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Research paper

Development of A Methodology and Hardware-Software Complex for Multi-Level Monitoring of High-Energy Particles

Sergey Medvedev, Roman Aleshko *, Ksenia Shoshina, Vladimir Berezovsky, Evgeny Evgenyev, Tatyana Desyatova

Northern (Arctic) Federal University, Russia
**Corresponding author E-mail: r.a.leshko@mymail.academy*

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Abstract

This article presents the development of a methodology and hardware-software complex for multilevel monitoring of high-energy particles in the Earth's atmosphere. The study is aimed at eliminating the deficit of complex experimental data on the distribution of radiation throughout the entire thickness of the atmosphere, obtained synchronously from ground stations, stratospheric probes and spacecraft. The authors describe the creation of a stratospheric probe equipped with radiation detector, GPS module, atmospheric parameter sensors and data transmission system. The software of the probe and ground station provides for the collection, processing and visualization of telemetry in real time. The experiment included synchronous measurements from three platforms: ground station, stratospheric probe and spacecraft, which made it possible to get a vertical radiation profile. The results showed a decrease in the radiation background in the surface layer and its increase with height, confirming the hypothesis of the weakening effect of the atmosphere. The developed complex is proposed as a flexible platform for further research in the field of space meteorology and radiation safety.

Keywords: *Cosmic Rays; High-Energy Particles; Radiation Monitoring; Stratospheric Probe; Vertical Radiation Profile.*

1. Introduction

The radiation background at the Earth's surface and in the near-earth layer of the atmosphere has a complex structure formed by a combination of different sources. Understanding these features is critically important for analyzing the altitude profile of near-earth radiation.
Despite the existence of studies analyzing space weather data from ground stations [1], balloon probes [2, 3], and spacecraft [4], there is a lack of comprehensive experimental data on the distribution of high-energy particles throughout the atmosphere, obtained synchronously from different altitude levels. Such data are critical for an accurate understanding of the processes of formation and attenuation of air showers and the validation of theoretical models, in particular, for a detailed study of the features of the radiation intensity profile in different layers of the atmosphere, where the transition from the dominance of the ground background and atmospheric absorption to a clear increase in the cosmic ray flux occurs. This gap in experimental data is one of the key unresolved issues that the study is aimed at.
Recent global initiatives have revealed the potential for coordinated radiation monitoring between separate atmospheric strata. For example, the EUSO-SPB2 mission utilized a stratospheric balloon to study ultra-high-energy cosmic rays and neutrinos and thus synthesize ground and flying measurements [5]. Lightweight balloon-borne detectors have also been successfully used to study energetic particle precipitation and atmospheric X-rays [6]. On the orbital level, satellite constellations such as the CORBES small-satellite mission offer multipoint radiation belt measurements and thus enhance multi-platform near-Earth space coverage [7].
The practical implementation of high-altitude experiments is associated with technical challenges, such as ensuring reliable data collection and transmission under conditions of extreme temperatures, low pressure, vibration, and potential physical damage to equipment. Existing solutions require expensive and difficult-to-use equipment. It is necessary to test more accessible and quickly deployable software and hardware systems capable of collecting data with sufficient reliability even in adverse conditions.
In addition, effective multi-level monitoring and particle distribution analysis requires the development of integrated ground station software capable of receiving, processing and visualizing heterogeneous telemetry measurements from various platforms, including geospatial information, in real time. The development of such software that combines the functions of data collection, storage and visualization is an important task for the implementation of the multi-level monitoring concept.
Methods of synchronous multi-level monitoring, in which data are collected simultaneously from several platforms, are the subject of active research, but their practical implementation is associated with a number of technical and organizational difficulties. Scientific publications describe projects that include coordinated launches of stratospheric balloons during satellite overflights or simultaneous measurements from ground stations and balloon probes. For example, paper [8] describes a method for detecting the atmospheric neutron profile

