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Investigation of the energy spectrum and chemical composition of primary cosmic rays in 1–100 PeV energy range with a UAV-borne detector

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Abstract: A new project is developed with the implementation of a relatively new method of studying primary cosmic rays — the detection of reflected from the snow surface optical Vavilov-Cherenkov radiation from extensive air showers. The aim of the new project is to study the cosmic ray mass composition in the energy range of 1–100 PeV. Silicon photomultipliers are planned to be used as the main photosensitive element of the detector and an unmanned aerial vehicle is going to be used to lift the measuring equipment over the snow surface.

Keywords: Cherenkov detectors; Photon detectors for UV, visible and IR photons (solid-state) (PIN diodes, APDs, Si-PMTs, G-APDs, CCDs, EBCCDs, EMCCDs, CMOS imagers, etc); Balloon instrumentation

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Contents

1 Introduction

The 1–100 PeV energy range is considered to be a transitional area from galactic to extragalactic cosmic rays. More than 50 years ago a change in the slope of the energy spectrum of primary cosmic rays (PCR) was detected at around 3 PeV (the "knee"), but even nowadays new features in the structure of the spectrum are being discovered. In this regard understanding the cause of these slope irregularities is of a prime interest. One of the mechanisms behind these irregularities may be a change in the mass composition of the PCR near this region. Presently used methods allow to estimate either the average mass of PCR particles or to divide them into "light" and "heavy" groups. Most of the primary particle mass reconstruction methods estimate the depth of the extensive air shower (EAS) maximum from the recorded data, but the relation between EAS maximum depth, zenith angle, energy and mass is derived solely from the models. Present day models of nucleon-nucleon interactions at high energies show such differences in the results that the methodological uncertainties are greater than the predicted differences between nuclei mass groups.

This project is focused on the development of a unique detector with photodetectors based on silicon photomultipliers (SiPM), to be installed on an unmanned aerial vehicle (UAV). Currently, there are no other devices and installations that would successfully use the reflected Cherenkov light (CL) detection method. This method allows to achieve the highest accuracy of estimation of the chemical composition of PCR in the analysis of the individual EAS events in comparison with existing ground-based installations. Successful implementation of the project will allow to obtain experimental data for the reconstruction of partial spectra for several mass groups of PCR particles (protons, helium, CNO and Fe groups) in the 1–100 PeV energy range.

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2 Method overview

We propose to apply the reflected Cherenkov light detection method [1] for this experiment. The main idea of this method is to detect the EAS CL reflected from the snow covered surface using a compact apparatus lifted above the ground. The initial idea was first introduced by A.E. Chudakov in [2]. Later the technique was successfully implemented in our earlier experiments [1, 3].

The properties of the snow surface play an important role when using the method of reflected CL detection. The results on the snow optical properties have been repeatedly published by several groups [4–8]. Simulation results show that in the wavelength range from 300 to 600 nm, the relative reflectance of pure snow is stable within 3% for light incidence angles from 0° to 80°. From these results and the known CL spectral characteristics it can be concluded that the snow surface reflects the CL with minor spectral distortions at up to 80° incidence angles and can be used as a "screen" for EAS CL detection.

2.1 Method advantages

The method of reflected CL detection has the following advantages over traditional EAS detection methods:

- The method provides a significant area of CL detection using a compact device;
- Accurate estimation of PCR energy in an individual event thanks to the quasi-calorimetric method of energy detection;
- The field of view of individual sensitive elements of the device covers a significant part of the surveyed area, what allows to observe the EAS CL near the shower axis, usually inaccessible to ground-based CL detector arrays. This circumstance significantly increases the accuracy of the primary particle type estimation;
- Allows to measure the same PCR energy range with different resolution (distance between the centres of the fields of view of neighbouring sensory elements) by variating the elevation of the detector, thus allowing to control the magnitude of systematic errors;
- The small size of the required detector allows to combine the calibration techniques accessible currently only to imaging air Cherenkov telescopes (direct calibration) with large scale measurements that are accessible only for conventional ground-based arrays;
- Precise timing and high level of synchronization for better primary particle arrival direction reconstruction what has a direct impact on the precision of the EAS energy estimation.
- The compact and tight arrangement of the detector electronics and sensitive elements allows the use of complex local topological trigger conditions that can greatly decrease random coincidences thus allowing to lower the energy threshold for the measurements.

