Radio detection of extensive air showers Precision measurements of the properties of cosmic rays

«ETTORE MAJORANA» FOUNDATION AND CENTRE FOR SCIENTIFIC CULTURE

INTERNATIONAL SCHOOL OF COSMIC-RAY ASTROPHYSICS «MAURICE M. SHAPIRO»

23rd Course: "Multi-Messenger Astroparticle Physics" 20 – 28 July 2024

PRESIDENT AND DIRECTOR OF THE CENTRE: PROFESSOR A. ZICHICHI

DIRECTORS OF THE COURSE: PROFESSORS J.R. HÖRANDEL, T. STANEV, R. SPARVOLI - J.P. WEFEL (director emeritus)

offers opportunities for the participants to present their own research in order to obtain. feedback and to gain experience presenting to an international audience of kindred spirits.

characterize cosmic rays: -direction

- **-energy**
- **-mass**
- **@100% duty cycle**

 \mathbf{j} Cosmic Rays - 1982 l Cosmic Radiation in Contemporary Astrophysics - 1984 l Genesis and Propagation of Cosmic Rays - 1986 l Cosmic Gamma Rays and Cosmic Radiation - 1988 l Cosmic Rays,

Jörg R. Hörandel RU Nijmegen, Nikhef, VU Brussel http://particle.astro.ru.nl

Radio detection of extensive air showers Precision measurements of the properties of cosmic rays

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"Multi-Messenger Astroparticle Physi

characterize cosmic rays: -direction -energy -mass @100% duty cycle

Jörg R. Hörandel KU Nijmegen, Nikhef, VU Brussel

First radio detection of air showers 1965

Blackett's Field ~1967 Porter MSc

 $\mathbb{B}(\mathbb{R}^d)$, $\mathbb{B}(\mathbb{R}^d)$, $\mathbb{B}(\mathbb{R}^d)$, $\mathbb{B}(\mathbb{R}^d)$

8

Jelley et al Nature 1965 R. A. Porter MSc Thesis 1967

The renaissance of radio detection of cosmic rays

TIM $HUEGE¹$

Figure 1: Number of contributions related to radio detection of cosmic rays or neutrinos to the ICRCs since 1965. The field has grown very impressively since the modern activities started around 2003. Data up to 2007 were taken from $[11]$.

Radio Detectors

Radio detection of extensive air showers around the world

air showers.

nd <u>Antennas (LBA) eth. A 767 (2014)</u> 339

A measured air shower

Jörg R. Hörandel, ISCRA Erice 2024 9

LBA 10-90 MHz Simulations & Measurements

Jörg R. Hörandel, ISCRA Erice 2024 10

zenith angle 31° 336 antennas χ2 / ndf = 1.02

$1 - 3$ **Auger Engineering Radio Array ~150 antennas ~17 km2 30-80 MHz**

- - ٠

COFAR COre 23 stations ~5 km2

>2000 antennas

1 km

-8

$1 - 3$ **~150 antennas ~17 km2 30-80 MHz**

$1 - 3$ **Auger Engineering Radio Array ~150 antennas ~17 km2 30-80 MHz**

25 stations since August 2010

23 stations ~5 km2

1

+25 stations

100 stations since March 2013

 \mathbb{R}

Robert Allen Barnetter

Jörg R. Hörandel, ISCRA Erice 2024 13

 $\frac{1}{2}$ KIT Campus North

Calibration

Simulating Galaxy Noise

Visible galaxy at 00.00,6:00,12:00,18:00 Local Sidereal Time

$$
P(\nu)=\frac{2k_B}{c^2}\nu^2\int T_{\rm sky}(\nu,\theta,\phi)\frac{|\vec{H}(\nu,\theta,\phi)|^2Z_0}{2Z_a}d\Omega\quad WHz^{-1}
$$

Average antenna response at 55 MHz

K. Mulrey et al., Astropart. Phys., 111 (2019) 1

Astronomy Astrophysics

Uncertainties of the 30–408 MHz Galactic emission as a calibration source for radio detectors in astroparticle physics Büsken, M., et al.: A&A, 679, A50 (2023)

M. Büsken^{1,2}, T. Fodran³, and T. Huege^{4,5}

Fig. 2. Sky maps showing the temperature ratio of each model to the average from all seven models at 50 MHz in Galactic coordinates. The models are denoted as ω L Emen (b) $CSM(\omega)C$ are denoted as α μ and μ , α and α , α $h(16/a)$ i ECM (a) CMOCC (6) CCM (a) III C are denoted as (a) LFmap, (b) GSM, (c) GSM16, (d) LFSM, (e) GMOSS, (f) SSM, (g) ULSA.