using a probing balloon carrying a nuclear radiometer. Article [9] presents the experience of using a stratospheric balloon with a PIN diode dosimeter.
However, operational multi-level monitoring covering a wide range of altitudes (from the ground to orbit) and allowing for synchronized data acquisition for detailed altitude profile analysis has not yet become a common practice. Existing systems can be complex to deploy, require significant resources, or do not provide sufficient data density at all altitude levels simultaneously. In addition, integrating data from different types of detectors installed on different platforms requires the development of unified methods for processing, calibration, and conversion of readings to common units of measurement.
Thus, despite the understanding of the importance of multi-level approach and the existence of individual projects aimed at its implementation, the creation of accessible, quickly deployable and reliable software and hardware systems for synchronous multi-level monitoring of the distribution of high-energy particles in the atmosphere remains an urgent task [10]. The solution to this problem will allow obtaining more complete and accurate data for scientific analysis and applied applications. The development of a software and hardware system for monitoring in stratospheric conditions requires the integration of various modern technologies in the field of electronics, communications, navigation, data processing and software. The operation of such a system is based on the optimal selection and application of appropriate technical solutions for each component of the system.

2. Methodology

To perform a multi-level analysis of the distribution of high-energy particles in the Earth's atmosphere, an experimental methodology was developed based on the synchronous collection of information from three measurement platforms: on the ground, in the stratosphere and in space. Its key principle is to ensure the most accurate temporal and spatial consistency of the results coming from each level.
In November 2024, the ArcticSat-1 small spacecraft, developed at the Northern (Arctic) Federal University (NArFU), was launched. To conduct a multi-level study of atmospheric permeability, a stratospheric probe was created, the development and testing process of which is given in this paper.
The high-altitude experiment scenario involves launching the ArcticZond stratospheric probe on a stratospheric balloon filled with helium, with the goal of reaching an altitude of 30-35 kilometers. Such a flight covers the troposphere and stratosphere, including the Pfotzer Maximum region.
The launch is planned to be carried out considering the schedule of the ArcticSat-1 space satellite flyby over the experiment area. The optimal launch time is 45–60 minutes before the flyby, so that the probe is in the ascent phase at the time of the satellite flyby. This will allow obtaining data on the radiation situation at different altitude levels simultaneously or with a minimum time shift, which is critically important for constructing a correct "instantaneous" vertical particle distribution profile. The choice of launch location should take into account the capabilities of the NArFU ground station to receive telemetry measurements from both the probe and the ArcticSat-1 satellite in communication sessions. The general scheme of the experiment is shown in Fig. 1.

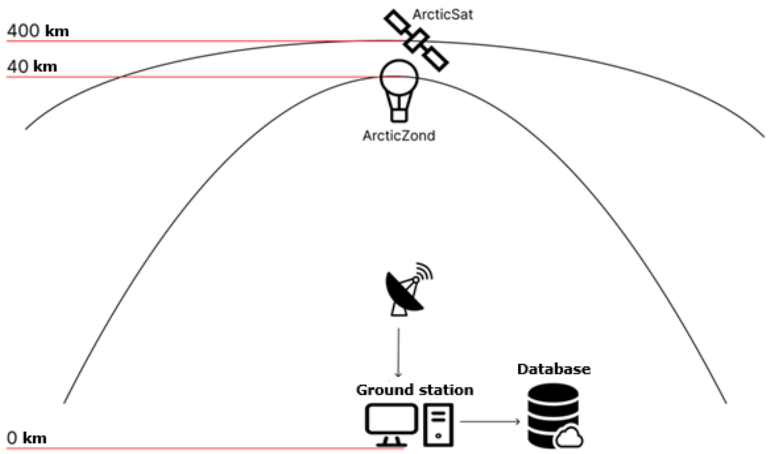

Fig. 1: Experimental Scheme.