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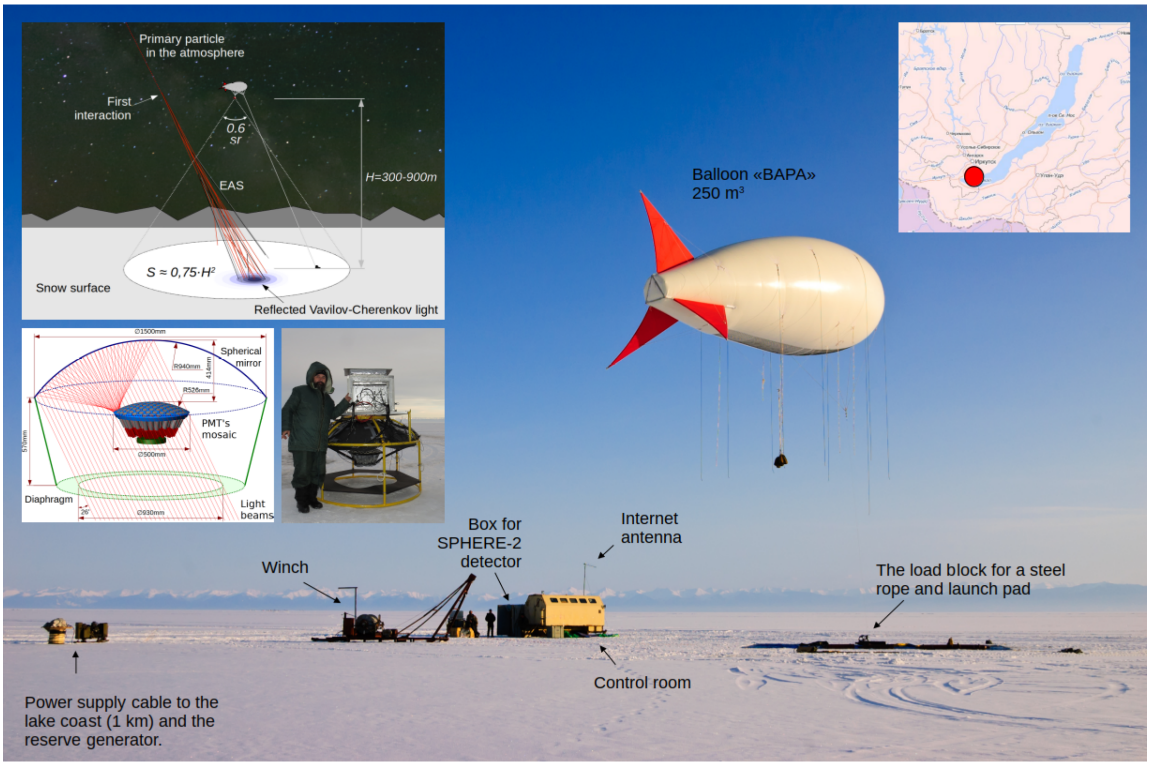

Figure 1. Experiment with the SPHERE-2 installation on lake Baikal.

2.2 SPHERE-2. Previous detector version

In the period from 2008 to 2013, a series of measurements of reflected Cherenkov light was carried out using the SPHERE-2 [1, 3, 9] balloon detector.

The SPHERE-2 apparatus was constructed with a 1.5 m diameter spherical mirror with a 0.93 m Shmidt diaphragm window. Cherenkov light was detected by a 109 PMT mosaic located near the focal surface of the spherical mirror. The scheme of the optical part of the detector is shown on the left in figure 1. The full description of the SPHERE-2 detector can be found in [1, 10].

Measurements were made over the snow-covered ice of Baikal lake. The figure 1 shows the landing point on the Baikal lake surface and the special BAPA balloon designed for the experiment.

The energy spectrum of all particles was measured and published [3]. The energy spectrum detected by the SPHERE-2 detector is shown in figure 2 (left) in comparison with some other ground-based arrays. The systematical error of the SPHERE experiment is compatible with the one of the KASCADE Grande and is smaller than the Tunka experiment systematical error [11]. The light nuclei part estimation is shown in figure 2 (right).

