Future instrumentation in cosmic ray research

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Abstract. This paper is based on a rapporteur talk given at the 24th European Cosmic Ray Symposium (Kiel, Germany, September 1 - 5, 2014). The object of the talk and paper is a summary based on oral talks and posters presented in the frame of the session “Future instrumentation in cosmic ray research (INS)”.

1. Introduction
The program of the session "Future instrumentation in cosmic ray research (INS)" included three highlight talks, 11 contributed oral talks and 9 posters. Apart from the INS session, 12 talks and posters related to the topic of the session were given. Four themes dominated the presentations: future space missions (two highlight and two contributed talks), the TAIGA project (one highlight and two oral talks, one poster), radio detection of EAS (two oral talks and two posters) and the experimental complex NEVOD (three posters). Other talks and posters were devoted to different aspects of the development of experimental techniques and new apparatus for cosmic ray research.

2. Orbital and space missions
2.1. Fluorescence orbital detectors
There are three projects of space-born apparatus towards the realization of an idea proposed three decades ago [1], the idea to observe ultra-high energy air showers via fluorescence light in a huge atmospheric volume from space: the TUS (Tracking Ultraviolet Setup) detector on board of the “Mikhail Lomonosov” satellite to be launched in 2015 [2]; the JEM-EUSO project [3] which represents a large space-borne fluorescence detector proposed to be installed on the ISS, and the KLYPVE project recently started in SINP MSU and to be installed on board of the Russian segment of the ISS. A vital feature of future space measurements is the variable noise intensity of background UV light of the atmosphere below the satellite. First estimates of the light background have been obtained on board of Universitetsky-Tatiana-2 satellite by a single pixel of TUS camera design, at about the same orbit as that planned for the Lomonosov satellite [4]. Temporal profiles of transients in UV and red wavelengths in a FOV of 300 km diameter were measured in the atmosphere. Comparing the intensities of UHECR events and the intensity of transients from Tatiana-2 data one finds that transient events exceed the number of expected UHECR events by about two order of magnitude. Above the equatorial regions of continents, the transient rate in the TUS detector will be as high as 1 per minute. Comparison of the space-time structure of transients and UHECR showers will likely allow
distinguishing both types of events, but the high trigger rate from transients challenges storage of the data before they are transmitted to Earth.

The TUS detector (see Figure 1) is developed in SINP MSU (Moscow) in cooperation with several Russian and foreign institutions and consists of a 1.8 m$^2$ Fresnel mirror-concentrator read out by 256 PMT pixels which will be able to monitor an area of 6400 km$^2$ from the orbit height of 500 km. The energy threshold for UHECR particles is about $7 \times 10^{19}$ eV. The presently estimated event rates at the lowest energies seem to be rather optimistic. They will be checked in a final energy calibration during space operation. However, it is evident that three years of TUS operation will not yield decisive statistics of UHECR events beyond the GZK limit. The main goal of the TUS experiment is providing a proof of principle and acting as a “pathfinder” detector for the next large-scale space experiments (KLYPVE, JEM-EUSO).

![Figure 1. The TUS detector on board of the Lomonosov satellite[1].](image1)

![Figure 2. The KLYPVE segmented mirror-concentrator and photodetector.](image2)

Considerably improving the TUS characteristics, SINP MSU finished the preliminary design of the KLYPVE apparatus with a reflector type telescope [5]. It will be located on the outer side of the Russian segment of ISS. The optical system of this detector contains a larger primary mirror (10 m$^2$), which allows to considerably increase the FOV of the detector in comparison with TUS and to decrease the energy threshold (see Figure 2). The optical system has a focal distance of 3 m and a total effective FOV of 15º diameter. The angular resolution is the same as in the TUS detector, i.e., 5 mrad (pixel size 15 mm × 15 mm). The annual exposure of KLYPVE will exceed the exposure of existing ground-based experiments.

In contrast to the projects TUS and KLYPVE which use reflecting mirrors, the JEM-EUSO project uses high-transmittance Fresnel lenses. The Extreme Universe Space Observatory (EUSO) project aims observing cosmic rays between $10^{20}$ and $10^{22}$ eV and is the most ambitious and sophisticated of the three projects. JEM-EUSO is also designed for the ISS. It comprises a UV telescope and an atmospheric monitoring system. The telescope consists of three Fresnel lenses with an optical aperture of 4.5 m$^2$, and a focal surface detector formed by 137 photodetector modules composed of ~ 5000 multi-anode PMTs in total. The focal surface detector thus includes ~ $3 \times 10^5$ channels providing a spatial resolution ~ 0.074º, equivalent to ~ 0.5 km at ground. The 60º opening angle provides an observational area of ~ $1.4 \times 10^5$ km$^2$ in nadir mode. The annual exposure of JEM-EUSO for UHECR above 100 EeV is estimated to be an order of magnitude larger than that of Auger [6]. At the ISS orbit (400 km), JEM-EUSO is able to survey the entire celestial sphere almost uniformly. Detailed simulations show that due to these factors JEM-EUSO will be able to detect significant anisotropies of UHECR practically in all feasible astrophysical scenarios [7] thus providing a huge step towards finding sources of UHECR. In December 2013, the Japanese Space Agency (JAXA) refused to deploy the instrument on board of the JEM. The development of the full instrument of the JEM-EUSO project
is currently facing certain problems, but two successful test experiments (EUSO-Balloon [8] and TA-EUSO [8]) demonstrated the capability of all sub-systems of the EUSO instrument to observe the fluorescence background from the edge of the atmosphere. The flight of the EUSO-Balloon on 24 August, 2014 was used to test a number of components of the telescope and the atmospheric monitoring system and represents a strong basis for the successful development of JEM-EUSO.