2.1. Stratospheric probe hardware

The ArcticZond stratospheric probe is a compact, self-contained device designed to collect measurements of atmospheric parameters, its own position, and radiation conditions during high-altitude flight. The probe hardware is designed to meet the weight, size, power consumption, and ability to operate over a wide range of temperatures and pressures typical of the troposphere and stratosphere.
The probe is based on the ESP32 microcontroller, chosen due to its high performance, dual-core architecture, sufficient memory capacity and, most importantly, built-in wireless Wi-Fi and Bluetooth interfaces. This allows for interaction with the dosimeter and the use of Wi-Fi for configuration in ground conditions. A set of peripheral devices and sensors is connected to the ESP32 microcontroller, ensuring the collection of all necessary telemetry.
The radiation detector is the main payload sensor. The Atom Fast model is used, equipped with a scintillation detector. Communication with the microcontroller is carried out via the Bluetooth Low Energy (BLE) interface. The dosimeter, calibrated by the manufacturer, provides two key readings: the count rate of registered events (pulses per second) and the dose rate (in microsieverts per hour), converted from the count rate. In addition, the dosimeter transmits information about its temperature and battery charge. The GPS module is used to determine the precise geospatial position of the probe (latitude, longitude), altitude above the ellipsoid, speed, course and an accurate timestamp. The BMP085 sensor is used to measure atmospheric pressure and barometer temperature. These parameters are critical for calculating the barometric altitude. The HTU21D and DHT11 sensors are used to measure air temperature and humidity, providing data on atmospheric conditions to clarify the barometric altitude calculation. The inertial measurement unit (IMU) is represented by the MPU6050 sensor, which includes a gyroscope and an accelerometer, and is used to measure the angular velocities and accelerations of the probe. By processing this data, the orientation of the probe in space can be determined. The QMC5883L electronic compass is used to

determine the direction relative to the Earth's magnetic field. The INA226 sensor measures voltage, current, and calculates the power consumption of the onboard systems. This data allows you to track the state of the probe's power supply system. The ebyte e32 radio module is used to transmit telemetry measurements to the ground station. Communication with the microcontroller is carried out via a serial interface (SoftwareSerial). An OpenLog module with an SD card is used for backup recording of all collected telemetry measurements. Communication is also via a serial interface. This function is critical for the reliability of data collection, allowing you to save information even if radio communication is lost or the probe is physically damaged. The device is equipped with a radio beacon to facilitate the search for the probe after landing.
Fig. 2 shows the layout on the breadboard of all modules connected to the microcontroller.

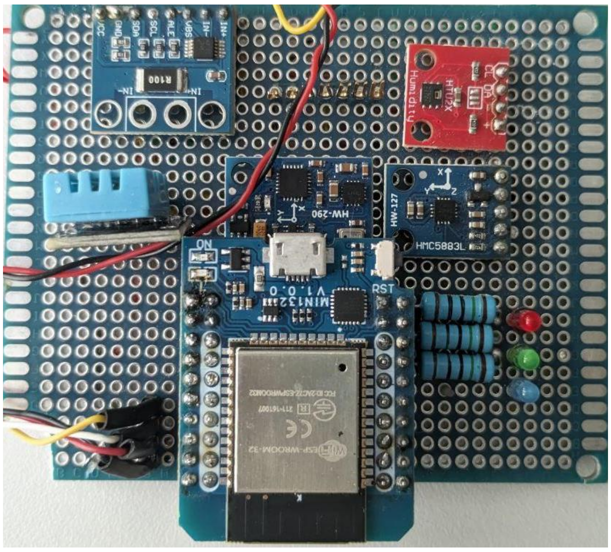

Fig. 2: Layout of Modules on A Breadboard.

The design of the probe is developed to minimize weight while maintaining the necessary functionality and resistance to stratospheric conditions. The assembled stratospheric probe is shown in Fig. 3.

Fig. 3: External Appearance of the Arcticzond Stratospheric Probe.