The SPHERE-2 apparatus had not fully utilized all the possibilities of the method due to two main reasons. First was the low sensitivity of the PMT matrix. The FEU-84 PMT [14] had a low quantum efficiency and covered only 30% of the total surface leaving 70% insensitive to light. This reduced the expected statistical material by more than 5 times due to the increase in the detection energy threshold. The second reason were the technical difficulties associated with the need to maintain the balloon in working conditions for the multiple launches of the detector. Each 10-day

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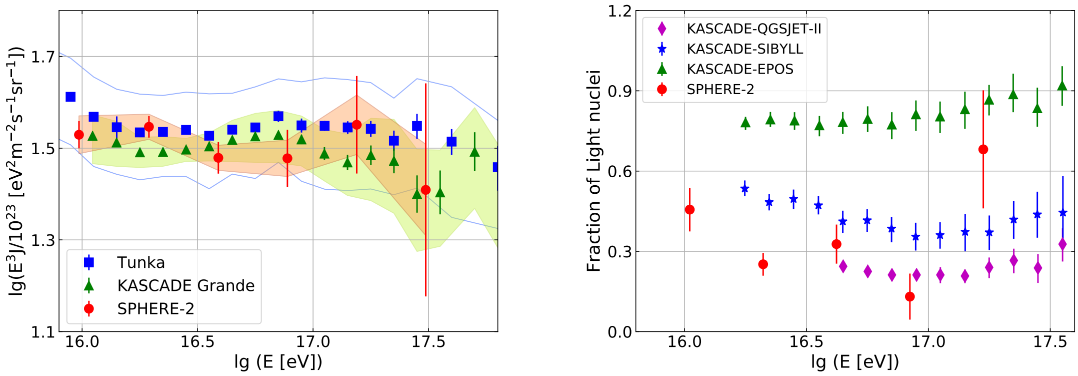

Figure 2. Results of the SPHERE-2 experiment. On the left the energy spectrum of the PCR (red circles) is shown in comparison with the results of the Tunka-133 [11] (blue squares) and KASCADE Grande [12] (green triangles) experiments. On the right the chemical composition estimates are shown (red circles) in comparison with the results of the KASCADE Grande experiment [13].

measurement session required at least 6 tons of cargo with helium cylinders to be transported to the measurement site, so no more than one session was possible per year. While theoretically during the winter season it is possible to perform up to 5 sessions per year.

Taking into account all of the mentioned difficulties we have developed a new detector based on a SiPM light sensor. The small mass of the detector will allow to abandon the cumbersome and time-consuming to use balloon and switch to a UAV as a carrier. This experimental setup has never been used before for the study of ultra high energy PCR. Currently, in the field of ultrahigh energy cosmic rays astrophysics, UAVs are used only for solving auxiliary tasks such as atmosphere monitoring and calibration of ground detectors.

3 The detector

Good methodological measurement accuracy is required for the development of new experiments. Based on the operating experience of the SPHERE-2 detector it is possible to design a new detector that will be superior in its capabilities.

Advantages of the described above technique and progress in the field of microelectronics already allow to design a compact detector of reflected EAS CL with a big effective area of detection, a wide viewing angle (for PCR) and high spatial resolution.

In comparison to a ground detector array (with an effective area of about 1 km^2 and more, service infrastructure etc.) a compact detector weighing up to 10 kg with similar characteristics (geometric factor) will cost less in terms of the amount of material and labor providing comparable scientific results.

A compact detector that will have the following characteristics is currently in design:

- Optics sensitive area (aperture input window) around 0.1 m^2;
- Mirror diameter 0.8 or 1 m;

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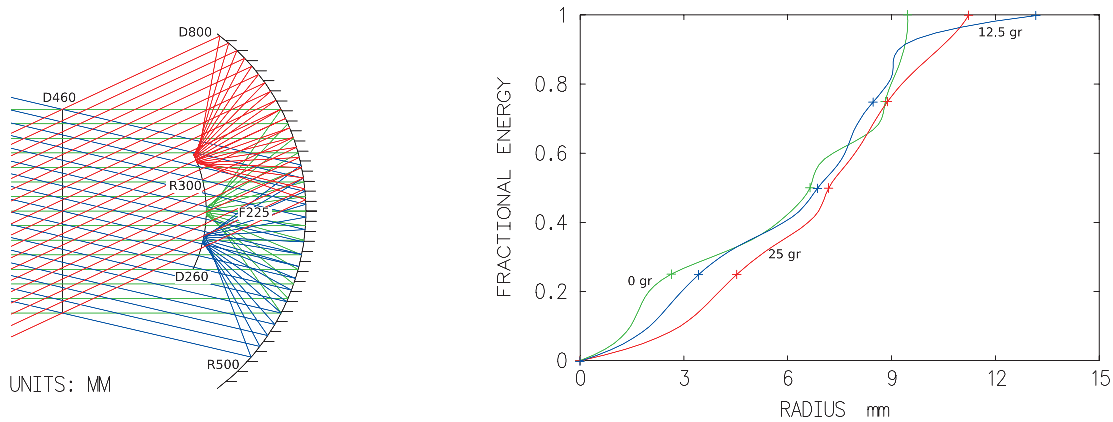

