Towards Determining the energy of the UHECRs observed by the ANITA detector.

Konstantin Belov

UCLA

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Introduction

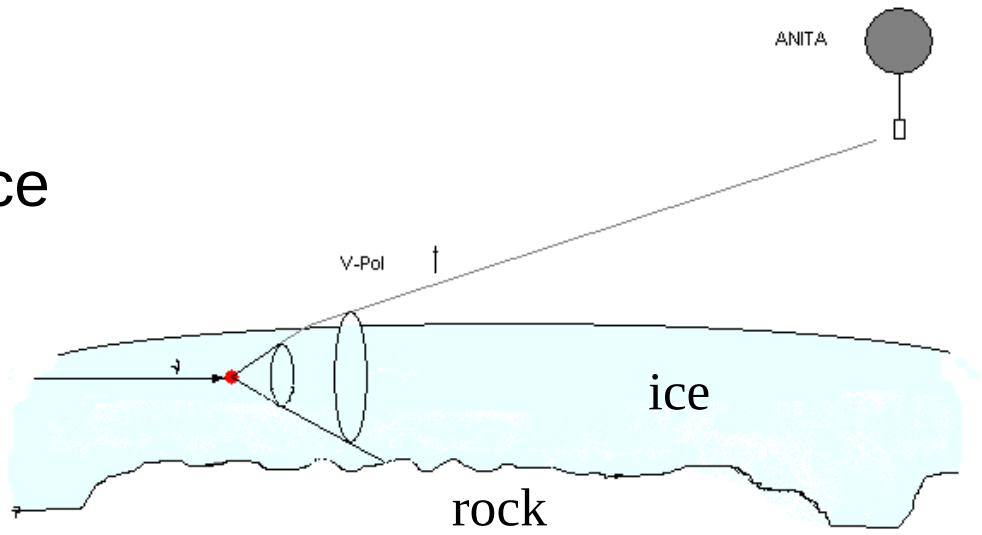
- Radio detection is a very efficient method for observing the extensive air showers caused by the ultra-high energy cosmic rays (UHECR)
- Advantages of the radio detection are 100% duty cycle and lower deployment and operational costs
- Unfortunately, the interest in the radio detection diminished after the initial experiments in the 1960s
- New breed of experiments appeared in the last 5 years: LOPES, CODALEMA , AERA, LOFAR and others
- ANITA I balloon detector reported the observation of the UHECRs in radio, PRL **105**, 151101 (2010)
- This is the first observation of the UHECRs in radio:
  - by a self-triggered radio detector
  - in 200-1200 MHz frequency range
  - in the far field
- New methods and MC simulations have to be developed in order to determine the energy of the UHECRs from the radio data alone

Antarctic Impulsive Transient Antenna (ANITA)

ANITA is a UHE *neutrino* experiment

- Balloon-borne experiment to detect UHE cosmic *neutrinos*
- Using Askaryan effect in ice
- RF impulse detection
- 37 km altitude provides large detector aperture
- 2.5 km deep ice provides huge detector volume

The ANITA concept



Expect vertically polarized (V-pol) e-m impulse

ANITA timeline

Dec 03 - Jan 04: ANITA-lite flight

June 2006: ANITA I beamtest (SLAC)

Dec 06 - Jan 07: ANITA I flight

Dec 08 - Jan 09: ANITA II flight

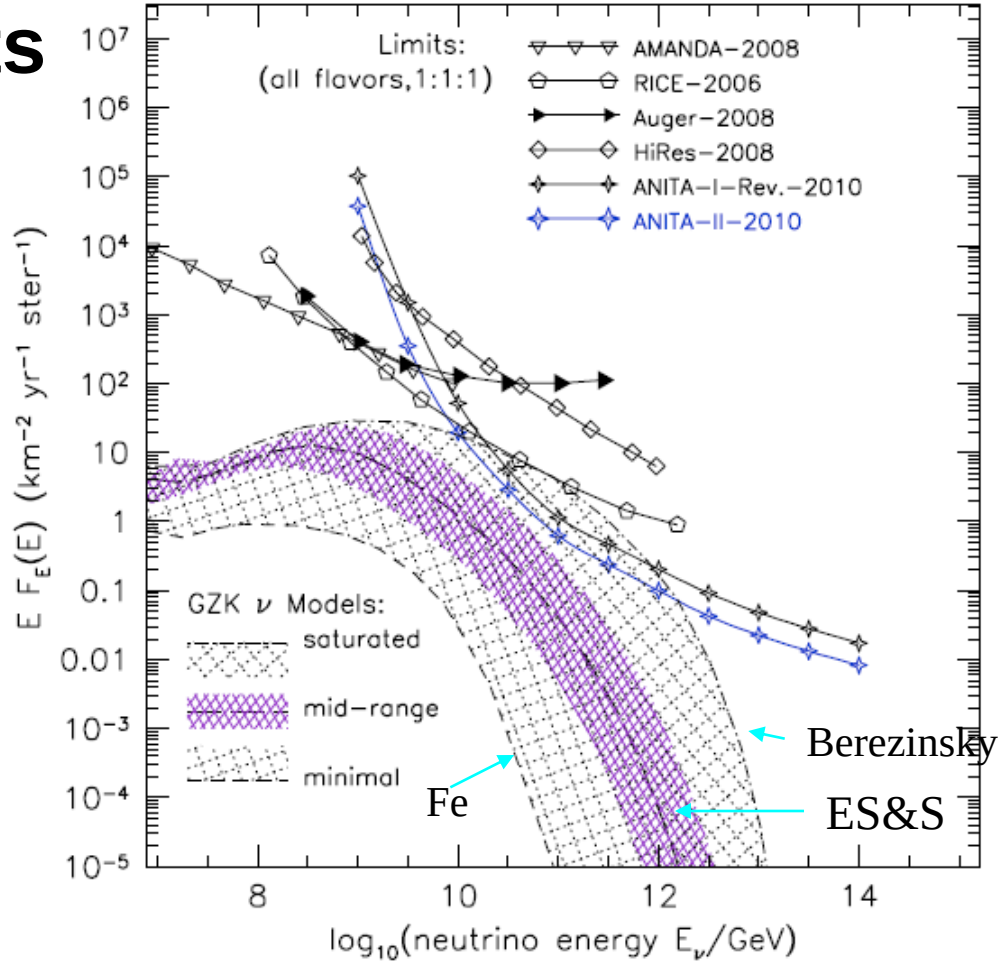
ANITA III flight is approved for 2013-2014 season.