2.2. Probe software (firmware)

The internal software of the ArcticZond stratospheric probe is developed in C++ using the PlatformIO development environment, which ensures ease of use with ESP32 microcontrollers and dependency management in the project. The main task of the firmware is the initialization and continuous polling of all connected sensors, primary processing of the received data, their packaging in a structured format and transmission to the ground station and logger for further analysis. The software architecture is based on the execution of periodic tasks for collecting and transmitting data using non-blocking delays, which allows for efficient use of the microcontroller's resources.
The firmware implementation includes several key functional modules, each of which is responsible for interacting with a specific hardware component or performing a specific task of processing and transmitting data.

- The module for initialization and interaction with sensors is responsible for the correct activation and configuration of all peripheral devices and sensors connected to the ESP32 microcontroller. It includes functions for initializing communication interfaces (Serial for debugging/logger, Serial1/Serial3 for GPS, SoftwareSerial for radio modem, Wire for I2C) and the sensors themselves. Interaction with the Atom Fast radiation detector is carried out via the Bluetooth Low Energy (BLE) wireless interface. The dosimeter, calibrated by the manufacturer, provides two key readings: the count rate of registered events (pulses per second) and the dose rate (in microsieverts per hour), while the dose rate value is calculated by the dosimeter based on the registered pulses using an internal coefficient.

- The module for processing and generating telemetry messages performs primary processing and formatting of raw data read from sensors before transmission. The firmware implements a function that is the main program cycle. Within this cycle, with a certain frequency (2000 ms for data sent via cable/to the logger, and 6000 ms for data sent via radio channel), all sensors are polled and data is collected. After collecting data from all sources, a telemetry message is generated in JSON format.

The firmware provides for sending two types of JSON messages via the radio channel: short and extended. The short message contains a minimum set of critical parameters (count rate, pressure, temperature, humidity, coordinates, GPS altitude, message counter) and is sent more frequently. The extended message includes a full set of data from all sensors. Using two message formats allows you to save the transmission of the most important information even with limited radio channel bandwidth and partially implement data redundancy. Data is sent by calling a function that converts the JSON object into a string.

- Using the Data Transfer and Recording Module, the generated JSON messages are transmitted over multiple channels to ensure reliable data collection. Wired Channel (Serial): Data is sent to the serial port, which can be used for debugging or to connect to the ground station computer via a cable during ground tests. Logging Channel (Serial2): Data is sent to another serial port, which is connected to the SD card logging module. This ensures that all collected data is backed up and can be recovered even if radio communication is lost or the probe is damaged after landing. Radio Channel (SoftwareSerial): Short and extended messages are sent to the radioSerial port, which is connected to the ebyte e32 radio modem, for wireless transmission to the ground station.

Thus, the stratospheric probe software implements a comprehensive logic for collecting, processing and transmitting telemetry measurements, ensuring continuous monitoring of flight parameters and radiation conditions, as well as providing data duplication mechanisms to increase the reliability of the system under high-altitude experiment conditions.

2.3. Ground station software

The ground station software is an integral part of the hardware-software complex and is a developed software product designed to receive, process, visualize and store long-term telemetry measurements from the stratospheric probe and other platforms, such as the ground station and space satellite. The development was carried out in the Python programming language using specialized libraries and frameworks, which made it possible to create a functional and flexible application. The appearance of the application is shown in Figure 4.

