Since an ideal spherical joint connects the two bodies, the interaction between them can be described by only one force $-\vec{R}_{cc}$, applied at the joint. As a result, the equations of motion of the system of these two bodies can be written as follows, with the force $\vec{R}_{cc}$ represented as an external force for each of the bodies.

As aviation practice shows, the main tool for damping oscillations is improving helicopter control manoeuvres, the main manoeuvre being the movement of the attachment point to the position of the external device. Thus, the problems with damping oscillations are contained not in the dynamic system itself, but in the complex manoeuvres of the helicopter and external influences (wind gusts, rotation of the device, etc.).

It is known from theoretical mechanics that the dynamics of motion of a closed independent mechanical system with two degrees of freedom is nonlinear:

$$(3) \quad \frac{(F_1 + F_2)}{g} \ddot{x} + \frac{F_2}{g} a \ddot{\varphi} \cos \varphi - \frac{F_2}{g} a \dot{\varphi}^2 \sin \varphi = 0,$$

$$(4) \quad I_{cf} \ddot{\varphi} + \frac{F_2}{g} a \ddot{x} \cos \varphi = F_2 a \sin \varphi.$$

After some transformations and partial linearization, we obtain:

$$(5) \quad (F_1 + F_2) \ddot{x} + F_2 a \ddot{\varphi} - F_2 a \dot{\varphi}^2 \varphi = 0,$$

$$(6) \quad I_{cf} \ddot{\varphi} + \frac{F_2}{g} a \ddot{x} + F_2 a \varphi = 0.$$

The frequency of natural oscillations of the individual elements in antiphase around the centre of mass depends on the length of the central cable l_{cc} and the ratio of the masses m_1 and m_2 .

Maneuvering methods to suppress oscillations of the external fire-extinguishing device

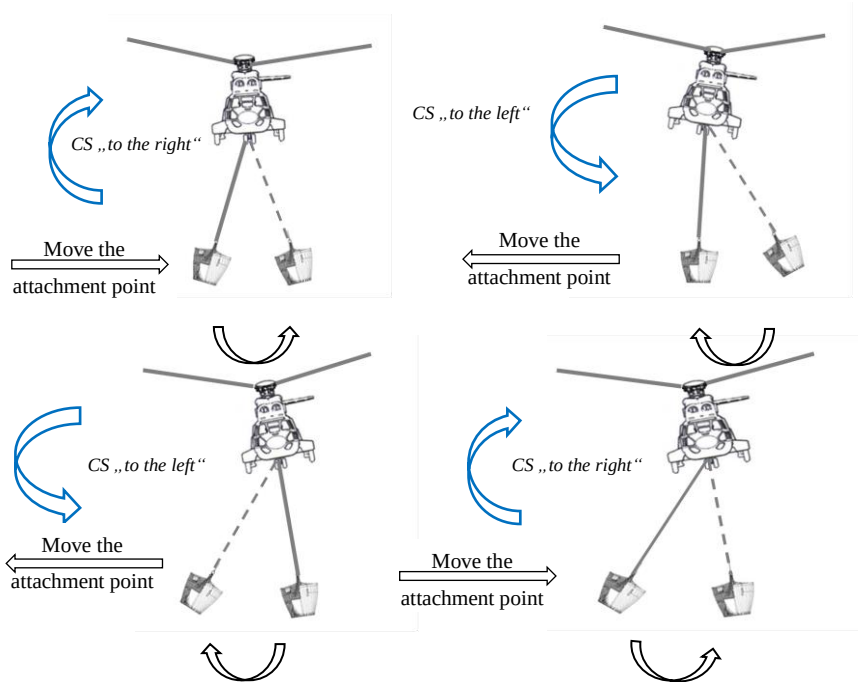


Fig. 2. Maneuvering scheme for extinguishing transverse oscillations of the external fire extinguishing device using the Cycle Stick

Several scientific studies [13–15] confirm that the “Helicopter–external fire extinguishing device” system is a conservative dynamic system without damping. The main method for damping the oscillations of the external device is to control the helicopter by moving the Cycle Stick (CS) to perform manoeuvres to “move” the attachment point of the central cable of the device to the helicopter in all phases of oscillations.

The most general and rational way to extinguish the lateral sway of the external device is (if possible) synchronisation of the movement of the helicopter and the external fire extinguishing device [16, 17], as shown in Fig. 2. For example, if the external device in the process of swaying has “moved” to the right with a sufficiently large amplitude and period of oscillation. The crew should create a right bank and glide, and in this way try to “catch up” with the device. With the next movement to the left, the next “catch up” can be done faster and easier.

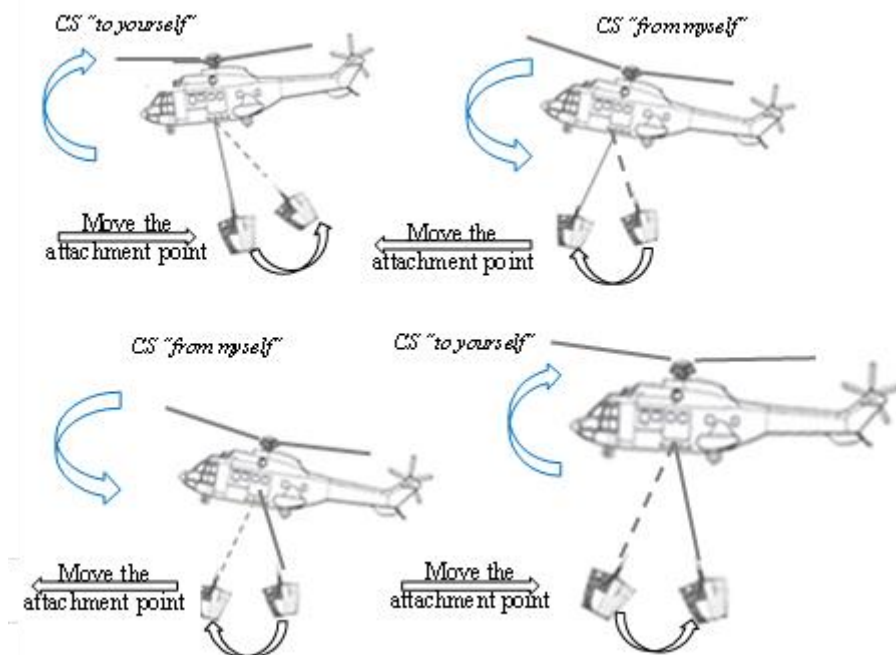


Fig. 3. Manoeuvring scheme for extinguishing longitudinal oscillations of the external fire extinguishing device

A similar method can be applied to eliminate the longitudinal sway of the external fire-extinguishing device, as shown in Fig. 3. The only difference is that the longitudinal oscillations of the external device are significantly more dangerous for the safe completion of the flight. This is due to the fact that in order to “calm down” the oscillations, it is necessary to apply multidirectional movements of the

helicopter control stick in the longitudinal direction, so that by changing the pitch angle $\vartheta_{,1}$ a normal (vertical) force can be created for the “Helicopter–external fire extinguishing device” system. However, these manoeuvres pose a potential danger of the main propeller blades approaching the tail propeller blades. It should be noted that such a method of extinguishing oscillations is significantly complex for the flight crews and requires significant professional experience and long-term training in helicopter piloting techniques.

Conclusion

To improve the algorithm for performing aviation procedures for extinguishing natural fires with a helicopter with an external fire-extinguishing device and to increase the productivity of activities, it is proposed to use a technology for working in the fire area in pairs. While one helicopter fills the “BB4453” with water, the other helicopter empties its external device in the fire area. Then the first helicopter flies to the fire area, and the other flies along the route to fill the “BB4453” with water, etc.

Based on the study of the mechanism for the occurrence of oscillations of the external device and the mathematical description of the dynamics of the movement of the “Helicopter-external fire extinguishing device” system, methods for stabilising the external device in flight have been proposed. This involves targeted control-unit movement to synchronise the helicopter and the external device in flight and create rotational motion around the vertical axis, coinciding with the central cable for attachment to the helicopter.

The possibility of extinguishing the oscillations of the external fire-extinguishing device by performing manoeuvres by the helicopter flight crew has been studied. Recommendations have been developed for eliminating the longitudinal and transverse oscillations of the external fire-extinguishing device in flight.

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ОСИГУРЯВАНЕ НА БЕЗОПАСНОСТ НА ХЕЛИКОПТЕР С ВЪНШНО ПОЖАРОГАСИТЕЛНО УСТРОЙСТВО ЗА ГАСЕНЕ НА ПОЖАР ПРИ ЕКСТРЕМАЛНИ МЕТЕОРОЛОГИЧНИ УСЛОВИЯ В ПОЛЕТ

Н. Загорски

Резюме

В настоящата статия са изследвани и са предложени способности за стабилизация на външното пожарогасително устройство на основата на изследване на механизма за възникване на колебания на външното устройство и на математическо описание на динамика на движение на системата „Хеликоптер–външно пожарогасително устройство“, състоящи се в синхронизация на движението на хеликоптера и на външното устройство в полет и създаване на въртеливо движение на устройството около вертикалната ос, съвпадаща с централния кабел за закачване към хеликоптера.

ADAPTIVE ALGORITHMS FOR ENERGY RESOURCE OPTIMIZATION IN ELECTRONIC COUNTERMEASURES TO UAV SWARM ATTACKS

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Keywords: Counter-UAV systems, drone swarms, electromagnetic compatibility, adaptive jamming, electronic countermeasures, AI-based security

Abstract

Coordinated swarm attacks with unmanned aerial vehicles (UAVs) require a reassessment of classical electronic countermeasure (ECM) approaches. Broadband jamming methods are limited by high energy consumption and insufficient spectral selectivity and controllability. These limitations motivate the development of algorithmic models in which counteraction is formulated as an optimisation problem rather than implemented as static emission. This paper presents an approach to countering coordinated drone swarm attacks against high-value assets based on an algorithm for adaptive control of electronic countermeasure (ECM) signals. A real-time decision-making model is proposed to optimise the energy usage of jamming systems by selectively impacting the command and navigation channels of the attacking platforms.

Introduction

The increasing availability and rapid technological evolution of unmanned aerial vehicles (UAVs) are reshaping the modern security paradigm. At present, one of the most significant threats is posed by so-called UAV swarms – groups of drones operating in a coordinated manner to saturate and overwhelm defence systems [4]. It has been established that the use of conventional broadband jamming in urban environments leads to unacceptable levels of electromagnetic pollution, potentially disrupting critical services such as 5G networks, GNSS navigation, and specialised security communications.

