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P.A. Bezyazeekov[1*], **O. Fedorov**[2], **D. Kostunin**[3]

[1]Applied Physics Institute of Irkutsk State University, Russia, Irkutsk
[2]Astroparticle Physics Lab of JetBrains Research, Russia, St. Petersburg
[3]DESY, Germany, Zeuthen
*e-mail: almarac@astroparticle.online

PROSPECTS OF THE AIR-SHOWER RADIO ARRAY AT THE TIEN SHAN HIGH-ALTITUDE SCIENTIFIC STATION

High energy astrophysics has been actively developed since the last decades. The photons and neutrinos produced at astrophysical sources were detected up to energies of PeV, while the measured spectrum of cosmic rays lasts from GeV to ZeV energies. The challenges of modern detectors are not only pushing towards higher energies to reach the cosmic acceleration limit, but also increasing the resolution of the reconstruction of the energy, arrival direction and the type of the cosmic particle. Due to low flux of these particles, their detection is feasible only by measurement of air-showers, atmospheric cascades of secondary particles induced by the primary one. One of the promising methods of the air-shower detection is the sparse digital radio arrays, a young, but cost-effective technique aimed at the cosmic particles with energies beyond PeV. The future detectors aimed at detection of cosmic rays, photons and neutrinos of extreme energies are based on the antenna arrays located either in ice or on mountain slopes. The latter are sensitive both to downward-directional air-showers induced by cosmic rays, and upward-going ones produced by skimming neutrinos interacting with rock. The prototyping of such an array requires appropriate location (high-altitude mountains) with corresponding infrastructure and ideally additional cosmic-ray detector for the cross-calibration of antennas. The-Tien Shan High-altitude Scientific Station (TSHSS) located near Almaty, Kazakhstan, and equipped with air-shower instruments, is an ideal place for this prototype. In this work we discuss the prospects of the radio technique, its current challenges and report the recent advances of the prototype radio installations at TSHSS.

Key words: astroparticle physics, cosmic rays, radio antennas, Tien-Shan High-altitude Scientific Station.

П.А. Безъязыков[1*], О. Фёдоров[2], Д. Костюнин[3]

[1]Иркутск мемлекеттік университетінің қолданбалы физика ҒЗИ, Ресей, Иркутск қ.
[2]Астрофизика және бөлшектер физикасы зертханасы, «ДжетБрейнс»
ғылыми-зерттеу және білім беру орталығы, Ресей, Санкт-Петербург қ.
[3]Неміс электронды синхротрон, Германия, Цойтен қ.
*e-mail: almarac@astroparticle.online

Тянь-Шань биік таулы ғылыми станциясында кең атмосфералық нөсерді тіркеуге арналған антенна торларының болашағы

Жоғары энергиялы астрофизика соңғы онжылдықта белсенді дамып келеді. Астрофизикалық көздерде туындаған нейтринолар мен фотондар ПэВ энергиясына дейін тіркелген, ал ғарыштық сәулелердің өлшенген спектрі ГэВ энергиясынан ЗэВ-ке дейін созылады. Қазіргі заманғы детекторлардың міндеті – ғарыш кеңістігінде жылдамдатылған жоғары энергиялардың бөлшектерін тіркеуге ұмтылу ғана емес, сонымен қатар энергияны қалпына келтіруге арналған қондырғылардың, келу бағыттары мен ғарыштық бөлшектердің түрлерін шешуге қабілеттілігін арттыру. Бұл бөлшектердің аз ағымына байланысты оларды кең атмосфералық нөсердің (КАН), бастапқы бөлшектен туындаған қайталама бөлшектердің атмосфералық каскадтарын өлшеу арқылы ғана анықтауға болады.

КАН анықтаудың жобалы әдістерінің бірі – таратылған сандық радио массивтері болып табылады, бұл жаңа, бірақ экономикалық тұрғыда үнемді әдіс, ПэВ-тен жоғары энергиялы ғарыштық бөлшектерді тіркеуге бағытталған. Ғарыштық сәулелер, фотондар және экстремалды энергиялы нейтринолардың болашақ детекторлары мұзда немесе тау бөктерінде орналасқан антенналық торларға негізделген. Соңғылары ғарыштық сәулелерден туындаған КАН-ге де, тау жыныстарымен әрекеттесетін нейтриноны тудыратын жоғары бағытталған нөсерге де сезімтал. Мұндай тордың прототипін жасау үшін тиісті инфрақұрылымы бар қолайлы орын (таулы жер) қажет және, ең дұрысы, антенналарды көлденең калибрлеу үшін КАН тіркеуге арналған басқа қондырғылар бар болғаны жөн. Алматы (Қазақстан) маңында орналасқан және КАН тіркеуге арналған кешенді қондырғылармен жабдықталған Тянь-Шань биік таулы ғылыми станциясы (ТШБТҒС) осы прототип үшін тамаша орын болып табылады. Бұл жұмыста біз радиотехниканың перспективаларын, оның қазіргі проблемаларын және ТШБТҒС-тегі радиоқондырғылардың прототипінің соңғы ғылыми жетістіктері туралы талқылаймыз.