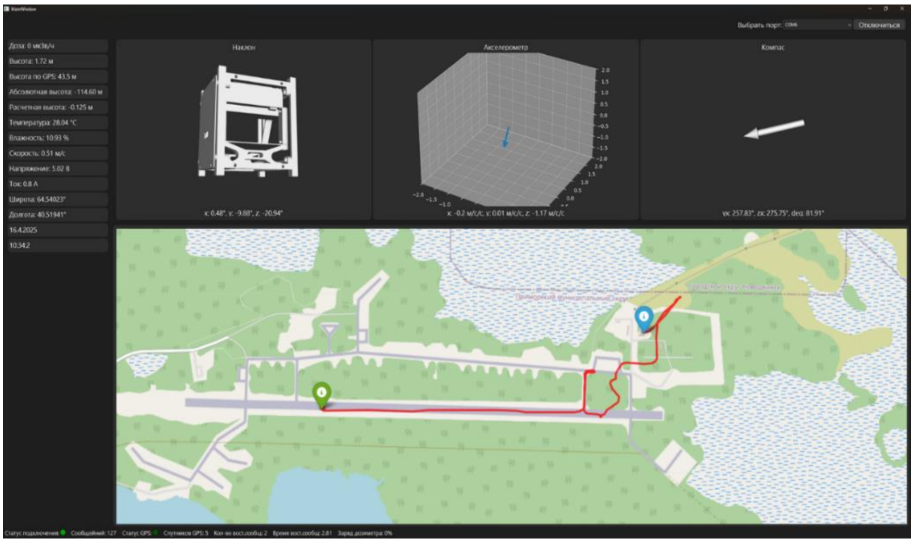

Fig. 4: Ground Station User Interface.

The interface is logically divided into several areas. At the top is the connection control panel, which contains a drop-down list for selecting a COM port, the "Refresh" and "Connect/Disconnect" buttons, and a connection status indicator.

The left part of the window contains a vertical panel displaying text telemetry indicators. Here are the numerical values of the parameters received from the probe sensors and calculated by the program: dose, altitude (barometric), altitude by GPS, absolute altitude (barometric), calculated altitude (according to the developed algorithm), temperature, humidity, speed, voltage, current, latitude, longitude, as well as date and time by GPS.

The central and right areas of the window are reserved for visual widgets that provide a graphical representation of the data. Above the map are three widgets that display the spatial position and motion of the probe: "Tilt" (displays the orientation of the device), "Accelerometer" (visualizes the acceleration vector), and "Compass" (direction). Below these widgets is the main area, occupied by an interactive route map that displays the probe's flight path using GPS coordinates.

At the bottom of the window there is a status bar that provides service information: port connection status, total number of received messages, GPS fixation status and number of visible satellites, as well as message recovery status and dosimeter battery charge.

Thus, the developed software for the ground station provides the operator with a convenient and visual tool for monitoring the flight of the stratospheric probe in real time and accessing the collected telemetry information.

2.4. Performing the experiment

Before the experiment, the calibration alignment of the measuring devices was performed, which was necessary to match the readings between different measuring systems. Calibration consistency between the detectors was verified by simultaneous exposure to a controlled radiation source at ground level, ensuring uniform response and cross-alignment of the measurement channels. All components of the experimental setup were synchronized by GPS time, which ensured precise time coordination of the launch and subsequent comparison of disparate data. The probe was launched from the ground complex at a strictly defined moment, synchronized with the active movement phase of the satellite. During the measurements, the ArcticZond probe crossed key atmospheric layers, simultaneously recording radiation and meteorological parameters, while the ground complex received telemetry and conducted control measurements, and the ArcticSat-1

satellite recorded cosmic radiation indicators. All obtained data had precise time marks for subsequent in-depth analysis and post-processing. The probe's ascent covered the region of the so-called Pfotzer Maximum — the altitude range (typically around 15–20 km) where the intensity of secondary cosmic radiation reaches its peak due to interactions between primary cosmic rays and atmospheric particles.
The Atom Fast dosimeter used on the stratospheric probe and ground station is equipped with a scintillation detector based on a cesium iodide crystal. According to technical specifications, this detector is capable of registering photon (gamma and X-ray) radiation and electron flows. The energy range of the registered photon radiation is at least 25 - 3000 keV. Thus, the readings of the Atom Fast dosimeter mainly reflect the intensity of the flow of gamma quanta and high-energy electrons.
The ArcticSat-1 spacecraft carries the DeCoR-2 radiation detector. This device is also a scintillation detector. It is designed to register X-ray and gamma radiation with an intensity of up to 20,000 photons/s in the energy range from 0.01 to 3.0 MeV. It also registers electron fluxes with energies above 0.3 MeV. Thus, the detectors on the probe and the satellite, being scintillation detectors, register similar types of particles - photons and electrons, although they can have different effective registration ranges and sensitivity to different types of secondary radiation particles (for example, neutrons or muons).
During the processing of the results, the altitude data were corrected using a combination of GPS measurements and barometric readings, including calibration relative to the geoid for each time interval. Radiation measurements from three platforms were analyzed in relation to time and space coordinates, which made it possible to calculate the attenuation coefficients of high-energy particles in the atmosphere. Interpretation of changes in the radiation background was carried out with mandatory consideration of current atmospheric conditions – pressure, temperature and humidity, which made it possible to assess the degree of influence of various atmospheric layers on the passage of high-energy particles.

