New Antenna for Radio Detection of UHECR

O. Krömer[‡], H. Gemmeke[‡], W.D. Apel[*], J.C. Arteaga[†,xiv], T. Asch[‡], F. Badea[*], L. Bähren[§], K. Bekk[*], M. Bertaina[¶], P.L. Biermann[‖], J. Blümer[*,†], H. Bozdog[*], I.M. Brancus[**], M. Brüggemann[††], P. Buchholz[††], S. Buitink[§], E. Cantoni[¶,‡‡], A. Chiavassa[¶], F. Cossavella[†], K. Daumiller[*], V. de Souza[†,xv], F. Di Pierro[¶], P. Doll[*], R. Engel[*], H. Falcke[§,x], M. Finger[*], D. Fuhrmann[xi], P.L. Ghia[‡‡], R. Glasstetter[xi], C. Grupen[††], A. Haungs[*], D. Heck[*], J.R. Hörandel[§], A. Horneffer[§], T. Huege[*], P.G. Isar[*], K.-H. Kampert[xi], D. Kang[†], D. Kickelbick[††], J. Kuijpers[§], S. Lafebre[§], P. Łuczak[xii], M. Ludwig[†], H.J. Mathes[*], H.J. Mayer[*], M. Melissas[†], B. Mitrica[**], C. Morello[‡‡], G. Navarra[¶], S. Nehls[*], A. Nigl[§], J. Oehlschläger[*], S. Over[††], N. Palmieri[†], M. Petcu[**], T. Pierog[*], J. Rautenberg[xi], M. Roth[*], H. Rebel[*], A. Saftoiu[**], H. Schieler[*], A. Schmidt[‡], F. Schröder[*], O. Sima[xiii], K. Singh[‡‡,§], G. Toma[**], G.C. Trinchero[‡‡], H. Ulrich[*], A. Weindl[*], J. Wochele[*], M. Wommer[*], J. Zabierowski[xii], J.A. Zensus[‖]

[*]*Institut für Kernphysik, Forschungszentrum Karlsruhe, Germany*
[†]*Institut für Experimentelle Kernphysik, Universität Karlsruhe, Germany*
[‡]*Institut für Prozessdatenverarbeitung und Elektronik, Forschungszentrum Karlsruhe, Germany*
[§]*Department of Astrophysics, Radboud University Nijmegen, The Netherlands*
[¶]*Dipartimento di Fisica Generale dell' Universita Torino, Italy*
[‖]*Max-Planck-Institut für Radioastronomie Bonn, Germany*
[**]*National Institute of Physics and Nuclear Engineering, Bucharest, Romania*
[††]*Fachbereich Physik, Universität Siegen, Germany*
[‡‡]*Istituto di Fisica dello Spazio Interplanetario, INAF Torino, Italy*
[x]*ASTRON, Dwingeloo, The Netherlands*
[xi]*Fachbereich Physik, Universität Wuppertal, Germany*
[xii]*Soltan Institute for Nuclear Studies, Lodz, Poland*
[xiii]*Department of Physics, University of Bucharest, Bucharest, Romania*
[xiv]*now at: Universidad Michoacana, Morelia, Mexico*
[xv]*now at: Universidade de São Paulo, Instituto de Fîsica de São Carlos, Brasil*
[xvi]*now at: KVI, University of Groningen, The Netherlands*

Abstract. **The antenna is the key component for radio detection of cosmic air showers. For large-scale radio detector arrays we designed a crossed polarized short aperiodic loaded loop antenna (SALLA) with only 100 cm diameter, less than 2 kg weight and material cost of about 60 Euro. It is a special type of the well-known Beverage antennas. The E-plane and H-plane directional diagram features a wide main lobe towards zenith with a 3 dB beam width of 150°. SALLA systematically uses internal losses by resistor loading and their sensitivity reaches the theoretical limit given by the omnipresent galactic noise. In return SALLA has in comparison to dipoles and other standard antennas the widest main lobe, the lowest calibration uncertainty, dispersion, weight, material costs, and production time, the smallest dimension, and the highest robustness. SALLA has practically the same directional sensitivity in the E- and H-plane. Thus the sensitivity is rotational invariant. The properties of this new antenna including its delay and transfer function are given.**

***Keywords*: extensive air showers, radio emission, antennas**

I. INTRODUCTION

Cosmic ray air showers produce pulsed wideband geosynchrotron radio signals in the frequency range 10 to 100 MHz [1]. Due to man made radio frequency interferences (RFI), see Fig. 1, the useable bandwidth range from 30 to 80 MHz.