Quite recently, a new project, K-EUSO, was initiated. Its aim is to develop a new optical system with an increased FOV for KLYPVE which would improve the spatial and angular resolution and the overall performance of the instrument [8]. This work started in a close cooperation with the JEM-EUSO Collaboration. The new detector will combine the capabilities of optical systems based on mirror-concentrator and on Fresnel lens-corrector, respectively. The diameters of the reflector and the lens-corrector are 3.4 m and 1.7 m, respectively. The total length of the system is 4 m, the distance from the lens to the focal surface 70 cm. For such a system it is possible to expand the FOV up to ±14°. The diameter of the image from a point-like light source (point spread function) is not larger than 6 mm in the entire FOV. The expected angular resolution of the system is ~0.057°, which is equivalent to ~0.4 km at ground [8].

Another approach proposed in SINP MSU is the construction a Multi-Eye Telescope System (METS) consisting of several wide-field large aperture and K-EUSO optics systems (see Figure 3).

Figure 3. Two possible ways to build METS telescope.

The main idea of METS is to divide a wide FOV into several FOVs of identical smaller telescopes, with the following advantages: smaller dimensions of individual telescopes with narrower FOVs, lower cost and easier testing, calibration and launch to orbit. Table 1 compares spot size \(d\), effective area \(S_{\text{eff}}\), FOV \(\Omega\) and throughput \(\Omega S_{\text{eff}}\) of the five projects [5].

| Project  | \(S_{\text{eff}}\), m² | \(d\), mm | \(\Omega\), sr | \(\Omega S_{\text{eff}}\), m²sr |
|----------|------------------------|----------|--------------|--------------------------|
| TUS      | 1.2                    | 20       | 0.025        | 0.03                     |
| KLYPVE   | 5                      | 20       | 0.05         | 0.25                     |
| JEM-EUSO | 2                      | 3        | 0.8          | 1.6                      |
| K-EUSO   | 3.5                    | 3.5      | 0.2          | 0.7                      |
| METS     | 2.1                    | 3        | 0.3          | 0.63                     |

2.2. The CALET mission

The CALET (CALorimetric Electron Telescope) space experiment [9] will measure the flux of cosmic-ray electrons up to 20 TeV, of gamma rays up to 10 TeV and of nuclei up to 1000 TeV over five years. These measurements are essential to investigate possible nearby astrophysical sources of high energy electrons, to study the details of galactic particle propagation and to search for dark matter signatures. CALET consist of a charge detector, a 3 radiation length (r.l.) deep imaging
Tungsten/SciFi (scintillating fiber) calorimeter, and a 27-r.l. deep “total absorption calorimeter” made of segmented lead tungstate crystals (see Figure 4). CALET performances have been verified at accelerator beam tests. Flight hardware is currently under final integration and test, approved for launch by the HTV-5 Japanese carrier within end of March 2015 and to be installed on the Japanese Experiment Module (Kibo) on-board of ISS. CALET is much smaller than the Fermi-LAT apparatus but is optimized to measure high-energy electrons, mainly through its calorimeter of 30 radiation lengths depth (vs. 10.1 r.l. for LAT). A deeper calorimeter provides better energy resolution (~2% vs. 7−10% above 100 GeV), and improved hadron rejection [9]. The charge detector on CALET is designed to have excellent charge resolution for light elements. Last but not least, the addition of a veto counter makes CALET also an effective gamma-ray measuring instrument.

![Figure 4. Layout of the CALET payload. The main components are a charge detector (CHD), a thin imaging calorimeter (IMC) and a total absorption calorimeter (TASC).](image)

2.3. The new superconducting magnet facility
A new idea proposed in [10] suggests to equip an innovative calorimeter with an intense superconductivity magnet. In past, there were several attempts to put a superconducting (SC) magnet in space for measuring the momentum of cosmic rays. But for various reasons, the development of SC magnets ended at the design stage and only balloon experiments with prototypes were carried out. All these projects were based on the same technology: the coils are realized in NbTi SC cable, and are cooled to about 2 K by liquid super fluid He, delivered from a tank launched to orbit together with the magnet.

Nowadays, due to the development of cryogenic equipment and materials (new SC cables based in new materials such as the MgB\(_2\) cables that can be operated up to 20 K in a few Tesla magnetic field; available commercial reliable new cryo-cooler systems), the SC magnetic system can be substantially simplified, and more complex coil system can be designed for the new generation of an ‘innovative’ 3D calorimeter for identifying and measuring energy and momentum of the particles in orbital experiments. Such calorimeter can have a cubic shape, allowing to increase the aperture by an order of magnitude, up to several m\(^2\)sr. The facility consists of a cubic, homogeneous, isotropic deep calorimeter equipped with a magnetic field at 4 of its faces. The complex magnet system named the “magnetic bubble” represents 4 coils at 4 sides of the cube and constitutes a null dipole magnetic torus wrapping the cube. Four detector telescopes can be lodged between each couple of coils, the fifth side of the cube is left free for a non-magnetic telescope and the sixth side is used for the mechanical support, the electronics and services. To take full advantage of the cubic shape of the calorimeter, the facility should be operated in a high orbit, possibly outside the terrestrial magnetic field. With the cubic calorimeter the facility could have an aperture of about 5 m\(^2\)sr and measure spectra of positrons and antiprotons up to several TeV, of electrons up to >10 TeV, of protons up to 3 PeV, and ion fluxes up to the actinides.
2.4. The JUICE mission

