PIERRE
AUGER
OBSERVATORY

First results from the AugerPrime Radio Detector

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1. Introduction

- AugerPrime Radio Detector (RD) antenna is comprised of two orthogonally oriented short aperiodic loaded loop antennas (SALLAs) of 1.2 m diameter and is triggered by the water-Cherenkov detectors (WCDs).
- RD role in the AugerPrime upgrade is to:
  - ➢ Detect the radio emission from air showers in the frequency range from 30 to 80 MHz, arriving from zenith angles in the range from 65° to 85°.
  - ➢ In combination with the WCD, measure the ratio of the electromagnetic energy and the number of muons for horizontal air showers, increasing the aperture of the Observatory for mass-sensitive investigation.

This work

- *Pilot end-to-end Absolute Calibration of the AugerPrime Radio Detector by using the Galaxy radio emission.*
  The calibration is necessary to correct for uncertainties in the system response before any scientific work.
  The Calibration process:
  - ➢ Measured dataset preparation
  - ➢ Simulation of the Galactic signal
  - ➢ Calibration method application
  - ➢ Results
- *First Cosmic ray air-showers measured by the AugerPrime Radio Detector stations.*

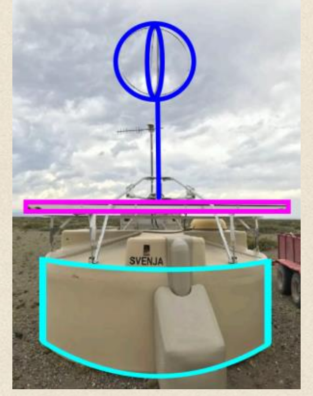

Figure 1: Upgraded station. The RD antenna is in blue, the scintillator detector in pink, the WCD is in cyan color.

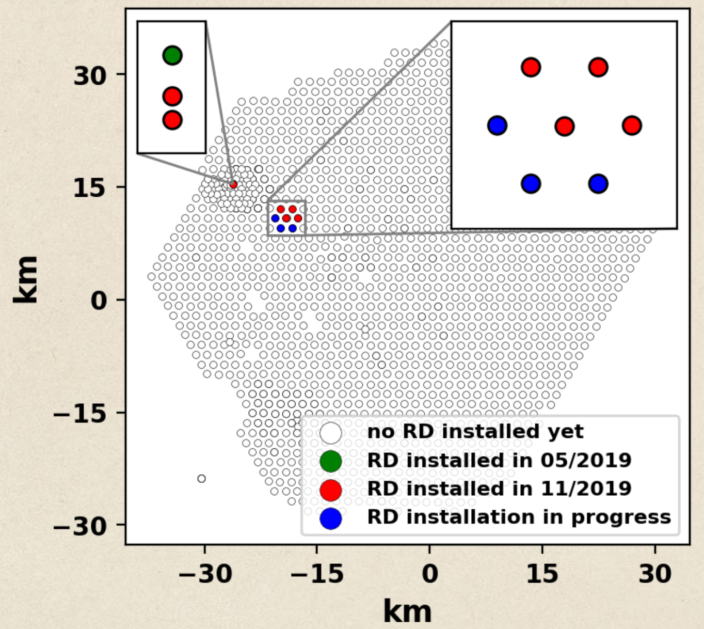

Figure 2: Pierre Auger Observatory. RD installation status.

2. Measured dataset

- Five months of data from a RD engineering array station located in the regular 1500 m grid.
- In addition to the signal from Galaxy, the measured signal by RD may contain:
  - ➢ CR signals
  - ➢ External transient noise
  - ➢ External periodical noise
  - ➢ Internal (thermal) noise
- Exclude 1% of traces to clean from CR signals and transient noise.

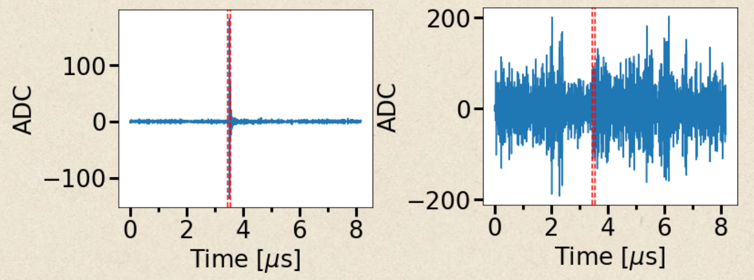

Figure 3: Example of excluded traces. Left is a CR signal, right is a transient external noise.