The necessary antenna influences the achievable bandwidth, the RFI suppression, and the calibration uncertainty decisively. The different types of antennas have especially different directional diagrams (sky coverage), frequency dependencies, noise immunity and sensitivity to environmental conditions (e.g. conductivity, dielectricity and distance to the ground). On the other hand the antenna design has to be robust, low-cost, and easy to assemble.

The limitation of our antenna-sensitivity to radio signals is given in this frequency range by the galactic noise, first time identified by Jansky 1933 [2], and solar flairs and lightning. But the latter two are limited to short time periods - giving no serious problem for long term radio observation of cosmic rays. The noise level of Galactic noise is frequency dependent [3] and limits by its field strength value in the order of $10\,\mu V/m$ the sensitivity of obersavtion to cosmic radio emission. Furthermore the

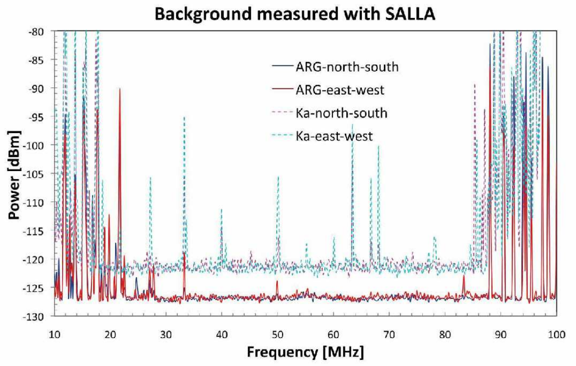


Fig. 1: Measured radio background at Karlsruhe (dashed line, Ka) and at Pierre Auger Observatory, Argentina (solid line, Arg). The differences in the background are due to overload protection outside the shown measuring range.

noise intensity varies over the day as the galactic center is moving through the field of view. In the framework of LOPES (LOFAR PrototypE Station) and $LOPES^{STAR}$ a Self-Triggered Array of Radio antennas is developed. To obtain an optimized design we explored different types of antennas. We started with dipole like antennas, logarithmic periodic dipole antenna (LPDA) and arrive now at a short loop antenna derived from the Beverage antenna [4].

II. Dipole Antennas

Most of cosmic ray radio detectors use dipoles due to their easy assembly and cost effectiveness. For instance the CODALEMA [6] receiver uses short planar dipoles or the LOPES30 [5] experiment uses inverted V-dipoles (Fig. 2a). With a receiver bandwidth a little bit more than one octave most of classical antenna types like dipoles are difficult to handle, because their antenna impedances and directional diagrams are frequency dependent (Fig. 2b). Furthermore due to their double-sided directional diagram (zenith and ground) up to 50% of the antenna output signal may originate from reflections at ground. Thus their characteristics change with ground properties like humidity, conductivity, dielectricity or distance as can be seen in Fig. 2b. The on the first view simple and low cost dipole antennas produce a high calibration uncertainty and possibly require at weather changes an individual antenna calibration.

III. Logarithmic Periodic Dipole Antennas (LPDA)

To avoid the uncertainties of dipoles $LOPES^{STAR}$ uses custom-built wideband directional antennas with a single-sided directional diagram. The first approach was the logarithmic-periodic dipole antenna (LPDA) with crossed polarisation (east/west and north/south), see Fig. 3a. The excellent wideband properties of the LPDA assures an almost frequency independent directional diagram, antenna gain, and impedance. Within the receiver bandwidth the return loss in a $50\,\Omega$ system is less than $15\,dB$. The E-plane directional diagram features a wide main lobe towards zenith with a $3\,dB$ beam width of 100^o at an average antenna gain of $4\,dBi$ (Fig. 3b). The high side lobe attenuation in the horizontal and backward direction suppresses man-made RFI with flat elevations, minimizes the interactions with ground and thus enables a very low calibration uncertainty without individual antenna calibration. In particular this is an important advantage for large scale radio detector arrays. LPDAs widely fulfil all required electrical properties. Only their overhanging dimensions of $4\times4\times4\,m^3$ cause mechanical problems under harsh weather conditions and the construction is not very cost-effective.

