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MEASUREMENT EQUIPMENT FOR QUASI-STATIC AND ALTERNATING LOW-FREQUENCY ELECTRIC FIELDS IN EARTH-SURROUNDING PLASMA

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Abstract

The paper describes a method, sensors, and measurement equipment for quasi-static (DC) and alternating (AC) electric fields in the ULF/VLF frequency range in earth-surrounding plasma on-board satellites. The major requirements with respect to the equipment and electric fields' registration methods when using dedicated satellite scientific complexes are formulated. Moreover, the paper describes the major parameters of satellite on-board low-frequency electromagnetic effects measurement equipment, as well some original authors' developments intended for the a.m. purposes. The peculiarities of sensors' solutions, their interface with the measurement complex, the specific requirements for the latter resulting from the resolved scientific tasks, and the satellite's characteristics are also described.

1. Tasks solved

The designed equipment is intended to study the wave processes taking place in earth-surrounding plasma, the mechanisms of mass and energy transfer in the magnetosphere-ionosphere-atmosphere system and the influence of solar wind parameters; the processes of particles' acceleration and the mechanisms of generation, propagation and interaction of various types of electromagnetic waves and waves generated by geodynamic or anthropogenic activity [1,2,3].

It measures electric field components from 0 to 30 kHz. This frequency range is divided into several subranges of various maximal frequencies. The processing block also includes a 10-channel spectrum analyzer intended for preliminary processing and reduction of the device's output information flow under the monitoring operation mode [4,5].

A main task in modern space experiments is to carry out correlated observations, intended to separate spatial and time relationships, providing to highlight the causal relation between the studied processes, and guaranteeing the devices' high-resolution in phase space, thus enabling the study of small-specific-scale processes [6,7].

2. Measurement method and sensors

The device operates after the Langmuir double-probe method. The method is used to measure the potential difference between two opposite spherical sensors. Each component can be measured either by an individual sensor couple or using some other component's sensor couple. Each of the device's sensors measures the potential at the measurement point. When measuring the potential difference between two sensors, the intensity of the electric current for the individual components of the DC and AC fields is determined [8,9,10].

The electric sensors used in the device are made of glass-carbon-coated spherical monoblock and fixing elements. The construction of the spherical sensor is shown in Fig. 1. The major sensor components are: a sensitive element – sphere with diameter of 80 mm covered by glass-carbon; symmetry-providing electrodes; protective electrode; preamplifier PA, assembled within the sphere; preamplifier screening box, and disconnector. The use of spherical sensitive elements is substantiated by the requirement for high symmetry level. The symmetry-providing electrodes are intended to ensure identical conditions for the electrodes with respect to the Sun. The protective electrode is intended to reduce the influence of the photoelectrons from the satellite structure components.

The sensors' potential is determined by the balance of their surface electric currents, which depend on the material and the characteristics of the sensors' operating surface. For this reason, we use spherical sensors with glass-carbon coating obtained after a unique Bulgarian method [11]. Within the spherical sensor, a preamplifier is mounted, intended to harmonize plasma impedance with the input impedance of the satellite measurement block. The preamplifier is two-stage, containing high-resistance voltage reproducer, made of operation amplifier featuring a PEC input, and an alternating-current amplifier, amplifying the smaller-amplitude alternating-current voltage fluctuations. Thus, the sensor has two information outputs, one for constant, and one for alternating field. The diagram also contains high-voltage protection, switch-over and calibration circuits etc.

