Overview on Radio Detection of Air Showers with focus on LOPES, Tunka-Rex, and AERA

Frank G. Schröder
Advantages of radio technique

- Accurate measurement of energy and $X_{\text{max}}$ around the clock
Emission mechanisms

geomagnetic effect $\sim 90\%$

Askaryan effect $\sim 10\%$
Conical radio emission with asymmetric footprint

shower inclination: 
\[ \theta = 45^\circ \]

CoREAS simulations
By T. Huege et al., ARENA2012
Do simulations describe reality?

- CoREAS (+ other codes) reproduce measured amplitudes within ~20% uncertainty.

![Graph showing CoREAS and measured amplitudes comparison](image-url)
1st Answer: How well do we understand the radio emission?

- To a level of 10-20%
  - better than for muon content of air-showers
  - similarly good as fluorescence detection, but various systematics are not yet extensively studied

Open questions for becoming even better

- What is the impact of atmospheric humidity?
- Is the proportionality with geomagnetic field exact?
- How exactly behaves the emission for near-horizontal showers?
Experiments: First Detection

- Qualitative features discovered 50 years ago, but measurements lacking accuracy

Location of selected experiments and geomagnetic field

Underlying map (Mercator projection)
Main Geomagnetic Field Total Intensity with contour intervals of 1000 nT according to US/UK World Magnetic Model - Epoch 2015.0

developed by NOAA/NGDC & CIES
http://ngdc.noaa.gov/geomag/WMM
Map reviewed by NGA and BGS
Published December 2014

Overlaid
Location of radio experiments for cosmic-ray air showers added on underlying map by Frank G. Schmidt
Karlsruhe Institute of Technology (KIT), Germany
Designs of modern radio arrays (mostly externally triggered)

AERA (153)

LOFAR - LBA outers
(7 x 48)

LOPES
(30)

Tunka-Rex
(25)

CODALEMA3
(57)

Compilation by A. Zilles
Detectors: antennas

- Many working solutions with only slight differences in
  - threshold (typical $10^{17}$ eV) and frequency band (typical 30-80 MHz)
  - accuracy (systematic uncertainties, e.g., due to ground conditions)

- inverted v-dipole at LOPES
- SALLA at Tunka-Rex
- LPDA at Auger
- Butterfly at CODALEMA
Reconstruction of shower parameters

- Direction
  - example: LOPES

- Energy
  - example: AERA and others

- Shower maximum
  - example: Tunka-Rex (for LOFAR see next talk)
Interferometric beamforming at LOPES

- Cross-correlation of traces after time shift according to arrival direction
- Direction precision < 0.7° (by comparing LOPES to KASCADE)

Auger Engineering Radio Array

- 153 autonomous stations on 17 km²

Auger Engineering Radio Array

▲ LPDA antenna
▼ Butterfly antenna

Auger Muon and Infill Ground Array

- Surface Detector
- with Muon Detector

750 m
Auger Engineering Radio Array

- 153 autonomous stations on 17 km²
- Auger Engineering Radio Array
- LPDA antenna
- Butterfly antenna

Auger Muon and Infill Ground Array
- Surface Detector
- with Muon Detector

Butterfly

LPDA
Energy reconstruction by AERA

Total energy in radio signal scales quadratically with electro-mag. shower energy

- Position in $\vec{\theta} \times \vec{B}$ [m]
- Energy density $\dot{\nu} [\text{eV/m}^2]$
- Energy $E_{30\,\text{MHz}}$ [eV]
- Slope $= 1.98 \pm 0.04$
- Energy resolution: 17%

Pierre Auger Coll., PRL 116 (2016) 241101
Similar energy precision by other experiments

Moscow experiment: Vernov et al. (1968)

+ several other experiments

LOPES Coll., AIP Conf. Proc. 1535 (2013) 78

Tunka-Rex, JCAP 01 (2016) 052
Comparing energy scales via radio

Tunka-Rex + LOPES Colls., submitted to PLB
Shower maximum: proof by Tunka-Rex

- One of several methods: slope of lateral distribution

precision: 40 g/cm²
Radio Detection of Cosmic Rays

Auger fluorescence 2015
-Tunka-133 air-Cherenkov 2015
-LOPES lateral slope
-LOPES wavefront
-LOFAR top-down
-Tunka-Rex lateral slope

![Graph showing mean depth of shower max. vs. log energy.](image-url)
2nd Answer: What is the accuracy for shower observables?

