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First upper limits on the radar cross section of cosmic-ray induced extensive air showers

R.U. Abbasi[a], M. Abe[b], M. Abou Bakr Othman[c], T. Abu-Zayyad[a], M. Allen[a], R. Anderson[a], R. Azuma[d], E. Barcikowski[a], J.W. Belz[a,*], D.R. Bergman[a], D. Besson[e,f], S.A. Blake[a], M. Byrne[a], R. Cady[a], M.J. Chae[g], B.G. Cheon[h], J. Chiba[i], M. Chikawa[j], W.R. Cho[k], B. Farhang-Boroujeny[c], T. Fujii[l], M. Fukushima[l,m], W.H. Gillman[n], T. Goto[o], W. Hanlon[a], J.C. Hanson[e], Y. Hayashi[o], N. Hayashida[p], K. Hibino[p], K. Honda[q], D. Ikeda[l], N. Inoue[b], T. Ishii[q], R. Ishimori[d], H. Ito[r], D. Ivanov[a], C. Jayanthmurthy[c], C.C.H. Jui[a], K. Kadota[s], F. Kakimoto[d], O. Kalashev[t], K. Kasahara[u], H. Kawai[v], S. Kawakami[o], S. Kawana[b], K. Kawata[l], E. Kido[l], H.B. Kim[h], J.H. Kim[a], J.H. Kim[w], S. Kitamura[d], Y. Kitamura[d], S. Kunwar[e], V. Kuzmin[t], Y.J. Kwon[k], J. Lan[a], S.I. Lim[g], J.P. Lundquist[a], K. Machida[q], K. Martens[m], T. Matsuda[x], T. Matsuyama[o], J.N. Matthews[a], M. Minamino[o], K. Mukai[q], I. Myers[a], K. Nagasawa[b], S. Nagataki[r], T. Nakamura[y], T. Nonaka[l], A. Nozato[j], S. Ogio[o], J. Ogura[d], M. Ohnishi[l], H. Ohoka[l], K. Oki[l], T. Okuda[z], M. Ono[A], A. Oshima[B], S. Ozawa[u], I.H. Park[C], S. Prohira[e], M.S. Pshirkov[D,t], A. Rezazadeh-Reyhani[c], D.C. Rodriguez[a], G. Rubtsov[t], D. Ryu[w], H. Sagawa[l], N. Sakurai[o], A.L. Sampson[a], L.M. Scott[E], D. Schurig[c], P.D. Shah[a], F. Shibata[q], T. Shibata[l], H. Shimodaira[l], B.K. Shin[h], J.D. Smith[a], P. Sokolsky[a], R.W. Springer[a], B.T. Stokes[a], S.R. Stratton[a,E], T.A. Stroman[a], T. Suzawa[b], H. Takai[F], M. Takamura[i], M. Takeda[l], R. Takeishi[l], A. Taketa[G], M. Takita[l], Y. Tameda[p], H. Tanaka[o], K. Tanaka[H], M. Tanaka[x], S.B. Thomas[a], G.B. Thomson[a], P. Tinyakov[t,I], I. Tkachev[t], H. Tokuno[d], T. Tomida[J], S. Troitsky[t], Y. Tsunesada[o], K. Tsutsumi[d], Y. Uchihori[K], S. Udo[p], F. Urban[I], G. Vasiloff[a], S. Venkatesh[c], T. Wong[a], R. Yamane[o], H. Yamaoka[x], K. Yamazaki[o], J. Yang[g], K. Yashiro[i], Y. Yoneda[o], S. Yoshida[v], H. Yoshii[L], R. Zollinger[a], Z. Zundel[a]