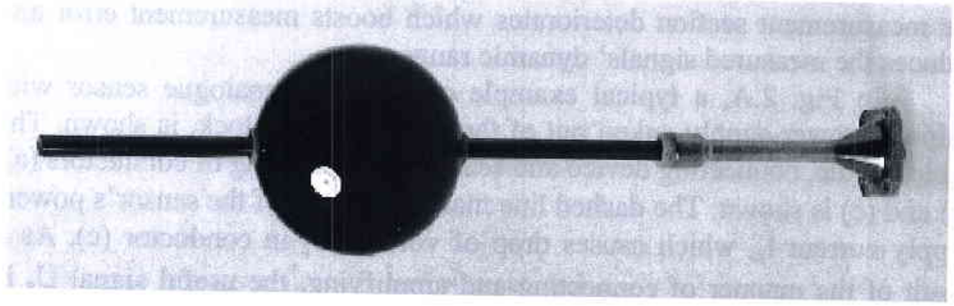


Fig.. 1

In electric-field-measurement experiments, the probes must be positioned sufficiently far off the satellite, so as to escape the disturbed area around it. For the purpose, it is sufficient that the distance *d* from the sensors to the closest convex part of the satellite be no less than 5 times the satellite's radius. Here, some of the most successful experiments measuring satellite electric fields may be given, where the distance between the sensors is, accordingly: GEOS – 42 m, S3-3 – 36 m, ISEE-1,2 – 74 m, GEOTAIL – 160 m, WIND –50 m, POLAR – 100 and 130 m, CLUSTER – 1,2,3,4 – 100 m.

To make potential distribution around the spherical sensors symmetrical, several solutions are applied depending on the satellite's type – whether it is a microsatellite or a large object. The relatively large satellites are fed shifting voltage. This method was used on the satellites S3-3, ISEE, GEOTAIL, INTERBALL, CLUSTER etc. In microsatellites, the preamplifier's output is connected to the protective and symmetry-ensuring electrode, which makes it possible to maintain one and the same potential over the whole sensor.

3. Connection between sensors and equipment

The electric fields and other quantities are measured by sensors with built-in amplifiers, transducers etc. Their power-supply is usually provided by the equipment to which they are connected. The equipment's power supply and the sensor's power supply are common and there is a galvanic link between them. Some of the circuits connecting the sensor with the measurement block participate in both the contour of the output signal and the sensor's power supply. As a result, these circuits interact and the accuracy of the analogue information's transfer from the sensor's output to the measurement section deteriorates which boosts measurement error and reduces the measured signals' dynamic range.

In Fig. 2.A, a typical example of an active analogue sensor with unipolar power-supply, taken out of the measurement block, is shown. The cable bundle, connecting device and sensor and consisting of conductors (a), (b) and (c) is shown. The dashed line marks the route of the sensor's power-supply current I_z, which causes drop of voltage U_z in conductor (c). As a result of the manner of connecting and amplifying, the useful signal U_s is mixed with the voltage drop U_z in (c), and thus gets amplified by A.

To eliminate the problem, the following solution is suggested. Obviously, the adding up of U_s и U_z during the signal's transfer from the sensor to the device should be eliminated. The suggested solution is represented in Fig. 2.B; it is accomplished through additional link (d) and the signal's amplifying by differential amplifier DA, which carries away and amplifies the signal from sensor U_s, eliminating its mixing up with U_z.

This technical solution was applied to carry away the signals from the electric and magnetic sensors of the ULF/VLF complex of the COMPAS Project. It is reflected in the equipment's electric filed measurement block to be considered further on. The application of this solution resulted in material increase of the measurement accuracy of the sensor-fed signals.

4. Equipment parameters for studying ionospheric and magnetospheric fields

Measurement of electric fields are important as for the decision of questions in the ionosphere and magnetosphere plasma, and the processes connected from anthropogenous activity. Microsatellites, and heavy satellites are used to carry out complex measurements in the ionosphere and magnetosphere plasma. The parameters of the equipment for electric fields measurements on satellites of project CLUSTER and the planned project the RESONANCE are presented in Table 1. The results can be used for comparison of similar equipment for microsatellites (as example the COMPAS microsatellite).

5. Equipment parameters for studying ionospheric seismoelectromagnetic effects

Frequency range: Electromagnetic emissions within the range from fractions of the hertz to dozens of kilohertz have been observed. The detailed analysis of experimental data evidences that persistent seismoelectromagnetic signals are observed at frequencies lower than 800

Hz, but alongside with them, signals with frequencies of 10 kHz and 15 kHz have also been recorded.

Table 1.