In this context, developing algorithms that optimise transmitted power while ensuring electromagnetic compatibility (EMC) becomes a priority research direction in contemporary security and defence technologies.

To address this challenge, the paper proposes an adaptive algorithm for controlling electronic countermeasure (ECM) signals based on EMC principles. Unlike conventional broadband jamming techniques, the proposed model applies dynamic target prioritisation and selective spectral suppression using notch

filtering. This approach enables effective disruption of UAV command and navigation links while minimising interference with critical communication infrastructure and legitimate radio networks within the protected area.

1. System Architecture of the Detection and Countermeasure Framework

For this study, a multi-layer counter-UAV architecture is considered, based on the “Antidrone” system concept. The framework is organised into three functionally interconnected layers [6]:

1. *Sensor Layer* – This layer employs multi-sensor data fusion using RF scanners and radar subsystems. Radar sensors provide kinematic parameters such as range, azimuth, and velocity, while RF scanners identify the frequency profile and control protocol characteristics of the detected UAVs.

2. *Processing and Decision Layer* – At this level, incoming sensor data are aggregated and processed, and the decision-making logic is executed. A dynamic threat priority score is computed for each detected target, and an appropriate countermeasure strategy is selected. Instead of activating all transmitters simultaneously, the system calculates the required transmission power and determines the spatial sectors that must be covered, thereby improving energy efficiency and spectral discipline.

3. *Execution Layer* – This layer consists of multiband transmitters with directional antennas and frequency-selective emission capability. Advanced techniques such as beamforming and notch filtering are applied, which are fundamental for maintaining electromagnetic compatibility (EMC) while performing effective electronic countermeasures.

The hierarchical organisation of the architecture, illustrated in Fig. 1, enables clear functional separation between detection, decision, and execution processes. Sensor data from radar and RF subsystems are consolidated within a central decision module, allowing parallel processing and reduced reaction time. This structure supports reliable delivery of software-defined transmission parameters to the antenna subsystems and enables rapid adaptive response under dynamic threat conditions.

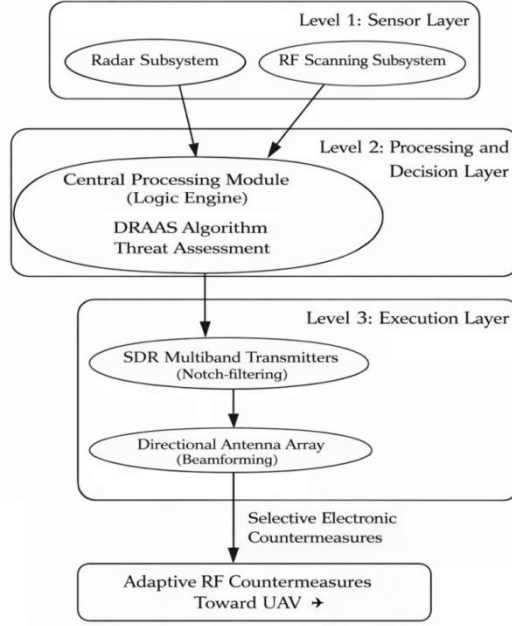


Fig. 1. Hierarchical architecture of the counter-UAV detection and electronic countermeasure system

2. Theoretical Model of the Adaptive Control Algorithm

The study examines the operation of the DRAAS (Dynamic Resource Allocation Anti-Swarm) algorithm, designed to transform a static jamming system into a dynamic, adaptive countermeasure unit. The operational logic is structured as a closed-loop adaptive process consisting of sequential evaluation, selective action, and feedback-based verification.

2.1. Algorithmic Logic and Threat Prioritisation

At the core of the intelligent control mechanism lies a closed-loop decision-support cycle whose primary function is the accurate assessment and prioritisation of detected targets. For each UAV within the swarm, the algorithm computes a dynamic threat coefficient (T_q) based on a weighted combination of key parameters:

$$(1) \quad T_q = w_1 \cdot \frac{V_{app}}{D} + w_2 \cdot S_{int} ,$$

approach velocity V_{app} , distance to the protected perimeter D , and received signal intensity S_{int} (serving as an indicator of command-link strength). By applying configurable weighting factors w_1 , w_2 , the system can automatically prioritise

highly dynamic and high-risk targets – for example, assigning greater weight to rapidly approaching objects. As a result, maximum energy resources are directed toward the most critical threats (those with the highest T_q), while lower-risk targets remain under secondary monitoring with reduced countermeasure intensity.

The logical sequence of the algorithm unfolds in three main phases:

1. *Spectral Analysis Phase* – Immediately after detection, the system performs rapid spectrum scanning to identify active legitimate frequencies within the protected area. Based on this scan, protected spectral regions (guard bands) are defined to prevent interference with authorised communications.

2. *Execution Phase* – Using the computed threat coefficient T_q , the algorithm activates selective transmission by combining frequency-domain notch filtering with spatially selective beamforming. Countermeasure energy is therefore concentrated only where and when it is required.

3. *Verification Phase* – RF sensors continuously evaluate the target response in real time (failsafe-state monitoring). Upon confirmation of successful neutralisation or link disruption, transmission resources are automatically reallocated to the next highest-priority target within the swarm [1]. This feedback loop ensures efficient resource reuse and prevents unnecessary prolonged emission.

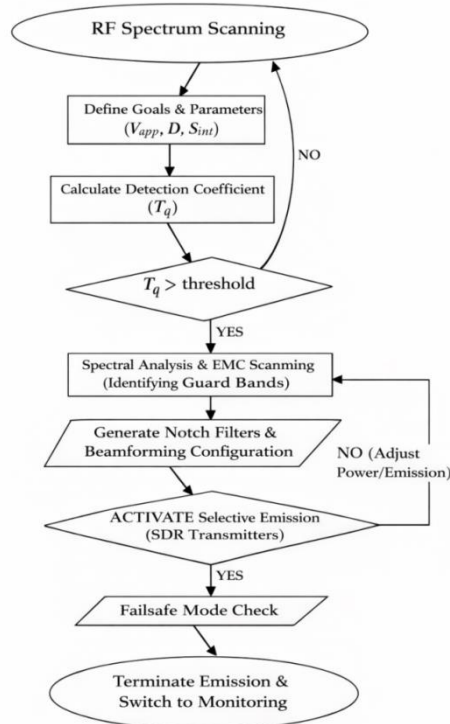


Fig. 2. Adaptive decision-making cycle of the DRAAS algorithm

The graphical representation of the algorithm in Fig. 2 illustrates the dynamic real-time threat-processing cycle. The system operates in a continuous monitoring mode and transitions to an active emission phase only when the critical threshold of the threat coefficient T_q is exceeded. A key element of the algorithmic logic is the introduction of an intermediate spectral analysis stage that precedes signal transmission. This verification step ensures that countermeasures are not initiated before protective guard bands for authorised communications have been properly defined. Such a closed-loop feedback mechanism enables precise adjustment of the countermeasure effect until complete target neutralisation is achieved, while minimising the risk of software conflicts and unnecessary energy allocation within the system.

2.2. Frequency-Selective Isolation Algorithm (EMC-Notch Method)

The primary challenge in countering UAV threats is not merely signal suppression itself, but the prevention of electromagnetic degradation affecting legitimate communication systems operating within the same spectrum – including Wi-Fi networks, Bluetooth devices, cellular infrastructure, and specialised operational radio services.

To achieve full electromagnetic compatibility (EMC), the proposed approach applies a form of “surgical” jamming. Instead of emitting conventional wideband noise across the entire band, the algorithm adaptively synthesises spectral notches around authorised signals. This enables dynamic spectral isolation, allowing security and operational communications to remain functional while UAV command-and-control links are selectively disrupted through digitally synthesised interference generated in real time [2].

The process is implemented in four principal stages:

1. *Spectral Monitoring and Identification* – The RF scanner performs continuous real-time spectrum monitoring. It reports active legitimate frequencies within the protected area (for example, a local Wi-Fi channel centre frequency). These signals are classified as protected spectrum users.

2. *Dynamic Notch Filter Computation* – The algorithm calculates protective guard bands with adaptive bandwidth around each identified legitimate signal. The guard band width Δf is selected to ensure sufficient isolation margins and to eliminate the risk of harmful interference [7].

3. *Adaptive Spectrum Shaping* – The transmitter generates controlled broadband interference across the target band (for example, within the 2.4 GHz range), while digitally carving out spectral notches at the frequencies reserved for legitimate communications. This produces a shaped emission spectrum that preserves authorised channels while suppressing hostile control links.

4. *Dynamic Spectrum Tracking* – The system performs high-speed continuous monitoring to detect frequency-hopping behaviour and other rapid spectral changes. When such shifts are detected, the notch filters are repositioned in near real time, ensuring that protected spectral windows continuously follow legitimate signals regardless of their frequency agility.

The effect of the proposed algorithm on the radio-frequency spectrum is illustrated in Fig. 3.

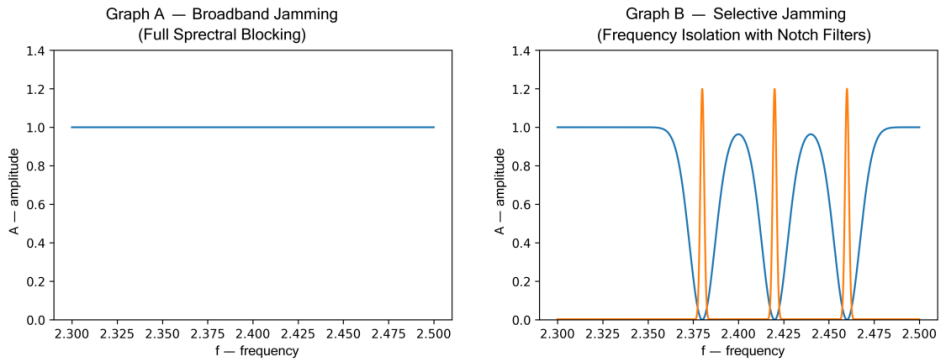


Fig. 3. Comparative spectral diagrams of radio-frequency impact

The visual comparison of the energy spectrum in Fig. 3 demonstrates the practical realisation of the frequency-isolation concept. Under conventional broadband jamming (Graph A), full suppression across the operating band is observed. In contrast, the adaptive model (Graph B) clearly reveals software-synthesised notch filters within the emission spectrum. These precisely defined spectral notches allow legitimate signals within the protected area to preserve their integrity and amplitude, even under active electronic countermeasure conditions. The presented diagrams confirm the algorithm's ability to concentrate energy resources exclusively on UAV command-and-control links while maintaining reliable protective guard bands for critical infrastructure communications.