[a] *High Energy Astrophysics Institute and Department of Physics and Astronomy, University of Utah, Salt Lake City, Utah, USA*
[b] *The Graduate School of Science and Engineering, Saitama University, Saitama, Saitama, Japan*
[c] *Department of Electrical and Computer Engineering, University of Utah, Salt Lake City, Utah, USA*
[d] *Graduate School of Science and Engineering, Tokyo Institute of Technology, Meguro, Tokyo, Japan*
[e] *University of Kansas, Lawrence, Kansas, USA*
[f] *Moscow Engineering and Physics Institute, Moscow, Russia*
[g] *Department of Physics and Institute for the Early Universe, Ewha Womans University, Seodaaemun-gu, Seoul, Korea*
[h] *Department of Physics and The Research Institute of Natural Science, Hanyang University, Seongdong-gu, Seoul, Korea*
[i] *Department of Physics, Tokyo University of Science, Noda, Chiba, Japan*
[j] *Department of Physics, Kinki University, Higashi Osaka, Osaka, Japan*
[k] *Department of Physics, Yonsei University, Seodaemun-gu, Seoul, Korea*
[l] *Institute for Cosmic Ray Research, University of Tokyo, Kashiwa, Chiba, Japan*
[m] *Kavli Institute for the Physics and Mathematics of the Universe (WPI), Todai Institutes for Advanced Study, the University of Tokyo, Kashiwa, Chiba, Japan*
[n] *Gillman & Associates, Salt Lake City, Utah, USA*
[o] *Graduate School of Science, Osaka City University, Osaka, Osaka, Japan*
[p] *Faculty of Engineering, Kanagawa University, Yokohama, Kanagawa, Japan*
[q] *Interdisciplinary Graduate School of Medicine and Engineering, University of Yamanashi, Kofu, Yamanashi, Japan*
[r] *Astrophysical Big Bang Laboratory, RIKEN, Wako, Saitama, Japan*
[s] *Department of Physics, Tokyo City University, Setagaya-ku, Tokyo, Japan*
[t] *National Nuclear Research University, Moscow Engineering Physics Institute, Moscow, Russia*
[u] *Advanced Research Institute for Science and Engineering, Waseda University, Shinjuku-ku, Tokyo, Japan*
[v] *Department of Physics, Chiba University, Chiba, Chiba, Japan*

* Corresponding author.
E-mail address: belz@physics.utah.edu (J.W. Belz).

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[w] Department of Physics, School of Natural Sciences, Ulsan National Institute of Science and Technology, UNIST-gil, Ulsan, Korea
[x] Institute of Particle and Nuclear Studies, KEK, Tsukuba, Ibaraki, Japan
[y] Faculty of Science, Kochi University, Kochi, Kochi, Japan
[z] Department of Physical Sciences, Ritsumeikan University, Kusatsu, Shiga, Japan
[A] Department of Physics, Kyushu University, Fukuoka, Fukuoka, Japan
[B] Engineering Science Laboratory, Chubu University, Kasugai, Aichi, Japan
[C] Department of Physics, Sungkyunkwan University, Jang-an-gu, Suwon, Korea
[D] Sternberg Astronomical Institute, Moscow M.V.Lomonosov State University, Moscow, Russia
[E] Department of Physics and Astronomy, Rutgers University - The State University of New Jersey, Piscataway, New Jersey, USA
[F] Brookhaven National Laboratory, Upton, New York, USA
[G] Earthquake Research Institute, University of Tokyo, Bunkyo-ku, Tokyo, Japan
[H] Graduate School of Information Sciences, Hiroshima City University, Hiroshima, Hiroshima, Japan
[I] Service de Physique Théorique, Université Libre de Bruxelles, Brussels, Belgium
[J] Department of Computer Science and Engineering, Shinshu University, Nagano, Nagano, Japan
[K] National Institute of Radiological Science, Chiba, Chiba, Japan
[L] Department of Physics, Ehime University, Matsuyama, Ehime, Japan