Figure 3. Optical scheme of the developed detector (without shadow from the mosaic) and the fractional light energy distribution on the focal plane taking into account the shadow from the mosaic. Red color corresponds to the rays coming at an angle of 25° from the optical axis, blue — 12.5° and green — paraxial.

- Optical system viewing angle up to ±25 degrees;
- Number of mosaic elements 133–259 SiPM;
- The mass of the detector less than 10 kg;
- Detector flight altitude — 300–700 m;
- Expected number of EAS events (with E_0 = 1–100 PeV) up to 3 000 per season.

One of the optical scheme variants based on the simplified Schmidt scheme (no corrector plate) is shown in figure 3 (left). The calculations were performed using the OSLO EDU program. The rays are shown without absorption on the backside of the SiPM mosaic for illustration only. The detector is planned to have a spherical 800 mm in diameter mirror with a 500 mm curvature radius. The 460 mm in diameter diaphragm is to be situated 550 mm from the mirror centre.

The image of the reflected CL is formed on a photosensitive spherical surface with a 260 mm diameter and 300 mm curvature radius. The optimum distance for this set of parameters is 225 mm from the mirror. Maximum observation angle is ±25°.

In figure 3 (right) the relative amount of light collected within a certain radius is shown. Different colors show different incidence angles relative to the detector optical axis. In figure 4 the light spots on the photosensitive detector surface are shown for different conditions — three light incidence angles on the detector (0°, 18.1° and 25°) and five offsets of the photosensitive surface. For reference a 20 mm scale line is shown in the lower left corner. The spots were calculated for the 420 nm wavelength.

The mirror for the detector is planned to be constructed of composite materials with cellular aluminum for the base. This design has sufficient rigidity and low weight.

The main element of the new device will be a segment of seven Micro FC-60035 SiPMs. The tests of a matrix of seven such segments (49 SiPM) was successfully completed (see figure 5). Each segment was equipped with seven preamplifiers and a temperature sensor to account for the effects

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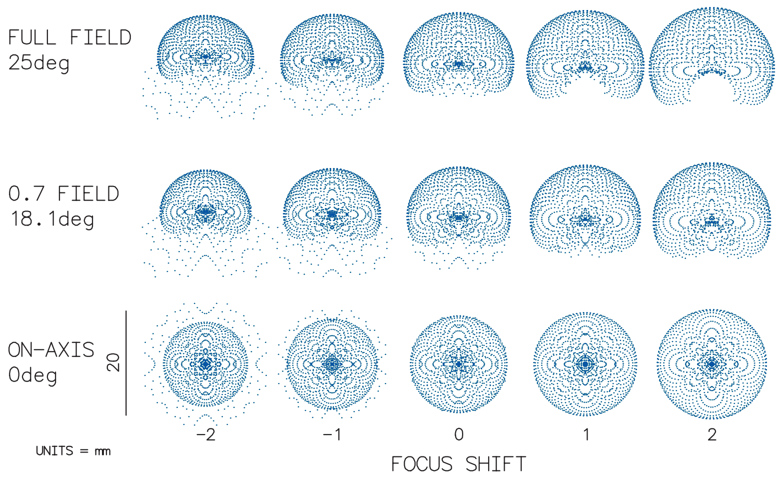

Figure 4. Images of light spots on the focal surface of the detector from parallel light beams taking into account the shadow from the mosaic. All values are given in mm.