IV. Short Beverage antenna

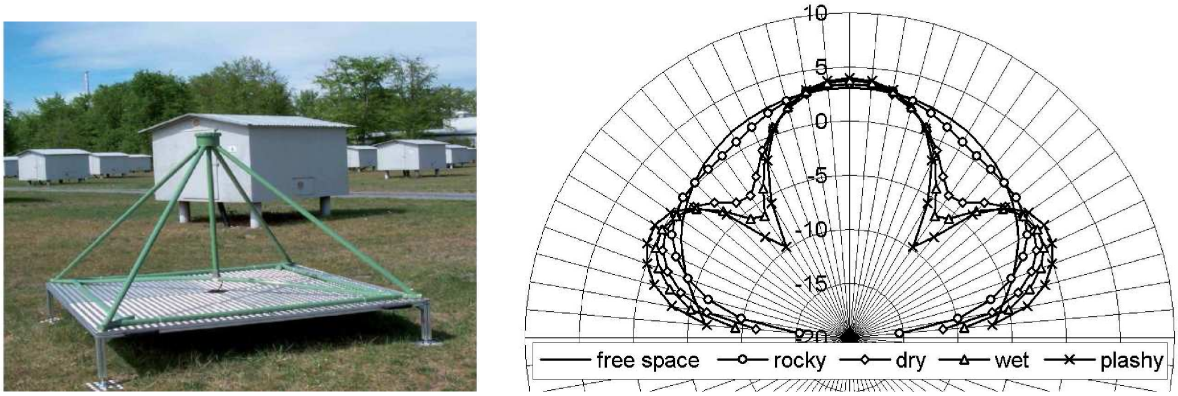
Another way to design wideband directional antennas with dimensions much smaller than the LPDA is given by resistively loaded aperiodic antennas with internal losses. They also have excellent wideband properties as the resistor load dominates in comparison with the capacitive or inductive reactance. The question is whether internal antenna losses are tolerable or not: In this application at frequencies below $100\,\mathrm{MHz}$ the noise is dominated by external noise sources. The omnipresent and unavoidable galactic noise N_e ($T_e = 5000\,K\,@\,60\,\mathrm{MHz}$ [3]) is about 10 dB larger than the internal receiver noise $N_i(T_{Rec} \approx 500\,K)$. Thus the effective signal-to-noise ratio SNR remains unaffected even if antennas with internal losses are used. The maximum permitted antenna loss α_{Ant} without significant lowering of the signal-to-noise ratio is given when the internal receiver noise remains below the attenuated external noise, e.g. $\alpha_{Ant} = 10\,dB$ at 60 MHz.

For large scale radio detector arrays we designed a crossed polarized short aperiodic loaded loop antenna (SALLA) with only $100\,cm$ diameter, less than $2\,kg$ weight and material cost of about 60 Euro (Fig. 4a). It is a special type of the well-known Beverage antennas. The principle of the antenna with its damping resistor responsible for the wide bandwidth is shown in Fig. 4b. The E-plane directional diagram (Fig. 4c) features a wide main lobe towards zenith with a $3\,dB$ beam width of 150^o which is 50^o wider than the LPDA directional pattern an thus enables enough sensitivity also for showers with low elevation angles. The insensitivity to ground properties is better than with the LPDA and enables the lowest calibration uncertainty compared to a dipole as the inverted V-dipole (Fig. 4c).

SALLA is designed to achieve the minimum required gain even at the sole presence of galactic noise (Fig. 5). At the additional presence of man-made noise in a rural environment like the Pierre-Auger-Observatory the antenna gain is about $5\,dB$ above the required minimum.

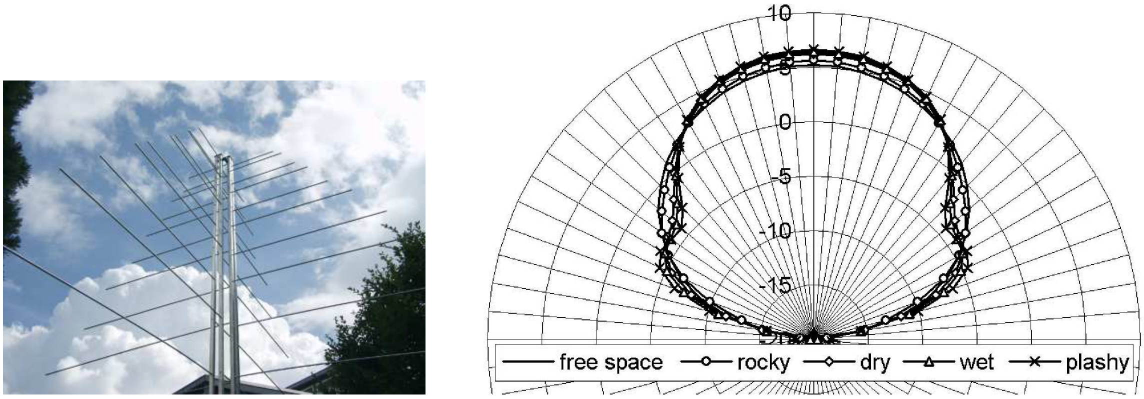
V. Antenna delay and dispersion

Due to the passive antenna design the LPDA but also SALLA may be used for both transmitting and