A group from the European Space Agency presented the JUpiter ICy Moons Explorer (JUICE) mission that will fly by and observe the Galilean satellites Europa, Ganymede and Callisto, characterize the Jovian system in a lengthy Jupiter-orbit phase, and ultimately orbit Ganymede for in-depth studies of habitability, evolution and the local environment [11]. The main focus of the mission is the investigation of the moon Ganymede. Other targets of the JUICE mission will be the investigation of the Jovian magnetosphere, combined with two close flybys at Europa and 8 flybys at Callisto. For the first time the high latitude magnetosphere up to 30 degrees will be studied in detail and for an extended period of time. Ganymede's magnetosphere and its boundaries will be investigated in an elliptic orbital phase while its surface and its underneath subsurface ocean will be studied in circular orbital phases at different altitudes. The science payload consists of in-situ and remote sensing instrumentation with the newest technologies onboard. Launch of JUICE is currently planned in 2022. After Jupiter orbit insertion in 2030, the spacecraft will perform a 2.5 year tour of the Jovian system focusing on observations of the atmosphere and magnetosphere of Jupiter itself. Then, gravity assists at Callisto will shape the trajectory to perform two targeted Europa flybys and raise the orbit inclination up to 30 degrees. The Europa flybys are currently planned to observe regions of likely recent activity and possible shallow liquid water. The mission will culminate in a dedicated 8 month orbital phase around Ganymede in 2032. The Ganymede phase will include high (5000 km), medium (500 km), and low (200 km) circular orbits that will have different observation conditions optimized for particular science investigations. The total mission duration is about 11 years.

3. Radio detection of air showers

A large number of contributions at this conference were devoted to the detection of cosmic rays using the MHz emission from air showers due to either geomagnetic synchrotron radiation or the Askaryan effect. The principal feasibility of this technique in terms of the measurement of the arrival direction, energy estimate and self-triggering is already established. The presentations focused on the better understanding of the signal and the way towards physics measurements with radio arrays.

3.1. LOPES radio array

The LOPES project (LOar PrototypE Station) [12] was initiated in 2001, as a prototype station of LOFAR (The LOw-Frequency Array), with the aim to detect radio emission from EAS in coincidence with the KASCADE-Grande particle detector experiment. Although the experiment was stopped together with the KASCADE experiment, the data analysis still continues. The objectives of the LOPES project were to understand the principles for radio detection of cosmic rays with modern interferometric methods, to study and calibrate the radio emission in the energy regime up to \( \sim 10^{18} \) eV, and to develop and optimize the radio technique for large scale application at ultra-high energies. The LOPES array consists of 30 east-west aligned dipole antennas installed in co-location with KASCADE-Grande at the KIT, Germany (Figure 5). In [13], results of LOPES data analysis were presented.

The KASCADE-Grande array detects EAS from a high-energy cosmic ray event (\( 10^{15} - 10^{18} \) eV) and triggers LOPES which then digitally records the radio signal in the frequency band from 40 to 80 MHz. 316 measured LOPES events with \( E > 10^{17} \) eV and \( \theta < 45^\circ \) were selected [14]. For each measured event two corresponding CoREAS [14] simulations were performed, one for a proton as primary particle, and one for an iron nucleus. The data analysis uses interferometric methods, based on beamforming (digital shift of all traces in time by distance to wave-front) and analysis of relative timing of triggered antennas with 1 ns precision. The angle reconstructed by LOPES was compared with that obtained from the KASCADE-Grande and KASCADE reconstructions of the same events (Figure 6).
The best fit indicates that the radio wave front is sufficiently well described by a hyperbolic form. At larger distances it can be approximated by a simple cone. According to the simulations with CoREAS, the cone angle is clearly correlated with the shower maximum. Also the reconstructed $X_{\text{max}}$ is correlated with the slope of the lateral distribution. The experimentally achieved LOPES precision for the shower maximum is limited by measurement uncertainties to $\sim 140 \text{ g/cm}^2$. But CoREAS simulations indicate that under better conditions the method might give an accuracy of the shower maximum, $X_{\text{max}}$, better than 30 g/cm$^2$.

The analysis of the simulated lateral distribution of the LOPES events reveals that the radio pulse amplitude at specific distances depends linearly on the primary energy $E$. The theoretical estimate of the energy reconstruction accuracy was obtained as about 9%. Practically, the LOPES energy reconstruction is at least as precise as that from KASCADE-Grande particle detectors, namely $\sim 20\%$. Finally, the preliminary analysis of data obtained during 10 years showed that LOPES was a successful prototype for LOFAR and radio extension of KASCADE EAS array, but was not a precision experiment due to the high background. The precision for direction ($< 0.7^\circ$) and for energy ($< 20\%$) is competitive with other EAS detection techniques, that for $X_{\text{max}}$ ($\sim 90 \text{ g/cm}^2$) is worse.