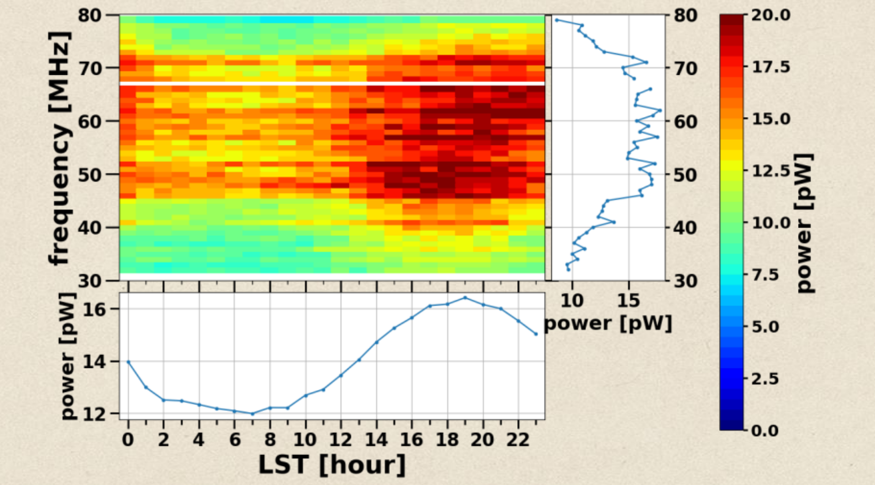

Figure 4: Example of calculated dataset containing: Galactic signal, internal noise, external periodical noise and excluding narrow-band radio frequency interference.

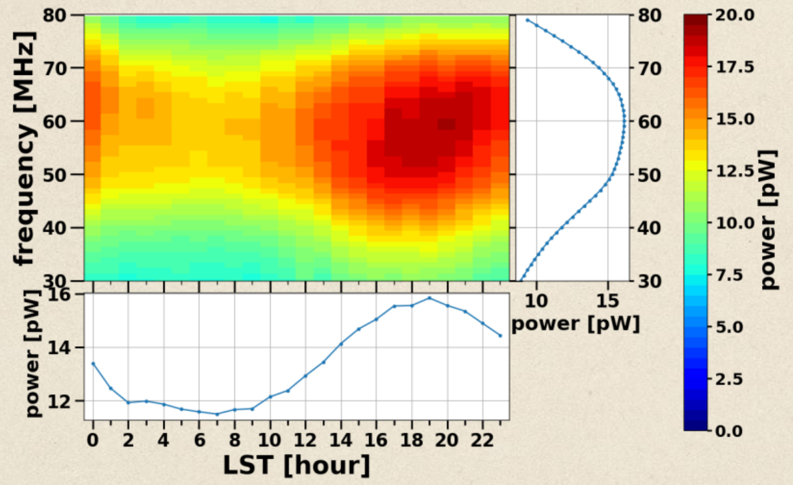

Figure 5: Baseline from Fig.4. The dataset now contains Galactic signal and internal noise.

3. Simulated Galactic signal

Two ingredients:

- Sky Temperature maps (T_{sky}): LFmap, LFSS, GSM2008, GSM2016, Haslam.
- Antenna model (*H*): We use various modification of the default setup to investigate the effect on the calibration constant.

The power is calculated by folding the antenna model with the sky temperature and integrating over the sky and frequencies.

Formula:

$$P_{\mathrm{sky}}(\tau, f) = \frac{2k}{c^2} \int_{f}^{f+\delta} f'^2 \frac{Z_0}{R_r(f')} \int_{\Omega} T_{\mathrm{sky}}(\theta, \phi, \tau, f') \langle |H(f', \theta, \phi)|^2 \rangle \, d\Omega \, df'$$

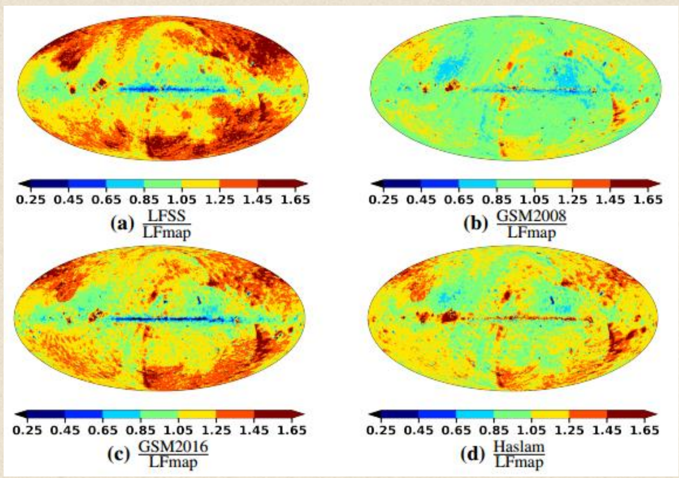

Figure 6: Comparison of the sky temperature maps in galactic coordinates at 45 MHz. Temperatures relative to LFmap are shown.