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A B S T R A C T

TARA (Telescope Array Radar) is a cosmic ray radar detection experiment colocated with Telescope Array, the conventional surface scintillation detector (SD) and fluorescence telescope detector (FD) near Delta, Utah, U.S.A. The TARA detector combines a 40 kW, 54.1 MHz VHF transmitter and high-gain transmitting antenna which broadcasts the radar carrier over the SD array and within the FD field of view, towards a 250 MS/s DAQ receiver. TARA has been collecting data since 2013 with the primary goal of observing the radar signatures of extensive air showers (EAS). Simulations indicate that echoes are expected to be short in duration (∼ 10 μs) and exhibit rapidly changing frequency, with rates on the order 1 MHz/μs. The EAS radar cross-section (RCS) is currently unknown although it is the subject of over 70 years of speculation. A novel signal search technique is described in which the expected radar echo of a particular air shower is used as a matched filter template and compared to waveforms obtained by triggering the radar DAQ using the Telescope Array fluorescence detector. No evidence for the scattering of radio frequency radiation by EAS is obtained to date. We report the first quantitative RCS upper limits using EAS that triggered the Telescope Array Fluorescence Detector.

1. Introduction

Ultra-high energy cosmic ray (UHECR, primary energy $E_0 > 10^{18}$ eV) research is limited primarily by low flux. There are currently two dominant detection techniques, surface detectors (SD) comprised of plastic scintillator or water Cherenkov detectors, and fluorescence telescope detectors (FD). Conventional detection methods have been successful in mapping out the UHECR spectrum, observing the GZK cutoff [1–3] and locating a potential "hotspot" in CR arrival directions [4]. However, large SD arrays are expensive to build and maintain, and FD telescopes have limited statistics due to their low duty cycle (∼ 10%).

Recently proposed alternative detection methods include those using the geo-magnetic synchrotron [5] and Askaryan [6] effects, both of which require a large instrumentation area. Radar detection has the potential to be a remote detection technique with 100% duty cycle. The idea was initially suggested in 1941 [7] when reflections from extensive air showers (EAS) were proposed as a possible explanation for anomalous atmospheric radar echoes.

Telescope Array Radar (TARA) seeks to observe radar echoes in coincidence with the Telescope Array (TA) and determine the viability of the radar technique for UHECR detection. TARA is the most advanced CR radar detection experiment to date, improving upon other experiments with several key attributes:

- The transmitter is under the direct control of experimenters, and in a radio-quiet area isolated from other radio frequency (RF) sources. The power and radiation pattern are known at all times.
- Forward power up to 40 kW and gain exceeding 20 dB maximize energy density in the radar field.
- Continuous wave (CW) transmission gives 100% duty cycle, as opposed to pulsed radar.
- TARA utilizes a high sample rate DAQ (250 MS/s).
- TARA is colocated with a large state-of-the-art conventional CR observatory, allowing the radar data stream to be sampled at the arrival times of known cosmic ray events.

Each of these attributes of the TARA detector has been discussed in detail in the literature [8]. A map showing the TA SD array and the location of the TARA transmitter and receiver is shown in Fig. 1.

Section 2 of this paper includes a description of air shower plasmas and possible radio scattering mechanisms. Theoretical and experimental parameters that influence radio scattering are presented and discussed. We justify use of the *thin wire model* in a radar echo simulation that predicts echo waveforms, which we will subsequently (Section 6) use in placing limits on the air shower radar cross section (RCS). Sections 3 and 4 describe TARA data and offline processing techniques. In Section 5, we describe the signal search using simulated waveforms as matched filter (MF) templates in order to maximize sensitivity. Section 6 describes the procedure for calculating a scale factor to the RCS model described in Section 2, the results of which are used in placing the first quantitative upper limit on the EAS radar cross-section (RCS). In Section 7 we summarize these results and discuss the viability of radar detection of cosmic rays in light of the TARA findings.

2. EAS radio scattering

We begin with an overview of the issues relevant to RF scattering by EAS, focusing on those which inform the design of the TARA detector and its data analysis.