Radio arrays are useful extensions to particle detectors, if they are dense and are deployed in a radio-quiet environment.

In future, the LOPES data will be accessible through the public data centre KCDC (KASCADE Cosmic Ray Data Centre) which is mainly based on the data of the KASCADE experiment [15]. The developed approaches and experimental results and techniques are used for development of a new generation of EAS radio emission detectors as for instance LOFAR [16], AERA [17] and Tunka-REX [18] which were also presented in the INS session.

### 3.2. LOFAR

LOFAR is a novel distributed radio telescope for radio astronomy in the low frequency range. It is under construction in the northern part of the Netherlands and the north-eastern part of Germany, with baselines up to 300 km. LOFAR has the capability to measure radio emission from cosmic-ray induced air showers. In the core of the array about 2300 antennas are installed within about 4 km$^2$ (see Figure 7). There are two distinct antenna types: the Low Band Antenna (LBA) which operates between 10 and 90 MHz, and the High Band Antenna (HBA) between 110 and 250 MHz. For the

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**Figure 5.** Layout of LOPES. Stars mark two antennas with east-west and north-south alignment at the same position, triangles antennas with either one alignment.

**Figure 6.** Comparison of the reconstructed KASCADE-Grande and LOPES directions. All stated numbers are determined with Gaussian fits [13].
purpose of cosmic-ray measurements a trigger is currently generated by a deployed particle detector array - the LOFAR Radboud Airshower Array (LORA) [16]. It consists of 5 stations with 4 particle scintillator detectors from the KASCADE experiment, spaced by 50–100 m distances. A trigger is sent to LOFAR when an air shower with energy $E \geq 2 \cdot 10^{16}$ eV is detected. The corresponding radio emission from showers of this energy corresponds to the LOFAR detection threshold. The basic approach for detection of radio emission from EAS was elaborated during LOPES, the LOFAR experiment is targeted to solve the following tasks: emission mechanisms; air shower simulations; shape of the shower front; arrival directions; polarization; High-Band measurements; measuring Cherenkov rings; optimal parametrization of the shower front.

Figure 7. Layout of the central part of LOFAR. Left: the crosses indicate the LBA inner and outer antenna sets, respectively. The open squares show the positions of the HBA tiles, which are split into two groups per station. The filled squares indicate the positions of the LORA particle detectors. Right: the photo of the central part.

The measured emission is strongly polarized. The geomagnetic emission mechanism clearly dominates the polarization pattern. However, a sub-dominant charge-excess component can also be seen, and it increases with increasing observer distance from the EAS axis. For a clear understanding of the radio emission pattern of air showers detected by LOFAR, a CoREAS simulation was used. The air shower simulations had to follow all individual particles and to include a realistic atmosphere, the asymmetry through interference of emission mechanisms with different directions of electric fields (geomagnetic and Askaryan effects) and the additional relativistic time-compression (arising of Cherenkov effects for suitable geometries at frequencies above 100 MHz).

The analysis of the wave front with LOFAR confirms the LOPES result, that the shape of the wave front is best parameterized as a hyperbolic curved one near the shower axis and approximately conical further out [19].

The distribution of arrival directions of the cosmic rays detected with the LBAs radio antennas demonstrated a clear north-south asymmetry; this means that the pulse power is not a simple function of the distance to the shower axis.

One of the most important goals for radio detection is to reliably reconstruct the energy and mass of primary cosmic rays. Figure 8 illustrates two important aspects that such analyses have to take into account. The CoREAS-simulated footprint of the radio signal total field strength exhibits significant asymmetries related to the superposition of the dominant geomagnetic and sub-leading charge excess components of the radiation. The significant differences between the LDF of radio signals emitted by proton-induced and iron-induced air showers are clearly seen.
Figure 8. Footprints of the 40-80 MHz total field strength for vertical $10^{17}$ eV air showers induced at the LOFAR site by a proton (left) and an iron (right) primary.

LOFAR is the only dedicated experiment with high band antennas 110-250 MHz. Signals are expected to be more affected by Cherenkov enhancement and are concentrated on a ring of emission. These visible effects are related with the influence of the non-constant refractive index of the atmosphere which leads to relativistic time-compression at higher frequencies and amplification of emission for a specific angle with respect to the shower axis. The diameter of the ring thus provides information on the depth of the shower maximum. Finally, as it follows from the analysis, measuring the same air shower with both types of antennas is very promising.

This pattern is further influenced by the non-constant and non-unity refractive index of the atmosphere, which leads to visible effects of relativistic time compression of the signal. Time compression of the pulse also allows shower emission to be detectable at GHz frequencies where coherence would otherwise be lost.

3.3. AERA

The Auger Engineering Radio Array (AERA) [17] is the radio extension of the Pierre Auger Observatory located inside the infill low-energy EAS detector AMIGA [20] near the fluorescent detector site Coihueco. It allows a radio multi-hybrid measurement of EAS with the fluorescence telescopes, the water-Cherenkov and the muon detectors. Based on experience of LOPES and CODALEMA [21], AERA is deployed over 6 km$^2$ with 124 radio stations and constitutes two sub-arrays (see Figure 9). The first one, AERA-24, was deployed in 2011 and constitutes a dense core of 24 stations with 144 m spacing. The second part of additional 100 antennas spaced by 250 or 375 m was installed in 2013. The range of detected radio signals with AERA is 30 - 80 MHz.