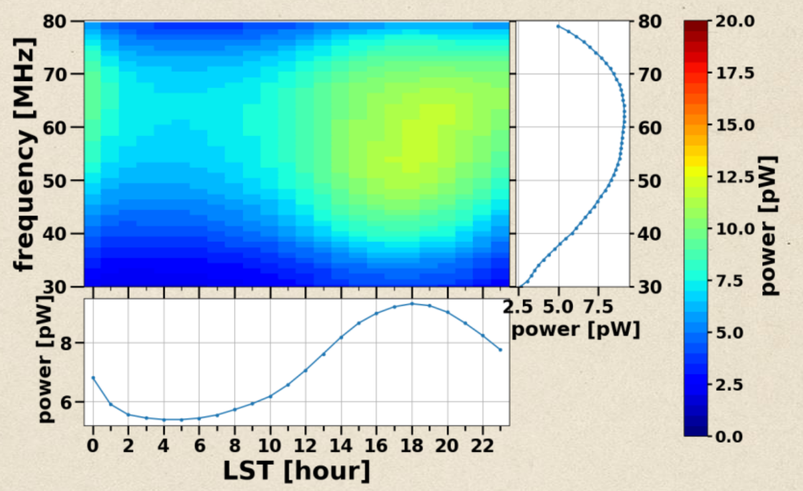

Figure 7: Simulated Galactic signal.

4. Calibration methods

- Calibration methods are used to model the relationship between the simulated and measured datasets in order to determine the calibration constant.
- Calibration methods:
  - ➢ **LOFAR method**: Assumes that the background noise is only the internal (thermal) noise. We use the method with same or separate noise parameters for each channel.
  - ➢ **Individual fits on each frequency band**: The fitted background noise represents sum of the internal and external (periodic) noise. Calibration constant is obtained as the mean of the fitted slopes from the individual frequency band fits or the fits are performed a priori with a conditions of the same slope for each band.

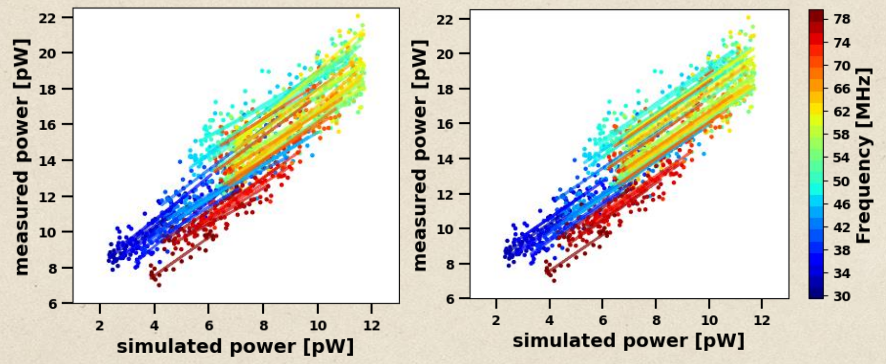

Figure 8: Left: Example of a linear regression applied on each band separately. Right: Linear regression applied on each band separately with a condition of the same slope for all bands. The fitted intersection represents background noise consisting of internal and external repeating noise in a particular frequency band.

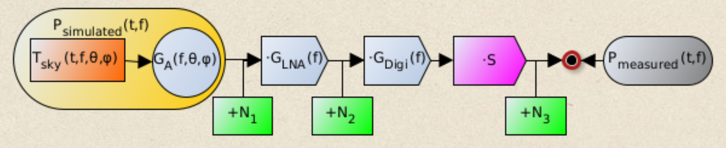

Figure 9: RD signal chain. The thermal noise contributions entering the signal chain at different levels (in green color) are used as free parameters while determining the scaling (calibration) constant (in pink) by minimizing differences between measured and simulated datasets. The "*G*" stands for the gain of a component.

5. Results

- Calibration constants were calculated for all combinations of:
  - ➢ 5 different sky maps
  - ➢ 17 different antenna models
  - ➢ 4 different calibration methods

  = 340 calibration constants in total
- Smear the constants to account the quoted uncertainty of the underlying sky temperature maps.
- The calibration constant was calculated to

  1.03±9.6%(sys.)±2%(stat.)

  0.96±9.7%(sys.)±2%(stat.)

  for East-West and North-South channel, respectively.

- Additional findings:
  - ➢ Linear propagation of the calibration constant uncertainty to electromagnetic energy.
  - ➢ Gaussian errors on sky maps and antenna model are affecting the calibration constants negligibly.
  - ➢ Effects of the various factors on the calibration constant (Table 1.).