3. Results and Discussion

In the lower layers of the atmosphere, immediately after the launch, a level of background radiation is observed that corresponds to the ground background in the area of the experiment. According to the flight data, this level is on average about 0.065 µSv/h. This value corresponds to the expected background radiation level at the Earth's surface in combination with radiation from natural radioactive sources. With further increase in altitude within the first hundreds of meters, a decrease in the registered dose rate is observed, and then fluctuations in the range up to ~1000 meters. Such behavior in the ground layer may be associated with a gradual removal from local ground sources of background radiation and the beginning of the manifestation of the effect of atmospheric absorption, which in the lowest layers may dominate over the growth of the cosmic ray flux.
Above 1000-2000 meters, a steady and significant increase in the intensity of cosmic radiation is observed with increasing altitude. By the time 10,000 meters are reached, the dose rate increases to approximately 0.2 µSv/h. This increase is an expected effect of the reduced shielding effect of the atmosphere on secondary cosmic ray particles. The higher the probe rises, the thinner the air above it, and the more intense the flux of secondary particles becomes. The observed increase in radiation intensity with altitude in the range from ~1000-2000 m to 10,000 m confirms the hypothesis of an increase in the flux with altitude in the troposphere/lower stratosphere. It should be noted that the Pfotzer maximum is at significantly higher altitudes (18-25 km), and the flight to 10,000 m covers only the initial section of the zone of active intensity increase before reaching this maximum.
In addition to the altitude profile analysis, the conceptual feasibility of obtaining synchronous data from different monitoring levels was demonstrated. Fig. 5 shows a graph of the flux intensity recorded simultaneously at a ground station (ground level, Atom Fast detector), a stratospheric probe (during test launches, Atom Fast detector), and the ArcticSat-1 space satellite (DeCoR-2 detector). The results clearly show a consistent increase in radiation intensity with altitude—lowest at ground level, intermediate at the probe altitude, and highest on the spacecraft. Short-term peaks, particularly those observed in the spacecraft data around minute 40, indicate transient increases in high-energy particle fluxes likely associated with variations in geomagnetic or solar conditions. The parallel structure of the curves confirms the synchronization and cross-comparability of the measurements across platforms, thus validating the functionality of the multi-level monitoring concept.

