The Tunka Radio Extension, an antenna array for high-energy cosmic-ray detection

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Cosmic rays

Main puzzles of high-energy cosmic rays:
✓ Sources of cosmic rays?
✓ Acceleration mechanisms?

Need to know:
✓ Direction
✓ Primary energy
✓ Mass composition

$10^{16}-10^{19}$ eV: a transition from galactic to extragalactic sources
TAIGA - **Tunka Advanced Instrument** for cosmic rays and Gamma Astronomy:

**Cosmic ray detectors**
- Tunka-133 air-Cherenkov
- Tunka Radio Extension (Tunka-Rex)
- Tunka-Grande scintillators

**Gamma ray detectors**
- HiSCORE
- IACT
Tunka-133

✓ 175 optical modules (7 per cluster, 25 clusters) on 3 km²
✓ E resolution: ~ 15 %,
    $X_{\text{max}}$ resolution: ~ 28 g/cm²
✓ Measurement during moonless winter nights (only ~10% of duty cycle)

Tunka-Grande

✓ 19 scintillator stations with spacing of 200 m over 1 km²
✓ Each station consists of electron (8 m²) and muon (5 m²) detectors
  (Electron/muon ratio → information about mass composition)
✓ Almost full time duty-cycle

Tunka-133

Tunka-Grande

Trigger for the Tunka-Rex
# Tunka-Rex

<table>
<thead>
<tr>
<th>Upgrade</th>
<th>Achieved:</th>
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| expected more than 2000 events per season triggered by Tunka-133 & Tunka-Grande | * Cross-calibration of radio and air-Cerenkov signal  
* Determine achievable precision of the radio technique |

<table>
<thead>
<tr>
<th>18 antennas</th>
<th>25 antennas</th>
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<td>2012</td>
<td>2013</td>
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<th>44 antennas</th>
<th>63 antennas</th>
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<td>2015</td>
<td>2016</td>
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**Plan:**
* Core reconstruction with radio  
* Joint reconstruction of electromagnetic (Tunka-Rex) and muon (Tunka-Grande) components of air showers  
* Mass composition study
Tunka-Rex station

- Effective frequency band: 35-76 MHz
- Antenna type SALLA (Loop antenna with isotropic pattern)
- Absolute scale

Tunka-Rex is the most cost-effective of all radio arrays
Example of Tunka-133 triggered event

Searching of the signal power trace:
- Digiting filtering
- N antennas ≥ 3
- SNR ≥ 10

Rejecting false positive events:
- Comparison with Cherenkov reconstruction (Ω < 5°)
- Rejecting outliers from the LDF (using Tunka-133 core coordinates)
- Reconstruction of arrival direction with plane fit

Quality cuts for $X_{\text{max}}$: reconstruction at least one antenna at $d_{\text{axis}} > 200$ m

For analysis we use the radio part of the Auger Offline software
Pierre Auger Collaboration, NIM A 635 (2011) 92
Reconstruction method

✓ LDF correction for the azimuthal asymmetry and for the geomagnetic angle
✓ Gaussian LDF, three parameters: $A_{120\text{m}}$, slope and width (fixed)
✓ $E_{pr} \sim A$ at 120 m, $X_{\text{max}}$ depends on slope at 180 m

(doi:10.1016/j.astropartphys.2015.10.004)
Cross-check with Tunka-133 (2012-2014 seasons)

Resolution:
- Cherenkov energy (EeV): 15%
- Shower maximum: 38 g/cm²

Tunka-Rex Collaboration, JCAP 1601 (2016) no.01, 052 [doi:10.1088/1475-7516/2016/01/052]
Amplitude calibration

✓ Absolute reference source for Tunka-Rex, LOFAR and LOPES
✓ CoREAS amplitude scale confirmed (17%)

(doi:10.1016/j.nima.2015.08.061)
Comparison of energy scales of Tunka-133 and KASCADE-Grande

[Graph showing comparison of energy scales]
Conclusion

✓ Tunka-Rex provides competitive precision of energy and shower maximum

✓ Absolute amplitudes compatible with CoREAS simulations and LOPES measurements

✓ After its upgrade, Tunka-Rex focuses on the mass-composition study jointly with Tunka-Grande