33RD INTERNATIONAL COSMIC RAY CONFERENCE, RIO DE JANEIRO 2013
THE ASTROPARTICLE PHYSICS CONFERENCE
ICRC 2013

Test of Radar Echo Detection using the Electron Beam from the ELS at the Telescope Array Site: A Test for Future Large Scale Extension of the Air Shower Observatory

D. IKEDA[1], J. BELZ[2], W. HANLON[2], I. MYERS[2], T. NAKAMURA[3], H. SAGAWA[1], T. TERASAWA[1], G.B. THOMSON[2] FOR THE TARA AND TELESCOPE ARRAY COLLABORATION.

[1] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[2] *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA*
[3] *National Institute of Polar Research, Tachikawa, Tokyo, Japan.*

ikeda@icrr.u-tokyo.ac.jp

Abstract: We are carrying out an R&D project to search for radar echoes from cosmic ray induced extensive air showers, called TA RAdar (TARA). To test and develop this technique, we have used the Electron Light Source (ELS) electron beams at the Telescope Array site as artificial air showers. A radio transmitter and receivers have been constructed and placed them 140m from the accelerator beam to search for radar echoes from the trail of the electron beam. In September and December 2012, we have have tried to detect radio signals from ELS electron beams of 40MeV, 10^9 electrons with two different beam duration. We have not found any radio echo signals, but we have observed a radio emission from the electron beam. The properties of this emission have also been studied.

Keywords: ultra-high energy cosmic rays, radar echo, electron accelerator, telescope array

1 Introduction

Currently, thousands of km^2 scale experiments such as the Telescope Array (TA) [1] and the Pierre Auger [2] are running to observe the Ultra-High Energy Cosmic Rays (UHECRs). Those experiments employ two established techniques for the observation, the surface detectors and the fluorescence detectors. The surface detectors sample the Extensive Air Shower (EAS) particles at the ground by ~ 1 km spacing array [3]. The fluorescence detectors observe the UV lights emitted by the excitation of atmospheric molecules excited with the EAS along the shower axis as the image on the telescope cameras [4].

Those two techniques have complementary characteristics for the UHECR observation. The fluorescence detectors have a capability to measure the UHECR energy calorimetrically and to determine the longitudinal development of air showers which is sensitive to the mass composition of the primary cosmic ray [5]. Moreover, since one fluorescence telescope covers the large observation area, the installation and the maintenance are slightly easy compared with the surface detector array. However, the operation of the fluorescence detector is limited in clear and moonless nights with the order of 10% effective duty cycle, and the atmospheric attenuation for the UV lights should be monitored by the independent installation such as laser facilities during every observation period [6]. On the other hand, the surface detector can be operated regardless of the whether and the time of day and night. Therefore, the surface detector have the capability to give a high statistic observation of the cosmic rays with an uniform exposure for the universe. However, the reconstruction of the primary cosmic ray energies depends on the interaction model of cosmic rays and atmospheric molecules in the unmeasurable energy region directly by the current acceleration experiments.

Recently, a radar echo technique is revisited as the possibility to be the detection method for a future huge UHECR observatory [7]. The principle of this technique is to detect the radar echo from the ionized electrons along the trail of the air showers, like "radar" (see Fig. 1). This radar echo method is particularly suitable to construct a huge UHECR detector, since it has the capability of covering a large detection area by one radar system like fluorescence detectors and of operating with 100% duty cycle like surface detectors. In addition, the atmospheric attenuation, which is one of main uncertainties on the fluorescence technique, is negligible in the radio band. This technique is in practical use in the low-VHF band to detect meteorites, which has almost same kinetic energy as UHECRs. Several experiments such as MARIACHI [8] and MU Radar [9] have tried to observe radar echoes from extensive air showers, but up to now there is no clear detection confirmed as cosmic ray induced signal.

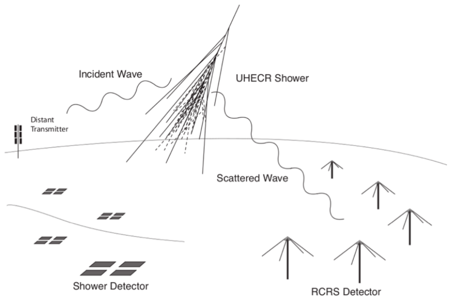

Fig. 1: The geometry for a radar echo technique.

