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

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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.

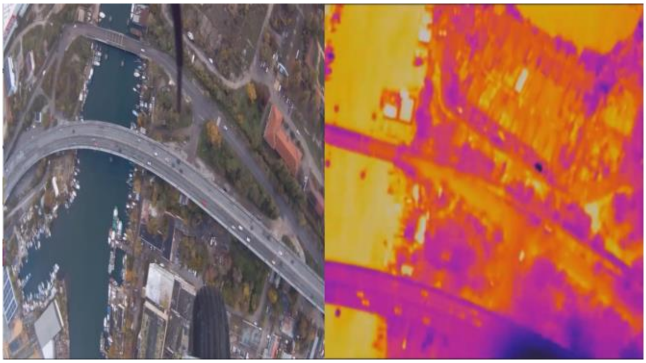

Fig. 2. Video image and thermal image of Asparuhov Bridge

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^0VV), 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^0VH), which are primarily sensitive to natural objects such as forests and agricultural areas.

Fig. 4 presents a radar image in VV polarisation (σ^0VV) 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).

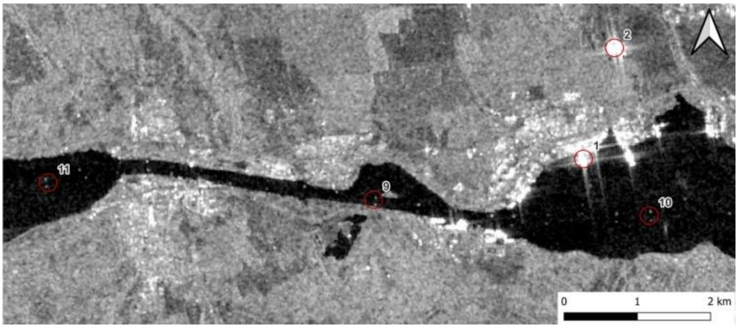

Fig. 4. Sentinel-1 radar image of Varna Lake in VV polarisation (σ0VV)

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.

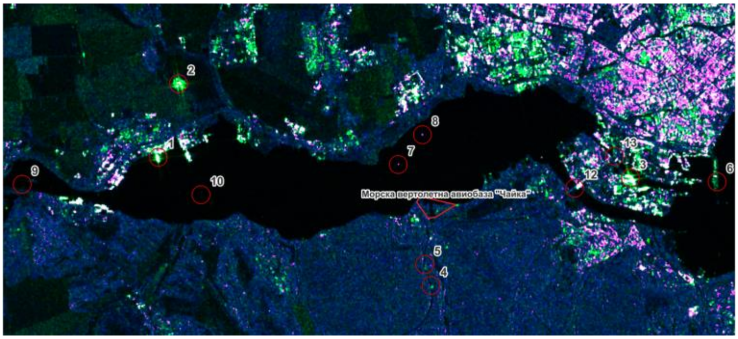

Fig. 5. The "SAR Urban" RGB composite (SH) of Sentinel-1 SAR image along the channel area of the city of Varna

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.

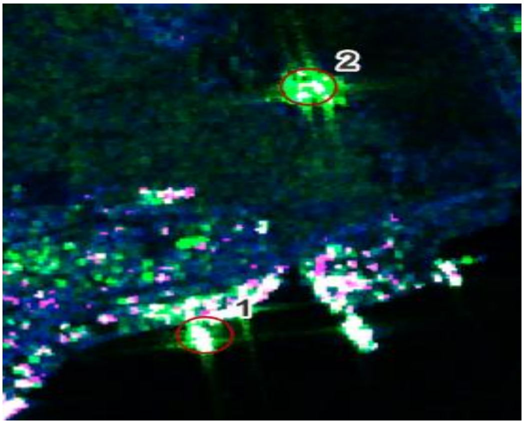

Fig. 6. Detail from “SAR-Urban” RGB composite from Sentinel-1 SAR image

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.

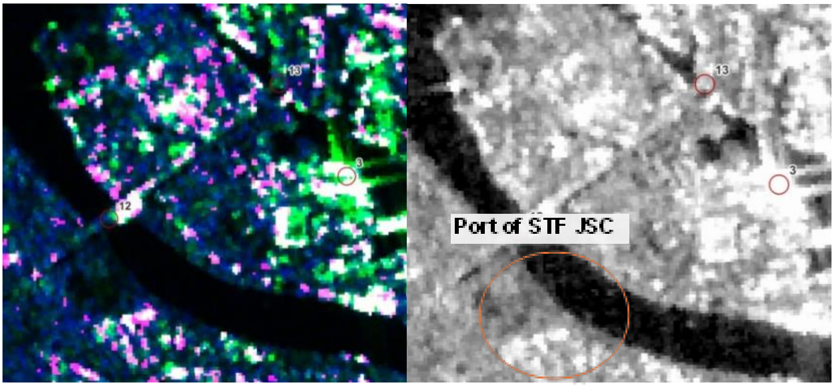

Fig. 7. Left: "SAR Urban" RGB composite image by Sentinel Hub; Right: VV-polarized radar image in the area of the "Asparuhov Bridge" over the channel of Varna

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].

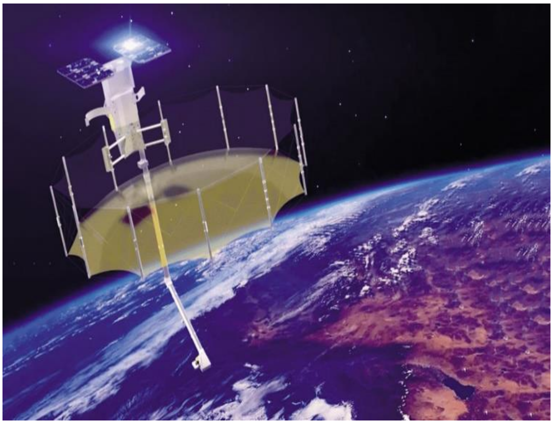

Fig. 8. General view of the Capella 2 radar observation satellite

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 $\sigma0VV$ 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 достоинствата 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.