ANITA I detector in Antarctica

ANITA neutrino limits

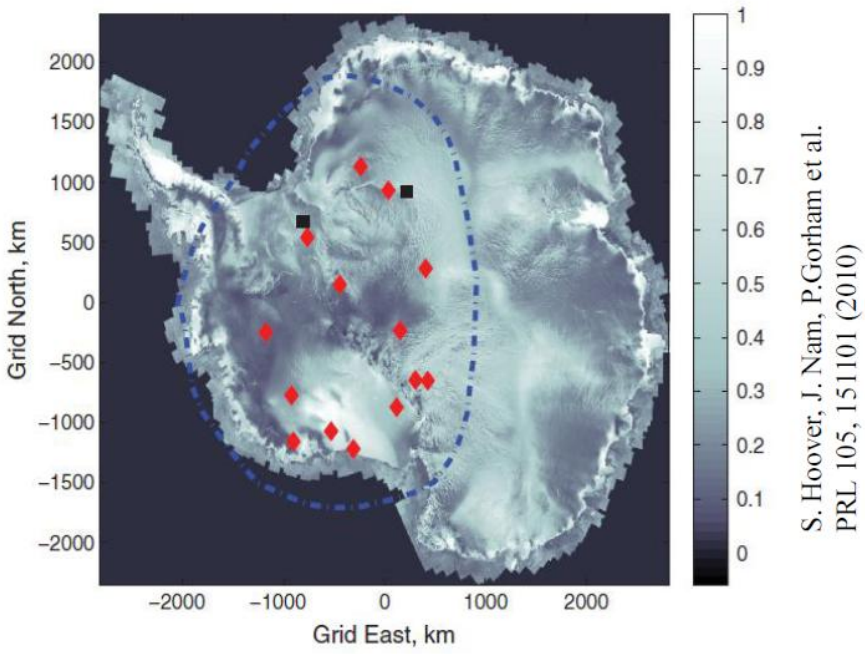
- Two successful ANITA flights give the best published limit on the UHE neutrino flux

- In addition, the analysis of the ANITA I data reveals 16 isolated H-pol events consistent with UHE *cosmic rays*

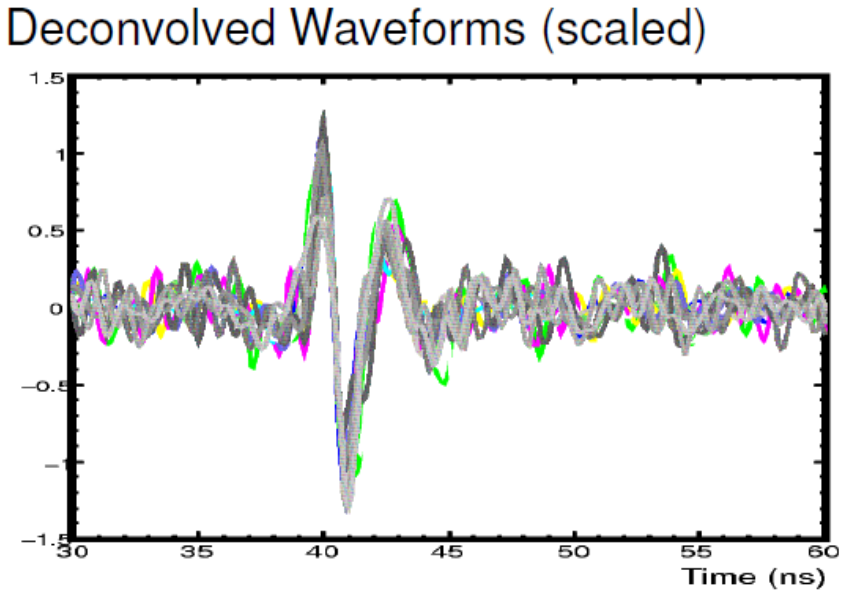


GZK Neutrinos: Theoretical fluxes & Current Limits
Phys. Rev. D 82, 022004 (2010)