K. Mulrey et al., Astropart. Phys., 111 (2019) 1

LOFAR

K. Mulrey et al., Astropart. Phys., 111 (2019) 1

 T_{RCU} Noise from amplification in RCU

 $\mathbf{G}_{\text{RCU}}(\nu)$ RCU passband filter

scale factor between S voltage and ADC units

 $\mathbf{T}_{\mathrm{ADC}}$ time jitter noise from digitization

K. Mulrey et al., Astropart. Phys., 111 (2019) 1

LOFAR

K. Mulrey et al., Astropart. Phys., 111 (2019) 1

LOFAR

K. Mulrey et al., Astropart. Phys., 111 (2019) 1

Calibration Results

- Galaxy model now limits systematic uncertainties
- Uncertainties from electronic noise are found by comparing resulting calibration constants for different antennas

OFAR

K. Mulrey, ARENA 2018

Radiation Processes

"I think you should be more explicit here in step two."

Radio Emission in Air Showers LANCOLON IN VINC ANIHOOMI III AII YI

with the LOFAR radio telescope array. However, the threshold of the threshold of the particle array. However, the figures than the threshold of the particle array. However, the figures than the threshold of the figures tha \blacksquare A required alignment as the pattern per element as t be stated and different. Such a detail between stations and tiles with differences between tiles. Gain differences between til a station are corrected for using standard LOFAR calibration tables. These tables are generated regularly using the algorithms are generated regularly using the algorithms are generated values of α beamforming has a negative effect on the accuracy as it affects n at shawers with sh arrival time. Thus, in a similar analysis as presented in [18], the angular resolution was determined to be 7! with respect to the particle data. This angular resolution strongly decreases as a series as function of \mathbf{u} age worse than with the LBAs. Thus, a cosmic-ray candidate event is now as a cosmic-ray event when the directions reconnections reconomic reconomic reconomic reconomic reconom structed from particle data and radio agree within 20!, instead of no event arrived directly (< 1!) from the direction in which the beam of the observation was pointing. The main effect of tile-beamforming in the direction of the tion threshold. The main effect of beamforming in another direc- \mathbf{t} the arrival direction is a direction is a distortion of the pulse shape. This makes events of low signal strength harder to detect. Strong $$ we lead the position of the maximum will be affected. This effect of the maximum will be affected. This effect of detection is plotted as a function of angular distance between **north-south asymmetry** determined by the energy threshold of the HBA tiles, which is the HBA tiles, which is the HBA tiles, which is the HBA depends on the arrival direction of the cosmic ray relative to the current pointing of the tile-beam, an observed asymmetry in air shower arrival directions might be the result from an asymmetry in the beam pointing rather than caused by the intrinsic air shower **Arrival direction of showers with strong radio** with typical wavelength k and detector size D, gives a full width half width half width half width half width

 \mathcal{A} field at LOFAR. W_{eff} recorded with the same trigger settings, the detection \mathcal{C} \mathbb{N} in a an air shower based on its radio signal is \mathbb{N} \mathbf{v} coinn

Relative)fraction)of)events)[%]

\overline{a} the radio signal scales with the energy of the shower. Higher scales with the shower. Hi 110 - 190 MHz

A Nelles et al. Astroparticle Physics 65 (201 The FULLS of any Astroparticle Fitzgales of $\overline{201}$ **A. Nelles et al., Astroparticle Physics 65 (2015) 11**

Jörg R. Hörandel, ISCRA Erice 2024 27

P. Schellart et al.: Detecting cosmic rays with the LOFAR radio telescope **v x B effect Arrival direction of showers with strong radio signals north-south asymmetry**