3. Comparative Analysis of Operational Effectiveness and Energy Characteristics

The effectiveness of the proposed adaptive model is evaluated through comparison with conventional broadband electronic countermeasure techniques. The comparative assessment focuses on electromagnetic compatibility, spectral purity, energy efficiency, operational resilience under swarm attack conditions, and response autonomy. The results of the theoretical and architectural analysis are summarised in Table 1.

Table 1. Comparative Analysis of Key Performance Indicators

Performance Indicator	Broadband Jamming	Adaptive DRAAS Model	Contribution
Electromagnetic Compatibility (EMC)	Low – full disruption of Wi-Fi, cellular, and operational radio services is likely.	High – notch filtering enables isolation of legitimate signals.	Preservation of more than 85% of protected network capacity.
Spectral Purity	Low – generates wideband electromagnetic noise across the operating range.	High – selective spectral suppression using software-defined radio techniques.	Minimisation of frequency collisions in dense electromagnetic environments.
Energy Efficiency	Constant maximum power consumption (P_{max}), with increased thermal stress and reduced hardware longevity.	Dynamic power control based on the computed threat coefficient T_q .	Estimated energy savings of approximately 40–50% during sustained operation.
Resilience Under Swarm Attack Conditions	Risk of overload due to lack of target prioritisation.	Automatic resource focusing on high-priority or leader nodes within the swarm.	Improved neutralisation capability against multiple simultaneous targets.
Response Autonomy	Manual operator configuration of frequency ranges and emission parameters.	Cognitive adaptation to real-time spectral conditions with self-adjusting logic.	Reduction of response time to the millisecond scale.

The comparison indicates that the proposed algorithm achieves a practical balance between countermeasure effectiveness and infrastructure preservation. Reduced energy consumption directly improves hardware reliability and supports longer autonomous operating cycles, which is critical for continuous protection scenarios.

4. Prospects for Artificial Intelligence Integration for Autonomous Cognitive Control

In the context of rapidly evolving autonomous UAV technologies, the future development of countermeasure systems is closely linked to the integration of cognitive modules based on artificial intelligence (AI) and machine learning (ML). The incorporation of such methods enables a transition from operator-defined response scenarios toward fully autonomous, real-time adaptive protection. Three principal development directions can be identified.

- **Autonomous Signal Signature Recognition (RF Fingerprinting)**

Instead of relying solely on static libraries of known frequency profiles and protocols, AI-based models enable deep signal decomposition and feature extraction. By applying neural network architectures, the system can identify previously unknown or modified control protocols based on micro-anomalies and fine-grained spectral features. This capability supports detection of zero-day or

obfuscated command links that may not be recognised by conventional RF scanning techniques [8].

- **Predictive Energy Resource Management**

Predictive analytics models enable forward-looking allocation of countermeasure energy resources during swarm attack scenarios. An AI module can estimate likely trajectories and behavioural patterns of UAV groups and pre-position directional countermeasure beams accordingly. Through predictive beam steering and timing optimisation, countermeasure energy can be concentrated within a narrow spatial sector milliseconds before a target enters a critical zone. This approach reduces total emission time and prevents unnecessary load on high-power amplifier stages.

- **Self-Adaptive Electromagnetic Compatibility Control (Self-Healing EMC)**

One of the most significant advantages of AI integration is the ability to construct and continuously update dynamic spectral maps of the protected environment. The system can autonomously identify and classify legitimate communication signals – including next-generation wireless and broadband services – and maintain real-time protected-frequency whitelists. This reduces operator dependency and minimises configuration errors in notch filter placement. As a result, stable electromagnetic compatibility can be maintained even in rapidly changing and congested spectral conditions [5].

Conclusion

The results of the study demonstrate a substantial improvement in counter-UAV protection effectiveness under high-density aerial threat scenarios. The proposed algorithm replaces static broadband jamming with a dynamic, resource-optimised model of selective electronic countermeasures, directly addressing the key practical constraint in modern systems – the trade-off between required transmission power and electromagnetic compatibility [3].

The developed DRAAS algorithm introduces a formalised framework for threat prioritisation, frequency-selective spectral isolation, and a closed-loop verification process with real-time feedback. The combined application of these mechanisms leads to measurable gains in energy efficiency, reduced spectral interference, and increased resilience against large-scale swarm attacks. The integration of optimisation-driven control logic, EMC-oriented spectral shaping, and adaptive transmission management forms a unified architectural basis for algorithmically controlled electronic countermeasure systems.

Future extension through AI-based modules for signal signature recognition, predictive resource allocation, and autonomous EMC adaptation outlines a transition toward cognitive counter-UAV platforms with a high degree of operational autonomy. This positions the proposed approach as a sustainable technological foundation for next-generation intelligent electronic protection systems based on balanced active intervention and controlled spectral impact.

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АЛГОРИТМИ ЗА АДАПТИВНО УПРАВЛЕНИЕ НА ЕНЕРГИЙНИЯ РЕСУРС ПРИ РАДИОЕЛЕКТРОННО ПРОТИВОДЕЙСТВИЕ НА ГРУПОВИ АТАКИ ОТ БЛА

Ф. Илиев, Г. Сотиров

Резюме

Координираните атаки с рояци БЛА налагат преосмисляне на класическите подходи за радиоелектронно противодействие. Основните ограничения на широкополосните методи за заглушаване се изразяват не само във високата енергийна консумация, но и в липсата на спектрална селективност и контролируемост на въздействието. Това налага разработването на алгоритмични модели, при които противодействието се реализира като оптимизационен процес, а не като статично излъчване. В статията се изследва проблемът с нарастващата заплаха от координирани атаки с дроне (рояци) срещу обекти с висока степен на значимост. Фокусът е върху разработването на алгоритъм за адаптивно управление на сигналите за радиоелектронно противодействие. Предлага се модел за вземане на решения в реално време, който оптимизира енергийния ресурс на системите за заглушаване чрез селективно въздействие върху каналите за управление и навигация на атакуващите платформи.

INVESTIGATION OF THE CORROSION BEHAVIOR OF B95 (AA7075) ALUMINUM ALLOY REINFORCED WITH NANODIAMOND AND TUNGSTEN AFTER EXPOSURE TO OUTER SPACE

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Keywords: aluminium alloy 7075, corrosion-resistant alloy, corrosion behaviour of alloys

Abstract

This study investigates the corrosion behaviour of aluminium alloy AA7075 (B95), reinforced with 0.1 wt.% nanodiamond powder and tungsten. Two sets of alloy samples were stored for 28 months under different conditions: "reference" – under natural terrestrial conditions, and "space" – in outer space, mounted on the International Space Station (ISS). The corrosion resistance of both sample types was evaluated using gravimetric and electrochemical methods in a 3.5% NaCl solution. Despite similar average corrosion rates (~0.06 mm/year), significant differences in surface corrosion morphology were observed. The „space” samples exhibited deeper pitting and localised corrosion along specific microstructural phases, whereas the „reference” samples demonstrated more uniform surface degradation. Electrochemical tests confirmed enhanced corrosion resistance of the „space” alloy, showing a threefold reduction in corrosion current density and a more positive corrosion potential compared to the "reference" samples. This behaviour is attributed to microstructural changes induced by prolonged exposure to outer space, including the formation of a denser protective Al_2O_3 layer and the migration of alloying elements (Zn, Cu).

Introduction

The safe operation of high-strength aluminium alloys, which are widely used as primary structural materials in the aerospace, marine, and automotive industries, requires accurate data on their corrosion resistance under various climatic conditions and in aggressive environments. Maintaining the mechanical properties of aluminium alloys while enhancing structural weight efficiency without compromising strength and technological performance is a strategic priority in the development of materials intended for extreme environments, particularly for applications in outer space. To improve mechanical performance,

the high-strength aluminium alloy B95 (AA7075) [1–5] was modified with nanodiamond powder [6] and tungsten.

The 7000-series aluminium alloys possess complex chemical compositions. The primary role of alloying elements is to enhance mechanical properties; however, their effects on corrosion resistance vary significantly depending on the type and concentration of the added elements. Zinc has a minimal effect on corrosion resistance, but in 7000-series alloys, its presence in combination with other elements may accelerate corrosion processes [7]. Copper reduces corrosion resistance in high-strength aluminium alloys [8]. The influence of magnesium on corrosion resistance is complex and not exclusively positive [9], whereas manganese typically exerts a slight beneficial effect [10]. Silicon is not a principal alloying element in AA7075, but when present, it may exert a neutral or slightly negative effect on corrosion resistance [11]. Iron decreases corrosion resistance and should be kept at low concentrations to ensure optimal performance in corrosive environments [8].

In various engineering applications, preliminary data on the corrosion behaviour of aluminium alloys are essential for material selection and design. The objective of this study is to perform a comparative analysis of the corrosion behaviour of aluminium alloy AA7075 (B95), modified with ultrafine diamond powder and tungsten, after 28 months of exposure to two different environments: natural terrestrial conditions and outer space.

Materials and Methods

Materials

A material based on the high-strength aluminium alloy AA7075, modified with 0.1 wt.% ultradispersed diamond powder (UDDP) with particle sizes ranging from 4 to 7 nm and tungsten, was investigated (Table 1). The initial raw materials, including aluminium powder, alloying elements, UDDP, and tungsten, were homogenised using a planetary ball mill. The resulting mixture was melted and then cast. For the purposes of the study, cylindrical specimens with dimensions of $\varnothing$ 6 mm and a height of 6 mm were prepared. The specimens were stored for 28 months under two different environmental conditions. One set, designated as “reference” samples (R), was kept under natural terrestrial conditions. In contrast, another set, designated as “space” samples (S), was mounted on the exterior of the Russian module “Zvezda” aboard the International Space Station (ISS) [12]. In space, temperature fluctuated within a broad operational range from -120°C to $+150^{\circ}\text{C}$ every two hours, depending on the ISS's position. Radiation measurements were conducted using the Radiation Risk Dosimeter Radiometer (R3D)-R2 solid-state detector [13], which was also installed on the exterior of the ISS. The accumulated radiation dose was estimated to be approximately 425 kGy [13–14].