Түйін сөздер: ғарыштық бөлшектер физикасы, ғарыштық сәулелер, радиоантенналар, Тянь-Шань биік таулы ғылыми станциясы.

П.А. Безъязыков[1], О. Фёдоров[2], Д. Костюнин[3]

[1]НИИ прикладной физики Иркутского государственного университета, Россия, г. Иркутск
[2]Лаборатория астрофизики и физики частиц, Научно-исследовательский и
образовательный центр "ДжетБрейнс", Россия, г. Санкт-Петербург
[3]Немецкий электронный синхротрон, Германия, г. Цойтен
*e-mail: almarac@astroparticle.online

Перспективы антенных решеток для регистрации широких атмосферных ливней на Тянь-Шаньской высокогорной научной станции

Астрофизика высоких энергий активно развивается в последнее десятилетие. Фотоны и нейтрино, рожденные в астрофизических источниках, зарегистрированы до энергий ПэВ, в то время как измеренный спектр космических лучей длится от энергий ГэВ до ЗэВ. Задача современных детекторов заключается не только в регистрации частиц все более высоких энергий, ускоренных в космическом пространстве, но и в повышении разрешающей способности установок для восстановления энергий, направлений прибытия и типов космических частиц. Из-за малого потока этих частиц их обнаружение возможно только путем измерения широких атмосферных ливней (ШАЛ), атмосферных каскадов вторичных частиц, индуцированных первичной частицей. Одним из перспективных методов обнаружения ШАЛ являются распределенные цифровые радиомассивы, новый, но экономически эффективный метод, нацеленный на регистрацию космических частиц с энергией выше ПэВ. В основе будущих детекторов космических лучей, фотонов и нейтрино экстремальных энергий лежат антенные решетки, расположенные во льду или на горных склонах. Последние чувствительны как к направленным вниз ШАЛ, вызванных космическими лучами, так и к направленным вверх создаваемым нейтрино, взаимодействующим с горными породами. Для создания прототипа такой решетки требуется подходящее место (высокогорье) с соответствующей инфраструктурой и, в идеале, ряд других установок для регистрации ШАЛ, для перекрестной калибровки антенн. Тянь-Шаньская высокогорная научная станция (ТШВНС), расположенная недалеко от Алматы, Казахстан, и оснащенная комплексными установками для регистрации ШАЛ, является идеальным местом для этого прототипа. В этой работе мы обсуждаем перспективы радиотехники, ее текущие проблемы и сообщаем о последних научных достижениях прототипа радиоустановок на ТШВНС.

Ключевые слова: физика космических частиц, космические лучи, радиоантенны, Тянь-Шаньская высокогорная научная станция.

Introduction

When the measurements of cosmic rays have reached energies of the GZK [1,2], the main challenge for the physics of ultra-high cosmic rays is to increase the statistics and the measurement quality close to the breakdown of the cosmic ray flux at approximate 60 EeV. To obtain sufficient statistics one needs to build economically reasonable large-area detectors with high duty-cycles. The radio detection could be one of the prospective techniques for future investigations of ultra-high energy cosmic rays.

Radio detection of ultra-high energy (>PeV) particle cascades in media was proposed [3,4] and detected [5] more than half a century ago. Due to limitations of the data acquisition and data analysis with the technologies available at that time, the radio technique has been disregarded until the first decade of the 21st century. Development and mass production of fast digital-analog converters, boards and computers enabled the installation of large wide-angle digital radio arrays for radio astronomy as well as for air-shower detection. In the last years digital radio arrays operating in the MHz frequency band have proven their feasibility, hardware and software for them were developed and successfully applied.