Relative)fraction)of)events)[%]

8

Fig. 4. Radio pulses (top) arising from the time-variation of the geomagnetically induced transverse currents in a 10¹⁷ eV air shower as observed at various observer distances from the shower axis and their corresponding frequency spectra (bottom). Refractive index effects are not included. *Source:* Adapted from [18]. *Source:* Adapted from [18]. **Fig. 8. Fig. 4. Radio pulses (top) arising from the time-variation of the time-variation of the time-variation of the geometrical contraction of the geometric and the geometrical at various as observed at various and vari**

Radio Emission in Air Showers

Mainly: Charge separation in geomagnetic field $\vec{E} \propto \vec{v} \times \vec{B}$ **Theory predicts**

additional mechanisms:

- **excess of electrons in shower: charge excess**
- **superposition of emission due to Cherenkov effects in atmosphere**

polarization of radio signal

Polarization footprint of an individual air shower

Jörg R. Hörandel, ISCRA Erice 2024 31

Charge excess fraction 50 100 m (13*.*71 *±* 0*.*47)% (11*.*15 *±* 0*.*25)% (5*.*84 *±* 0*.*43)% 100 150 m (16*.*91 *±* 0*.*66)% (12*.*80 *±* 0*.*21)% (9*.*93 *±* 0*.*46)%

Footprint of radio emission on the ground

Properties of incoming cosmic ray

 - direction - energy - type

Direction

Shower Front

 t_{total} hyperbolic (top), conical (middle) and spherical (bottom) fit has been continuous fit has b

A. Corstanje et al., Astropart. Phys. 61 (2015) 22
Jörg R. Hörandel, ISCRA Erice 2024 36 \mathbf{u} and \mathbf{v} and \mathbf{v} and \mathbf{v} and \mathbf{v} in Fig. 2 where the radius of the the best fitting see and there open a hyperbolic panel) and deviations from the best fit scaled to the uncertainty for each datapoint (bottom panel). Note that the shower core position is a free parameter in each fit, the points of the points of the points of the p the *x*-axis dier between fits, as is in particular evident for the spherical fit. the best fitting shape shape shape solutions. A contract (contract (contract \mathbf{A} (contract (bottom) fitting (contract (contract (contract (contract (contract (contract (contract (contract of the spherical (contract of \mathbf{r} respectively. The arrival times as \mathbf{r} function of the shower axis (top) for the shower axis (top) for

Accuracy of Shower Direction

Number $\frac{a}{b}$

20

Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy ⁶

Λ Agh at al **DDI** 116(2016) no 24 **EXAUGER ALONG THE LORENT FORCE FOR THE LORENTZ FOR CHARGE PARTIES.** be described well with the power law **A. Aab et al., PRL 116 (2016) no.24, 241101**

Measurement of the Radiation Energy in the Radio Signal of Extensive Air Showers as a Universal Estimator of Cosmic-Ray Energy ⁶ 6

Λ Agh at al **DDI** 116(2016) no 24 **EXAUGER ALONG THE LORENT FORCE FOR THE LORENTZ FOR CHARGE PARTIES. A. Aab et al., PRL 116 (2016) no.24, 241101**

Y **Energy Estimation of Cosmic Rays with the Engineering Radio Array of the Pierre Auger Observatory** is community and an increases with the atmospheric depth increases with the atmospheric depth increases with the vertical showers. Hence, we expect an additional dependence $\nabla = 15$ 8 MeV ϖ 1018 eV E_{30-80} MHz = 15.8 MeV @ 10¹⁸ eV

A. Aab et al., PRD 93 (2016) no.12, 122005 $\frac{1}{10}$ sinab et and i RD 30 (2010) R0.12, 122000 **A. Aab et al., PRL 116 (2016) no.24, 241101**

Mass

2

low-frequency radio domain below a few hundred MHz, representi Since the discovery of radio emission from the Milky Way (Jans cont Follo $\overline{}$ Ω \mathbb{R}^{∞} . uo k $-$

