

Complex Analysis of Askaryan Radiation: UHECR Reconstruction with Askaryan Radio Array

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Ultra-high energy cosmic rays (UHECR) can produce relativistic cascades that emit radio-frequency (RF) pulses in the 10-1000 MHz bandwidth via two distinct effects: the geomagnetic effect, and the Askaryan effect. The geomagnetic effect occurs when the cascade moves through the magnetic field of the Earth, causing electrons and positrons to form a transverse current that radiates linearly polarized radiation aligned with the Lorentz force direction. The Askaryan effect is caused by a net negative charge excess in the cascade that radiates linearly polarized radiation along the Cherenkov cone. When UHECR cascades enter solid, RF transparent matter at altitudes where the cascade develops, Askaryan radiation can propagate through the solid matter to RF detection channels. This is precisely how UHECRs are observed by the Askaryan Radio Array (ARA) at the South Pole. Designed to detect ultra-high energy neutrinos (UHE- ν), ARA is also sensitive to UHECR interactions when the Askaryan effect dominates. Recently, the ARA collaboration published evidence of 13 UHECR candidates. We present an analytical model that confirms the events are UHECRs. Our includes the Askaryan effect and the ARA RF channel response. We show that the coherently summed waveforms (CSWs) from the UHECR candidates match our model with correlation coefficients greater than 0.8, and with minimal fractional power differences. The fit between model and data allows us to extract the observed Askaryan pulses from the raw ARA RF channel data, and to measure their properties.

Keywords: Ultra-high energy neutrino; Askaryan radiation; Mathematical physics

I. INTRODUCTION

1. Define UHECRs
2. Brief summary of radio detection of UHECRs
 - Geomagnetic effect
 - Askaryan effect
3. Why Askaryan effect can dominate UHECR signals in ARA
 - Cite recent paper
 - When cascade interacts directly with ice
 - Do models exist for this? Likely not
 - Gives us a measurement of the E-field
4. This paper is organized as follows...

II. UNITS, DEFINITIONS, AND CONVENTIONS

1. Define $s(t)$, and parameters E_0 and σ_t
2. Define $r(t)$, and parameters f_0 and γ
3. Define convolution $s * r$
4. Define cross-correlation $d \star x$
5. Define CSW

III. THE ASKARYAN RADIO ARRAY

1. Detector diagram of ARA
2. Event diagram of UHECR interaction
3. Cite recent detection of UHECR events
4. Calibration of f_0 from data itself
5. Calibration of γ from data itself

IV. RECONSTRUCTION ANALYSIS

1. Waveform reconstruction
 - Present graphs and tabulated results for CSWs by event
 - Present graphs and tabulated results for subsets of channels by event
2. E-field calculations
 - E-field of UHECRs from CSWs
 - E-field of UHECRs from channel subset CSWs

V. CONCLUSION

What did we learn? How to reconstruct the E-field, and the product $\sigma_t \propto a\Delta\theta$ tells us about the event geometry and energy

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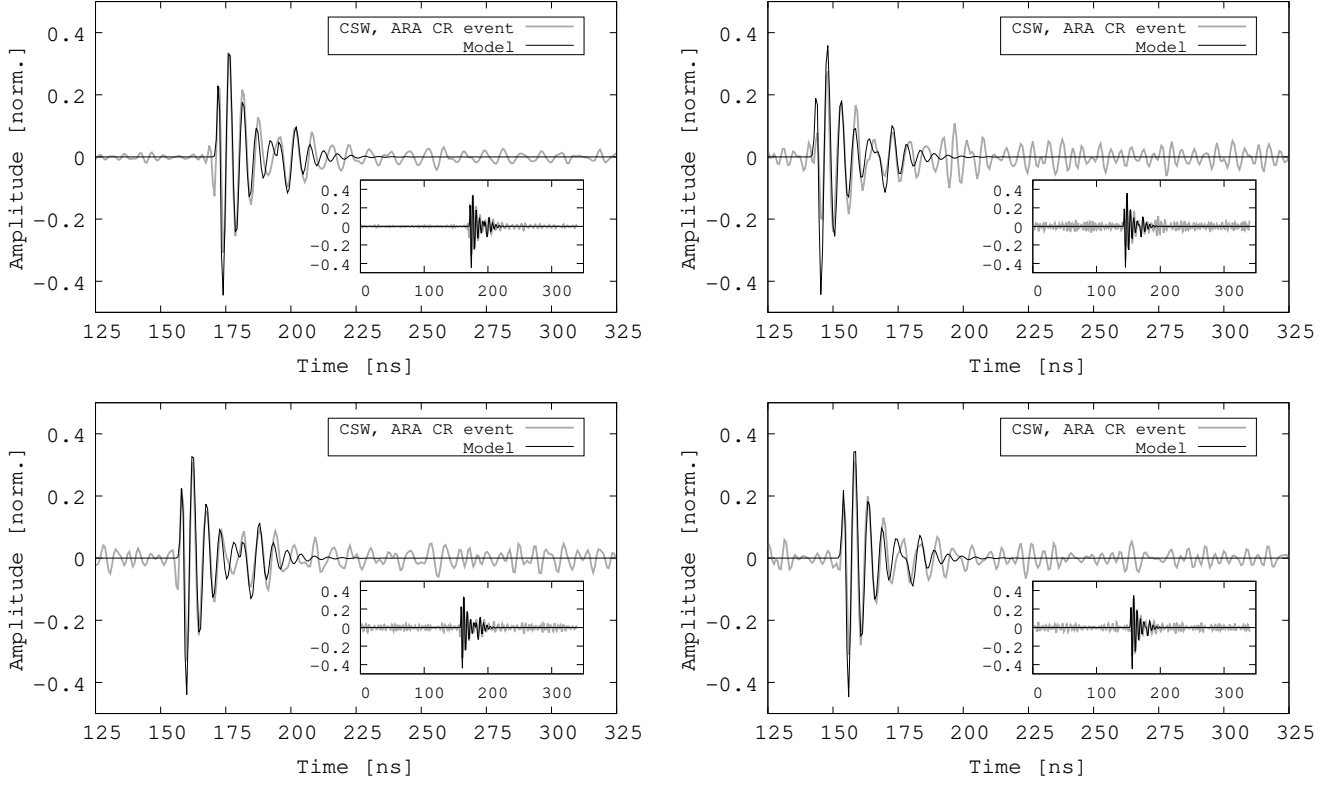