Measured quantity	Frequency range	Dynamic range	Satellite
DC Electric Field (2 components) AC Electric Field (2 components)	0 – 10 Hz 0 – 200 Hz 0 – 5000 Hz 0 – 10000 Hz 10 – 5000 Hz	700 mV/m – 0.1 mV/m 700 mV/m – 0.1 mV/m 700 mV/m – 0.1 mV/m 700 mV/m – 0.1 mV/m 10 mV/m ≈ 1 μV/m	CLUSTER
DC Electric Field (2 components) AC Electric Field (2 components)	0 – 30 Hz 0.01 Hz- 30 kHz	100 dB 80 dB	REZONANS

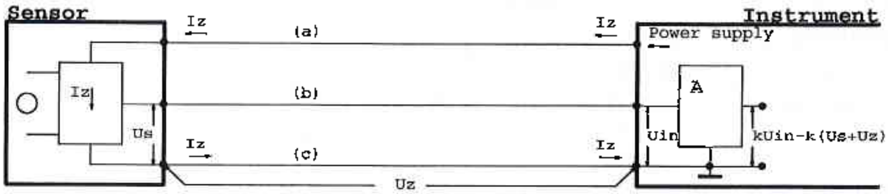
Amplitude: Judging from reference data based on the analysis of large arrays of satellite experimental results, seismic-activity-related signals are those for which the signal-to-noise ratio is > 3. The studies of the signal amplitude's dependence on Δt, the time offset between the earthquake's occurrence and the time of measurement, reveal that the seismoelectromagnetic effects are manifested most strongly at frequencies < 1 kHz in the vicinity of the earthquake's epicentre.

Spectral density: It varies with frequency, being higher with lower frequencies. For emissions within the frequency range from 0.1 kHz to 0.5 kHz, the absolute value of the magnetic component's spectral density is > 0.3 – 3 $pT/Hz^{1/2}$.

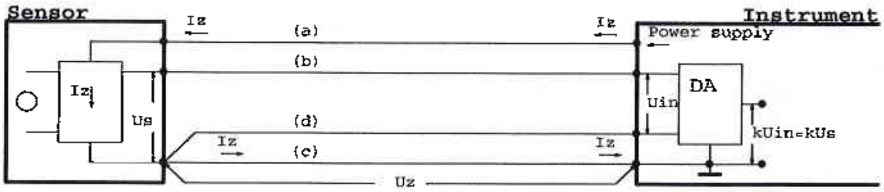
Duration: The earthquake electromagnetic precursors can be recorded within a couple of days prior to the earthquake's occurrence. The duration of observation of seismoelectromagnetic emissions on-board satellites depends on the satellite's orbital characteristics (height and inclination), i.e., the height at which it crosses a force tube related with the earthquake's epicenter.

Experiments have shown that it takes from a couple of seconds to a couple of minutes.

The separation of ionospheric seismoelectromagnetic effects from the background values of such emissions at satellite orbital height is a key task, since the field's generation mechanisms and the propagation conditions for various types of waves are strongly influenced by solar activity, geomagnetic circumstances, season, local weather etc. Moreover, in earth-surrounding plasma, various physical processes take place, which generate signals similar to seismoelectromagnetic effects.



A



B

Fig. 2

6. Peculiarities of on-board equipment in recording geomagnetic-activity-related electromagnetic fields in earth-surrounding plasma

To solve the scientific tasks related with studying electromagnetic and plasma earthquake precursors, three basic on-board-satellite measurement modes should be used [12,13]:

Monitoring mode or minimal telemetry mode. Under this mode, key physical parameters are measured continuously on a 24-hour basis within selected channels and with a small inquiry frequency (of about one inquiry per second). This mode presumes continuous monitoring. In accordance with the selected mode the equipment measures the quasi-static field's components, while the alternating field' measurements include only measurement of local frequencies by a spectral analyzer to reduce data flow.

Local monitoring mode. Under this mode, the full set of the physical parameters provided by the scientific equipment complex is monitored, during all satellite orbits passing over some of the Earth's seismoactive regions. The EMC operates in its most informative mode, measuring the actual signal "wave" forms within a wide frequency range, but only for the time while passing over the region.

Physical experiment mode. This mode is used when targeted experiments are carried out, implying the use of other space or ground-based instrumentation. Under this mode, the satellite's full scientific complex operates with maximal telemetry and jointly with other on-board geophysical and radio-physical provision instrumentation. The operating mode resembles the description provided in item *Physical experiment mode.*

Operating conditions restrictions on-board small satellites. For the purpose of studying various environmental parameters and processes taking place in Earth-surrounding space and on Earth, recently, small satellites have been widely used.