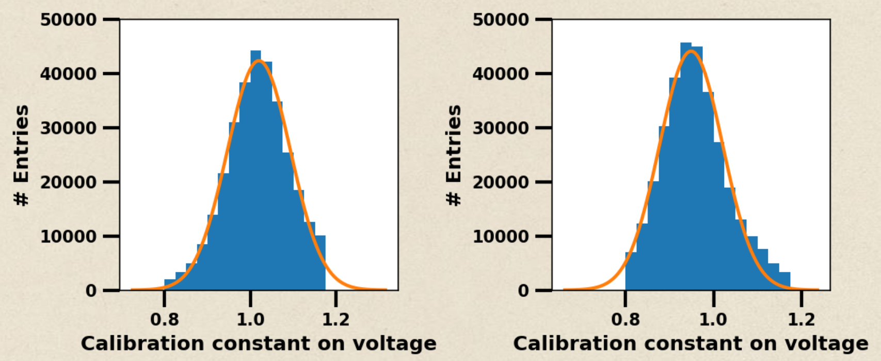

Figure 10: Distribution of the calculated calibration constants for the EW and NS channel, respectively. The mean of the distributions represents the calibration constants.

factor	min	max	mean
choice of the sky map	4.0	5.1	4.5
choice of calibration method	1.6	5.0	3.6
*	(8.4)	(11.2)	(10.0)
antenna model	0.3	1.4	0.9
antenna - different ground	0.2	1.8	1.0
antenna - shifted components	0.1	0.7	0.4
antenna - missing components	0.2	1.9	0.6

Table 1: Effect of the different factors (in precents) on the calibration constant. *When the LFSS map is fixed, the methods yield higher inconsistency compared to when the other maps are used.

6. Measured air-showers

- WCD reconstructed showers in the 1500 m array in coincidence with signal in at least 1 RD station.
- 28 shower observed (No quality cuts).
- Corsika/CoReas simulations of these showers based on the WCD reconstructed quantities.
- Pearson's test showed positive significant correlation between the simulated and measured traces ADC peak amplitudes.

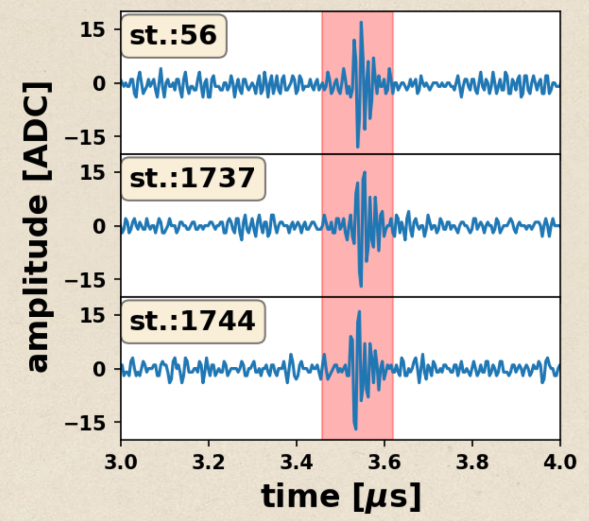

Figure 11: Simultaneously measured radio signals from an air-shower in three RD stations in the EW channel.

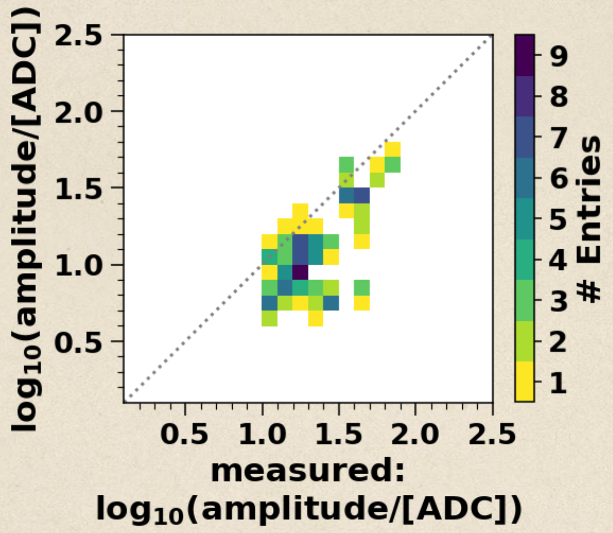

Figure 12: Peak amplitude comparison.

7. Summary

- We derived the first calibration constants for the AugerPrime Radio Detector, demonstrating that the full Radio Detector array calibration with the Galactic signal is feasible.
- We confirmed that the installed AugerPrime Radio Detector stations are measuring cosmic ray signals.