To acquire sufficient data in the EeV energy domain, it is necessary to cover areas from tens to thousands of square kilometers, which implies the deployment of sparse arrays with distances between antenna stations from tens to thousands of meters. The hardware and methods for the sparse antenna arrays were developed and successfully tested in AERA and Tunka-Rex [6-12], which has shown that radio arrays for air-shower detection are ready for the installation on the large areas. This success has brought a motivation to build large-scale radio arrays with areas of thousands square kilometers. The first step will be done with the AERA setup which will be extended to the full area of the Pierre Auger Observatory, namely by attaching an antenna station to each water-Cherenkov tank. The first successful stand-alone array ARIANNA aimed mainly for neutrino detection is being deployed in Antarctica and has already shown that a self-trigger can be implemented and successfully used in very radio-quiet locations [13].

The achievements listed above are planned to be used in the proposed extremely-large scale setup GRAND, a distributed radio array tuned for the detection of very inclined air-showers for neutrinos, cosmic rays and gamma [14]. This ambitious project has many challenges starting from industrial production and maintenance of hundreds of thousands of antennas and corresponding electronics and finishing with precision methods for the reconstruction of upward-going and highly inclined air-showers. Achieving these challenges requires building prototypes in the environments close to the real ones, i.e. high-altitude mountains. One of the best locations for such a prototype is the Tien-Shan High-altitude Scientific Station (TSHSS). At TSHSS there are several installations for the study of EAS: Horizon-T installation, HADRON-55, burst detector etc.

In this work we discuss the prospects of the radio technique, its current challenges and report the recent advances of the prototype radio installations at TSHSS.

Radio detection technique and analysis methods

The interest in radio detection of air-showers was rekindled due to the following features of this technique:

– *Cost-efficiency*. The cost of a single detection element (antenna) of a radio array is an order of magnitude lower than for particle detectors (scintillators) and optical detectors (PMTs). At the same time, deployment and maintenance of radio arrays require less human, time and financial resources than for optical arrays or telescopes.

– *Duty-cycle*. Since the air is transparent for MHz radio, the detection is almost unaffected by the atmospheric conditions (temperature, density and humidity, see Ref. [15] for details) and can be performed around-the-clock except during thunderstorms.

– *Precision for energy and shower maximum.* In the last years it was proven that the resolution of radio detectors can achieve 10-15% for the energy and 20-40 g/cm^2 for the depth of shower maximum [16,17] depending on energy and on the configuration of the detector. These numbers are comparable with the precision achievable using optical methods of air-shower detection.

– *Sensitivity for inclined events.* Since the secondary particles as well as Cherenkov and fluorescent light are absorbed during the propagation through the atmosphere, optical and particle setups have difficulties detecting very inclined air showers (with inclination υ>60°) with full efficiency. Contrary to it, radio waves can propagate tens of kilometers in the atmosphere and be seen by an antenna array from a very far distance. Although the power of the emission falls with distance squared, the air-shower footprint increases as $1/\cos\upsilon$, which allows one to detect these air-showers with very sparse arrays.

The combination of these features makes the detection of ultra-high energy messengers (>EeV) the perfect science case for the radio technique. For the time being most of the digital radio arrays serve as extensions for the existing cosmic-ray setups, and only few operate in stand-alone mode. The main obstacle for large-scale stand-alone arrays is the high radio background. To achieve high efficiency under this background one needs to select the optimal frequency band and develop sophisticated *self-trigger* [18] as well as develop optimal methods for the signal processing and EAS parameters reconstruction.

Common approach to the measurements of air-showers in radio bands is using sparse time-synchronized antenna arrays. Single station detects the integrated radio emission of an air-shower at the point of the surface of the array. Air-shower radio pulse is short peak with tens of nanoseconds characteristic length. With known timestamps of the detection of these pulses at different stations one can reconstruct the arrival direction of the air-shower. Position of shower core is reconstructed by the lateral distribution of amplitudes of measured pulses. With reconstructed arrival direction and shower core one performs reconstruction of the main parameters of the shower: electromagnetic energy, related to energy of the primary particle, and depth of shower maximum (depth in atmosphere associated with maximal number of particles in shower lifecycle), related to the mass of the primary particle.

These parameters are usually reconstructed using analysis of lateral distribution of measured amplitudes in the plane perpendicular to the shower axis. Measured amplitudes are fitted with some type of exponential function (lateral distribution function, LDF) depending on experimental conditions and used approach. For example, in the first-years analysis of data collected by Tunka-Rex the following parameterization is used:

$$E(r) = E_{r0} \sin \alpha_g \, exp[f_\eta (r - r_0)] \, ,$$

where E_{r0} is amplitude of radio pulse at the distance r_0 from the shower axis, α_g is angle between the geomagnetic field vector and the shower axis, r is distance to the shower axis. With this approach the shower energy and depth of maximum are defined as amplitude and slope of the LDF at specific points [19].