Measurement cfaptesticle mass

30

 $\sigma_F \approx 32\%$ the energy resolution of 32% is given by the distribution of the ratio between the energy scaling factor of the radio reconstruction and the particle reconstruction from the LORA array

[6] The uncertainty on Xmax is found with a Monte Carlo study. For this sample the mean uncertainty is 17 g/cm²

S. Buitink et al., PRD 90 (2014) 082003

Depth of the shower maximum

LETTER **nature**

A large light-mass component of cosmic rays at 1017–1017.5 electronvolts from radio observations

S. Buitink^{1,2}, A. Corstanje², H. Falcke^{2,3,4,5}, J. R. Hörandel^{2,4}, T. Huege⁶, A. Nelles^{2,7}, J. P. Rachen², L. Rossetto², P. Schellart²
O. Scholten^{8,9}, S. ter Veen³, S. Thoudam², T. N. G. Trinh⁸, J , M. J. Bentum^{3,15}, G. Bernardi^{16,17}, P. Best¹⁸, A. Bonafede¹⁹, F. Breitling²⁰, J. W. Broderick²¹, W. N. Brouw^{3,13}, M. Brüggen. M. Brüggentin^{3,15}, G. Bernard^{16,17}, P. Best¹⁸, A. Bonafede¹⁹, E. de Geus H. R. Butcher²², D. Carbone²³, B. Clardf²⁴, J. E. Conway²⁵, F. de Gasperin⁹, E. de Geus¹³⁶, A. Deller¹, P. C. Detruar²⁷, M. A. Carelt¹³², J. M. Graecti³⁻²³, J. M. Griefsheige^{33, 24}, A. M. Graecti³⁻²

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Cosmic rays are the highest-energy particles found in nature.
Measurements of the mass composition of cosmic rays with energies
of 10^{17} –10¹⁸ electronvolts are essential to understanding whether
they have galactic or capable of producing cosmic rays of these energies². Cosmic component of cosmic rays contributes substantially to the total flux
rays initiate air showers—cascades of secondary particles in the below 10^{17.5} electronvol atmosphere—and their masses can be inferred from measurements
of the atmospheric depth of the shower maximum³ (X_{max}; the depth
of the air shower when it contains the most particles) or of the
composition of shower part **measurements⁵ have either high uncertainty, or a low duty cycle** built-in air-shower-detection capability14. LOFAR continuously **and a high energy threshold. Radio detection of cosmic rays⁶⁻⁸ is records the radio signals from air showers, while simultaneously
a rapidly developing technique⁹ for determining X_{max} (refs 10, 11)** running astrono **with a duty cycle of, in principle, nearly 100 per cent. The radiation** (LORA) that triggers the read-out of buffers, storing the full waveis generated by the separation of relativistic electrons and positrons
in the geomagnetic field and a negative charge excess in the shower
fron^{6.12}. Here we report radio measurements of X_{max} with a mean
uncertainty of

Université Paris Diderot, 5 place Jules Janssen, 92190 Meudon, France.

initiated by cosmic rays with energies of 10^{17} – $10^{17.5}$ electronvolts.
This high resolution in X_{max} canbles us to determine the mass
spectrum of the cosmic rays: we find a mixed composition, with
a light-mass f of an additional galactic component, to account for the light
composition that we measured in the 10¹⁷-10¹⁷⁵ electronvolt range.
Observations were made with the Low Frequency Array (LOFAR¹³),
a radio telescope consis

forms received by all antennas.
We selected air showers from the period June 2011 to January 2015
with radio pulses detected in at least 192 antennas. The total uptime
was about 150 days, limited by construction and commis

S. Buitink et al., Nature 531 (2016) 70 $\frac{1}{\sqrt{1-\frac{1$

600

700

800

 X_{max} [g/cm²]

900

1000

1100

A. Abdul Halim et al., Phys. Rev. Lett., 132 (2024) 021001 **A. Abdul Halim et al., Phys. Rev. D, 109 (2024) 022002**

Radboud University
Results: AERA vs other (radio) experiments

- No general radio-bias w.r.t other techniques (within uncertainties).
- Highlights that systematic uncertainties are key to interpret and compare.
- **LOFAR**-**AERA** differences are being investigated in a working group

—> come talk to us during coffee and lunch!