The small size and mass of such space apparata call for reduction of some of their office systems, operation time, power resource, as well as for material telemetry restrictions etc. However, this results in significant reduction of the price per on-board load (equipment). The equipment to be mounted on such objects should comply with their specific features.

7. Structural diagram of the measurement complex

The structural diagram (Fig. 3) of the measurement complex provides for changing the number of the measured field components and their frequency range, making preliminary processing of collected data, such as spectral analysis of some components, switching over of components, selection and changing of operation regimes by a command from the Earth [14]. By varying the operation regime, the complex's options as well as the amount of output data vary greatly, too. Below, the major components and the operation of the ULF/VLF-complex are described. On the presented structural diagram, the analogue signals to be processed and converted in the digital section are shown. These signals are output at control coupling T.

The signals M1-M4 controlling the complex's operation regimes as well as the signals Ft, R, A, Ct, Fms, D0-D7 providing for the protocol and data exchange with on-board telemetry are also shown. They are duplicated and output at control couplings IO1 and IO2.

The ULF/VLF-complex is intended to measure one of two optional components of the AC electric field and one component of the alternating magnetic field in the following frequency ranges:

- from 1Hz to 30Hz - denominated on the flow-chart as MVF1 and EVF1;
- from 30Hz to 1000Hz - denominated on the flow-chart as MVF2 and EVF2;
- from 30Hz to 8000Hz - denominated on the flow-chart as MVF3 and EVF3;

- parallel spectral analysis of one electric and one magnetic field component with ten local frequencies (7.5, 14, 30, 70, 140, 560, 1300, 4500, 8500, and 15000Hz) - signals from ED1 to ED10 and from MD1 to MD10.

Apart from these, the ULF/VLF-complex measures: - two components of the quasi-DC electric field within the range 0-2Hz - signals PP1-2 and PP2-3; - the temperature in the electronic block and the electric and magnetic sensors coupled with it - signals BT1-BT5.

The complex consists of: - electric sensors ED1, ED2, and ED3 with preamplifiers for measurement of one of two optional electric components; - a block of magnetic sensors, BMD, consisting of two magnetic sensors in different frequency regions with preamplifiers for measurement of one magnetic component;- An electronic block housed within a single case, and consisting of a block for study of electric fields, EPS, a block for study of magnetic fields, MPS, a data acquisition block, BSD, consisting of a microprocessor system for collection of data from 36 analogous channels, generation of calibration signals, complex control, processing of obtained data, and connection with the object's telemetry, a block for galvanic disconnectio and duplication of signals for data exchange with telemetry - BGRD, and a power-supply block for galvanic disconnection from the on-board power-supply, VIZ.

The analogue data obtained at the outputs of the above-named blocks is processed by a quick 12+1 data acquisition bit system of the LM12458 type, and a microprocessor system based on the processor 80C188XL. The system also includes a block for generation of calibration signals providing for autocalibration during flight.

8. Approbation of equipment and sensors under the conditions of real experiments

Electric sensors measuring electric fields on-board satellites, that have been developed at the SRI – BAS with our participation have operated successfully on eight satellites: IC Bulgaria 1300 (1981); IC-24 Activen (1989); Magion-2 (1989); IC-25 – APEX (1991); Magion -3 (1991); Magion -4 (1995); INTERBALL-2 (1996) and Magion -5 (1996).

Measurement equipment and sensors intended for the COMPAS microsatellite, featuring the a.m. parameters, have been developed and have passed technological tests. The equipment is intended to study ionospheric electromagnetic effects caused by geodynamic activity.