Table 1. Chemical composition of alloy B95

Al [wt. %]	Zn [wt. %]	Mg [wt. %]	Cu [wt. %]	Mn [wt. %]	Cr [wt. %]	Fe [wt. %]	Si [wt. %]	Ti [wt. %]	W+UDDP [wt. %]
86.3-91	5-7	1.8-2.8	1.4-2	0.2-0.6	0.1-0.025	to 0.5	to 0.5	to 0.1	to 0.1

The microstructure of both types of samples (R and S) consists of an Al α -solid solution, intermetallic compounds, and several types of structural phases exhibiting Chinese script-like morphology [15]. After exposure to open space, the alloy's microstructure exhibited coarsening. The average size of the Al grains increased from 30.4 nm (before exposure) to 36.8 nm (after exposure). Additionally, in the intermetallic MgZn₂ phase present in the “reference” sample, isomorphic substitution of zinc with copper cations occurred, leading to the transformation of this phase into Mg(Zn_{1.98}Cu_{0.02}), accompanied by an increase in particle size from 15.1 nm to 22 nm [16].

A HIROX 5500 scanning electron microscope (SEM, HIROX Europe, Limonest, France) equipped with a BRUKER EXDS system (BRUKER Co., Berlin, Germany) was used to observe the morphology of the corroded surface after the uniform corrosion tests and electrochemical studies.

Corrosion test methods

A: Uniform Corrosion Test

Uniform corrosion tests were performed by continuously immersing “reference” and “space” samples in 3.5% NaCl for 240 hours at 25°C in a laboratory thermostat. Before testing, the samples were degreased in acetone and treated in dilute HNO₃. The samples were weighed on an analytical balance (KERN ABS-N_ABJ-NM). The corrosion rate (CR) was calculated in mm per year according to ASTM G31 [17]. All CR results obtained are averages of three parallel tests. After the corrosion test, the samples were repeatedly washed with warm distilled water, dried, and analysed by scanning electron microscopy (SEM) and energy-dispersive X-ray spectroscopy (XEDS).

B: Linear Polarisation Test

The electrochemical tests were carried out in the 3.5 wt% NaCl solution in a 3-electrode cell at room temperature. The working electrodes, with a surface area of 1.0 cm², were made from the investigated samples. A silver chloride (Ag/AgCl) electrode and a platinum (Pt) plate were used as reference and counter electrodes, respectively. The samples were cleaned with 800-grit sandpaper, degreased with alcohol, treated with dilute HNO₃, and dried before testing.

Linear polarisation was measured vs stable E_{ocp} over a potential range of ± 10 mV, at a scan rate of 0.1 mV/s. Potentiodynamic curves were recorded at 1 mV/s potential scan rate, starting at 250 mV negative to the stable E_{ocp} .

The electrochemical tests were performed using an Autolab galvanostat-potentiostat model PGSTAT 204 and computer software NOVA 2.1. Corrosion current density (j_{corr}) and corrosion potential (E_{corr}) were obtained from the polarisation curves.

Results and Discussions

The results of the uniform corrosion tests of the “reference” and “space” samples are presented in Fig. 1, Fig. 2 and Fig. 3. The calculated average corrosion rate of the “reference” samples is 0.0600 mm/y, which is close to the average corrosion rate of the “space” samples – 0.0573 mm/y.

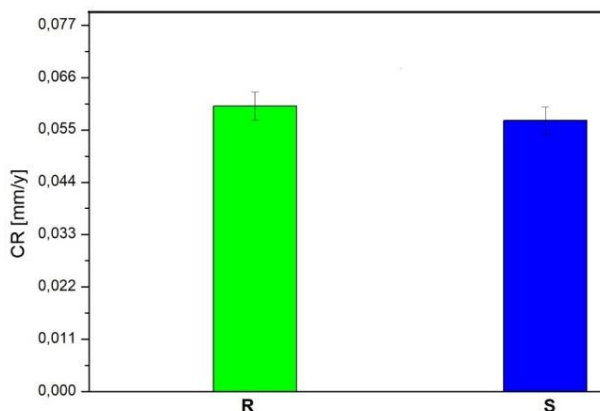


Fig. 1. Average corrosion rate of “reference” (R) and “space” (S) samples

Despite the similar average corrosion rates of the two types of samples (R and S) in 3.5% NaCl solution, the nature of the corrosion damage differs, as evidenced by the surface morphology images. The “reference” sample exhibited surface corrosion characterized by areas with scale formation and shallow cracks (Fig. 2a, b), whereas the “space” sample showed wider corrosion ditches and deep pits (Fig. 3a). Energy Dispersive Spectroscopy (EDS) analysis revealed a decreased concentration of aluminum in the ditches and pits, accompanied by elevated levels of copper, manganese, and oxygen within these areas (Fig. 2d and Fig. 3d). The observed differences in corrosion behavior between the two types of samples are attributed to structural changes in the alloy induced by exposure to the outer space environment. Radiation exposure led to the formation of defects in the crystal lattice, facilitating elemental migration, particularly of Zn and Cu [16]. Due to temperature fluctuations, these migration processes were accompanied by interdiffusion, resulting in the segregation of aluminium and magnesium oxides,

which localised on the surface of the samples [16]. This led to the formation of partially protected regions with limited access to oxygen and aggressive ions from the corrosive medium, thereby promoting corrosion development along the observed Chinese script-like morphology phases (Fig. 3b).

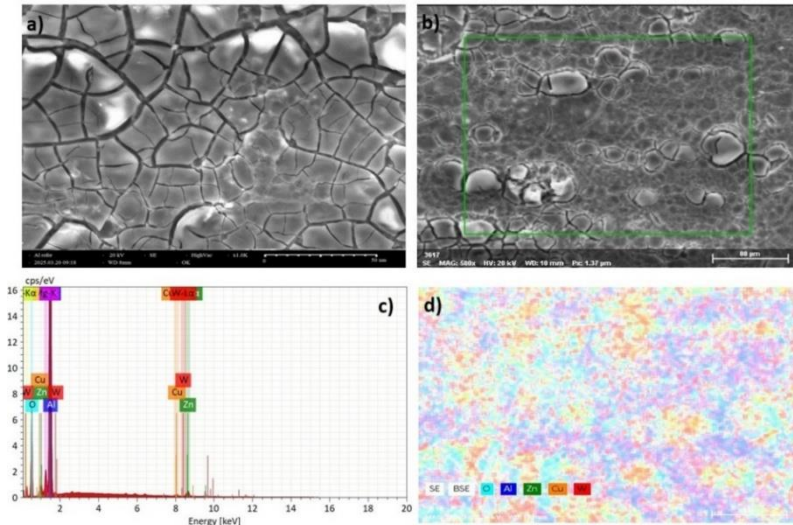


Fig. 2. Morphology and elemental composition of the surface of the “reference” sample after uniform corrosion test. a) SEM image of the corroded surface, b) Analysed area, c) EDS spectrum, d) EDS map of the analysed area

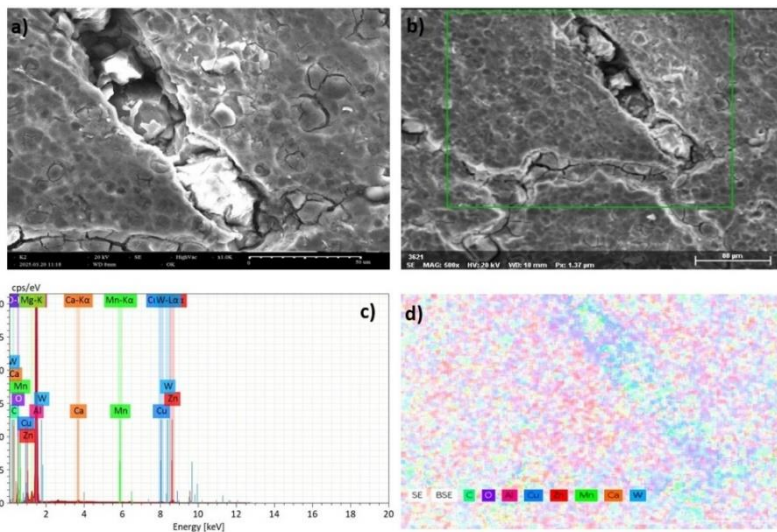


Fig. 3. Morphology and elemental composition of the surface of the “space” sample after uniform corrosion test. a) SEM image of the corroded surface, b) Analysed area, c) EDS spectrum, d) EDS map of the analysed area

Fig. 4 displays the electrochemical behaviour of both sample types (R and S), which shows notable similarities. The linear polarisation curves of both the “reference” and “space” samples (Fig. 4) are dominated by the anodic region, corresponding to the dissolution of the aluminium matrix. The anodic curves exhibit multiple fluctuations, likely caused by the formation of a thin hydrated aluminium oxide layer, $\text{AlO}(\text{OH})$, during the test [18]. Due to the inhibited anodic dissolution by the denser Al_2O_3 layer, the fluctuating anodic region in the “space” sample is shorter, ranging from -0.500 V to $+0.600$ V (Fig. 4), compared to the “reference” sample. It was established that the $\text{AlO}(\text{OH})$ layer predominantly forms in aluminium alloys exposed to terrestrial conditions, while exposure to space conditions favours the formation of a denser, protective Al_2O_3 layer, with an $\text{Al}_2\text{O}_3\text{:AlO}(\text{OH})$ ratio of approximately 3:1 [16].

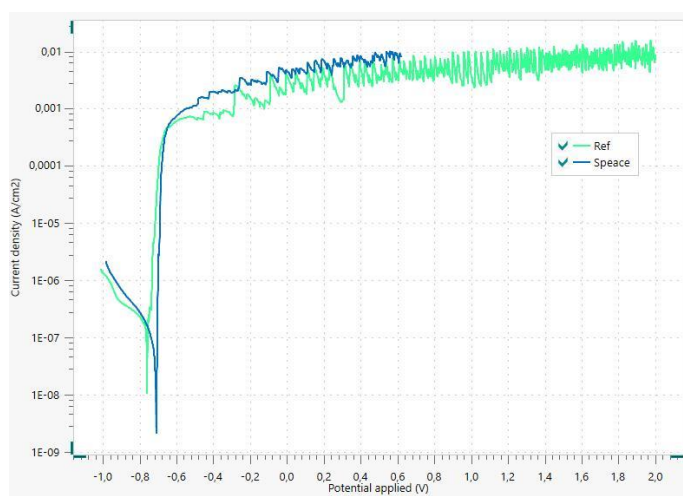


Fig. 4. Linear polarisation curves of “reference” (R) and “space” (S) samples in 3.5 % NaCl solution

Table 2. Electrochemical parameters

Sample	i_{corr} [A]	J_{corr} [A/cm ²]	E_{corr} [V]	CR [mm/y]
“Reference” sample (R)	1.696E-07	6.7848E-08	-0.759	0.0022
“Space” sample (S)	3.064E-08	2.188E-08	-0.724	0.0007

During the application of electrochemical methods for corrosion testing, real-time data on key electrochemical parameters were obtained. The shape of the polarisation curves provides both qualitative and quantitative information about the

development of the corrosion process, from the moment the specimen is immersed in the electrolyte until the end of the test [19].