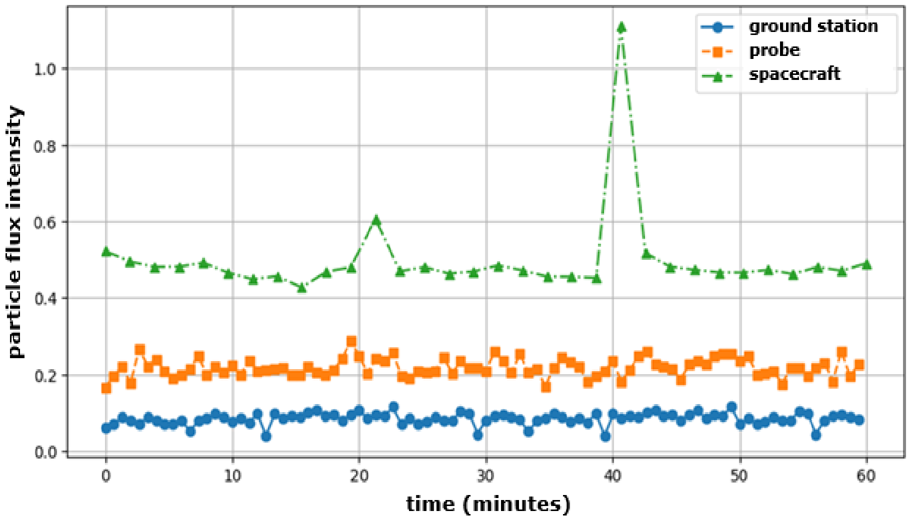

Fig. 5: Particle Flux Intensity Based on Synchronous Measurements at A Ground Station, Stratospheric Probe and Spacecraft.

The conducted experimental testing confirmed the operability of the developed software and hardware complex and demonstrated the applicability of the proposed method for obtaining data on the distribution of high-energy particles in the atmosphere. The results, including the identification of features of the radiation profile in the lower and middle layers of the atmosphere, create the basis for further research and improvement of the system.

The developed complex and data collection methodology can be used to refine models of atmospheric propagation of cosmic rays, assess radiation risks for aviation and develop measures to protect on-board electronics of spacecraft. Thus, the developed complex is a flexible platform for conducting a wide range of scientific and applied research in the field of space meteorology and radiation safety.

Nevertheless, certain limitations of the current study deserve notice. The maximum altitude that could be reached in the test flight (10 km) excluded the possibility of the Pfotzer Maximum area's immediate observation, where the secondary cosmic ray intensity has its maximum. Also, the measurement was done under fairly stable meteorological conditions, which limits the analysis of the system's performance for a wide variety of pressures, temperatures, and geomagnetic configurations. Future work needs to include high altitude ballooning experiments all the way to 30 km and also repetitive measurement experiments under a wide variety of seasonal and geomagnetic conditions so that the system's strength, calibration accuracy, and its flexibility are studied under a wider variety of environments.

4. Conclusion

As part of the study, a hardware-software complex and testing methodology for multi-level monitoring of high-energy particles in the Earth's atmosphere and space were successfully created and tested. The relevance of this topic is due to the need for a deeper understanding of the distribution of cosmic radiation and ensuring the safety of technical systems in the conditions of dynamically changing space weather factors [11-16].

A hardware-software system has been developed, including the ArcticZond stratospheric probe and ground station software. The probe hardware, built on the ESP32 microcontroller with an integrated Atom Fast dosimeter and a set of atmospheric and navigation sensors, has demonstrated its ability to collect the necessary telemetry. The probe software ensures the collection, processing and duplication of data, and the ground station software implements the reception, parsing, processing, visualization and storage of telemetry, including the developed algorithms for determining the altitude and visualization of geospatial data.

A methodology for conducting a multi-level experiment has been developed, focused on synchronous data collection from a ground station, a stratospheric probe, and the ArcticSat-1 space satellite with the DeCoR-2 detector. The methodology ensures that measurements are linked to time and spatial position, which is critical for constructing vertical radiation distribution profiles.

Experimental testing of the developed complex was conducted. The tests confirmed its operability, providing data suitable for partial analysis of radiation distribution by altitude. The flight results demonstrated the expected behavior of the flow: a decrease in the surface layer and an increase in intensity with altitude.

The data obtained during the experiment are of interest not only in terms of confirming hypotheses, but also as a geospatial sample suitable for applying intelligent analysis methods [17, 18]. Comparison of dosimetric measurements with coordinates and altitude allows us to move on to constructing models of the spatial-temporal distribution of radiation, visualizing data in GIS systems, and using machine learning algorithms. This is especially relevant when expanding the measurement base as part of future stratospheric launches, including synchronization with data from satellite monitoring systems.

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