ANITA 16 isolated H-pol events



S. Hoover, J. Nam, P.Gorham et al.
PRL 105, 151101 (2010)

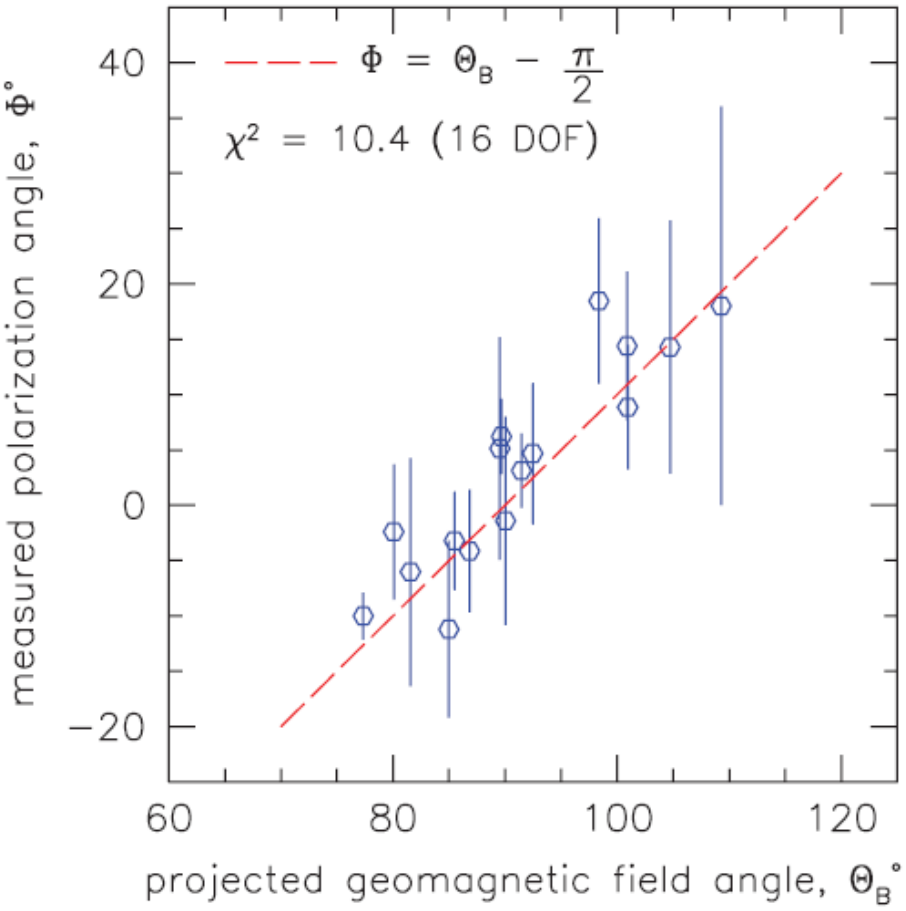


S. Hoover, Ph.D. thesis

16 single events
14 reconstructed on the ice
2 reconstructed above the horizon
H-pol and impulsive with very weak but measurable V-pol content

- 14 events similar to each other in shape and spectrum – reflected from ice
- 2 events have different polarity – direct (non-reflected) events.
- The polarity of the 16 ANITA events suggests the geosynchrotron mechanism is responsible for the RF emission from the air showers
- Residual V-pol is what we expect from geosynchrotron

Confirmation of the geosynchrotron mechanism



S. Hoover, J. Nam, P.Gorham et al.
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- Our CR candidates have some V-pol content – not enough to trigger ANITA, but enough to be measured once the event triggers on H-pol.
- Using known earth magnetic field we can compare the *predicted* V-pol signal with *measured* by ANITA.

ANITA – a balloon-borne Ultra-High Energy Cosmic Ray radio detector.