Therefore, we are carrying out an R&D project to search for radar echoes of 54.1 MHz radio band from cosmic ray induced extensive air showers in conjunction with the TA, called TA RAdar (TARA) [10]. In particular, to test and develop this technique, we have used the Electron Light Source (ELS) electron beams as artificial air showers at the TA site. Here, we present the design of the experiment, the results and the properties of the detected signals.

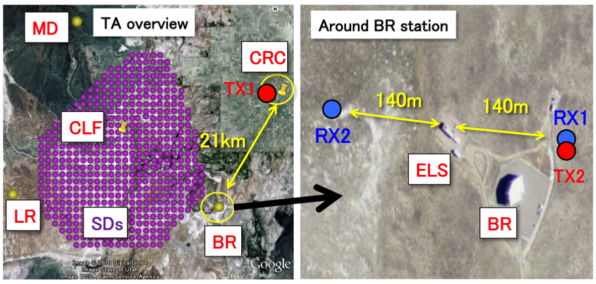

Fig. 2: The overview of the TA site. The positions of transmitters (TX), receivers (RX) and ELS are shown.

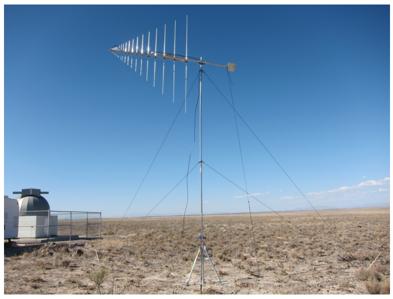

Fig. 3: Installed log-periodic antenna in TA site.

2 Design of the Experiment with Electron Beam at the Telescope Array

This experiment searches for radar echo signals from the electron showers induced by ELS. The positions of ELS, transmitters and receivers are shown in Fig. 2.

2.1 Electron Beam and Scatter Mode

ELS has been installed in the front of fluorescence detectors as the Black Rock Mesa (BR) station in the TA site as an absolute calibrator [11]. A single shot by ELS is a vertical electron beam vertically to the atmosphere to be equivalent to an electromagnetic cascade shower up to ∼200m height. In this experiment, we use this shower as a artificial air shower.

The beam property which we set is almost same as the normal calibration mode: the energy of 40 MeV, up to 10^9 electrons, 1 μs beam duration and 0.5 Hz repetition frequency. In addition, to increase the sensitivity, we have used a short pulse duration of 20 ns as well as a long pulse of 1 μs duration. Since the total output charges of those two beams are same, the difference of the beam duration is corresponding to the difference of the electron density.

The electron density is important for this experiment. When the ionization electron density is high enough where the plasma frequency exceeds the frequency of the incident radio wave, this region behaves as a metal surface ("overdence" mode). In the case of the electron density to be not enough, the electrons scatter independently according to the Thomson cross section ("underdence" mode). In our beam settings, the plasma frequency at the highest density, at the bottom of electron shower, is below 10 MHz. This is sufficiently small comparing with our incident frequency, 54.1 MHz. Thus, this experiment is searching for the underdence radar echoes. By the study with air shower simulations, almost all the regions in extensive air showers are underdence [7].

2.2 Transmitters

We have prepared two transmitters for this experiment. One is the 2 kW analog television transmitter of 54.1 MHz frequency with Yagi-antenna at 21 km far from ELS (TX1), which is used for TARA experiment [12]. Usually, this transmitter faces to Long Ridge (LR) station for the TARA equipment. Thus, for our test to detect ELS signals the TX beam direction has been changed to the ELS. The polarization of incident radio wave is also changed to the vertical.

Another transmitter has been especially installed for this experiment at 140m far from the ELS (TX2). This transmitter consists of the Yagi-antenna, function generator and amplifier and is operated up to 100W output power. In this experiment, two polarization modes, vertical and horizontal, are used to measure the polarization dependence.

Those transmitter emits the continuous radio wave. We have used either TX1 or TX2 in each observation period.

2.3 Receivers

In the case of the extensive air showers, the frequency of the radar echo signals should be significantly shifted [13]. Since the lifetime of the ionization electrons at the height of several kilometers is not so long, the order of 100 ns [14], the reflection point moves together with the shower front near the light speed. This phenomenon causes the phase modulation, like Doppler shift. Typically, the frequency of the echo signals is increased by several ten MHz for the downward shower. This feature requires large bandwidth for the detector.