For AERA-24, the Log-Periodic Dipole Antennas (LPDA) antennas are used. Each of them is composed of two independent planes 4 m×4 m, placed at 3.4 m from the ground. The new stations use Butterfly type antennas similar to those designed and developed for the CODALEMA [21] and Tunka-REX experiments [18]. The AERA Butterfly antenna consists of two 2 m×2 m active bowtie antennas. AREA can be operated in a self-trigger mode in 100% duty cycle, a part of the radio stations can get an external trigger from the water Cherenkov detectors or from AMIGA scintillators.

One of the main physics tasks of AERA is the investigation of the radio emission process of air showers in geographic locations and geomagnetic fields different to those of LOPES and Tunka-REX. The distribution of reconstructed shower arrival directions for AERA events triggered by the Auger SD array reflects a north-south asymmetry due to the geomagnetic emission mechanism [17]. The comparison of the polarization angle measured at the AREA radio stations with predictions based on a model of the components (the geomagnetic separation and the Askaryan effect) reveals a clear evidence for a radial component in the radio emission process amounting 14±2% of the geomagnetic component [17]. A preliminary test on 100 externally triggered events shows that the energy estimator can describe the Auger surface detector energy measurements with a deviation of less than 30%. Current studies are focused on evaluating the precision of AERA for estimating the arrival direction, energy and composition of air showers in the energy range from $10^{17}$ to $10^{19}$ eV.
3.4. Tunka-REX

Tunka-REX (Tunka Radio Extension) enhances the Tunka-133 air-Cherenkov array placed near the southern tip of Lake Baikal [18]. Tunka-133 detects EAS induced by cosmic rays from initial particles with energies of $10^{16} - 10^{18}$ eV. The radio array Tunka-REX consists of 25 antenna stations connected to the DAQ of Tunka-133 and spread over an area of 1 km$^2$. This combination provides the possibility of hybrid measurements and cross-calibration between the air-Cherenkov and radio techniques. At each antenna position there are two orthogonally aligned short aperiodic loaded loop antennas (SALLA) with 120 cm diameter (Figure 10).

SALLA is a cheap, simple and stable antenna with a frequency range 30 – 80 MHz. One of the main goals of Tunka-REX is demonstrating, on the basis of a cross-calibration of the radio and the Cherenkov signal emitted by air showers, that the radio detection technique is competitive to traditional EAS detection techniques of ultra-high energy cosmic rays. The analysis of results of the 2012/2013 season has shown that Tunka-REX effectively detects the radio emission from EAS [22]. After quality cuts, a strong correlation between amplitude and energy was demonstrated. The study of the sensitivity to the shower maximum is continued. Tunka-REX has a high sensitivity to inclined air-showers. The deployment of one new antenna for each of the 19 scintillator stations of Tunka-Grande and 3 antennas close to HiSCORE stations is planned [22]. A very important step towards the Tunka-REX technique was made by direct calibration of all hardware components at the KASCADE array site in KIT [23]. For these purposes, a crane lifted a commercial reference radiation source to a position 10 m above the SALLA antenna, with a frequency range from 30 MHz to 1 GHz. Calibration results reveal that the behavior of the measured frequency dependence is in agreement with simulations of antenna, however the antenna simulation predicted a gain differing by a factor 11 [23].
4. TAIGA gamma-observatory

TAIGA (Tunka Advanced Instrument for cosmic ray physics and Gamma Astronomy) is a new hybrid detector system for ground-based gamma-ray astronomy for energies from a few TeV to several PeV, and for cosmic-ray studies from 100 TeV to several 100s of PeV. TAIGA will also be located in the Tunka valley, where since 2009 the Tunka-133 Cherenkov EAS detector is in operation [24, 25]. The huge progress in high energy gamma-ray astronomy has been obtained mainly from Imaging Atmospheric Cherenkov Telescopes (IACT). The sensitivity level of modern IACTs is optimized for the energy range of 100 GeV – 20 TeV. Gamma radiation with energies above 100 GeV was detected from more than 150 sources of different types, but gamma rays with energies higher than 10 TeV are detected only from about 10 sources. However, to access the energy range from 10 TeV up to several 100 TeV, a detection area of the order of 10 km$^2$ or more is required. Alternatively to imaging gamma telescopes, the shower-front sampling technique allows to install large effective areas and also naturally provides large viewing angles of the instrument. Its operating principle is based on the sampling of the density and timing (arrival-time and spread) of the air shower-front with distributed arrays of detector stations [26]. The TAIGA observatory includes HiSCORE – an array of wide-angle integrating air Cherenkov stations, furthermore an array of IACTs, an array of particle detectors, both on the surface and underground, and the Tunka-133 EAS detector. Tunka-133 is a wide-FOV (~2 sr) integrating air Cherenkov detector with 185 stations spread over an area of ~3 km$^2$. The individual stations consist of single large PMTs (diameter 20 cm or 37 cm).