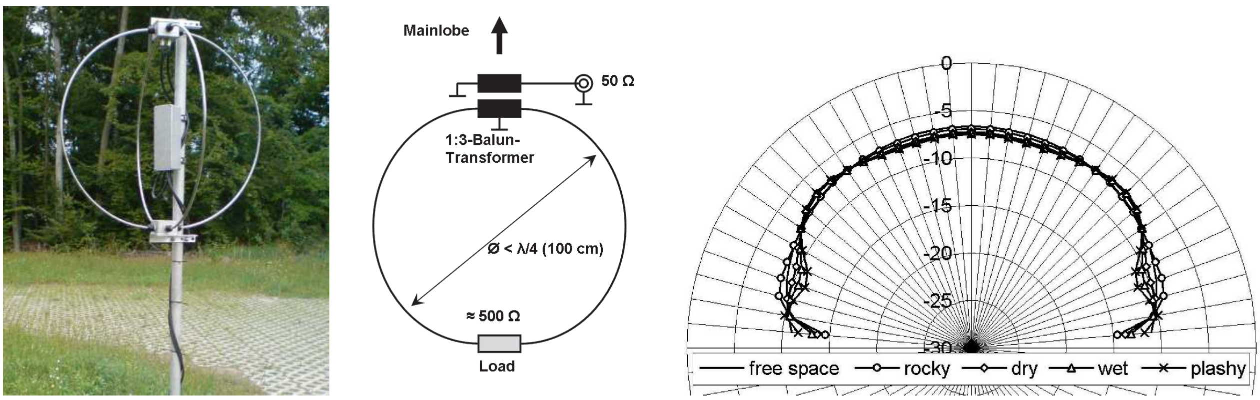
(a) (b)

Fig. 2: (a) Inverted V-dipole, and (b) its calculated E-plane directional diagram in dBi at 2.5 m height above ground for free space, and rocky, dry, wet, and plashy ground (with a dielectricity constant $\epsilon = 1, 3, 15, 30, 80$).



(a) (b)

Fig. 3: (a) Logarithmic Periodic Dipole Antennas (LPDA), (b) its E-plane directional diagram as in Fig. 2b.



(a) (b) (c)

Fig. 4: (a) Short Aperiodic Loaded Loop Antenna (SALLA), (b) its principle, (c) and its E-plane directional diagram.

receiving. Thus the antennas may be calibrated with the two-antennas-method with high accuracy without the need of a reference antenna. Using a vector-network-analyzer the antenna gain but as well the antenna phase-response and group-delay were analysed and used for the receiver calibration spanning the whole signal path. With the LPDA lower frequencies have a higher delay than frequencies at the upper band limit resulting in a dispersion of $30\,ns$. That is due to the different path lengths at different frequencies: Lower frequencies

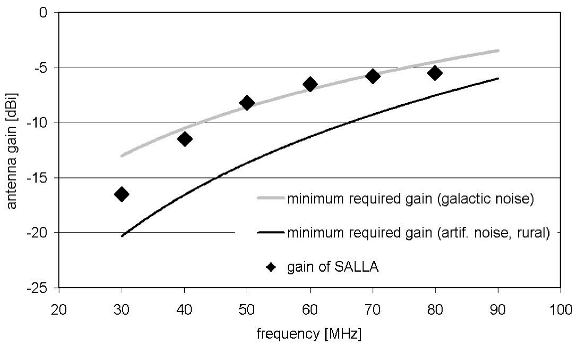


Fig. 5: Minimum required antenna gain without significant lowering the signal-to-noise ratio for external galactic noise (grey) and for man-made noise (black: rural environment) including a characteristic noise of the preamplifier of $2\,dB$. Frequency dependent galactic noise temperatures are derived from [3].