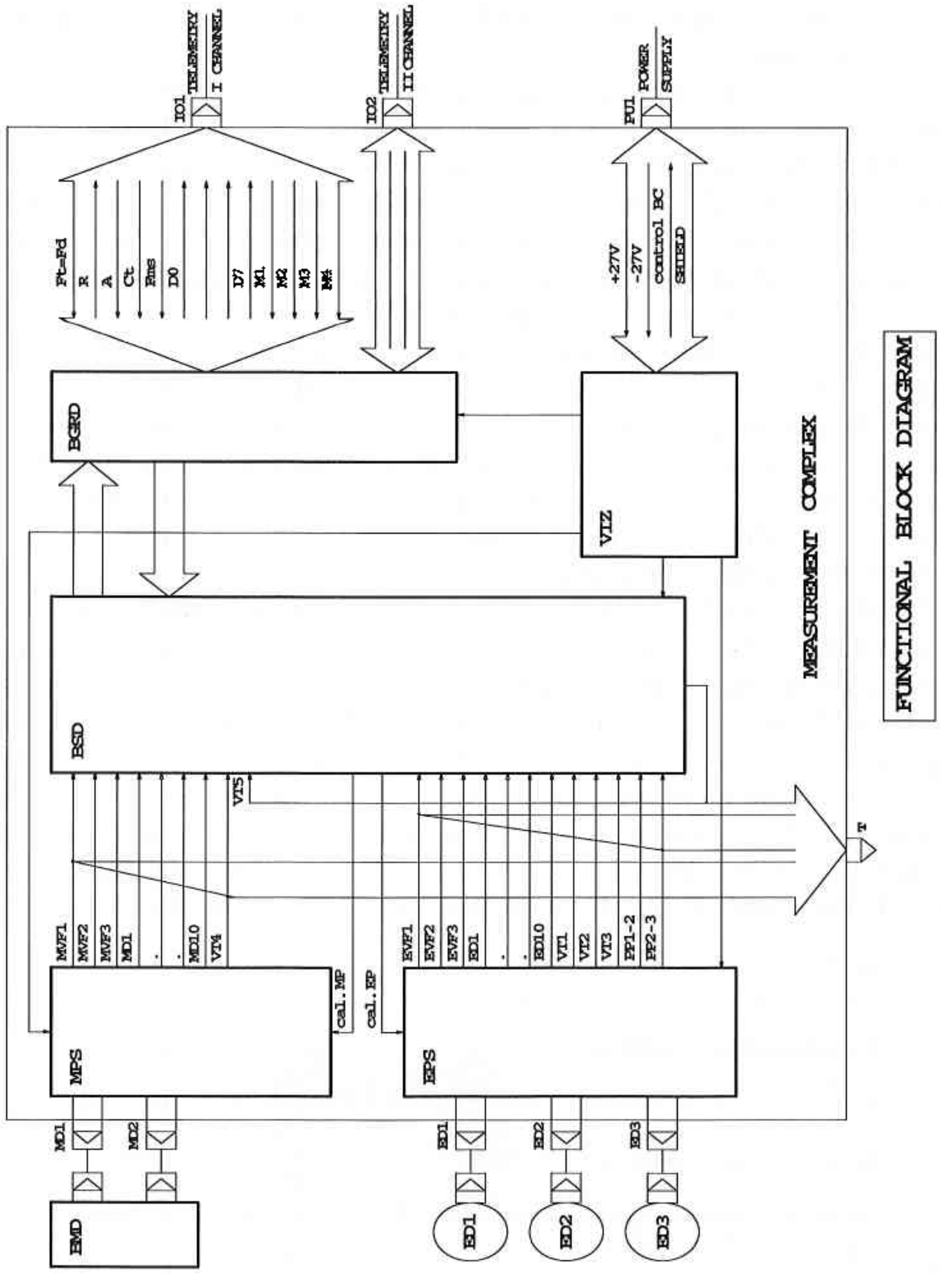

FUNCTIONAL BLOCK DIAGRAM
MEASUREMENT COMPLEX
TELEMETRY I CHANNEL
TELEMETRY II CHANNEL
POWER SUPPLY
IO1
IO2
PU1
+27V
-27V
control BC
SHIELD
BGRD
BSD
VTZ
MPS
EPS
EMD
cal.MP
cal.EP
MVF1
MVF2
MVF3
MD1
MD10
VT4
VT5
EVF1
EVF2
EVF3
ED1
ED10
VT1
VT2
VT3
PP1-2
PP2-3
MD2
ED2
ED3
T