Tunka-HiSCORE will be an array of wide-FOV (~0.6 sr) integrating air Cherenkov detector stations, placed at distances of 150-200m from each other, covering an area of initially ~1 km$^2$ and ~100 km$^2$ at a later phase of the experiment. Each station consists of 4 neighbored PMTs of size either 20 cm or 25 cm in diameter. The PMTs have Winston-cone shape light-guides, which increase their light collection area by factor of four (see Figure 11). DAQ and time synchronization system consists of 8-channel optical station board (OSB) for digitization of signals from anodes and dynodes of 4 PMTs of the optical station and synchronization boards (SB) placed in the DAQ center [28]. All boards are designed on the basis of DRS-4 chip and FPGA Xilinx Spartan-6. OSBs and SB are connected via single-mode optical fibers. To synchronize all stations of the array to sub-ns precision a hybrid approach, combining a custom-made synchronization technique (100 MHz clocks distributed over separate fibers from the array center), and the new White Rabbit Ethernet-based are used [29]. The accuracy of time synchronization is <1 ns. The dead time of OBS is smaller than 0.5 ms.

Methods for gamma-ray and cosmic-ray data reconstruction for HiSCORE are similar to the ones used for Tunka-133. The PMT outputs are summed up. The detector stations measure the light amplitudes and its arrival time differences over a distance of few hundred meters. This approach allows one to reconstruct with a high precision the arrival direction and the axis position of the EAS as well energy $E_0$ and shower maximum height $X_{\text{max}}$. The expected accuracy of the core location measurement is 5–6 m, that of the arrival direction about 0.1 degree, for $E_0 \sim 10\%$ and for $X_{\text{max}} \sim 15$-
The data can be used to reconstruct in detail the cosmic ray spectrum and its composition and will also improve gamma/hadron separation.

Since 2013, Tunka-HiSCORE operated as a 9-station prototype array. The array was arranged on a regular grid of 3×3 stations, with a side length of 300 m [27] (see Figure 12). The Tunka-HiSCORE stations (blue squares) are embedded in the Tunka-133 array (black circles) and cover a total area of roughly 0.1 km$^2$.

A test with a bright/wide-angle LED light source ~200 m outside the array has been performed to check single station performances and full array event reconstruction quality [29]. For the calibration experiment, 45°-inclined mirrors were installed on top of the stations. The event reconstruction precision estimate is obtained by fitting the relative trigger times of the 9 stations: RMS < 0.5 ns. The EAS reconstruction with the HiSCORE-9 prototype with EAS-model fit gave RMS ~ 0.6 ns.

The configuration of the Tunka-HiSCORE stations as of 2014 is shown in Figure 13 [27]. It comprises 28 detectors at 100 m spacing forming a super-cell structure. The total area of the setup is 0.25 km$^2$. To increase the observation time for the Crab Nebula, all optical boxes are tilted towards South by 25 degrees. The number of gamma-ray events from the Crab Nebula at energy > 40 TeV is estimated as 15-30 for one season of observations (100 hours).

The timing array Tunka-HiSCORE alone has a poor gamma-hadron separation at low energies (10–100 TeV), with a quality factor of the order of unity below 100 TeV and only reaching 2 above few hundreds TeV. To improve the selection efficiency, an underground muon detector is foreseen to determine the type of a primary particle. The possibility to select EAS initiated by a gamma-ray is based on the fact that the number of muons in a hadron-induced EAS is on average 30 times higher than in gamma-ray events. For clear separation of muon signature at energies above 100 TeV, the total area of muon detectors should be at least a few percent of the area of the whole installation. Therefore, the overall area of shielded muon detectors should be 2000-3000 m$^2$ of the total area of the Tunka-HiSCORE EAS detector. For the first stage of the muon array, scintillation detectors formerly operated as part of the EAS-TOP and the KASCADE-Grande arrays are used [27]. This so-called Tunka-GRANDE detector consists of 19 scintillation stations, each of them with a surface and an underground part. The stations are located at distances about 20 m from the centres of the Tunka-133 clusters. Each station includes 12 scintillation counters with a size 80×80×4 cm³ and is equipped with underground muon detectors with 8 identical counters in each.

The IACT array consists of up to 16 imaging Cherenkov telescopes with a reflector area of 10 m² equipped with imaging cameras of 400 PMT-based pixels. Single pixels will have an aperture of 0.36°.
FOV of the single telescope will be $8^\circ \times 8^\circ$. The inter-telescope distances will be optimized in the range of 300-600 m.

Tunka-REX (see above) may be also included in TAIGA facility in future.

The key advantages of the gamma-observatory TAIGA is the joint operation of wide-angle and narrow-angle detectors of Tunka-HiSCORE and Tunka-IACT. By operating the telescopes in monoscopic mode with distances of the order of 600 m between the telescopes, the total area covered per telescope is larger than the area that could be covered using the same number of telescopes as a stereoscopic system (requiring distances of roughly 300 m in the 10–100 TeV energy regime).

In Figure 14, the point-source survey sensitivity is shown for a 100 km$^2$ array after 1000 h of observation time (HiSCORE alone – beige, hybrid mode - red) [26]. For comparison, the point-source survey sensitivities of CTA [30], of a search for neutrinos by IceCube [31] (Milagro source stacking), and LHAASO [32, 33] (adapted to a minimum of 50 gamma-rays) are shown. For a reference, also the 50-hour pointed-observation sensitivity of CTA [34] is given.

![Figure 14. Point-source survey sensitivity of a 100 km$^2$ HiSCORE array after 1000 h of observation time [26].](image)

5. Experimental complex NEVOD

The NEVOD-DECOR group started significant upgrades of the existing facility with new additional detection systems extending the complex research capabilities. The layout of NEVOD-DECOR complex is shown in Figure 15.