In order to use not only for the ELS beam experiment but also for the air shower detection, we have developed a wide bandwidth receiver system. The log-periodic antenna of 3 meters length, 50-1300 MHz bandwidth and ∼10dBi gain (Creative Design; CLP5130-1D) has been installed at 6 meters height from the ground (see Fig. 3). The signal from the antenna is transferred through 20 meters of LMR-400 coaxial cable into the data acquisition (DAQ) system, which consists of a band pass filter, pre-amplifier and a digitizer. The schematic view of the DAQ system is shown in Fig. 4. First the signal passes the band pass filter to avoid the saturations of amplified signals. In order to eliminate the FM radio signal, which is one of the main noise source in low-VHF band, an FM cut filter is employed in addition to the low pass and the high pass filters. Second the signal inputs to the wideband pre-amplifier (Anritsu; MH648A) with a bandwidth of 100 kHz to 1.2 GHz and with a variable gain adjustable at 10dB intervals up to the maximum of 30dB. Finally, the signal is digitized by the Software-Defined Radio (SDR) system (Ettus; USRP) with the sampling frequency of 25 MHz, the resolution of 14 bits and with a quadrature detection method. The final acceptable frequency range of this receiver is 50 - 77 MHz when the frequency of the local oscillator in the USRP is set to 55 MHz.

The detection method of the USRP is selectable by changing the daughter board. We have used two types of USRPs here, one is for the RF signal from the antenna with a quadrature detection board with the variable gain up to 20dB, and another is for the trigger signal from the ELS with a simple Flash-ADC board. Those USRPs are synchronized with 1 PPS and 10 MHz clocks from the GPS receiver (Jackson Labs; FireFly-1A). This GPS receiver provides the exact timestamps with 50 ns accuracy. Both of the digitized

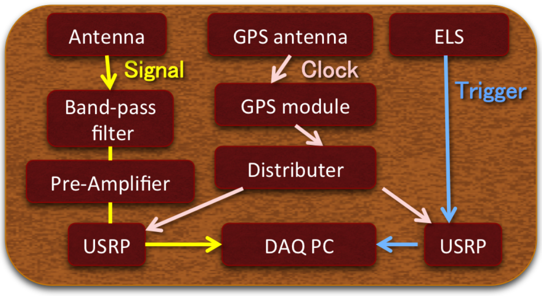

Fig. 4: The schematic view of the DAQ system.

signals from antenna and ELS are continuously sent to the PC via gigabit ethernet connection and are recorded to the data storage when the signal are triggered.

We have installed two receiver systems near the transmitter (RX1) and over the ELS (RX2) with same distance of 140 meters from ELS. The polarization of receiving radio wave is variable by rotating the antenna which is same as the transmitter.

3 Observation results

In July 2012, we have installed one receiver (RX1) and tried to measure radar echo signals by the ELS electron beams. In this observation we have used the transmitter at the 21 km far from the ELS (TX1) with the output power of 660 W. The polarization of the antennas both for the transmitter and the receiver is set to vertical. We have compared the observed signals with and without electron beams to confirm the radar echo signals scattered at the ionizations generated by ELS. In order to evaluate the noise strength emitted from ELS during the operation, we recorded signal coincident with ELS shots operated with a beam dump terminating ELS beams. For each configuration, about 1000 events are recorded and the averaged to reduce the background noise such as thermal noise and galactic noise. By considering the cable delays, the radar echo signal is expected to appear around 8 μs after observed ELS triggers.

3.1 Results of the Long Pulse Beam Experiment

For the observations of ELS beams operated with the long pulse beam of 1 μs duration, the gains of the pre-amplifiers are set to 30dB, and that of amplifier in USRP is set to 20dB. The observed signals with the long pulse beam are shown in Fig. 5. In both the observations with and without the electron beam, a signal appear at the 5 μs later from the ELS trigger. This signal corresponds to the discharge noise emitted from the thyratron switch in the ELS. We have not found any signals around the expected timing of the radar echoes.

3.2 Results of the Short Pulse Beam Experiment

For the observation with the short pulse beam of 1 μs duration, the gains of the pre-amplifier is also set to 30dB, but the amplifier in USRP is not used. The observed signals with the short pulse beam are shown in Fig. 6. We have observed a significantly strong signal at the expected timing of the radar echoes. However, this signal has also appeared without incident radio waves. On the other hand, when the electron beam is stopped, this signal disappears.