- 2 direct events
- 14 events reflected from the Antarctic ice
- What is the energy of the UHECRs?

atmosphere

ice

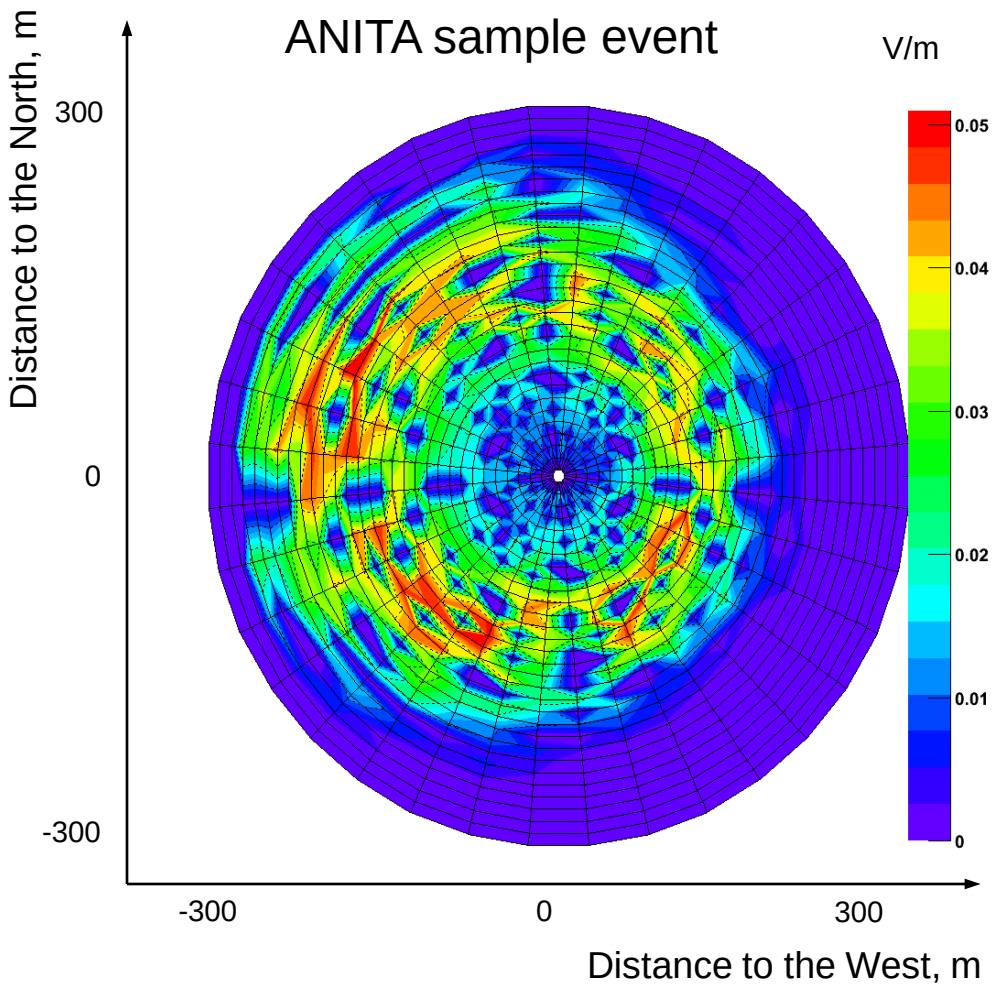
Not to scale

Towards the energy of the ANITA Cosmic Ray events

- MC simulations: Corsika-6960 + CoREAS (thanks KIT)
- Primary – *p*
- Energy 10^{17}-10^{21}
- Actual ANITA event geometry
- Atmosphere – South Pole January average
- Actual magnetic field at the event reconstructed location
- Effects of the Fresnel reflection, roughness, antenna response and e-m field propagation to the payload are included
- Realistic (changing with depth) index of refraction

ANITA sample event simulated

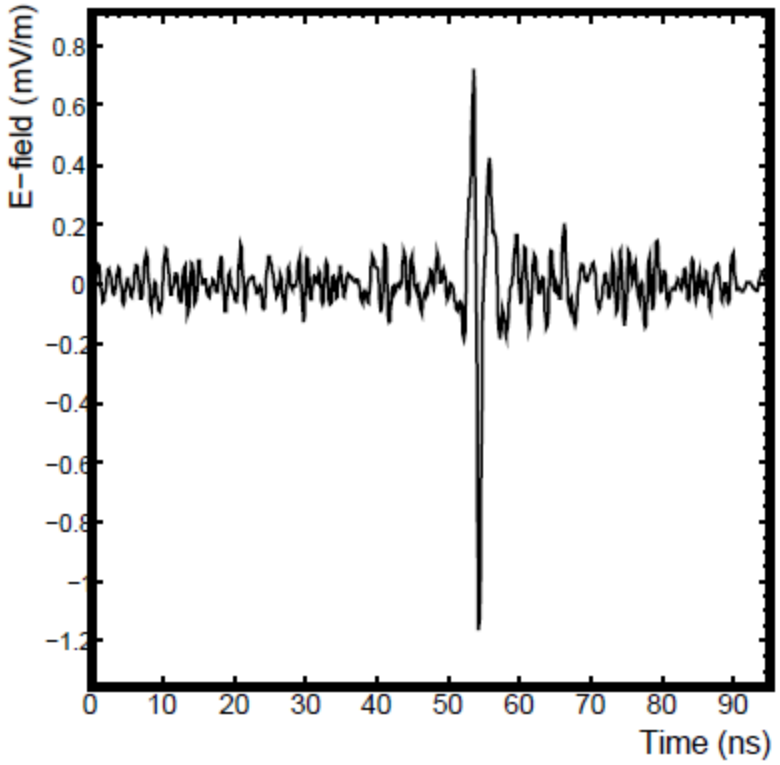
- Radio “footprint” on ice is a ring for n≠1.
- Relativistic effects:
  - Inside the ring, the time is reversed – the observer sees the end of the shower first
  - For the observer anywhere on the ring the shower happens instantaneously – “Cherenkov amplification”
- The opening angle for the ring is ~1.2 degree that corresponds to ~180 m radius for this ANITA event
- From what part of the ring the signal seen by ANITA is reflected?
- Azimuthal angle (φ polar coordinate) is known from the shower geometry with 180 degree degeneracy.
- How far from the shower core the signal is seen (r polar coordinate)?