A. Abdul Halim et al., Phys. Rev. Lett., 132 (2024) 021001 **A. Abdul Halim et al., Phys. Rev. D, 109 (2024) 022002**

Two independent estimates of systematic uncertainties

• Cross check: two independent estimates for total systematic uncertainties are in agreement. —> suggests systematic uncertainties are well-understood and no significant contribution is missing.

A. Abdul Halim et al., Phys. Rev. Lett., 132 (2024) 021001 **A. Abdul Halim et al., Phys. Rev. D, 109 (2024) 022002**

Determine the properties of the incoming particle with the radio technique

- **- direction ~ 0.1° 0.5°**
- **- energy ~ 15% 30%**
- $-$ **type (X_{max}) ~ 20 30 g/cm²**

(depending on energy, detector spacing, …)

—> radio technique is routinely used to measure properties of cosmic rays

[The Radio Detector of the Pierre](http://particle.astro.ru.nl/pub/epjconf-uhecr18-06005.pdf) Auger Observatory

radio antenna 30-80 MHz two orthogonal polarizations 250 MHz sampling e/γ

plastic scintillator 120 MHz sampling

µ **water-Cherenkov detect ** 120 MHz sampling**

µ

atmosphere of Earth is transparent in 30-80 MHz band

Horizontal air showers have large footprints in radio emission particles in upgrade of the surface of the surface of the surface detector surface α increased dynamic range; an underground muon detector to provide a direct measurement of muons in air change of the operation mode for the fluorescence telescopes, increasing their duty cycle to 20%.

this is MEASURED with the *small* 17km² AERA a function of the air-shower zenith and strive that pass that pass the 50 events that pass the 50 even

Pierre Auger Observatory

Figure 3: Left: The PAO10. Each dot corresponds to one of the 1600 SD stations. The FD sites are shown, **Water Cherenkov Detector,** *each with the field of view of its six telescopes. The Coihueco site hosts the low-energy extension HEAT. The 760 M dense scintillator Detector,* \overline{a} *bottom can be recognized: the communications antenna, the physics antenna – recording the air shower signals, and the solar panels with the electronics box underneath.* **1600 stations on 1500 m grid Surface Detector array: Radio Detector 61 stations on 750 m grid**

extend mass sensitivity to inclined showers $\theta > 60^{\circ}$

- **• increasing measurements of inclined show of magnitude**
- **• close to idea separation**
- **increase sky overlap with**
- **RD/WCD has systematic eff compared to !**
- *<u>clean measure</u>* **shower comp** \rightarrow independent **scale**
- **experience Research Council**
 e/m and µ components for Established by the European Commissi -10^{7} eV $(E_{CP}/10^{18}$ eV $)^{B}$, $A = 1.58 \pm 0.07$, $B = 1.98 \pm 0.04$ 3 - 4 stations with signa > 5 stations with signal 10^{8} Auger $30-80$ MHz ℓ sin² α [eV] \cap $10⁷$ $10⁶$ **[PRL 116 \(2016\) 241101](https://www.google.com/search?client=safari&rls=en&q=PRL+116+(2016)+241101&ie=UTF-8&oe=UTF-8)** 10^{5} 10^{18} 10^{19} $F_{\alpha\alpha}$ [αV] 2500 Axis distance of furthest station / m **[JCAP 10 \(2018\) 026](https://iopscience.iop.org/article/10.1088/1475-7516/2018/10/026)** FIG. 2. Correlation between the normalized radiation energy and the cosmic ray energy ECR as determined by the August ECR 2000 surface detector. Open circles represent air showers with radio signals detected in three or four radio detectors. Solid circles 1500 denote showers with five or more detected radio signals. The signals \mathbb{R}^n 1000 with respect to the geometric field by dividing its second by dividing its second by dividing its second by dividing its second by α $\begin{bmatrix} 500 \end{bmatrix}$ sin $\begin{bmatrix} 300 \end{bmatrix}$ for all incomending for all incomending for all incomending $\begin{bmatrix} 1 & 0 \ 0 & 0 \end{bmatrix}$ 500

