Frequency-optimised radio arrays for air-shower detection


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Motivation

To measure air showers from PeV $\gamma$-rays from the Galactic Centre at the South Pole ($\theta = 61^\circ$)

Radio signals survive until the ground

- antenna spacing $\approx 125$ m
- array area $\approx 1$ km$^2$
## Radio at PeV energies

- Successful air shower detection with radio only above $10^{16.5}$ eV
- Required: lowering of energy threshold by an order of magnitude
- Need to measure radio signals above noise at PeV energies

![Graph showing data points and labels](image)

**Graph Details:**
- **Energy (eV/particle):** Logarithmic scale from $10^{13}$ to $10^{21}$
- **Scaled flux $E^{-2} J(E)$ (m$^2$ s$^{-1}$sr$^{-1}$ eV$^{-1}$):** Logarithmic scale from $10^{13}$ to $10^{19}$
- **Equivalent c.m. energy $\sqrt{s_{pp}}$ (GeV):** Linear scale from $10^2$ to $10^6$
- **Experiments:**
  - HERA ($\gamma$-p)
  - RHIC (p-p)
  - Tevatron (p-p)
  - 7 TeV LHC (p-p)
  - 13 TeV LHC (p-p)
  - 100 TeV FCC (p-p)
  - Telescope Array
  - Pierre Auger Obs.
- **Data Sources:**
  - ATIC
  - PROTON
  - RUNJOB
  - KASCADE (SIBYLL 2.1)
  - KASCADE-Grande
  - Tibet ASg (SIBYLL 2.1)
  - IceTop

*arXiv:1601.07426*
Noise model

- Total noise = Galactic noise* + thermal noise (valid for radio-quiet zones)
- Noise temperature $\rightarrow$ power delivered to the antenna: $P = k_B T \delta\nu$

*H.V. Cane, MNRAS 189, 465478 (1979)
Comparison of noise and signal

CoREAS simulation of radio signals ($\gamma$-ray, $\theta = 61^\circ$, $\phi = 0^\circ$, $E = 10$ PeV)

- Signal-to-noise ratio, $\text{SNR} = \frac{S^2}{N^2}$
- $S = \text{max of the signal envelope}$, $N = \text{rms noise}$
Frequency optimisation

Eg: Station at the Cherenkov ring

This is the best frequency band
True for all stations/all regions of the footprint

Energy threshold

Threshold can be lowered to 1 PeV at 100-190 MHz

Thermal noise = 300 K

$\gamma$-ray, $\theta = 61^\circ$, $\phi = 0^\circ$

3 antennas with SNR > 10

arXiv:1907.04171 (ARENA 2018 proc.)
Threshold lowered by an order of magnitude in the optimal band 100-190 MHz

Integral sensitivity (5σ) to detect PeV γ-rays from the GC (Using H.E.S.S. flux [Nature 531, 476(2016)])
IceTop Radio Enhancement

- Prototype antennas deployed, first air-shower measurements expected in the next season
  PS1-210 [PoS(ICRC2019)418], PS3-207

- SKALA antennas developed for SKA (50-350 MHz)

Photo credits: Max Renschler
Other locations: GRAND

- Neutrino shower, $E = 0.5$ EeV, $3^\circ$ below the horizon
- Planned: 50-200 MHz

Already for GRANDProto300: CRI1f

Neutrino shower, $E = 0.5$ EeV, $3^\circ$ below the horizon
Planned: 50-200 MHz

About GRAND: NU10b

Station outside the Cherenkov ring


antenna spacing: 1 km
Proton shower, $E = 7.5$ EeV, $\theta = 80^\circ$

Optimal band 100-190 MHz

Station inside the Cherenkov ring

A. Balagopal V., PhD thesis, DOI: 10.5445/IR/1000091377

Auger radio upgrade: PS3-205
Conclusion

- Optimal band 100-190 MHz consistently obtained for IceTop, GRAND, Auger
- Improves efficiency, lowers energy threshold
- Difference between locations: magnetic field, observation level, atmosphere
- Nature of radio emission is the same
- Same noise is considered in all studies
  \[ \Rightarrow \text{Same optimal band} \]
- Advantageous to perform frequency optimisation for future expts.
Backup
Sensitivity of the radio array

For $5\sigma$ detection within 5 years

\[ E^2 \times \text{Flux (PeV cm}^{-2}\text{s}^{-1}) \]

- $\geq 3$ antennas, with direction and energy reconstruction
Footprint of $61^\circ \gamma$-ray showers

Footprint of a 10 PeV shower

Footprint of a 1 PeV shower
Lateral distribution

Filtered to different bands of 50 MHz width
Frequency behaviour

(a) Thermal noise = 300 K

(b) Thermal noise = 40 K