A large radio array at the Pierre Auger Observatory
Precision measurements of the properties of cosmic rays at the highest energies

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Measuring air showers with multiple techniques

The result of the fit yields $X_{\text{max}} \approx 15.8 \text{ MeV}$, a minute fraction of the energy of the primary particle. The observed quadratic scaling is expected for coherent radio emission, for which amplitudes scale linearly and thus the radiated energy scales quadratically.

The exposure of the Pierre Auger Observatory, the radiation energy arriving perpendicularly to the Earth's magnetic field at the primary particle. The observed quadratic scaling is expected for coherent radio emission, for which amplitudes scale linearly and thus the radiated energy scales quadratically.

In Fig. 2, we see the correlation between the normalized radiation energy and the cosmic-ray energy measured with the Auger surface detector. A log-likelihood fit taking into account threshold and the cosmic-ray energy.

$E_{\text{cal}} = \int \frac{dE}{dX} \, dX$

$\sigma_{E} / E \approx 8\%$

$\Delta_{\text{sys}} \approx 15\%$

$\sigma_{X_{\text{max}}} \leq 20 \text{ g/cm}^2$

$\Delta_{\text{sys}} \leq 10 \text{ g/cm}^2$

$X_{\text{max}}$, $E_{\text{cal}}$

$E_{\text{surface}} = f(S_{1000}, \theta)$

$S_{1000}$
Observation of a large-scale anisotropy in the arrival directions of cosmic rays above $8 \times 10^{18}$ eV

The Pierre Auger Collaboration

Anisotropy detected at $>5.2$ sigma dipole amplitude 6.5%

Fig. 3. Map showing the fluxes of particles in galactic coordinates. Sky map in galactic coordinates showing the cosmic-ray flux for $E \geq 8$ EeV smoothed with a 45° top-hat function. The galactic center is at the origin. The cross indicates the measured dipole direction; the contours denote the 68% and 95% confidence level regions. The dipole in the 2MRS galaxy distribution is indicated. Arrows show the deflections expected for a particular model of the galactic magnetic field (8) on particles with $E/Z = 5$ or 2 EeV.
Indication of anisotropy in arrival directions of ultra-high-energy cosmic rays through comparison to the flux pattern of extragalactic gamma-ray sources

Active Galactic Nuclei
- 2FHL AGNs
- flux proxy: $\Phi(> 50 \text{ GeV})$
- 17 objects within 250 Mpc

Star-forming of Starburst Galaxies
- Fermi-LAT search list (Ackermann+2016)
- $\Phi(> 1.54, \text{GHz}) > 0.3 \text{ Jy}$
- flux proxy: $\Phi(> 1.54, \text{GHz})$
- 23 objects within 250 Mpc

Likelihood ratio analysis
- smearing angle $\psi$
- $H_0$: isotropy
- $H_1$: $(1 - f) \times \text{isotropy} + f \times \text{fluxMap}(\psi)$
- $\text{TS} = 2 \log(H_1/H_0)$
Indication of anisotropy in arrival directions of ultra-high-energy cosmic rays through comparison to the flux pattern of extragalactic gamma-ray sources

Figure 3. Top to Bottom: Observed excess map - Model excess map - Residual map - Model flux map, for the best-fit parameters obtained with SBGs above 39EeV (Left) and AGNs above 60EeV (Right). The excess maps (best-fit isotropic component subtracted) and residual maps (observed minus model) are smeared at the best-fit angular scale. The color scale indicates the number of events per smearing beam (see inset). The model flux map corresponds to a uniform full-sky exposure. The supergalactic plane is shown as a solid gray line. An orange dashed line delimits the field of view of the array.

**Starburst**

- SBG fraction: 9.7%
- Search radius: 12.9°
- Pre-trial p-value: 3.8*10^{-6}
- Post-trial p-value: 3.6*10^{-5}
- Post-trial significance: 4.0 sigma

**AGN**

- Search radius: 6.9°
- Pre-trial p-value: 5.1*10^{-4}
- Post-trial p-value: 3.1*10^{-3}
- Post-trial significance: 2.7 sigma
Follow-up of GW170817 with PAO (neutrinos)