0

Veare of experience • based on 15 years of experience **with AERA**

 \mathbf{v} as a symmetric, two-dimensional signal distribution \mathbf{v} [J.R. Hörandel et al, EPJC Web of Conf. 210 \(2019\) 06005](https://www.epj-conferences.org/articles/epjconf/pdf/2019/15/epjconf_uhecr18_06005.pdf) Zenith angle / \degree

directions of cosmic rays except for a small region around \mathcal{C} the geomagnetic-field axis. In particular, it is valid for all

60 65 70 75 80 85

 $0\frac{1}{60}$ 65 70 $\frac{1}{2}$ $\frac{1}{2}$

~500 stations Nov 2023 ~1000 stations Mar 2024

~1360 stations July 2024

Jörg R. Hörandel, ISCRA Erice 2024 54

positions in DAQ

Current Status (22/07/2024 at 07h23) 1 **number of** 200k 100k **positions with signals in EAS** $10k$ count 1000 **nice horizontal** 100 **EAS** 10 **Total Operated:** 20 60 80 100 120 140 40 905 **Main Grid: 845/856** Number of Rd station InFill Grid: 47/2 **SuperDense Grid: 11/4**

Test Grid: 2/82

Jörg R. Hörandel, ISCRA Erice 2024 55

Calibration procedure

 $\overline{}$

JCAP01(2023)008

Eur. Phys. J. C (2020) 80:64 ps://doi.org/10.1140/epjc/s10052-020-8216

air showers simulated with CoREAS

Regular Article - Experimental Physics

Refractive displacement of the radio-emission footprint of inclined

THE EUROPEAN
PHYSICAL JOURNAL C

Journal of Cosmology and Astroparticle Physics

[Signal model and event reconstruction](https://iopscience.iop.org/article/10.1088/1475-7516/2023/01/008) for the radio detection of inclined air showers Ca
Astropor
Car **Signal model and event reconstruction for the radio detection of inclined air a**
Institut für Astro c
ir *b*Instituto de Tecnologias en Deteccion y Astroparticulas (ITeDA), e
Inter-university Institute
Energies (VUB), Vrije Universiteit Brussel (VUB), Vrije Universiteit Brussel (VUB), Vrije Universiteit Brussel

F. Schlüter^{*a,b,**} and T. Huege^{*c*} nu
.

f_{vxB} measured

 $-$ f_{vxB} modeled

 $\overline{f}_{\text{geo}}$ data

measurement of e/m energy by RD

75 with the Radio Detector. The reconstructed energy agrees within 10% with the one reconstructed **—> full end-to-end verification of complete chain**

Expected number of cosmic rays after 10 years

Particle physics in air showers

—> investigation of muon deficit inclined air showers

Particle type for each cosmic ray 50/50 p-Fe composition

7th International Symposium on Ultra-High-Energy Cosmic Rays

UHECR 2024 Malargüe, Argentina - November 17-21 2024

The symposium is the $7th$ edition of a series of meetings that bring together the UHECR community. It covers the latest results from UHECR observations, theoretical developments, and future plans in the field. The symposium will focus on the highest energy cosmic rays as well as on cosmic rays with energies above 1 PeV. The agenda includes invited reviews, contributed talks, and reports from inter-collaborative working groups, all in plenary sessions. Poster contributions are also foreseen.

International Advisory Committee

R. Engel (chair), P. Blasi, A. Castellina, I. De Mitri, T. Ebisuzaki, P. L. Ghia, F. L. Halzen, Y. Itow, K.H. Kampert, P. Klimov, P. Lipari, J. Matthews, S. Ogio, I. H. Park, E. Parizot, E. Resconi, M. Roth, G. Rubtsov, D. Ryu, H. Sagawa, P. Sokolsky, Y. Tsunesada.

Local Organizing Committee I. Allekotte, B. Andrada, F. Gollán, G. Golup, F. Sánchez.

For more information: https://indico.ahuekna.org.ar/event/768/ uhecr2024@auger.org.ar