- Accuracy competitive to fluorescence technique
  - direction < 0.7°
  - energy < 20% (precision + scale)
  - $X_{\text{max}}$ < 20 g/cm² (with high antenna density)

- Next steps currently under investigation
  - Can we reach an energy accuracy of 5-10%?
  - Can we achieve 20 g/cm² $X_{\text{max}}$ resolution with sparse arrays?
  - Can we exploit composition sensitivity beyond $X_{\text{max}}$?
3rd Answer: What ideas and plans are there beyond $X_{\text{max}}$?

- **Highest apertures for $10^{20}$ eV**
  - huge arrays for inclined showers, satellites, the Moon
  - drawbacks: poor energy resolution and composition sensitivity
  - science case, if composition at $10^{20}$ eV is not mixed, but either pure proton or pure iron

- **Neutrino search above $10^{16}$ eV**
  - radio arrays in and on ice – ARA, ARIANNA

- **Ultimate precision around $10^{17}$ eV**
  - the low-frequency core of the Square Kilometer Array (SKA)
Cosmic-Ray detection by ANITA

P. Gorham, et al. (ANITA Coll.)

Radio Detection of Cosmic Rays

Geomagnetic field

\[ n \approx 1.3 \text{ for ice surface} \]
Huge footprint for inclined showers

- Enables large-scale, sparse antenna arrays for reasonable costs

**Auger measurement**

\[ E = 3.6 \times 10^{18} \text{ eV}, \theta = 75.7^\circ \]

**CoREAS simulation**

\[ E = 10^{18} \text{ eV} \]

Pierre Auger Collaboration, PoS (ICRC2015) 615
Composition sensitivity for inclined showers

- Only radio emission + muons survive for inclined showers
- Complementary information on shower $\rightarrow$ primary particle type
Neutrino-induced showers in ice

ARA Collaboration

ARIA Collaboration

Central Station Electronics
Power and communications to ICL
Downhole instrumentation

FO Transmitter
Top Hpol
Top Vpol
Bottom Hpol
Bottom Vpol

Calibration antennas
Antenna clusters
Calibration antennas

Depth: 200 m
*Surface antennas are not shown

ICE SHELF
Solar panels
Satellite links
Electronics box

SEA WATER

Graphic adapted by A. Nelles from S. Brown / The Register

06 September 2016
ECRS 2016, Torino

Radio Detection of Cosmic Rays

frank.schroeder@kit.edu
Institut für Kernphysik
The Square Kilometer Array: ultra high precision

- Phase 1: ~ 60,000 antennas on ½ km²
- Scintillator array planned for E > 10^{16} eV
Conclusion

- Significant progress in last years
  - radio is on the way to a standard technique
  - emission understood to at least 10 - 20 % accuracy

- Competitive accuracy for air shower parameters
  - direction < 0.7°
  - energy < 20% (precision + scale)
  - $X_{\text{max}} < 20 \text{ g/cm}^2$ (with high antenna density)

- Radio ideal for particle-detector arrays at $E > 10^{17}$ eV
  - enhancement of accuracy for energy + composition

more in arXiv: 1607.08781
30 dipole antennas
- 40 – 80 MHz, east-west / north-south
- Trigger by KASCADE
Relative strength of Askaryan effect

LOFAR JCAP 10(2014)014
- $\theta = [0^\circ, 20^\circ)$
- $\theta = [20^\circ, 40^\circ)$
- $\theta = [40^\circ, 60^\circ)$

AERA
(scaled to LOFAR mag. field)
- polarization PRD 89(2014)052002
- LDF asym. PRD (2016) accepted

CoREAS sims. for Tunka-Rex
(scaled to LOFAR mag. field)
- proton
- iron
Astropart. Phys. 74 (2016) 79
Hyperbolic radio wavefront

- Hyperbolic shape seen by LOPES and LOFAR
- Slight east-west asymmetry not yet confirmed

LOFAR measurement
Astropp. 61 (2015) 22

\[
\chi^2 / \text{ndf} = 106/274
\]
\[
a = 4.49 \pm 0.38, \quad b = 0.026 \pm 0.000755
\]

CoREAS simulation, vertical shower
\( \rho \)

LOPES Coll., JCAP 09 (2014) 025

CoREAS for LOPES

LOPES Coll., JCAP 09 (2014) 025