PAO in pre-defined +/- 500 s window as sensitive as IceCube

Multi-messenger Observations of a Binary Neutron Star Merger

LIGO Scientific Collaboration and Virgo Collaboration, Fermi GBM, INTEGRAL, IceCube Collaboration, AstroSat Cadmium Zinc Telluride Imager Team, IPN Collaboration, The Insight-Hxmt Collaboration, ANTARES Collaboration, The Swift Collaboration, AGILE Team, The 1M2H Team, The Dark Energy Camera GW-EM Collaboration and the DES Collaboration, The DLT40 Collaboration, GRAWITA: GRAvitational Wave InAf TeAm, The Fermi Large Area Telescope Collaboration, ATCA: Australia Telescope Compact Array, ASKAP: Australian SKA Pathfinder, Las Cumbres Observatory Group, OZGrav, DWF (Deeper, Wider, Faster Program), AST3, and CAASTRO Collaborations, The VINROUge Collaboration, MASTER Collaboration, J-GEM, GROMETH, JAGWAR, Caltech-NRAO, TTU-NRAO, and NuSTAR Collaborations, Pan-STARRS, The MAXI Team, TZAC Consortium, KU Collaboration, Nordic Optical Telescope, ePESSTO, GROND, Texas Tech University, SALT Group, TOROS: Transient Robotic Observatory of the South Collaboration, The BOOTES Collaboration, MWA: Murchison Widefield Array, The CALET Collaboration, IKI-GW Follow-up Collaboration, H.E.S.S. Collaboration, LOFAR Collaboration, LWA: Long Wavelength Array, HAWC Collaboration, The Pierre Auger Collaboration, ALMA Collaboration, Euro VLBI Team, P of the Sky Collaboration, The Chandra Team at McGill University, DFN: Desert Fireball Network, ATLAS, High Time Resolution Universe Survey, RAMA and RATIR, and SKA South Africa/MeerKAT

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Energy spectrum and mass composition

energy spectrum of cosmic rays

\[ E \left[ \text{eV} \right] \]

\[ E^3 J(E) \left[ \text{eV}^2 \text{km}^{-2} \text{sr}^{-1} \text{yr}^{-1} \right] \]

\[ \log_{10}(E/\text{eV}) \]

mass composition of cosmic rays

\[ \langle X_{\text{max}} \rangle \left[ \text{g/cm}^2 \right] \]

- data \( \pm \sigma_{\text{stat}} \)
- \( \pm \sigma_{\text{sys}} \)

- EPOS-LHC
- Sibyll2.1
- QGSJetII-04
Upgrade of the Pierre Auger Observatory (astro-)physics of the highest-energy particles in nature

**Key science questions**

- What are the sources and acceleration mechanisms of ultra-high-energy cosmic rays (UHECRs)?

- Do we understand particle acceleration and physics at energies well beyond the LHC (Large Hadron Collider) scale?

- What is the fraction of protons, photons, and neutrinos in cosmic rays at the highest energies?

**upgrade PAO**
- electronics
- scintillator layer
- radio detector

**Figure**

- Left: The PAO (Auger Engineering Radio Array) in Argentina is the largest observatory for cosmic rays.
- Right: The surface detector array of the Pierre Auger Observatory with the enhancements (described above) and AERA; and a comparison of the relative distribution in the maximum-rigidity scenario (left panel) and one photo-disintegration scenario (right panel). The color coding of the model is as follows: maximum-rigidity scenario (left panel): protons – blue, helium – gray, nitrogen – green, and iron – red. The photo-disintegration scenario (right panel): protons – blue, helium – gray, nitrogen – green, and iron – red.

- Maximum rigidity: 0.2 < X_{\text{max}} < 1.2 \text{ km}^2\text{sr}^{-1}\text{yr}^{-1}
- Photo disintegration: 0.2 < X_{\text{max}} < 1.2 \text{ km}^2\text{sr}^{-1}\text{yr}^{-1}

**3000 km²**

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objective

• origin of cosmic rays
• type of particle up to highest energies
• isolate protons, photons, neutrinos
• extend e/m-muon separation to high zenith angles

--> horizontal air showers
(i.e. increase exposure of SSD analyses)
• increase the sky coverage/overlap with TA
• absolute energy calibration from 1\textsuperscript{st} principles
• independent mass scale
• clean e/m measurement

--> shower physics
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attention:
type of particle determined

for vertical showers:
size of footprint
geometrical measurement

for horizontal showers:
electron/muon ratio
important: radio emission not absorbed in atmosphere
A large radio array at the Pierre Auger Observatory
preparatory work & feasibility

atmosphere
muonic component
radio emission
hadronic component
e/m component
cosmic ray
Earth

expect large radio footprint from simulations

horizontal air showers registered and reconstructed with existing AERA

see e.g. T. Huege, Phys. Rep. 620 (2016) 1
Horizontal air showers have large footprints in radio emission