For increasing the precision of the reconstruction one can take into account the shape of the shower pulse, as shown in the latest analysis of Tunka-Rex [20]. With this approach the energy is pre-reconstructed using the LDF method. After that a set of simulations for each event with the fixed energy, but various masses of the primary particle is produced, and is fitted to the shapes of measured pulses to the simulated ones. Comparsion is performed using reducing chi-square fit. Using this approach the better precision is reached in comparison with the LDF method.

For the testing of new methods of the air-showers radio data processing the Tunka-Rex Virtual Observatory (TRVO) is developed [21]. It is a framework which provides an open access to the data of experiments measuring cosmic rays with radio technique. At the current moment it contains data collected by Tunka-Rex and Almarac experiments. Framework includes low-level information (timestamps and signal traces) and specific modules for processing the data, for example, denoising the traces with deep neural networks, modules for calculating the signal parameters and for testing the self-trigger techniques.

Preliminary results of deployment of antenna setups on TSHSS and discussion

Radio detection at the TSHSS began more that five years ago. The first installation has been done with the three low-frequency dipole antennas operating in the 1-8 MHz range (Fig. 1, left). [22]. Fig.2 shows day-night variation of background at low-frequency antenna caused by ionosphere features.

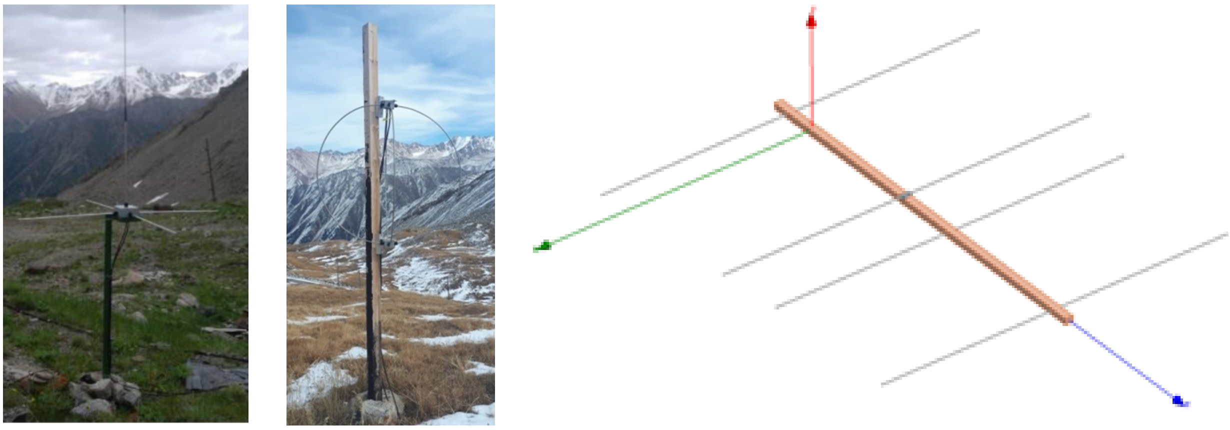

Figure 1 – Various antenna types at TSHSS.
Left: Low-frequency dipole antennas operating in 1-8 MHz range.
Middle: Short aperiodic loaded loop antenna (SALLA) from Almarac array.
Right: newly developed Uda-Yagi antenna to be installed with the Horizon-T array

Later, in cooperation with Tunka-Rex, the Almaty Radio Cluster (Almarac) was deployed in 2018. Almarac antenna cluster consists of 4 short aperiodic loaded loop antennas (SALLA) with arcs oriented at an angle of 45 degrees to the Earth's magnetic field (Fig. 1, middle). This orientation of the antennas ensures the highest efficiency of air-shower radio emission detection.