The electrochemical parameters recorded during the corrosion tests indicate that the “space” sample exhibits superior anodic protection compared to the “reference” sample. This is evidenced by the corrosion current density (i_{corr}) of sample S, which is three times lower than that of R (Table 2). Furthermore, the corrosion potential (E_{corr}) of S is more positive than that of R. The corrosion rate of the “reference” sample obtained from electrochemical testing was 0.0022 mm/y, which is higher than the rate for the “space” sample (0.0007 mm/y, Table 2). This difference is attributed to the rapid dissolution of the loosely bound $\text{AlO}(\text{OH})$ layer. In contrast, the presence of a dense Al_2O_3 layer on the surface of the aluminium matrix in the “space” samples limits the contact with the 3.5% NaCl electrolyte and slows down the corrosion process [16, 17].

Corrosion in both sample types (R and S) primarily initiates at sites where electrochemically active intermetallic cathodic phases such as MgZn_2 and $\text{Mg}(\text{Zn}_{1.98}\text{Cu}_{0.02})$ are localised within the anodic aluminium matrix.

Fig. 5 and Fig. 6 present SEM images of the corroded surfaces of the “reference” and “space” samples following the linear polarisation test. The “reference” sample shows corrosion distributed across the entire surface (Fig. 5a). In contrast, in the “space” sample, corrosion is primarily confined to the Chinese script-like morphology phases (Fig. 6a). Fig. 5d and Fig. 6d clearly show the Zn- and Cu-rich areas where corrosion has occurred.

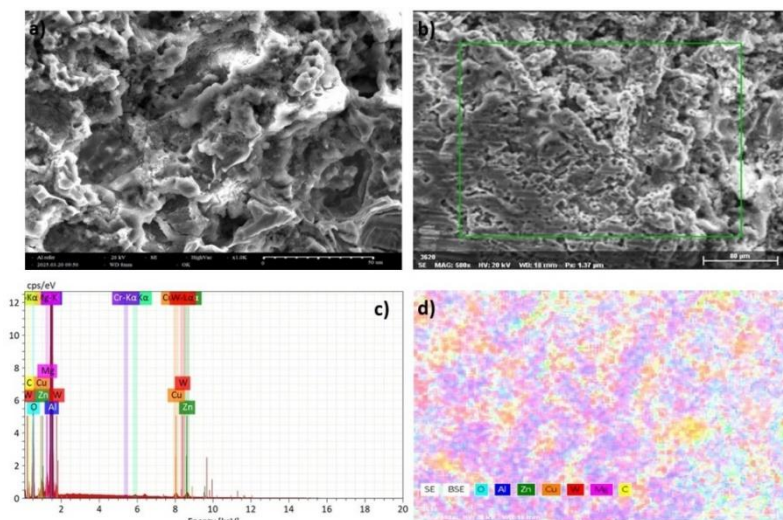


Fig. 5. Morphology and elemental composition of the „reference” sample (R) after linear polarisation. a) SEM image of the corroded surface, b) Analysed area, c) EDS spectrum, d) EDS map of the analysed area

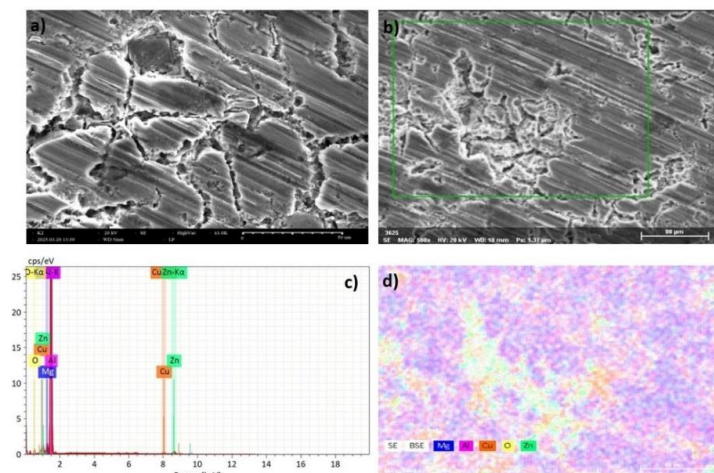


Fig. 6. Morphology and elemental composition of the “space” sample (S) after linear polarisation. a) SEM image of the corroded surface, b) Analysed area, c) EDS spectrum, d) EDS map of the analysed area

Conclusion

The average corrosion rate of AA7075 alloy samples modified with 0.1 wt.% ultrafine diamond powder and tungsten, which were exposed to terrestrial conditions for 28 months, is 0.060 mm/y, while those exposed to outer space conditions exhibit a rate of 0.057 mm/y. Surface corrosion developed on the “reference” samples, manifested in areas with scales and shallow cracks. In the “space” samples, wider corrosion ditches and pits were observed.

Electrochemical corrosion tests confirmed the results obtained from the general corrosion test and demonstrated better corrosion resistance of the “space” samples. The real-time corrosion rate of the “space” samples is three times lower than that of the “reference” samples, which is attributed to changes in the alloy’s microstructure and the migration of Zn and Cu elements during exposure in open space.

These findings suggest that exposure to outer space can beneficially alter the corrosion resistance of advanced aluminium-based composites used in aerospace applications.

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ИЗСЛЕДВАНЕ НА КОРОЗИОННОТО ПОВЕДЕНИЕ НА АЛУМИНИЕВА СПЛАВ В95 (7075) УЯКЧЕНА С НАНОДИАМАНТ И ВОЛФРАМ СЛЕД ПРЕСТОЙ В ОТКРИТИЯ КОСМОС

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Х. Спасова, А. Митева*

Резюме

Това проучване изследва корозионното поведение на алуминиева сплав AA7075 (B95), подсилена с 0,1 wt.% нанодиамант на прах и волфрам. Два комплекта образци от сплавта бяха съхранявани 28 месеца при различни условия: “референтни” – при естествени земни условия и “космически” – в открития космос, монтирани на борда на Международната космическа станция (МКС). Устойчивостта на корозия на двата типа образци беше оценена чрез гравиметрични и електрохимични тестове в 3,5% разтвор на NaCl. Въпреки сходните средни скорости на корозия (~ 0,06 mm/y), се наблюдават значителни разлики в морфологията на корозиралата повърхност. „Космическите“ образци показват по-дълбоки питинги и локализирана корозия, по специфични микроструктурни фази, докато “референтните” образци показват по-равномерно разграждане на повърхността. Електрохимичните тестове потвърдиха повишена устойчивост на корозия в изложената в космоса сплав, с плътност на корозионния ток три пъти по-ниска и по-положителен корозионен потенциал от този на “референтните” образци. Това поведение се дължи на индуцирани от престоя в открития космос микроструктурни промени на сплавта, включително образуването на по-плътен защитен слой Al_2O_3 и миграция на елементи (Zn, Cu).

HYBRID INTELLIGENT MODELLING OF ATMOSPHERIC POLLUTION FROM EARTH OBSERVATION DATA: A CRITICAL REVIEW OF DIGITAL TWINS, NEURAL SURROGATES AND GROUNDED LLM INTERFACES

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Key words: *Earth Observation, Atmospheric Pollution, Hybrid Modelling, Earth System Digital Twins, Neural Surrogates, Symbolic Regression, Uncertainty Quantification, Foundation Models, Grounded LLMs, Copernicus Observa AI*

Abstract

Atmospheric processes governing air pollution are inherently nonlinear, multi-scale, and characterised by substantial uncertainties arising from emissions, meteorology, chemical transformations, and sensor noise. This critical narrative review synthesises contemporary intelligent modelling paradigms for atmospheric pollution analysis using satellite (Sentinel-5P TROPOMI, Sentinel-3) and ground-based observations, identifying the operational role of each method family and their integration in a unified hybrid architecture. Building on our SES-2025 review [1], we synthesise individual method families into a modular five-layer pipeline. The framework delivers physical consistency via Earth System Digital Twins, predictive power via neural and Extreme Learning Machine surrogates, interpretability via symbolic regression, calibrated uncertainty via Monte Carlo ensembles, and natural-language accessibility via grounded LLM interfaces. A benchmarking strategy targeting Balkan-region NO₂ and PM_{2.5} episodes is outlined. The novelty lies in synthesising the complementary roles of these methods within an auditable modular architecture, with explicit separation between quantitative modelling backends and LLM-based interaction layers.

1. Introduction

Atmospheric composition and pollution dynamics constitute one of the most pressing environmental and public-health challenges of the Anthropocene. Accurate, timely, and uncertainty-aware modelling is indispensable for air-quality forecasting, source apportionment, population exposure assessment, health-impact studies, and evidence-based policy design at urban, regional, and continental scales [2, 3]. The Copernicus programme delivers petabyte-scale, heterogeneous, multi-temporal datasets, most notably from Sentinel-5 Precursor (TROPOMI) with daily global observations of NO₂, CO, SO₂, HCHO, tropospheric ozone, and aerosol optical depth (AOD); and Sentinel-3 SLSTR for fire radiative power and

smoke plume tracking. Extracting physically consistent, actionable intelligence from these streams demands methods that transcend traditional numerical weather prediction or chemical transport models (CTMs) alone. Physics-based CTMs remain essential for process understanding and long-term projections. Yet, they are computationally expensive and subject to structural uncertainties in emission inventories, boundary conditions, and sub-grid parameterisations. Data-driven and intelligent methods machine learning, deep learning, symbolic regression, uncertainty quantification, and, more recently, foundation models and LLM interfaces offer complementary strengths in speed, downscaling, pattern recognition, and accessibility.

2. Review Methodology

This work constitutes a critical narrative review and conceptual framework paper. Literature was identified through searches of Scopus, Web of Science, IEEE Xplore, ScienceDirect, and arXiv (2018–2026). Inclusion criteria: peer-reviewed publications or accepted conference papers on method families in atmospheric remote sensing or pollution modelling; preprints only for systems accepted at major venues (ICCV, Nature) or with official institutional documentation. Of approximately 85 sources reviewed, 30 are cited. Method families were categorised thematically: physics-based backbones (ESDTs, CTMs, system dynamics), ML surrogates (NN, ELM), uncertainty and explainability (Monte Carlo, Bayesian networks, symbolic regression), foundation and multimodal models, LLM/RAG interfaces, and complementary nonlinear methods (phase-space reconstruction, Markov chains, fuzzy logic, reinforcement learning).