Figure 5: Farthest axis distance at which a radio signal above noise background has been detected as a function of the air-shower zenith angle. Black dots represent the 50 events that pass the quality cuts for energy reconstruction, grey diamonds denote the remaining 511 events. The red bars show the profile of the distribution, i.e., the mean and standard deviation in each $2^\circ$ bin. Please note that, as the array is significantly smaller than the radio-emission footprints, the mean values might significantly underestimate the average footprint size.
Performance of radio array

Setup of simulation study

- 192 showers simulated with CoREAS, 50/50 proton and iron
- energies from 4 EeV to 40 EeV, $\theta$ from 60 to 80°, $\varphi$ from 0 to 360°
- full SD-HAS detector simulation and reconstruction
  - randomly throw each shower 10 times into regular SD array
  - perform full SD response simulation and reconstruction of N19
    (thanks I. Valino, H. Dembinski)
- simplified treatment of radio simulations
  - extract true radiation energy $E_{rad}$ from simulations
  - calculate normalized radiation energy $S_{rad}$ using corrections for geomagnetic angle and air density at Xmax based on SD direction reconstruction – see Glaser et al. (JCAP 2016), arXiv:1606.0164
  - smear out radiation energy to mimic reconstruction uncertainties
Radio detector provides good measurement of e/m energy

- good correlation
- scatter bigger for showers near magnetic field axis (we use reconstructed SD direction)
- as expected, p only very slightly above Fe
- caveat: uses MC Xmax info, using mean Xmax will degrade this slightly
Radio detector provides good mass separation

- can separate species with $S_{\text{rad}}$ and N19
- separation increases with energy
- scaling at highest energies probably artifact of maximum simulated energy

**Diagram:**
- **radio detector (e/m)**: 
  - $\sqrt{S_{\text{RD}}/\text{MeV}} \sim$ electromagn. energy
- **water Cherenkov detector (µ)**

**Graph:**
- No cuts
- No $S_{\text{rad}}$ smearing

**Note:**
- The atmosphere is transparent for radio emission in our band (30–80 MHz) and radio measurements are an ideal tool for a calorimetric measurement of the e/m component in horizontal air showers (HAS).
- HAS have a large footprint on the ground, covering several km$^2$, as illustrated in Fig. 9, right. For this example shower, 46 AERA stations measured a radio signal above the noise level. These measurements indicate that HAS will be well measured with RDs on a 1500 m grid, having a sufficient number of stations (>5) with signals above the noise level in order to reconstruct the e/m component with an accuracy of ~20%.

**Figure 9:**
- Left: Schematic view of a horizontal air shower.
- Right: Horizontal air shower measured simultaneously with AERA and the SD at the PAO.

**Section b. Methodology**

The work plan described above shall be implemented through 5 sub projects.

**Sub project #1: Antenna design, pre-amplifier, mechanical mounting - PI, PD 1, engineer.**

We aim to install radio antennas at SD positions in the 1500 m array and the 750 m dense sub-array. The antennas will be mounted on top of the WCD. Mechanically, we will attach the antennas to the mounting of the scintillators of the PAO upgrade. These mountings are a contribution of RU Nijmegen/Nikhef and the relevant experts are in-house. We aim to use Short Aperiodic Loaded Loop (SALLA) antennas as a dipole loop of 1.2 m diameter to record radio signals between 30 and 80 MHz. The SALLA has been developed to provide a minimal design that matches the need for both, ultra-wideband sensitivity, and low costs for production and maintenance of the antenna in a large-scale radio detector. The compact structure of the SALLA makes the antenna robust and easy to manufacture. The response of these antennas has been measured as part of the AERA R&D program, their characteristics is well known and suitable for our purpose. In particular, the antenna is almost insensitive to the ground conditions, i.e. ideal to be placed on top of an existing SD atmosphere.
Mass separation using ratio $S_{\text{rad}}/N_{19}$ (electron/muon ratio)

- N19 scales with energy and mass
- $S_{\text{rad}}$ ∼scales with $e_{\text{mag}}$. energy only
- ratio allows separation
- especially p distribution non-Gaussian, i.e. figure of merit not a good concept

![Graph showing mass separation using $S_{\text{rad}}/N_{19}$ ratio.](image)
Precision shower physics (for vertical showers) in dense region of Pierre Auger observatory

clean separation of shower components
radio detector $\rightarrow$ e/m
scintillator (SSD) $\rightarrow$ e/m + muons
water Cherenkov detector $\rightarrow$ e/m + muons

underground muon detector (AMIGA) $\rightarrow$ muons

direct verification of deconvolution matrices (SSD/WCD) with measured showers

study hadronic interactions
Origin of cosmic rays multi messenger technique
The new RDs at each SD will also help to increase our sensitivity to neutrinos and photons.
Neutrinos and Photons

The new RDs at each SD will also help to increase our sensitivity to neutrinos and photons.
Recent results are reviewed, which form the basis for the proposed AdG. Therefore, we have measured the properties of the radio emission with high precision.