(longer wavelength) have to pass through the dipole structure to reach the corresponding longest dipole sticks and then have to run back to the feed point via the centre wave guide. The SALLA delay response remains widely constant with a delay of $5\,ns$ and a dispersion of $5\,ns$ only. Thus the minimal linear distortion of the pulse shape is achieved with SALLA. These delays have to be included for a precise analysis of the data.

VI. Flatness of antenna transfer function Matched-filter design

The antenna transfer function $T_A(f)$ is the ratio of the antenna output voltage U_A to the electric field strength $|\vec{E}|$. Its dimension is a length, the so-called effective antenna length. The received power P may be calculated by the Poynting vector $|\vec{S}| = |\vec{E} \times \vec{H}| = E^2/\eta_0$ and the effective antenna plane $A_W = G_A(f)^2\lambda^2/4\pi$ and is fed via the output voltage U_A to the receiver input impedance Z_0.

$$P = S \cdot A_W = \frac{E^2 \cdot G_A(f) \cdot c^2}{\eta_0 \cdot 4\pi \cdot f^2} = \frac{U_A^2}{Z_0}, \qquad (1)$$

with the wavelength λ, the vacuum impedance η_0, the magnetic field H, the speed of light c, and the antenna gain related to the isotropic radiator $G_A(f)$. From eq. 1 we get the transfer function (effective length):

$$T_A(f) = \frac{U_A}{E} = \sqrt{\frac{Z_0 \cdot G_A(f) \cdot c^2}{\eta_0 \cdot 4\pi \cdot f^2}} \qquad (2)$$

As both the cosmic radio pulse frequency spectrum and the external noise frequency spectrum decrease at increasing frequencies with similar shape a matched-filter design requires an approximately flat amplitude frequency response [7]. A flat antenna transfer function $T_A(f)$ is not achieved by a frequency independent constant antenna gain but with an antenna gain increasing with frequency $G_A(f) \sim f^2$ (eq. 2).

This is well fulfilled with the SALLA design (Fig. 5). Thus a constant signal-to-noise ratio is enabled over the full frequency range. The LPDA with its widely constant antenna gain $G_A(f) \approx const. \approx 4\,dBi$ (Fig. 3b) produces a transfer function $T_A(f)$ with a $1/f$ characteristic (eq. 2), corresponding to an integration in the time domain. This emphasis of lower frequencies does not fulfil the matched-filter condition and thus has a suboptimal signal-to-noise ratio, if no amplitude frequency response correction is done.

VII. Discussion

The comparison clearly shows that the dipole antennas (as planar or inverted V dipoles) are not very well suited for the radio detection of cosmic ray air showers in large scale radio arrays, if they are mounted on poles with a distance of about $2.5\,m$ from the ground and because their dependence from environmental conditions, such as wetness of the ground, changes their calibration by more than $10\,dB$. These environment conditions cannot be neglected. As conclusion of these calculations and measurements it results, that antennas with no reasonable backward suppression, as dipoles, are not very simple to handle in a calibrated radio experiment with changing conductivity and dielectricity constant of the ground. The required low calibration uncertainties and frequency independent directional diagrams could be achieved more easily with wideband directional antennas, like the LPDA or SALLA. While the LPDA is a conservative approach with a high gain reserve of $10\,dB$ related to the minimum required antenna gain, SALLA systematically uses internal losses by resistor loading and their sensitivity reaches the necessary theoretical limit given by the omnipresent galactic noise. In return SALLA has the widest main lobe, the lowest calibration uncertainty, dispersion, weight, material costs, and production time, the smallest dimension, and the highest robustness. SALLA has practically the same sensitivity in the E- and H-plane and a flat transfer function from the field strength in $\mu V/m$ to the detected voltage in the receiver. In the range of a few dB it is still possible to enhance the sensitivity of the SALLA by its size and a more elaborated preamplifier.

References

[1] T. Huege et al., Astropart. Physics **27**, 392-405 (2007).
[2] K.G. Jansky, Nature **132**, 66 (1933).
[3] ITU 1982, Recommendations and Reports of the CCIR, Genf: Vol. I, Rep. 670 (1982), Vol. VI Rep. 258-4, (1990).
[4] H.H. Beverage, US Patent 2,247,743 (1938).
[5] H. Falcke et al. - LOPES Collaboration, Nature **435**, 313 (2005).
[6] D. Ardouin et al. (CODALEMA Collaboration), Astroparticle Physics **26** (2006) 341-350.
[7] O. Krömer FZKA report **7396**, Forschungszentrum Karlsruhe (2008), page 16-29 and page 89-91.