3. Identified Research Gaps

3.1. Absence of hybrid benchmarks. Existing EO benchmarks focus on single tasks (segmentation, regression, change detection) and rarely combine physics simulators, ML surrogates, policy scenarios, and human AI interaction with explicit metrics for physical consistency, uncertainty coverage, and decision quality. This is the primary structural gap the proposed framework and benchmarking strategy (Section 12) address.

3.2. Physical consistency of foundation models. Most multimodal pre-training objectives do not enforce conservation laws or atmospheric chemistry constraints. Hybrid pipelines embedding symbolic constraints inside fine-tuning loops constitute a promising remedy, prototyped in this framework using Copernicus-FM and Aurora backbones [11, 16].

3.3. LLM-model integration gap. Grounded LLM interfaces (e.g., Observia AI) are not yet coupled to validated atmospheric simulation backends in any peer-reviewed operational deployment. The proposed Layer 5 architecture provides a blueprint for this integration.

3.4. Regional data sparsity. The Balkans and South-Eastern Europe are under-represented in atmospheric AI benchmarks relative to Western European urban corridors. The case studies proposed in Section 12 explicitly target this gap.

3.5. Uncertainty propagation across interfaces. End-to-end propagation of uncertainty from satellite retrieval through CTM coupling to policy indicator is rarely performed; each layer interface that does not propagate uncertainty produces overconfident downstream outputs.

4. Atmospheric-Pollution-Specific Modeling Challenges

4.1. Satellite Column-to-Surface Conversion

TROPOMI delivers tropospheric vertical column densities (VCDs), not surface concentrations. Conversion requires knowledge of the vertical profile shape, which depends on planetary boundary layer height (PBLH), temperature inversion strength, and chemical gradients. PBLH uncertainties from ERA5 alone contribute 15–30% relative error in surface NO₂ estimates over complex terrain.

4.2. Spatio-Temporal Mismatch

TROPOMI has a single daily overpass (~ 13:30 local solar time) with a 3.5×5.5 km² pixel at nadir. Ground stations report hourly data at point locations. Simple co-location introduces representativeness errors of up to 40% for PM_{2.5} in complex urban environments [28].

4.3. Emission Inventory Uncertainty

National emission inventories carry relative uncertainties of 20–50% for road transport NO_x and up to 100% for agricultural NH₃. These propagate directly into CTM forecasts and data-assimilation backgrounds.

5. Earth System Digital Twins and System Dynamics

5.1. Earth System Digital Twins (ESDTs)

Earth System Digital Twins constitute dynamic, multi-scale virtual replicas that fuse real-time Earth-observation streams, numerical simulation ensembles, and AI surrogate models to enable "what-now", "what-next", and "what-if" analyses [2, 3]. In the atmospheric domain, they support high-resolution pollutant transport modelling, urban air-quality digital twins, wildfire-smoke plume forecasting, and policy-scenario comparison under varying emission trajectories and meteorological regimes [2].

5.2. System Dynamics

System dynamics (SD) modelling formalises delayed feedback loops, nonlinear couplings, and policy levers that govern emission generation, atmospheric dispersion, population exposure, health impacts, and mitigation effectiveness [4, 5, 29]. SD complements ESDTs by making the causal skeleton explicit and communicable to non-technical stakeholders, policy makers, local authorities, and the public. When embedded inside an ESDT, SD supplies the structural backbone for transparent "what-if" simulations.

6. Machine Learning Surrogates: Neural Networks and Extreme Learning Machines

6.1. Neural Networks and Physics-Informed Variants

Deep neural architectures excel at cloud classification, AOD retrieval, pollutant-plume segmentation and tracking, chemical-transform emulation, and fast surrogate modelling of expensive CTM components [10, 11]. Convolutional networks extract spatial features from multispectral imagery; recurrent and transformer models capture temporal dynamics; graph neural networks handle pollutant transport on irregular grids. Physics-informed neural networks (PINNs) embed governing equations (continuity of mass, advection-diffusion) as soft constraints in the loss function, improving generalisation under distribution shift relative to unconstrained architectures.

6.2. Extreme Learning Machines (ELMs)

Extreme Learning Machines [23] employ random hidden-layer projections with analytically solved output weights, offering training speeds two to three orders of magnitude faster than gradient-based deep networks while retaining competitive accuracy on streaming time-series, anomaly-detection, and nowcasting tasks. Online ELM variants support incremental learning as new observations arrive, directly addressing temporal distribution shift in operational monitoring.

7. Uncertainty Quantification and Equation Discovery

7.1. Monte Carlo Methods

Monte Carlo (MC) methods remain the reference technique for propagating uncertainties from emission inventories, meteorological fields, model-parameter ensembles, sensor noise, and structural model error into probabilistic risk metrics and forecast envelopes [6, 7]. In the hybrid context, MC is applied both to ESDT cores and to AI surrogate outputs, delivering calibrated confidence intervals indispensable for risk-sensitive decisions. Surrogate-based UQ methods (polynomial chaos expansion, Gaussian process emulation) can reduce the required model evaluations by one to two orders of magnitude relative to naive MC while preserving coverage properties.

7.2. Genetic Programming and Symbolic Regression

Genetic programming and symbolic regression extract compact, human-readable mathematical expressions directly from data, optionally embedding physical priors, conservation constraints, or known chemical reaction pathways [8, 9]. These techniques are valuable for reduced-order modelling of atmospheric processes, discovery of governing equations for sub-grid phenomena, and generation of interpretable relationships that complement black-box neural predictions. Recent benchmarks demonstrate that SR can recover known atmospheric scaling relations (e.g., simplified NO_x–O₃ titration relationships) with relative errors below 5% from synthetic data generated by full CTM runs [9].

8. Foundation Models for Earth Observation and Atmospheric Applications

The period 2024–2026 witnessed rapid growth in foundation-model research tailored to Earth observation [14, 17, 18, 21]. TerraMind [15] is a large-scale generative multimodal model designed for Earth observation, accepted at ICCV 2025, supporting any-modality generation and retrieval across optical, SAR, and auxiliary streams. Copernicus-FM [16] is a unified foundation model trained on the Copernicus data ecosystem for cross-mission, cross-sensor generalisation. Aurora [11, 30] is an Earth-system foundation model pre-trained on more than one million hours of geophysical reanalysis data, achieving competitive skill in medium-range weather forecasting at a fraction of operational NWP inference cost. SkySense++ [19] delivers strong performance on scene classification and change detection. Panopticon [20] demonstrates zero-shot generalisation across heterogeneous EO sensors.

9. Grounded LLM Interfaces: Case Study on Copernicus Observia AI

Large language models must not be treated as atmospheric models. Their scientific role in the proposed framework is precisely delimited: retrieval, orchestration, explanation, and human–model interaction. Quantitative prediction must remain grounded in observations, CTMs, ESDTs, validated ML surrogates, or statistically calibrated models.

9.1. Copernicus Observia AI: Documented Current Functionality

In June 2025, the European Environment Agency (EEA) launched the beta version of Copernicus Observia AI ("Ask Copernicus") [12, 13], a conversational assistant for finding, understanding, and using Copernicus products. Based on official documentation, the system implements a retrieval-augmented generation (RAG) pipeline on local EEA servers, with a vector database over CLMS and CAMS documentation and source-grounded responses; on-premise execution is stated as a GDPR/EUDPR design goal [13]. Independent peer-reviewed evaluation of its atmospheric-domain accuracy or TROPOMI-specific coverage is not yet available.

9.2 Proposed Integration in the Hybrid Workflow

Table 1 distinguishes documented current functionality from proposed future integration targets. In the hybrid pipeline (Section 11), Observia AI would function in two complementary roles: (a) front-end conversational interface translating user intent into pipeline actions (data retrieval, scenario launch, report generation) consistent with the documented beta capability; and (b) automated retrieval agent supplying fresh Copernicus scenes, metadata, or model diagnostics to upstream layers on demand requiring future API or agentic integration not yet available.

Table 1. Copernicus Observia AI – documented current capability vs proposed hybrid pipeline integration

Capability	Current Observia (beta) [12, 13]	Proposed hybrid pipeline extension
Copernicus data discovery	Yes – documented	Automated scene staging into Layer 1
Product explanation / QA guidance	Yes – documented	Model-aware metadata validation pre-ingest
Natural-language archive query	Yes – documented	Trigger structured data pulls into Layer 1
Scenario simulation	No direct evidence	Via ESDT/CTM backend (Layer 2); requires future API
Monte Carlo UQ	No direct evidence	Via Layer 4; results surfaced through Layer 5
Policy impact assessment	No direct evidence	Via coupled exposure health module; requires validation
Automated provenance reports	Partial – draft summaries documented	Full pipeline provenance; uncertainty-qualified indicators

Sources: [12] EEA announcement; [13] Ask Copernicus beta documentation. "No direct evidence" denotes a proposed future integration target, not an existing feature.

9.3. LLM/RAG Risk Register

Table 5 provides the full risk register. Key risks specific to the LLM/RAG layer include: (a) hallucination of atmospheric quantities LLMs can confidently generate incorrect numerical values without flagging uncertainty; (b) stale grounding if the vector database is not updated, the system may cite superseded TROPOMI algorithm versions or outdated CAMS forecasts; (c) prompt-injection vulnerability in agentic deployment; (d) attribution laundering users may trust LLM-synthesized text as the primary source rather than the underlying Copernicus datasets.

10. Complementary Nonlinear and Probabilistic Methods

10.1. Phase-Space Reconstruction and Nonlinear Dynamics

Takens' embedding theorem [24] guarantees that a scalar time series can be used to reconstruct the geometry of the underlying attractor via delay embedding, provided sufficient embedding dimension and lag [25]. These invariants serve as physically meaningful features for downstream neural and ELM predictors in Layer 3.

10.2. Bayesian Networks

Dynamic Bayesian Networks provide principled probabilistic graphical models for multi-sensor data fusion and sequential belief updating as new satellite overpasses or ground measurements arrive. They represent dependencies among

emissions, meteorology, satellite observations, and ground measurements while naturally propagating uncertainties. Strengths: explicit uncertainty representation; principled fusion of heterogeneous sources.

10.3. Markov Chains and Hidden Markov Models

Markov chains and HMMs capture regime transitions (clean ↔ moderately polluted ↔ smog episode) driven by synoptic meteorology, emission changes, or seasonal cycles. They supply compact state representations that improve sample efficiency for reinforcement learning agents and furnish stochastic scenario generators inside MC ensembles.