AERA 17 km$^2$ --> 3000 km$^2$

LOFAR combines a high antenna density and a fast sampling of the measured signals, and the solar panels with the electronics box underneath. It records the radio emission from extensive air showers in the atmosphere and thus measures the longitudinal development of air showers. Whereas the surface detector has a duty cycle near 100%, the fluorescence telescopes operate only during dark nights and under favorable meteorological conditions.

The fluorescence detector is equipped with over 1600 water Cherenkov detectors (WCDs) located with the enhancements (described above) and AERA; and an underground muon detector to provide a direct measurement of muons in air showers, covering an area of 3000 km$^2$.

The upgrade comprises of a plastic scintillator plane above the existing water Cherenkov detectors by 24 fluorescence telescopes grouped in units of six at four locations on its periphery. Each telescope consists of periodic dipole antennas and butterfly antennas. 1530 stations, covering an area of 17 km$^2$.

At present, the fluorescence detector site can be recognized: the communications antenna, the physics antenna, and the solar panels with the electronics box underneath.

LOFAR + AERA = Pierre Auger Engineering Radio Array (POA) in Argentina is the largest observatory for cosmic rays reaching to the highest energies with radio technique.
Integration of radio upgrade (RD), scintillator upgrade (SSD), and water Cherenkov detector in ONE unit

**Shared infrastructure** (solar power, battery, GPS timing, communications system) and integrated data acquisition
Block diagram of RD read-out

- PSU + Current limit + Bias enable
- Bias-T
- Gain?
- Input filter
- Gain?
- ADC 12-bit 200MSPS
- AD9613
- 200MHz clock oscillator Si540B
- PSU 1v8 LDO LP3961
- PSU 1v2 or 1V1 Switched (if needed)
- PSU 3v3 LTM8031
- Power filter
- 24V in
- Control/data interface
- Antenna with built-in LNA
- LNA
- Bias-T
- Gain?
- Input filter
- Gain?
- ADC 12-bit 200MSPS
- FPGA
  - Lattice EPC5 or
  - Altera MAX10
- Data interface (as seen from extension board)
  - Control (3 wires)
    - Trigger signal (in)
    - Data ready (out)
    - Start transfer (in)
  - Data (USART, 2 wires)
    - Data (out)
    - Data clock (out)
  - Housekeeping (SPI, 3 wires)
    - Reset
    - Housekeeping
    - Settings

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Piggy-back board using AD9613

Alternative: AD9613, Dual 12 bit ADC core @ max 250 MHz, 770 mW@250 MHz
→ using both sockets piggy-back
→ filter-amplifier cable-connected mounted on housing
First discussion with R. Assiro – no show-stopper, need to implement the FPGA vhdl block to read it.
Acquired evaluation-board for AD9613
Use Analog Device DAQ-board used by Lecce-Group
Ongoing performance tests of ADC with evaluation board
Radio Antenna - SALLA

Our default antenna is the SALLA antenna. Well known from Tunka-REX and prototypes at PAO.

Tunka-REX - 63 stations

measured antenna characteristics

P. Abreu et al., JINST 7 (2012) P10011
Antenna mounting

currently studying different scenarios for mechanical mounting
Prototype stations at PAO

since March 2017
R&D stations

prototype since November 2017

a measured inclined EAS

SNR

Distance to shower axis (m)

SALLA

preliminary!
**A large radio array at the Pierre Auger Observatory**

Precision measurements of the properties of cosmic rays at the highest energies

- origin of cosmic rays
- type of particle up to highest energies
- isolate protons, photons, neutrinos
- extend e/m-muon separation to high zenith angles
  - horizontal air showers
  (i.e. increase exposure of SSD analyses)
- increase the sky coverage/overlap with TA
- absolute energy calibration from 1st principles
- independent mass scale
- clean e/m measurement
  - shower physics

feasibility demonstrated through
- simulations
- AERA measurements
  - HASs are measured with RDs on 1500 m grid
  - technical implementation in progress

fundraising in progress
we already obtained:

R&D money from Germany
3.5 M€ ERC Advanced Grant for Hörandel

**taskleader radio at Pierre Auger Observatory, for the Pierre Auger collaboration**

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