H-pol component of E-field on ice
at the time of maximum E-field magnitude.

Total power in RF received by ANITA

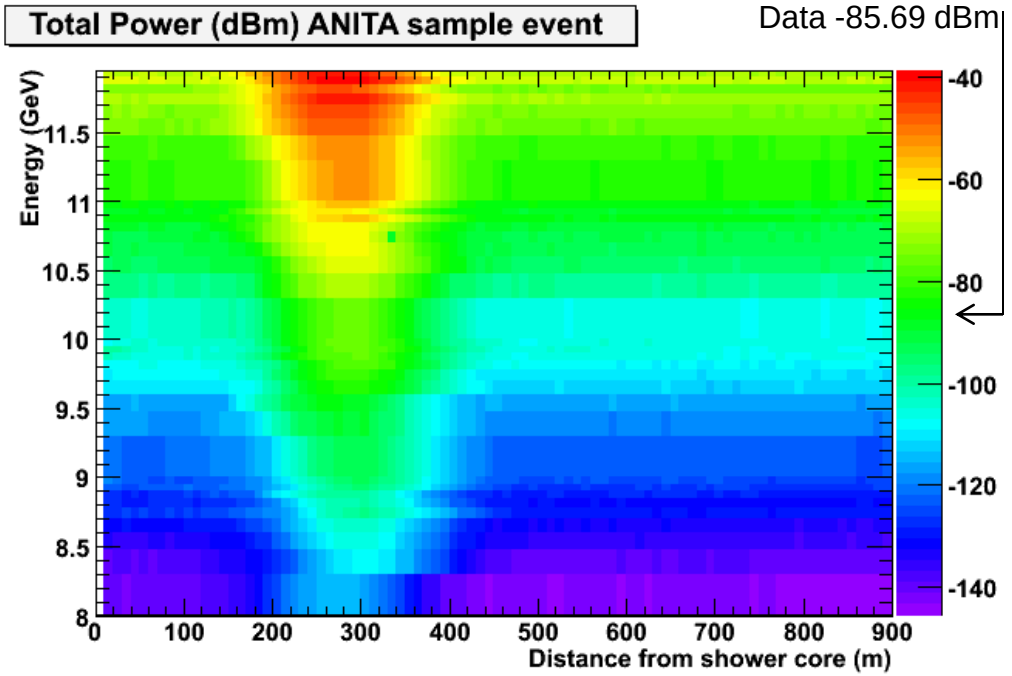
ANITA data. Sample event
Instrument response decovoluted



S. Hoover PhD thesis

- From the ANITA data, we know the total power of the signal received by ANITA
- Use MC simulations to match to the event total power to get the lower limit on the primary particle energy