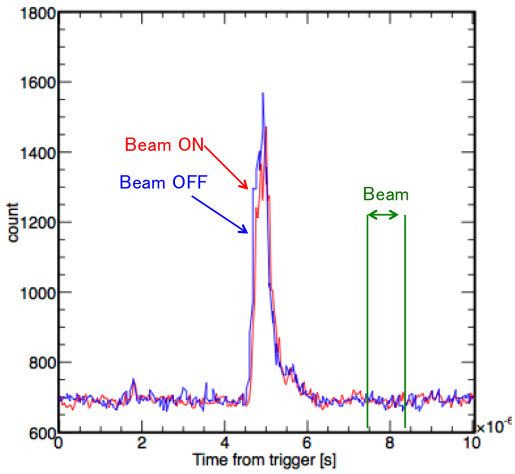

Fig. 5: The observed signal in the long pulse beam experiment with averaged about ∼1000 events. In this experiment, the total gain of the amplifiers is 50dB. The horizontal axis is the time from the ELS trigger. The vertical axis is the ADC cound. The red line is observed signal with shooting the electron beam, and the blue line is the signal without beam.

We have also measured the beam charge dependence of the observed signals. The output charge of each beam is measured at the ELS. The result is shown in Fig. 7. We found that the observed pulse height is proportional to the output beam charge. By these features, the observed signal seems to be a radio emission from the electron beam itself.

3.3 Additional Measurement for the Observed Radio Emission

In December 2012, we have implemented an additional measurement to understand the properties of the observed radio emission with the short pulse beam. We have installed additional receiver (RX2) over the ELS and transmitter (TX2) near the RX1. First we checked the reproducibility and confirmed to observe the signal again. Second the polarization dependence has been measured with observed both by the RX1 with a vertical polarization antenna and the RX2 with a horizontal polarization antenna at same time. The result is that the pulse height of vertical polarization is two times higher than that of horizontal polarization. Thirdly, we measured with the RX2 with rotating the antenna direction about 90 degrees counterclockwise as viewed from above. In this measurement the pulse height is reduced to 1/15 which is consistent with the expectation from the directional sensitivity of the antenna. This result has confirmed that the signal is actually radio emission observed by the antenna and is not coming from the ground path and so on. Finally the frequency dependence has been measured. The signal from the antenna is divided to three USRPs with an adjusted band pass filter. The ratio of the pulse height compared with the signal at the 55 MHz is as follows: 0.94 for 60 MHz, 0.02 for 175 MHz and 0.01 for 250 MHz. The pulse height is significantly reduced while the frequency goes to high.

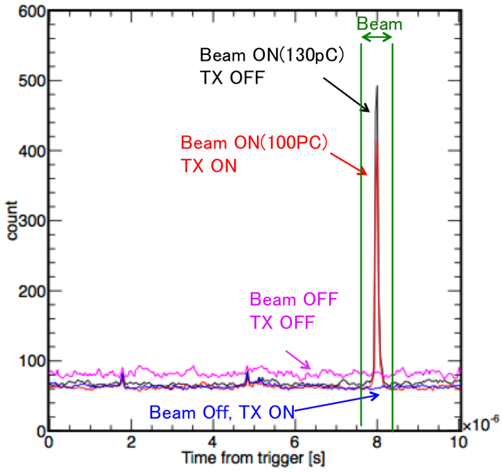

Fig. 6: The observed signal in the short pulse beam experiment, which is same format of Fig. 5. In this experiment, the total gain of the amplifiers is 30dB. Four signals obtained from the difference configuration are shown.

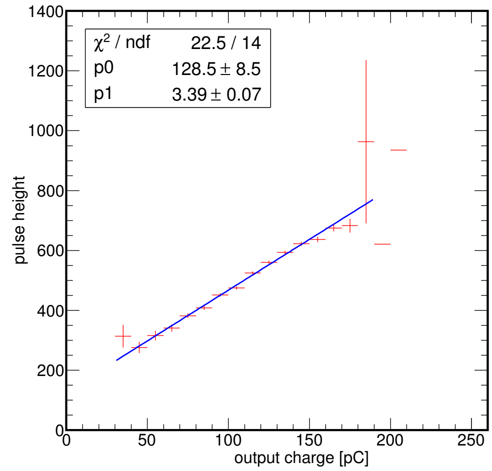

Fig. 7: The beam charge dependence of the observed signals. The horizontal axis is the output beam charge measured at the ELS. The vertical axis is the pulse height of the observed signal at the receiver.