The basis of the complex is the Cherenkov water detector (CWD) with a tank of 2 kt purified water, $9 \times 9 \times 26$ m$^3$. CWD NEVOD is a multipurpose detector designed for detection of all main components of CR on the Earth’s surface. Therefore, the NEVOD measuring system must have 4π-sensitivity. To provide this, a quasi-spherical measuring module (QSM) was designed [35]. The QSM comprises six PMTs FEU-200 (EKRA company, Russia) with flat 15 cm diameter cathodes directed along three orthogonal axes and placed in an aluminum housing (see Figure 16). Such a cluster of PMTs has practically isotropic sensitivity to the direction of incident Cherenkov light, since the sum of the squared amplitudes of triggered PMT signals is roughly independent of the arrival direction of the light. The detection system of CWD NEVOD is formed by a spatial lattice of QSM arranged in strings with a spacing 2.5 m along the water tank and 2.0 m across it and over the depth. Around CWD NEVOD, two systems of coordinate-tracking detectors – DECOR [36] and URAGAN [37] – are deployed. DECOR represents 8 supermodules (SM, in total 70 m$^3$) vertically arranged around the NEVOD water tank. Each SM consists of 8 layers of streamer tube chambers with external strip readout system. The angular and spatial resolution is $\sim 1^\circ$ and 1 cm respectively. The main task of the NEVOD-DECOR setup is the study of muon bundles over a wide range of multiplicities and zenith angles (up to the horizon).
During the 2005 – 2010 experimental series, a new approach to primary cosmic ray study based on a new EAS observable – the local muon density spectra (LMDS) was elaborated [38, 39]. The analysis of obtained LMDS reveals a significant excess of multi-muon events generated by PCR at energies $10^{15}-10^{18}$ eV in comparison with simulations performed within the framework of commonly used hadron interaction models (even under assumption of heavy primaries – iron nuclei). This problem is known now as “muon puzzle”.

To solve this problem, the NEVOD-DECOR group proposed the measurement of energy deposit of muon bundles in the CWD NEVOD [40]. However, DECOR SMs do not cover the entire aperture of the Cherenkov water detector and do not exclude the possibility of passing of part of muons between the super-modules, also the size of their cells limits two-track resolution by 3 cm. The new detector TREK [41] will completely cover the side aperture of the Cherenkov water detector NEVOD and significantly improve the resolution of close tracks. The TREK setup represents two vertical planes of drift chambers (IHEP, Protvino) with $X$-$Y$ orientation, mounted on the outer wall of the CWD building (see Figure 17).

Each drift chamber has a large effective area ($1.85 \text{ m}^2$), good coordinate and angular resolution with a small number of measuring channels. The detector will be operated as a part of the experimental complex NEVOD, in particular, jointly with Cherenkov water detector. There are 132 chambers in each plane. The effective area of the detector will be approximately $270 \text{ m}^2$. 
Another planned detector is a traditional EAS array which will be installed on the roofs of the laboratory buildings around NEVOD in the MEPhI University campus [42]. The reason for the deployment of a traditional installation is the fairly poor PCR energy resolution of the LMDS method: $\sigma_{\lg E} \approx 0.4$. The measuring system of the NEVOD-EAS setup is organized on a cluster principle. Each cluster includes 16 counters combined in 4 detector stations and is served by the Local Post (LP) of preliminary data acquisition. As a detector of the EAS electromagnetic component, the scintillation counters from the former KASCADE-Grande facility are used. Figures 18 and 19 show pictures of the scintillation detector of KASCADE-Grande and a NEVOD-EAS detector station housing.

The NEVOD-EAS extension of the NEVOD-DECOR complex will allow determination of the size, position of the axis and the arrival direction of EAS. It will enable registration of EAS with energies $10^{15}$-$10^{17}$ eV, as well as the verification of the technique of muon bundle registration using the DECOR detector. New data obtained with the NEVOD-EAS setup will allow narrowing the energy range of PCR particles responsible for the generation of muon bundles with certain multiplicity arriving at different zenith angles. The NEVOD group plans to study energy deposit of muon bundles generated by PCR with energies up to $10^{18}$ eV in the next upgrade phase of the NEVOD complex [40].