10.4. Fuzzy Logic Systems

Fuzzy logic systems provide a mathematically rigorous framework for handling inherent vagueness in air-quality index definitions, expert rules for episode classification, and multi-criteria decision support when combining health-protection and economic objectives.

10.5. Reinforcement Learning

RL agents can learn adaptive strategies for intelligent satellite tasking during detected pollution events, real-time control of urban traffic management, or active learning to identify the most informative Copernicus scenes for uncertainty reduction.

Table 2. Role of complementary nonlinear and probabilistic methods in the hybrid pipeline

Method	Atmospheric role	Strength	Limitation	Pipeline layer
Phase-space / CCM	Attractor geometry; causal inference	Nonlinear causality; no distributional assumptions	Requires long low-noise series	Layers 1, 3
Bayesian Networks	Multi-sensor fusion; UQ propagation	Principled uncertainty; heterogeneous fusion	Structure learning NP-hard	Layer 4
Markov Chains / HMMs	Regime transitions; scenario generation	Interpretable; low cost	Markov assumption may fail	Layers 4, 5
Fuzzy Logic	AQI; episode classification	Handles linguistic vagueness	Manual rules; limited scalability	Layer 5
Reinforcement Learning	Adaptive satellite tasking; control	Learns optimal strategy	Sample-inefficient; reward design	Layer 5

11. Proposed Integrated Hybrid Workflow

The five-layer hybrid pipeline for atmospheric pollution analysis (Fig. 1) is designed to be modular, auditable, and extensible. Each layer has defined inputs, outputs, and validation requirements. No single component is irreplaceable; the architecture supports incremental implementation starting from any subset of layers.

Table 3. Hybrid pipeline layer specifications

Layer	Inputs	Outputs	Key method(s)	Validation metric
1. Data Integration	TROPOMI VCDs; ERA5; EEA stations; AERONET; GIS layers	Harmonised feature space; uncertainty metadata; QA flags	Spatio-temporal alignment; QA filtering; gap detection	Data completeness (%); temporal coverage; QA pass rate
2. ESDT + SD Core	Layer 1 output; boundary conditions; emission inventories	Physically consistent pollutant fields; scenario trajectories	CTM / ESDT; SD feedback models	RMSE vs station holdout; mass-balance check
3. Neural / ELM Emulation	Layers 1–2 outputs; real-time sensor streams	Surrogate predictions; anomaly scores; real-time alerts	PINN; ELM; foundation model fine-tuning	MAE; RMSE; CRPS; 90% interval coverage
4. Symbolic + UQ Layer	Layers 2–3 outputs; observational data	Interpretable equations; MC ensembles; calibrated uncertainty intervals	Symbolic regression; Monte Carlo; Bayesian networks	Symbolic compactness; calibration curves; CRPS
5. LLM Orchestration + Analytics	All upstream outputs; user queries	Cited natural-language answers; provenance-tracked reports; pipeline triggers	Copernicus Observia AI (beta); RAG; LLM orchestrator	Grounding accuracy; hallucination rate (requires independent evaluation)

CRPS: Continuous Ranked Probability Score. Validation metrics for Layer 5 cannot yet be computed for Observia AI in the absence of independent benchmark datasets.

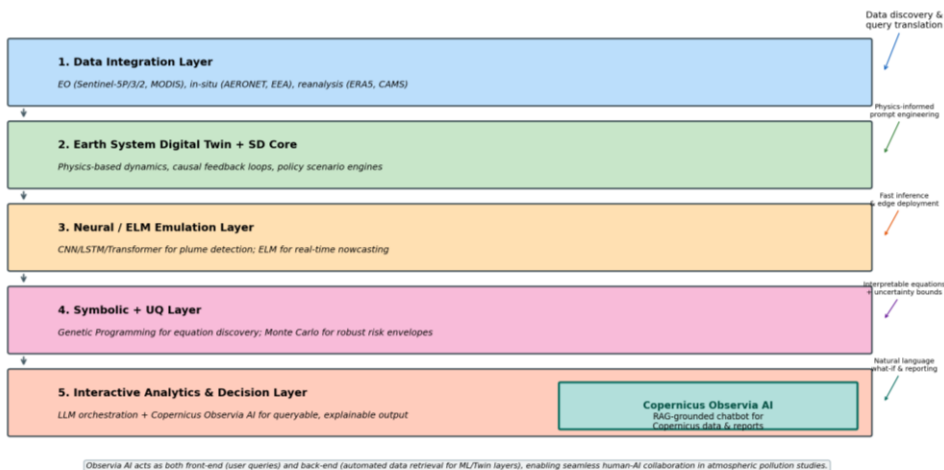


Fig. 1. Hybrid atmospheric modelling workflow integrating Sentinel-5P TROPOMI, Sentinel-3, ERA5, and EEA ground data into five layers: data integration, ESDT/CTM physics core, neural/ELM emulation, symbolic/UQ analysis, and LLM orchestration. Copernicus Observia AI supports user interaction and automated data retrieval.

12. Benchmarking and Validation Strategy

A validated hybrid pipeline requires a structured benchmarking approach that evaluates each layer independently and the integrated system end-to-end. The following strategy targets Balkan-region atmospheric pollution episodes, selected for their relevance to the identified regional data sparsity gap (Section 3) and for the availability of co-located TROPOMI and EEA ground data.

12.1. Case Study Candidates

1. Winter NO₂ inversion episodes, Sofia agglomeration (November–February). Rationale: strong PBLH suppression, topographic trapping, high satellite-to-surface discrepancy. Data: TROPOMI L2 NO₂ (QA ≥ 0.75); AQMD and EEA surface NO₂ (hourly); ERA5 PBLH and temperature profiles; AERONET Sofia.

2. Summer ozone episodes, Balkan urban corridor (June–August). Rationale: high photochemical activity; cross-border transport; health relevance. Data: TROPOMI tropospheric ozone and HCHO; EEA O₃ surface (hourly); CAMS regional ensemble forecasts.

3. Wildfire smoke transport, Balkan–Eastern Mediterranean (July–September). Rationale: extreme distribution shift; multi-sensor challenge. Data: Sentinel-3 SLSTR fire radiative power; CAMS fire emissions; AERONET AOD; EEA PM_{2.5}.

12.2. Performance Metrics

- **RMSE, MAE, bias:** standard point-prediction accuracy against held-out EEA surface observations
- **CRPS:** probabilistic forecast quality for MC ensemble outputs
- **90% interval coverage:** calibration of uncertainty estimates
- **Spatial generalisation:** leave-station-out cross-validation on withheld EEA sites
- **Symbolic compactness:** number of terms in SR-extracted equations; parsimony vs accuracy trade-off
- **Inference cost:** wall-clock time per prediction per layer; relevant for real-time deployment
- **Physical consistency:** mass-balance check; monotonicity of pollutant concentration with emission rate in sensitivity experiments.

13. Interrelationships, Synergies, and Comparative Discussion

No single method family suffices across the full spectrum of atmospheric remote-sensing tasks. Fig. 2 visualises the hierarchical synergies that emerge when the components are combined under a unified hybrid architecture.

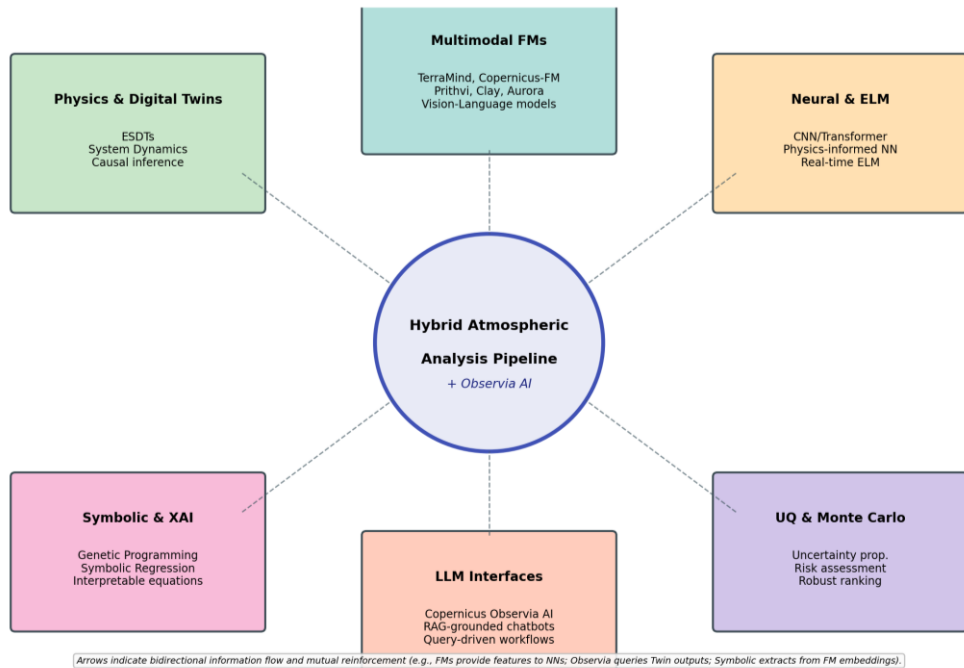


Fig. 2. Synergies among intelligent methods for atmospheric remote sensing. Foundation models and grounded LLM interfaces provide the user-facing integration layer, while neural, symbolic, Monte Carlo, and causal-validation components reinforce the hybrid workflow.

Table 4. Comparative characteristics of primary method families for atmospheric pollution modelling

Method Family	Predictive accuracy	Interpretability	Real-time	Physical consistency	Atm. maturity	Key limitation
Digital Twins + CTM	High	High	Low–Med.	Very High	High	High compute cost; emission inventory dependence
NN / PINN	Very High	Low–Med.	Medium	Med.–High (PINN)	High	Data-hungry; distribution shift without physical constraints
ELM	High	Low	Very High	Medium	Med.–High	Weaker spatial representation than deep nets
Symbolic Regression	Medium	Very High	High	High (w/ priors)	Medium	Instability on noisy high-dim. inputs
Multimodal FMs	High	Low–Med.	Medium	Emerging	Rapid growth	Physical consistency not guaranteed; high inference cost
LLM Interfaces	N/A	High (grounded)	High	Depends on backend	Beta 2025	Not a quantitative model; hallucination risk without grounding

Qualitative assessments based on reviewed literature 2018–2026. "Emerging" indicates rapid development with limited long-term validation in atmospheric pollution applications.