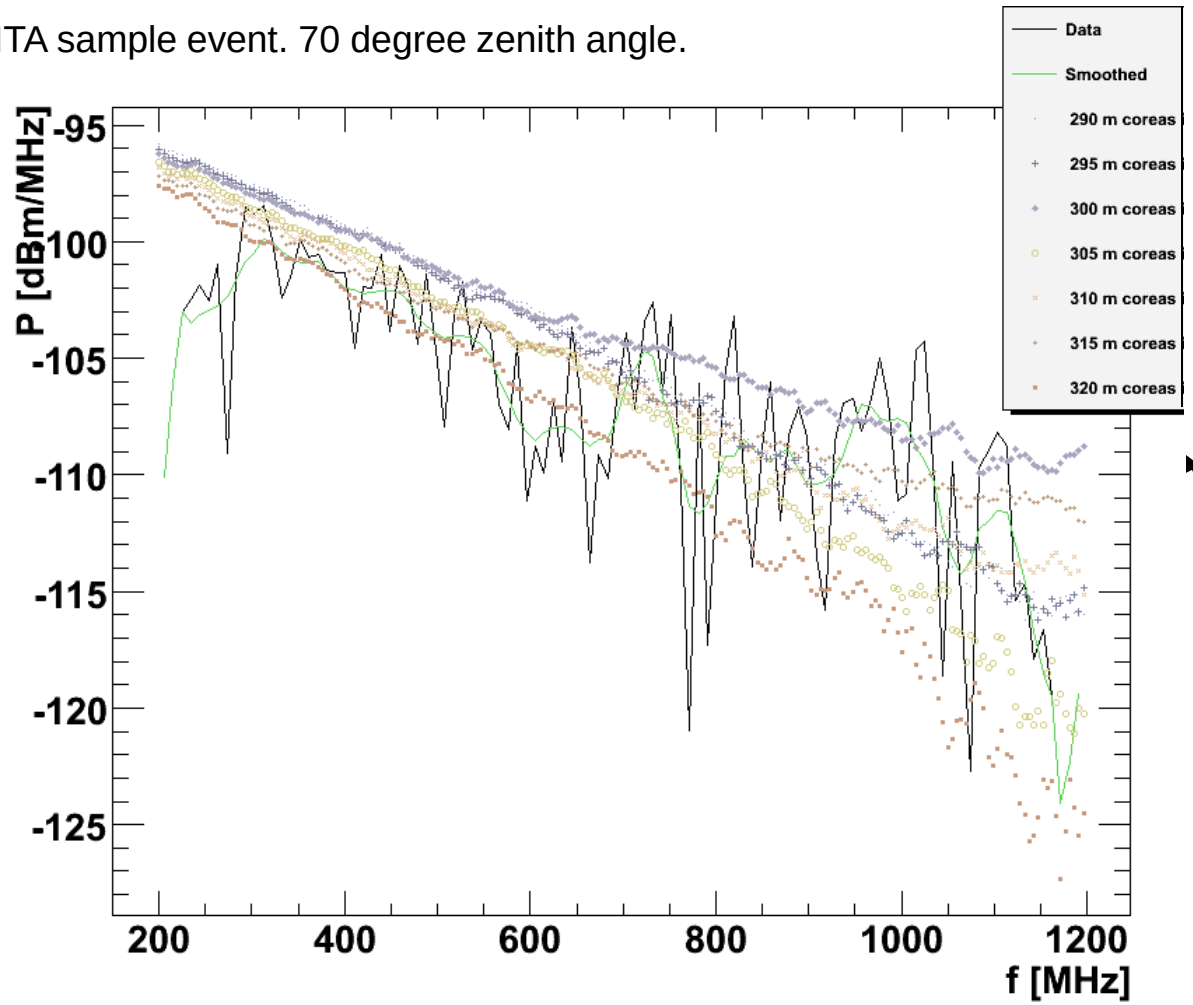
MC Simulations for ANITA sample event



Total power in RF received by the payload from air showers of different energies reflected at different distances from the shower core.
1/r, Fresnel, roughness, antenna response are accounted for.

Use the event spectrum to get the upper limit on the primary particle energy

ANITA sample event. 70 degree zenith angle.