4 Conclusion and Discussion

We are carrying out an R&D project to search for radar echoes of 54.1 MHz radio wave from cosmic ray induced extensive air showers in conjunction with the TA. In order to test and develop the radar echo technique, we have developed an experiment by using the electron beam at the TA site. The wideband receiver with quadrature detection was developed and worked well. In this observation we have not found any signals of the radar echoes. But we have observed a radio emission from the electron beam.

One of the possibilities to describe the observed radio emission is an electric field generated by the sudden appearing of the electron beam from the ELS container. The calculated pulse shape, which is obtained from the calculation for the time variation of the static electric field caused by beam electrons and simulation of the detector response, is good agreement in the observed signal shape. Recently, it has been suggested that the sudden vanishing of the secondary particles at the ground causes the radio emission [15]. Since these two phenomena are caused by the similar process, the observed radio emission will have a capability to use for the air shower detection.

The radar echo search with short pulse beam will be continued. In this experiment the observed radio emission from the beam covers the signal region of the radar echoes. In future, we will try to observe the radar echoes with eliminating this radio emission by using the properties which obtained from this experiment such as the polarization and the frequency dependences.

Acknowledgment: The Telescope Array experiment is supported by the Japan Society for the Promotion of Science through Grants-in-Aid for Scientific Research on Specially Promoted Research (21000002) “Extreme Phenomena in the Universe Explored by Highest Energy Cosmic Rays”, and the Inter-University Research Program of the Institute for Cosmic Ray Research; by the U.S. National Science Foundation awards PHY-0307098, PHY-0601915, PHY-0703893, PHY-0758342, PHY-0848320, PHY-1069280, and PHY-1069286 (Utah) and PHY-0649681 (Rutgers); by the National Research Foundation of Korea (2006-0050031, 2007-0056005, 2007-0093860, 2010-0011378, 2010-0028071, R32-10130); by the Russian Academy of Sciences, RFBR grants 10-02-01406a and 11-02-01528a (INR), IISN project No. 4.4509.10 and Belgian Science Policy under IUAP VI/11 (ULB). The foundations of Dr. Ezekiel R. and Edna Wattis Dumke, Willard L. Eccles and the George S. and Dolores Dore Eccles all helped with generous donations. The State of Utah supported the project through its Economic Development Board, and the University of Utah through the Office of the Vice President for Research. The experimental site became available through the cooperation of the Utah School and Institutional Trust Lands Administration (SITLA), U.S. Bureau of Land Management and the U.S. Air Force. We also wish to thank the people and the officials of Millard County, Utah, for their steadfast and warm support. We gratefully acknowledge the contributions from the technical staffs of our home institutions as well as the University of Utah Center for High Performance Computing (CHPC).

References

[1] H. Kawai *et al.* , J. Phys. Soc. Jpn. Suppl. A 78 (2009) 108-113.
[2] J. Abraham *et al.* , Nucl. Instrum. Meth. Phys. Res. A 523 (2004) 50.
[3] T. Abu-Zayyad *et al.* , Nucl. Instrum. Meth. Phys. Res. A 689 (2012) 87-97.
[4] H. Tokuno *et al.* , Nucl. Instrum. Meth. Phys. Res. A 676 (2012) 54-65.
[5] Y. Tsunesada *et al.* , 33rd International Cosmic Ray Conference, Rio, Brazil, in these proceedings.
[6] T. Tomida *et al.* , Nucl. Instrum. Meth. Phys. Res. A 654 (2011) 653-660.
[7] P.W. Gorham, Astropart. Phys. 15 (2001) 177-202.
[8] `http://www-mariachi.physics.sunysb.edu/` .
[9] T. Terasawa *et al.* , Proceedings of the 31st International Cosmic Ray Conference, Lodz, Poland (2009).
[10] J. Belz and W. Hanlon *et al.* , 33rd International Cosmic Ray Conference, Rio, Brazil, in these proceedings.
[11] T. Shibata *et al.* , Nucl. Instrum. Meth. Phys. Res. A A 597, (2009) 61-66.
[12] J. Belz *et al.* , Proceedings of the 32nd International Cosmic Ray Conference, Beijing, China (2011).
[13] D. Underwood, Proceedings of the 2008 IEEE Radar Conference, Rome, Italy (2008).
[14] R. Virmar, IEEE Trans. Plasma Sci. 18 (1990) 4.
[15] V. Marin and B. Revenu, arXiv:1211.3305 [astro-ph.HE]