The addition of grounded LLM interfaces lowers the activation energy for domain experts, local authorities, and policymakers to exploit sophisticated pipelines, while mandatory source citation and provenance tracking address the black-box concern in regulated environmental decision contexts. LLM interfaces must remain a communication and retrieval layer; they must not be treated as substitutes for validated quantitative models. The framework enforces this through the layer architecture in Table 3 and the risk register in Table 5.

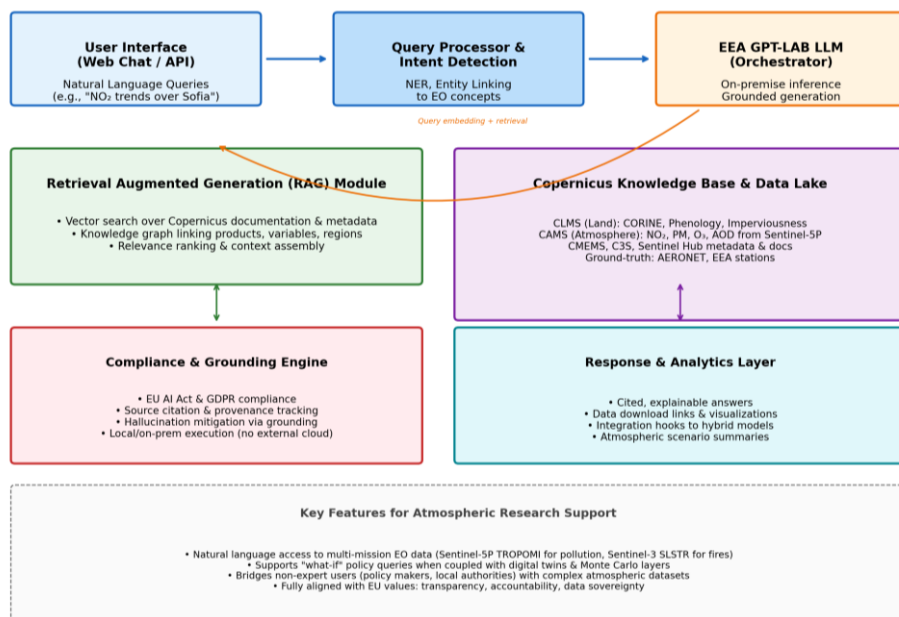


Fig. 3. Current and proposed roles of grounded LLM interfaces in hybrid atmospheric-pollution modelling: data discovery and product explanation vs scenario launch, MC-UQ queries, and provenance-tracked policy reports.

14. Limitations, Threats to Validity, and Future Research Directions

14.1. Scientific and Engineering Limitations

1. Cross-domain generalisation: neural surrogates and foundation models degrade under distribution shift from new sensors, extreme events, or under-sampled regions. Physics-informed regularisation, continual adaptation, and meta-learning are active remedies.

2. Physical consistency of foundation models: most pre-training objectives do not enforce conservation laws. Hybrid fine-tuning of Copernicus-FM and Aurora with embedded symbolic constraints is a promising remedy.

3. Absence of hybrid benchmarks: community-standard benchmarks combining EO streams, physics simulators, ML surrogates, and explicit physical-consistency metrics are largely absent. The benchmarking strategy in Section 12 addresses this gap for the Balkan domain.

4. LLM grounding and evaluation: independent evaluation of Observia AI's atmospheric-domain hallucination rate and factual accuracy on TROPOMI-specific queries is a near-term research priority.

Table 5. Threats to validity and proposed mitigations

Threat	Type	Proposed mitigation
Publication bias toward successful AI models	Literature selection bias	Explicit inclusion of failure-mode analyses; preprint coverage
Limited atmospheric-specific validation of EO foundation models	External validity	Restrict performance claims to validated tasks; cite benchmark datasets
Fast obsolescence of LLM tools (Observia beta may be superseded)	Construct validity	Version-controlled integration; modular LLM orchestration layer
Hallucinated metadata or unsupported causal claims from LLMs	Internal validity	Mandatory source citation; human-in-the-loop for policy outputs
Regional data sparsity in Balkan stations	External validity	Leave-station-out CV; spatial extrapolation uncertainty reporting
Satellite–ground mismatch confounds validation	Measurement validity	Explicit representativeness error quantification in Layer 1
SR instability on noisy inputs may yield spurious equations	Internal validity	Physical prior constraints; cross-validation against independent datasets

14.3. Near-Term Research Directions

Priorities for 2026–2027: (a) benchmarked hybrid pipeline prototype for Balkan NO₂ and PM_{2.5} episodes; (b) physics-constrained pre-training experiments using Copernicus-FM, TerraMind, and Aurora; (c) independent evaluation of Observia AI grounding accuracy for TROPOMI-specific queries.

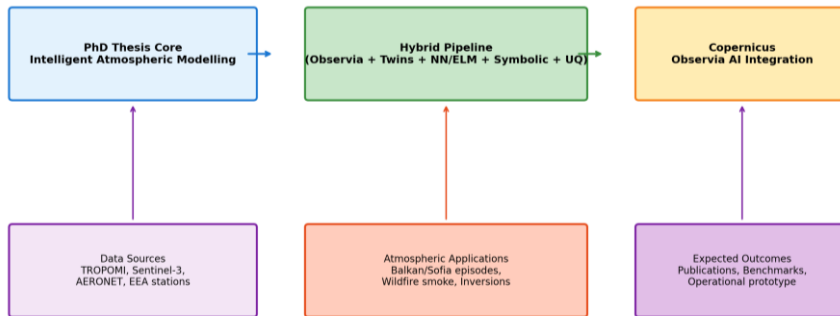


Fig. 4. Research and implementation roadmap for hybrid atmospheric-intelligence systems, organised by pipeline layer and covering near-, mid-, and long-term milestones for benchmarking, federated deployment, and LLM interface evaluation during 2025–2028.

15. Conclusion

This review has synthesised the contemporary landscape of intelligent atmospheric modelling into a modular five-layer hybrid framework integrating Earth System Digital Twins, system dynamics, Monte Carlo uncertainty quantification, neural and Extreme Learning Machine surrogates, symbolic regression, multimodal foundation models, and grounded LLM interfaces. The proposed architecture should be understood as a research agenda and integration blueprint rather than a validated operational system. Key conclusions are: (a) each method family occupies a specific, non-redundant role in the five-layer architecture with defined inputs, outputs, and validation metrics; (b) LLM interfaces are a communication and retrieval layer, not quantitative atmospheric models; (c) Copernicus Observia AI represents a promising but beta-stage grounded data-discovery interface whose atmospheric-domain performance requires independent evaluation; and (d) the primary outstanding gap is not the availability of individual method components but the absence of community-standard hybrid benchmarks combining EO streams, physics simulators, ML surrogates, and explicit physical-consistency and uncertainty-coverage metrics.

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ХИБРИДНО ИНТЕЛИГЕНТНО МОДЕЛИРАНЕ НА АТМОСФЕРНО ЗАМЪРСЯВАНЕ ЧРЕЗ ДАННИ ОТ ДИСТАНЦИОННИ НАБЛЮДЕНИЯ НА ЗЕМЯТА: КРИТИЧЕН ПРЕГЛЕД НА ДИГИТАЛНИТЕ ДВОЙНИЦИ, НЕВРОННИ СУРОГАТНИ МОДЕЛИ И ГОЛЕМИ ЕЗИКОВИ МОДЕЛИ

Д. Макариев, П. Тренчев

Резюме

Атмосферното замърсяване е нелинеен, многомащабен процес, повлиян от значителни неопределености, свързани с емисии, метеорология, химични трансформации и ограничения на сензорите. Настоящият обзор синтезира съвременни интелигентни подходи за моделиране на атмосферното замърсяване чрез данни от дистанционни изследвания и наземни наблюдения. Въз основа на предходния обзор от SES-2025 е предложена модулна хибридна рамка, интегрираща цифрови близнаци на земната система и химико-транспортни модели, невронни и Extreme Learning Machine емулятори, символна регресия, Монте Карло квантификация на неопределеността и grounded LLM интерфейси. Специално внимание е отделено на преобразуването на сателитни колонни измервания към приземни концентрации, пространствено-времето несъответствие между сателитни и наземни данни, метеорологичното влияние, неопределеността в емисионните инвентари и устойчивостта на моделите при екстремни епизоди на замърсяване. Разгледани са съвременни фундаментални модели за наблюдение на Земята, включително TerraMind, Copernicus-FM, Aurora, SkySense++ и Panopticon. Copernicus Observia AI е анализирана като нов бета-интерфейс за достъп до данни от Copernicus, като ясно се разграничават документираните възможности от предложените бъдещи интеграции.

AEROSPACE TECHNOLOGIES AGAINST NATURAL DISASTERS



The monograph **AEROSPACE TECHNOLOGIES AGAINST NATURAL DISASTERS** – author Prof. GARO MARDIROSIAN (Sofia, 2026. BAS Publishing House "Prof. Marin Drinov") is dedicated to the possibilities and realization of some of the highest scientific and technological achievements of humanity – aerospace methods and technical equipment in solving the eternal and current problem – the study of natural disasters and ecological catastrophes as a path to successful fight against them.

According to the performance of good practices of international publishing houses, terminological clarifications are made first, then general issues about natural disasters are briefly examined (their physical foundations and the possible consequences they cause), descriptions of the aerospace equipment on board which helps the research is carried out are given,

and the main directions in the fight against natural disasters are commented on, too.

They are successively described – earthquakes, floods, tropical cyclones, volcanic eruptions, tsunamis, dust storms, forest fires, lightning and some others. Their elements that can be most effectively studied with remote sensing are assessed. The goals are: forecasting, determining occurrence and location, monitoring temporal development, establishing negative consequences and damage, monitoring rescue and restoration activities, etc.

The method used by the author is chronologically developed – the method, technical means and acquisition of remote sensing data are presented. Their processing is also included. This is illustrated with elementary theory and practical applications (specific examples are given). Particular attention is paid to Bulgarian achievements in this field.

The book is intended for a wide interdisciplinary readership – scientists and specialists in ecology, geophysics, geography, geology, meteorology and hydrology, aviation and space research, fire and civil protection, military specialists, medical, mountain and other rescue services, insurance workers, engineers of various specialities, studying in civil and military higher educational institutions. Presented in a popular form, this publication expands opportunities to educate specialists and the general public to reduce the negative consequences of natural disasters on the population, infrastructure, and our entire society.

Prof. Boyko Rangelov

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