A similar arrangement of antennas has already been successfully used in the Tunka-Rex experiment. The signal track completely repeats the Tunka-Rex signal path, with one exception of a slightly longer cable length in the Almarac antenna cluster. To digitize the signal, a CAEN ADC with a sampling rate of 250 MHz is used, which makes it possible to detect radio emission up to 125 MHz and with a margin that overlaps the bandwidth of the signal path (30-80 MHz). A feature of the Almarac antenna cluster is its high-altitude location. This arrangement of the cluster makes it possible to reduce the energy threshold for cosmic-ray detection, due to the lower attenuation of radio emission from air-showers at threshold energies. The close proximity of the antenna cluster to other installations of the Tien Shan Station makes it possible to carry out cross-calibration. Closely located high mountains allow the installation to be naturally protected from man-made interference. For the moment, the data acquired by Almarac are converted to the TRVO format to be analyzed with Tunka-Rex software.

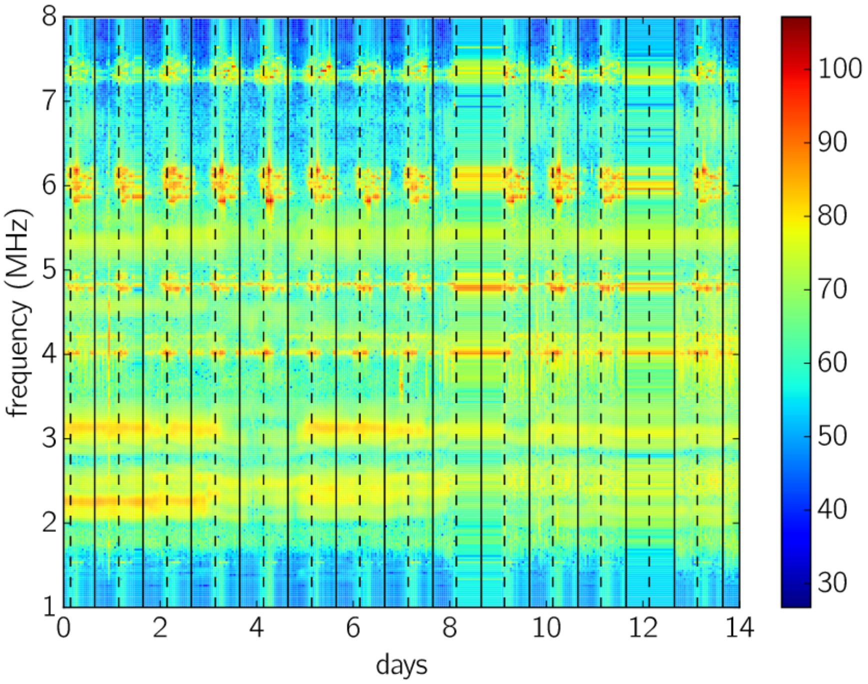

Figure 2 – Day-night variation of background at low-frequency antenna at TSHSS

One of the most important tasks of radio detection is to solve the problem of autonomous registration without using an external trigger. At the moment, there are no universally established methods for the implementation of autonomous radio installations with internal trigger systems. Although the solution of this problem is the most important stage in the development of new generation radio installations. Previous studies have shown the potential efficiency of compact antenna clusters for the tasks of autonomous cosmic-ray detection without reference to other types of detectors [18]. The Almarac cluster can be used to develop and implement in hardware the techniques for detecting radio emission from air-showers without using external triggers.

Recently a new Yagi-Uda antenna was created to detect radio emission from inclined air-showers in the frequency range of 55-65 MHz (as a potential extension to the Horizon-T setup [23]). First, a computer model of the antenna was designed and an experimental model (a real prototype) was created based on the simulations. The active vibrator half-wave length (0.5 λ) is 2.38 m, the reflector length, slightly larger than 0.5 λ, is 2.45 m, the directors are 2.26 m and 2.24 m, respectively (Fig. 1, right). All active and passive vibrators are made of aluminum pipe with an outer diameter of 10 mm. The length of the wooden boom (traverse) is 2.5 m. The deployment of these new antennas are in progress.

Conclusion

Tien-Shan High-altitude Scientific Station is a unique facility that provides a variety of setups measuring different components of air-showers as well as very inclined cascades induced by the ultra-high energy cosmic rays. Its high-altitude location allows for lowering the threshold of detection and studying hadronic components of air-showers as well as provide opportunity for the location of the detectors on the slope of the mountain. The combination of these features allows us to develop and test modern perspective techniques, such as radio detection of air-showers. The first results obtained with prototype radio setups installed there are very promising and bring an inspiration for the deployment of more complicated hardware for the solution of the actual problems of radio detection, like lowering the threshold, autonomous trigger system, very-large zenith angle observations. Achievement of these challenges will help community to make a step forward towards the next-generation ultra-large scale antenna arrays for the detection of particles of extreme energies.

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