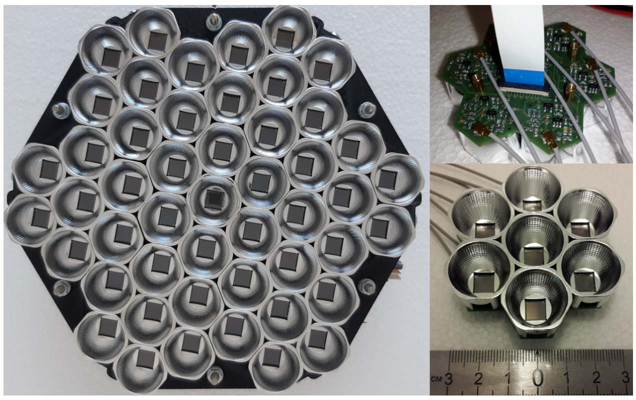

Figure 5. The prototype matrix of 49 SiPM assembled from seven electronic boards of 7 SiPM with preamplifiers.

of thermal emission and gain shift. Each SiPM was equipped with a CA10929 Boom-MC-W light collector with angular characteristic of ±24 degrees at 50% effectiveness. The assembled SiPM matrix was successfully tested as the sensitive element of the Small Imaging Telescope withing the TAIGA Project (for details see [15]). In this project, it is planned to modify and adapt the SiPM segment for the use in an ultra-wide angle optical system.

To detect analogue signals from SiPMs, a digitization board based on the AnalogDevices ADS5296A 8-channel fast analog-to-digital converter (FADC) chip will be developed. The sampling frequency of this chip is up to 80 MS/s (12.5 ns step) at 12-bit resolution and 100 MS/s (10 ns step) at 10-bit resolution. The board design allows to reduce the time of digitization by a factor of 2 by installing two FADCs on each SiPM. The small size of the chip (9×9 mm) allows to significantly reduce the detector weight and dimensions. Digitized signals from each channel are transmitted in serial code to the LVDS interface on a XILINX Zynq FPGA module. These modules are equipped with a built-in computer running on the Linux operating system. All internal logic of the measuring

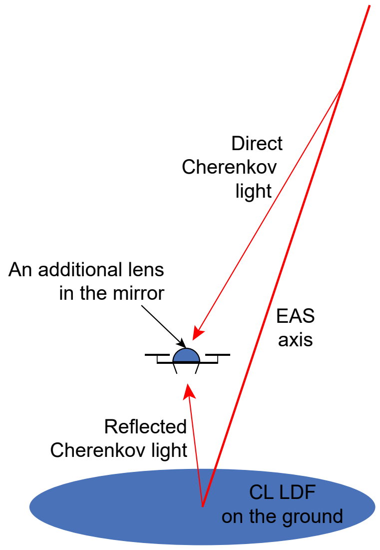

Figure 6. Scheme of direct and reflected Cherenkov light of EAS.

and the trigger systems are recorded in the chip as a configuration file (a program in the VHDL language of integrated circuit equipment description). This will allow more flexibility during testing and in real measurements depending on the conditions. The measurement results are to be recorded on a SSD drive of the on-board computer for further processing.

4 Evolution of the experiment concept

We generally follow the concept of the SPHERE-2 experiment with one improvement and one major change. The former refers to the new camera ensuring more detailed analysis of the lateral distribution of EAS CL. The other relates to the completely new information channel to be included in the SPHERE-3 detector.

The detector will use the simplified Schmidt optical system. In this system, the central part of the mirror is not used since it is in the shadow of the photodetector. A hole in the centre of the mirror with a wide-angle lens in it with an aperture of about 100 cm^2 will allow to detect direct CL (see figure 6). Calculations show that for a EAS form a 1 PeV particle the density of CL photons 100 m from the shower axis is around 100 photons/cm^2. Taking into account the SiPM quantum efficiency and losses on optical elements the total signal from the direct CL is expected to be at around 1000 photoelectrons.

The main function of the direct CL detection is to increase both the sensitivity and the specificity of the criteria for separating actual EAS events using the correlated signals of direct and reflected CL. It is already clear that accurate detection and analysis of the CL angular distribution can yield substantial information on the PCR mass composition [16, 17]. But such an experiment requires a large and more complex detector or even an array of such detectors placed wide apart, e.g. borne by a number of UAVs.