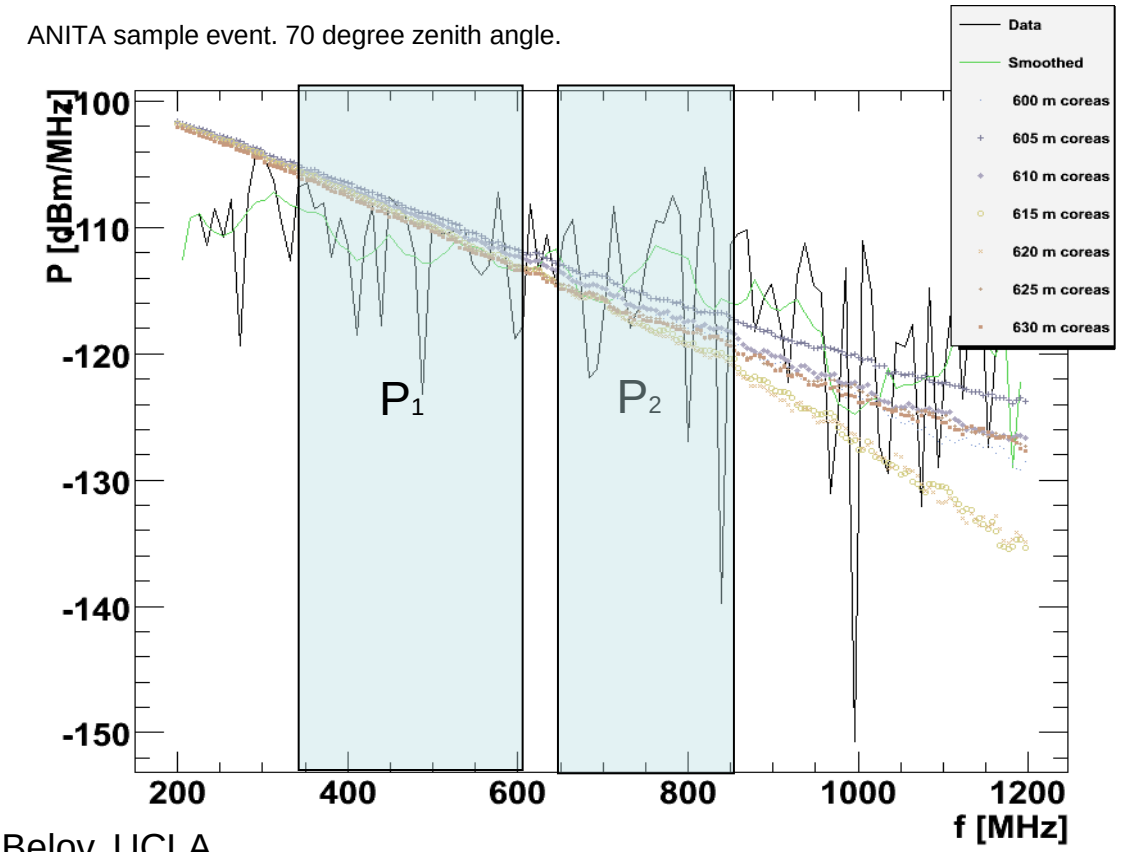


Note
5 m step

- We are sensitive to about 5 -10 m difference from the shower core.
- Black – ANITA I data. Green – smoothed ANITA I data.

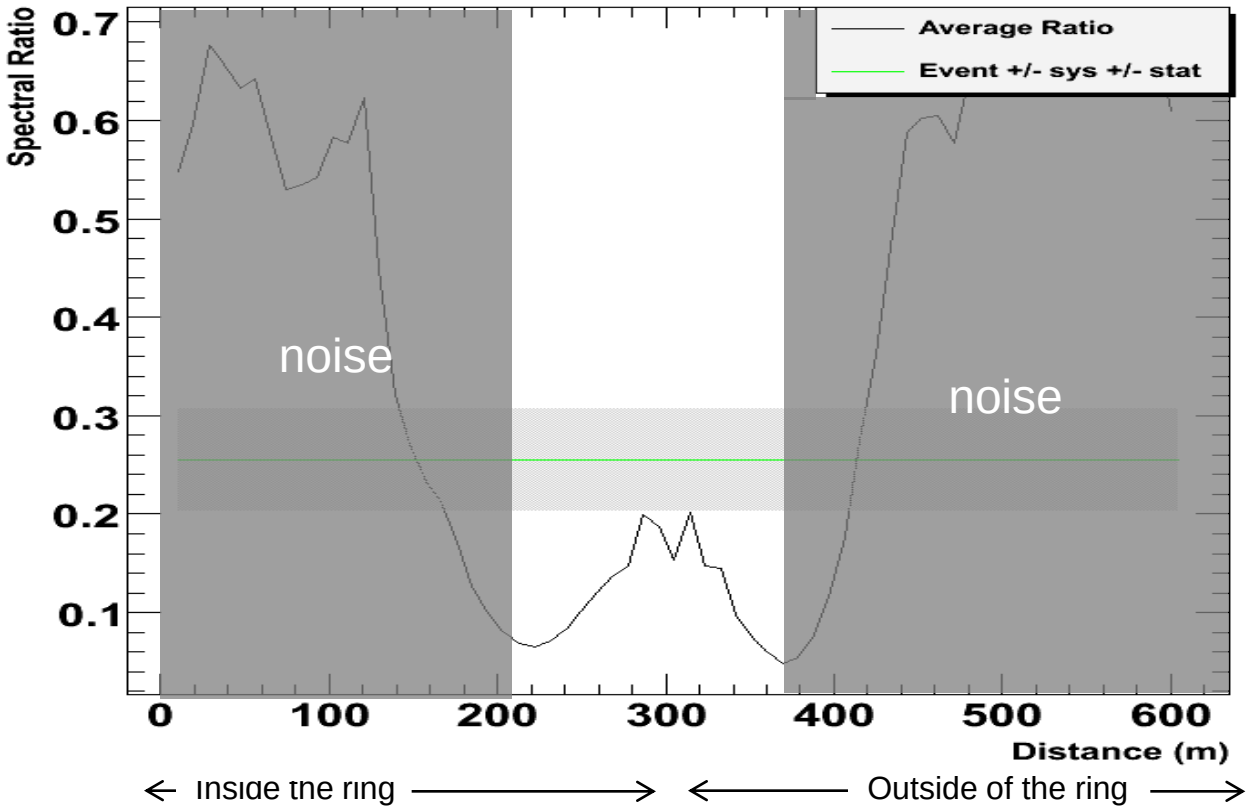
Spectral ratio – a quantitative measure of the spectral index.