**Figure 18.** NEVOD-EAS counter.  
**Figure 19.** Detector station.

### 6. Underwater neutrino projects

#### 6.1. KM3NeT

The KM3NeT Collaboration reported about the start in 2014 of the first phase of construction of a next generation high-energy neutrino telescope [43]. The main goal of KM3NeT is the discovery of high-energy neutrino sources. Its location is optimal to look directly at the Galactic centre, and it will complement the IceCube with respect to the field of view and exceed IceCube in sensitivity. The excellent optical properties of water (scattering and absorption lengths) allow the reconstruction of muon tracks with an excellent angular resolution for track events $\sim 0.1^\circ$ and for shower events $< 2^\circ$ above 100 TeV [43]. The digital optical module (DOM) used in KM3NeT is a 17-inch glass sphere, resistant to the high pressure at the sea bottom, housing 31 3-inch photomultiplier tubes and the active bases for power and the readout electronics. The total cathode area corresponds to the area of about three 10-inch PMTs. The simple requirement of a coincidence among 6-7 PMTs allows to effectively suppress the hits due to the decay of $^{40}$K dissolved in the sea water. The KM3NeT detector will have a modular structure with six building blocks, each consisting of about one hundred detection units (DU). Each DU will be equipped with 18 DOMs with $\sim 36$ m between the DOM. A single block has 115 DUs located at a distance of 90-120 m from each other (0.5 - 0.8 km$^3$) (see Figure 20). The total volume of the detector will be $\sim 3 - 5$ km$^3$. The first phase of construction has been started, and shore and deep-sea infrastructures hosting the future KM3NeT detector are being prepared offshore Toulon, France and offshore Capo Passero on Sicily, Italy.
The started phase 1 of KM3NeT, which is completely funded, foresees the construction and arrangement of 31 DUs, 7 at the Toulon site and 24 at Capo Passero. During the KM3NeT Phase-1.5 (2017 - 2020) two detector blocks will be installed. It will allow detect a flux of high energy cosmic neutrinos reported by IceCube on this conference already after 1 year operation (cascade channel) [43].

6.2. GVD

Significant progress was reported for the Gigaton Volume Detector (GVD) [44]. GVD will be a second Northern kilometer-scale neutrino observatory [45]. It is the successor of the first neutrino telescope NT200+, which registered in 1996 the first high-energy atmospheric neutrinos underwater. The location of the GVD facility is Lake Baikal (104°25' E; 51°46' N), about 3 km from shore at 1360 m depth [46]. The advantage of Baikal site is the possibility to deploy strings from ice in the period of March/April.

The scientific goals are essentially the same as for KM3NeT: exploration of the neutrino sky at energies above 10 TeV from the Northern hemisphere; indirect search for dark matter; search for exotic particles like magnetic monopoles; limnology and other environmental research. GVD will consist of strings of optical modules that will be grouped in clusters (see Figure 21). Basic elements of GVD, new optical modules, FADC readout units, and underwater communication systems, were investigated and tested in Lake Baikal with prototype strings in 2008–2010.

The project is divided into two phases. The first phase includes the creation of 12 clusters (0.4 km³, 24 strings, 2302 OMs) and is planned to be fully installed in 2019/2020. The completion of phase 2 (27 clusters, 1.5 km³) is scheduled for mid-2020s. An important step was made in spring, 2015 with the deployment of the missing last 3 strings of the first cluster (see Figure 22).

7. New instruments and techniques

A new facility for investigation of various processes of atmospheric and extra-terrestrial origin that cause modulations of cosmic rays detected at ground level was presented by the Tragaldabas collaboration [47]. TRAGALDABAS (TRAsGo for the AnaLysis of the nuclear matter Decay, the Atmosphere, the earth's B-field And the Solar activity) is a new RPC-based cosmic ray detector which has been recently installed at the Univ. of Santiago de Compostela, Spain. The detector consists of two 1.8 m² planes of two 1 mm-gap glass RPCs. Each plane is readout with 120 pads. The main performances of the detectors are: an arrival time resolution of about 300 ps, tracking angular resolution below 3º, detection efficiency close to 100%, and solid angle acceptance of 5 sr. Another two planes of RPC detectors will be added in future in order to improve both the resolutions and the acceptance.
A Hungarian group [48] presented the close cathode chamber (CCC) technology developed and proposed for the use as a portable tracking system operated under harsh and varying environmental conditions. The detector technique is based on an asymmetric multi-wire proportional chamber without outer support frames. A muon tomograph has been built with a sensitive area of 0.25 $m^2$ and an angular resolution of few mrad. The applicability of the sensor to detect underground rock density inhomogeneities has been demonstrated via reconstruction of an underground tunnel system. It is useful for material discrimination by measuring multiple scattering and absorption of muons.

A report of the group from Kiel was devoted to the research of material characteristics of the new Cerium doped LSO ($Lu_2SiO_5$) scintillator [49] that will replace BGO ($Bi_4Ge_3O_{12}$), widely used for the detection of high-energy particles in space applications. The LSO scintillator offers the same benefits with higher light output capabilities and a significantly shorter decay time. Characteristics of the LSO scintillator were investigated from the point of view of its use in space missions. Experiments with $^{176}$Lu source and the Heavy Ion Medical Accelerator in Chiba (HIMAC), Japan have shown that LSO is a promising candidate for future space missions.

**8. Conclusions**

The reports presented in the section INS demonstrate a wide frontier of new approaches and instruments in cosmic ray research, both for ground-based and orbital experiments. We note a significant progress of EAS radio detection techniques and detectors, as well as the pre-launch readiness of orbital experiments TUS and CALET. Another progress was achieved by the TAIGA Collaboration towards creating a new observatory for gamma-ray astronomy of ultrahigh energies in Tunka valley. The observatory is targeted to the search of gamma-ray sources with PeV energies and the study of the flux of UHE primary cosmic rays on the basis of a new approach. The collaboration NEVOD-DECOR offers a new multi-component approach to UHE EAS detection. The method is based on the precise study of spatial and energy characteristics of EAS muon bundles in a wide range of zenith angles and multiplicities. The creation of the first cluster of the new underwater detector GVD in the Lake Baikal demonstrates a considerable progress in the deployment of a kilometer-scale neutrino observatory in the Northern hemisphere. The development of a new generation of space born...
and ground based detectors will allow, in the near future, to make a significant step in understanding the nature of cosmic ray origin.

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