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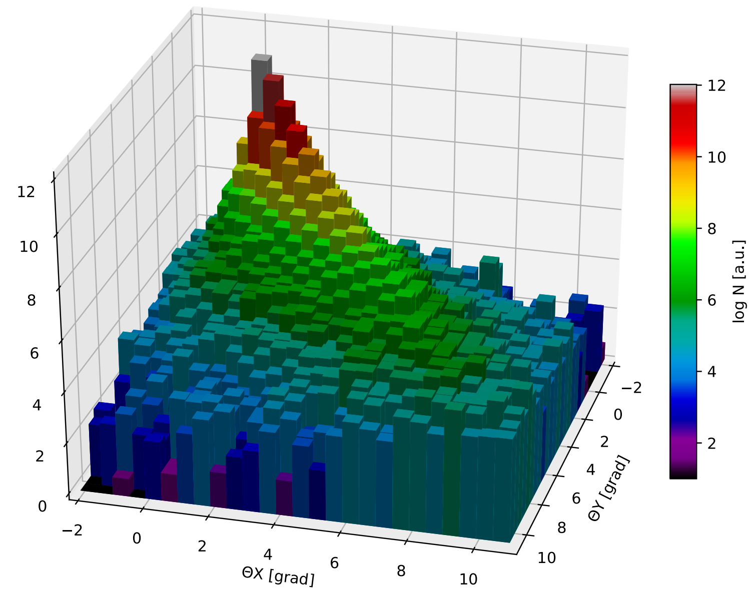

Figure 7. Angular distribution of direct Cherenkov light from EAS. Primary particle: vertical 1 PeV proton. Core distance: 100 m. Observation level: 220 m above snowed surface.

The second function of the direct CL detection channel is a preliminary study of the possibility to estimate the shape and angular size of the CL flash (see figure 7 for CL photons angular distribution example), which will help us to elaborate a new version of the detector capable of distinguishing between different primary masses using both lateral and angular CL characteristics.

Currently the main means of primary mass separation are the criteria based on the shape of EAS CL lateral distribution over the snowed surface seen by SPHERE-3 optical system. Presumably such criteria will work better than with SPHERE-2 due to the higher spacial resolution of the new detector.

Primary mass estimation is by far the most difficult part of the primary particle parameter evaluation problem. It is no wonder that the PCR mass composition is still poorly known after more than half a century of studies. Modeling of EAS CL characteritics [16–19] enables us to put forward some basic principles for choosing the criterial parameters for the primary mass separation:

- such parameter should be directly measurable or, at least, directly calculable from the measured quantities; this property may be called *observability*;
- another property is called *integrality*: the parameter must rely on the substantial part of the whole distribution measured (e.g., appreciable part of CL photons seen by the detector); this property ensures the suppression of fluctuations which hinder the process of classification/separation;
- one more important property of a criterial parameter is its *relativity*: it must reflect the shape of the distribution of the measured characteristic; this quality makes the parameter weakly dependent on the primary energy and, what is even more important, on the nuclear interaction model at super high energies; the latter feature has already been checked on EAS CL angular and lateral distributions [16–19] but will likely hold on other shower characteristic distributions.

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After all these points are taken into account one should optimize the definition of a criteria parameter with respect to fluctuations. In other words, parameter values must have minimum possible variations for a given primary mass.

5 The UAV as an experiment platform

As a detector carrier at first stage it is planned to use the DS1400 octocopter or a similar UAV. The continuous operation time of this drone reaches 40 minutes. To increase the exposure time several sets of charged batteries prepared before launch should be used. To ensure the continuity of measurements it is planned to use an additional UAV with the same detector (e.g. two detectors are to be built). At the second stage of project implementation it is possible that a group of several UAVs will be used to proportionally increase the geometric factor and statistical reliability of the results.

The use of hydrogen-air fuel cells or gasoline DELTA H1600H UAV (or its analog) with a continuous operation time of up to several hours will greatly simplify the measurement process and improve the efficiency of experimental data collection.

To control the density and transparency of the atmosphere an auxiliary small quadrocopter DS550 UAV can be used with pressure, temperature, humidity sensors and a fast LED flash to produce artificial EAS-like light spots on the snow (in full spirit of the original idea [2]). The flash will be used to control the reflective properties of the snow and its geometry. Control of the atmosphere and reflection from the snow will improve the accuracy of measuring the EAS CL.

6 Conclusion

This project is the next realization of the reflected EAS CL detection method. The successful work with the SPHERE-2 detector gave a better understanding of the advantages of this method and its perspectives. The small scale of the detector allows to bypass many obstacles in the EAS detection such as calibration, timing and trigger conditions. Successful design and operation of the TAIGA Small Imaging Telescope shows that the SiPM matrix can be used as a sensitive element in telescope systems.

The proposed detectors optical system is also aimed at expanding the detection technique to accommodate direct CL measurements what will allow to combine two sources of information on EAS in a single detector with a single sensitive element.

Acknowledgments

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