Fig. 3

9. Measurements in the High-Latitude near-Earth Magnetotail Region

ULF measurements aboard Magion–4 were performed during UT 13:00 – 13:45 while the spacecraft crossed the high-latitude near-Earth magnetotail at distance 11 R_E in the pre-noon sector [15]. Data are presented in Fig. 4. Initially till 13:28 UT we observe ULF electric fluctuations which are purely electrostatic. Magion-4 position and plasma data (not shown here) suggest that during this period measurements take place on field lines connected with the lobes, though at higher latitudes than the Day 20.04.1997 case. A sharp increase of wave activity begins at UT 13:28, the spectrum of the waves changes to electromagnetic. Plasma instruments aboard Magion-4 register density enhancement. We interpret the changes in medium characteristics as spatial, due to s/c entering a magnetosphere boundary layer. As IMF Bz <0, the mantle is supposed to be well developed so we conclude that measurements after UT 13:28 take place in the plasma mantle. Unfortunately, magnetic field and plasma measurements on board the Interball-1 satellite, which could facilitate region identification, are absent for this period. While the electrostatic spectrum is below 1 Hz, the electromagnetic one is up to 5÷6 Hz and its intensity decreases for higher frequency. Note that the absence of electric field component at higher frequencies (above ω_{ci}) could be connected with the worse sensitivity of our ULF electric field measurements compared to the magnetic field one. The intensity of the *E* waves is structured, and the *E* field component is orientated in the meridian plane. The electromagnetic spectrum observed in the mantle belongs probably to electromagnetic ion cyclotron modes.

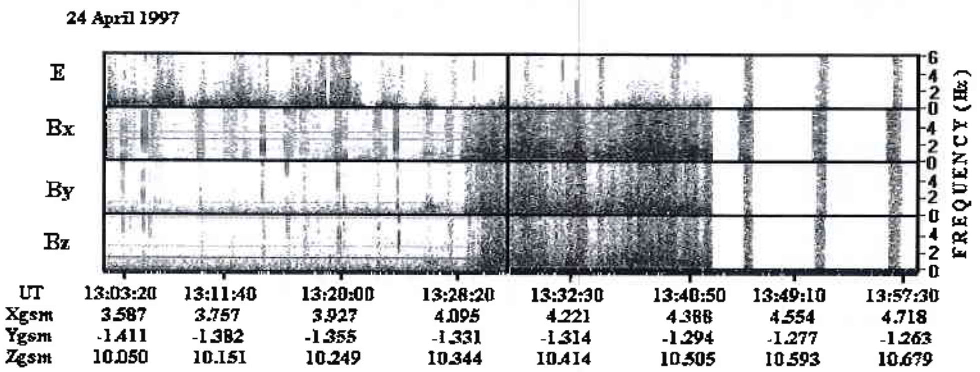


Fig. 4 Dynamic spectra of Magion-4 ULF electric and magnetic ield components on 24 April 1997 derived from waveform data. At ~ UT 13:28 the spectrum changes from electrostatic to electromagnetic.

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АПАРАТУРА ЗА ИЗМЕРВАНЕ НА КВАЗИПОСТОЯННИ И ПРОМЕНЛИВИ НИСКОЧЕСТОТНИ ЕЛЕКТРИЧНИ ПОЛЕТА В ОКОЛОЗЕМНАТА ПЛАЗМА

Бойчо Бойчев, Димитър Теодосиев

Резюме

В работата са представени метод, сензори и апаратура за измерване на квазипостоянни DC и променливи AC електрични полета в ULF/VLF честотните диапазони, в околоземната плазма, от борда на спътници. Апаратурата е разработена за целите на изследването на вълнови процеси, протичащи в околоземната плазма, механизмите на пренос на маса и енергия в системата магнитосфера-йоносфера-атмосфера и влиянието на параметрите на слънчевия вятър; процесите на ускоряване на частици и механизмите на генериране, разпространение и взаимодействия на различните видове електромагнитни вълни, както и такива предизвикани от геодинамична активност и антропогенна дейност.

Формулирани са основните изисквания към апаратурата и методите за регистриране на електрични полета с помощта на специализирани спътникови научни комплекси. Направено е разглеждане и обобщение на резултатите от характерните случаи на такива наблюдения. В работата са представени и основните параметри на апаратура за измервания на нискочестотни електромагнитни ефекти от борда на спътници, както и оригинални разработки на авторите за горепосочените цели.

Конкретно са разгледани особеностите на реализация на сензорите, свързването им към измервателния комплекс и специфичните изисквания към него, продиктувани от решаваните научни задачи, и характеристиките на спътника. Представената апаратура е резултат от натрупания опит на авторите от няколко спътникови експерименти, като предложените решения са илюстрирани с резултати от тях. В работата е направено обосновано предложение за прилагането на разработената апаратура в бъдещи проекти.