FIG. 1: UHECRs, by ID: (top left) 1915-26288, (top right) 1957-13330, (bottom left) 2171-31805, (bottom right) 2250-20189.

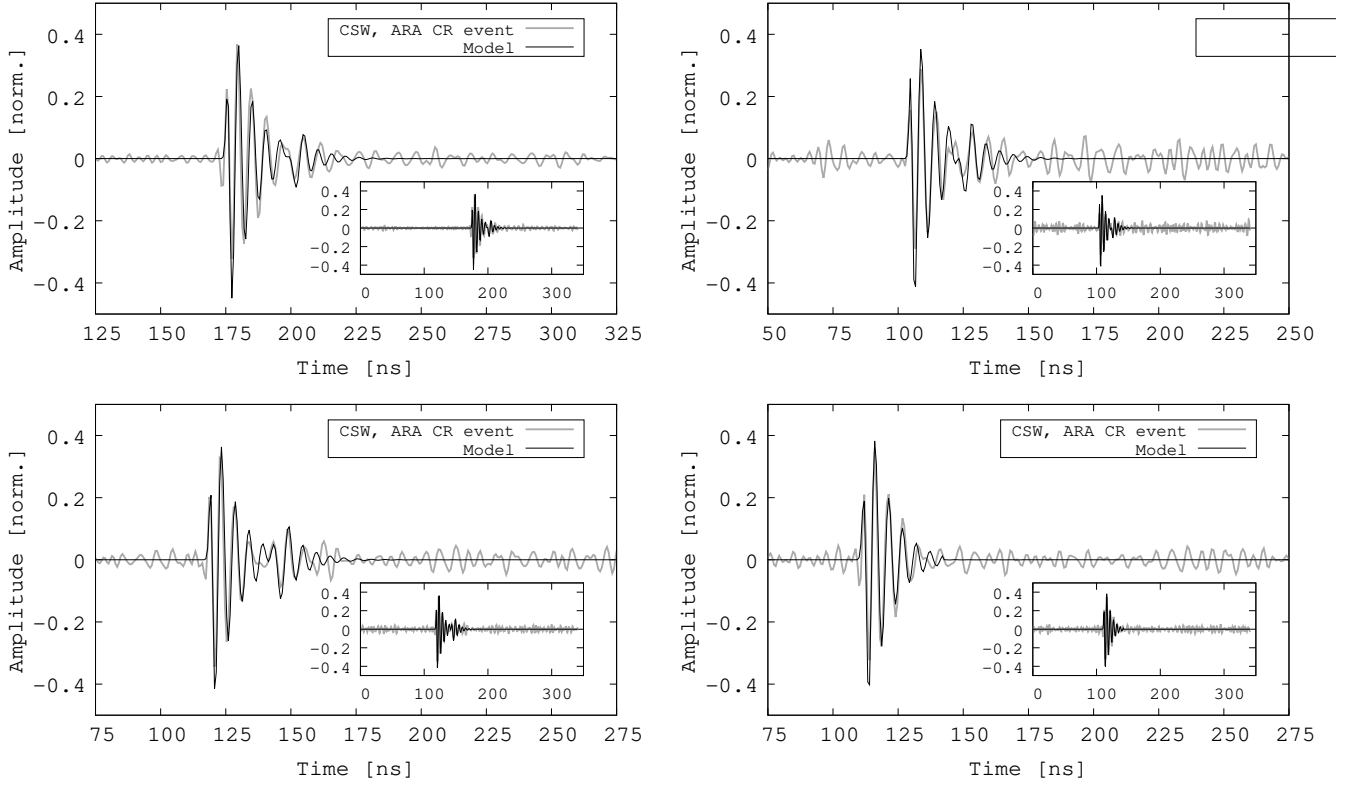


FIG. 2: UHECRs, by ID: (top left) 2352-85489, (top right) 2375-17342, (bottom left) 2529-09767, (bottom right) 2716-58611.

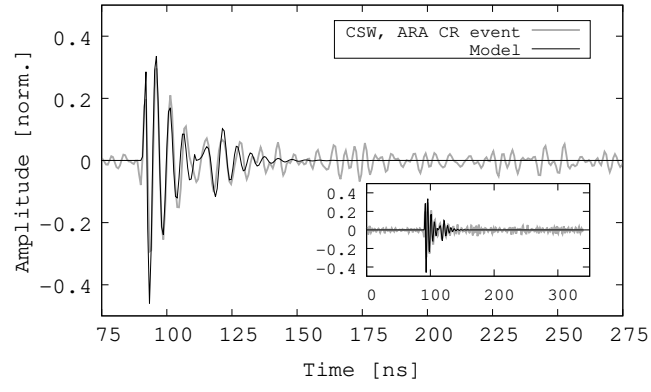


FIG. 3: UHECRs, by ID: 3352-89556

Appendix A: The appendix

Derivation of the $s * r$, maybe the code to do it