- We define spectral ratio (Ratio = P_2/P_1) to find the actual event's distance from the shower core (off axis angle)
- P_1 is the total power between 350 – 600 MHz, while P_2 is the total power between 650 – 850 MHz
- Spectral ratio is not energy dependent



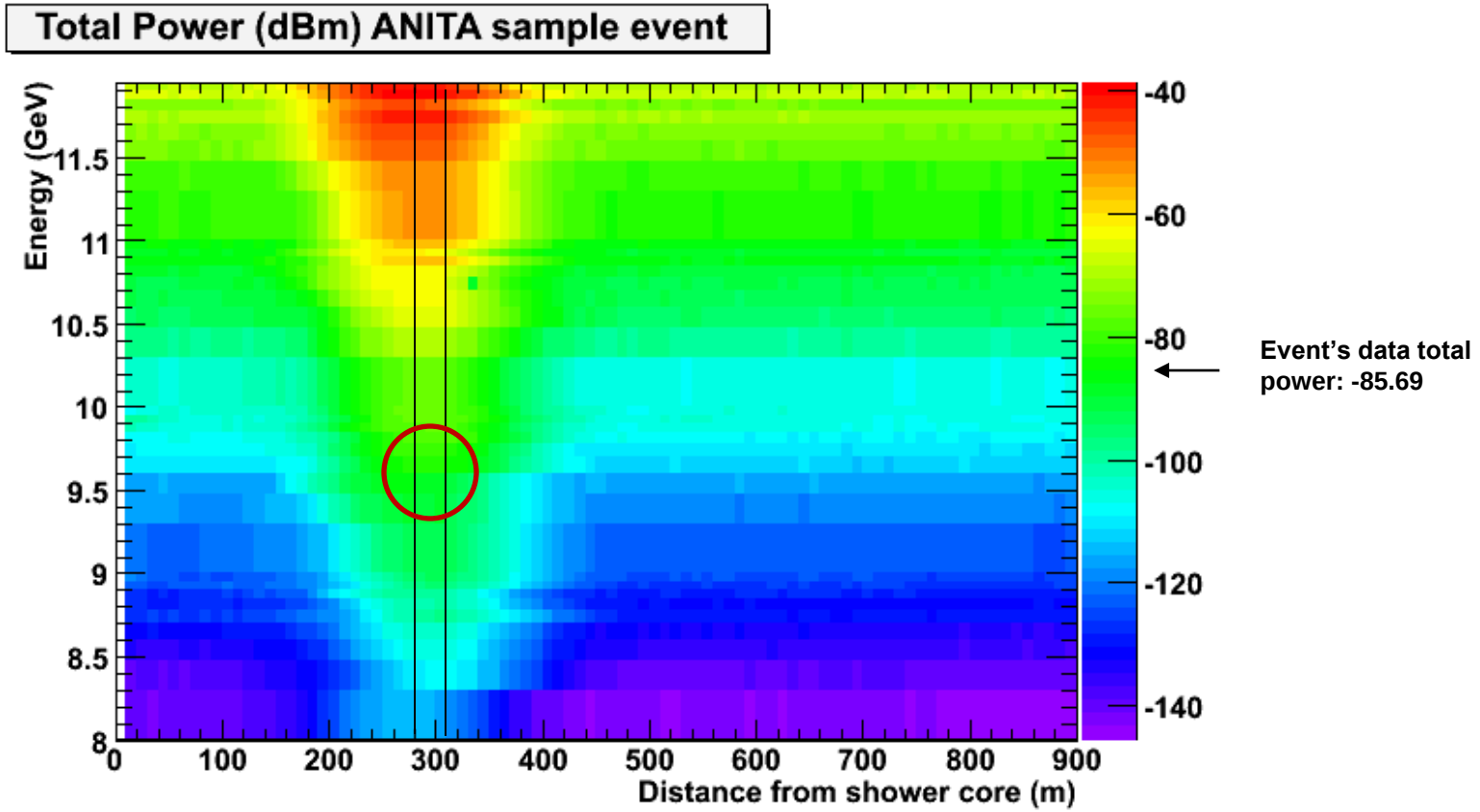
ANITA sample event spectral ratio

Spectral ratio. ANITA sample event. 70˚ zenith angle. 350-600 650-800 MHz



- Black line – spectral ratio for the simulated event
- Dark grey – noise dominated areas.
- Green line – spectral ratio for the data
- Light grey – estimated error on the spectral ratio for the sample event.
- We subtract 20% of the total power in the higher band when calculating the spectral ratio for the real data because we are hitting the noise floor at ~ -120 dBm/MHz
- MC data does not include the noise

The energy of the UHECR from radio



- Black lines - upper and lower limits on the distance from the shower core from spectral ratio
- Red circle – primary energy allowed by the total RF power and spectrum of the signal seen by the ANITA detector.

Conclusions

- Spectral shape of the electromagnetic impulse from the extensive air shower in conjunction with the total RF power received by the antenna can be used to obtain the energy of the UHECRs.
- Presented spectral analysis technique is a robust tool that can be used to measure the energy of the primary cosmic particle using stand alone radio observations on event by event basis.

- Special thanks to David Urdaneta and David Saltzberg who contributed to this work.

Work in progress

- At the moment, overall energy scale is probably wrong:
  - 1/r E-field scaling assumes the point-like RF source located at X_{max} while real source (the whole air shower) is extended.
  - Total power in RF is not uniform around the “ring” on ice => dual degeneracy of the power is built into the current analysis
  - Add integral over Fresnel surface of the ice
- Need to account for the detector trigger bias, that affects the signal spectrum
- Try to use a fit instead of the spectral ratio
- Systematic error analysis to be done