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ARRAY OF ANTENNAS FOR COSMIC RADIO OBSERVATIONS

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Abstract. We are investigating the possibility to construct a radio observatory for both high energy cosmic particles and extragalactic radio sources. The first step for a radio observatory formed by phased array of antennas would be to determine its optimal geometry. Second, the types of antennas together with their characteristic parameters should be determined. The main performances of the observatory (spatial resolution, sensitivity, energy threshold etc.) are also discussed.

Key words: cosmic rays, radio sources, radio observatory.

1. INTRODUCTION

During the last half century our knowledge of the Universe has been revolutionized by the astronomical observations at low frequencies. These observations have a large number of important advantages. Low radio frequencies are the lowest energy end of the accessible spectrum. The very broad span of astrophysical topics that can be investigated at frequencies smaller than 200 MHz using simple phased array of radio antennas are: transient sources, pulsars, planets and SETI, Sun and space weather, cosmic rays, radio galaxies and active galactic nuclei (AGN), wide area imaging surveys etc. The LOFAR experiment already observed multiple such sources: pulsars [1], bubbles produced by a super massive black hole at observation frequencies between 20 and 160 MHz [2], mergers of galaxy clusters [3] etc.

Pulsars are steep spectrum objects whose pulsed flux density usually peaks in the 100–200 MHz range. However the vast majority of pulsars have been discovered and studied at frequencies in the range 300–2000 MHz. In recent years some excellent studies have continued at frequencies between 20 and 110 MHz [4, 5] etc. These studies have begun to map pulsars but in some cases have been limited by the available bandwidths and tracking capabilities of these telescopes.

The process radiation emission at low frequencies is still not completely understood even though multiple observations were made [6, 7] thus further investigation is still required. This is the reason why a radio interferometer as the one investigated here will be extremely helpful.

The Earth is continuously hit by cosmic rays (CRs) or neutrinos that originate outside the atmosphere. When a high energy neutrino or CR enters the atmosphere it may interact with a nucleon or electron producing a secondary particle. The resulting particle will carry most of the energy of the initial neutrino. This secondary will interact to produce other secondary or will decay in lighter particles. The particle disk will move in the direction of the original particle and will grow up to a maximum. Together these particles form an Extensive Air Shower (EAS).

In 1965 Jelly considered the possibility that EASs produce radio emission at a frequency of about 40 MHz [8]. Radio detection technique is very efficient compared to other cosmic particle detection techniques (*e.g.* fluorescence detectors, surface detectors etc.) thus several radio experiments were set: CODALEMA [9], LOPES with the extension LOPES-3D [10], Pierre Auger Observatory.

The goal of this paper is to investigate if a radio interferometer with an improved geometrical shape can be used to measure efficiently both 'classical' cosmic radio sources and high energy cosmic rays. The main features of the observatory are also presented: the general design of the observatory – in section 2, followed by the observatory performances (section 3) and the main conclusions (last section).

2. GENERAL DESIGN OF THE OBSERVATORY

The observatory consists of electronically steered arrays of antennas. This represents a new generation of telescopes because its concept is to use a lot of inexpensive dipole antennas arranged in a way that movement of heavy dishes is not longer needed.

As known, the LOFAR stations are equipped with dipoles optimized for the 110–220 MHz band. We shall work under this assumption and use dipoles with a resonant frequency of 148 MHz. An electronic array allows all-sky monitoring, rapid electronic direction switching, and multiple simultaneous beams on sky. Rather than using expensive dishes, the dipoles form a distributed sensor network that combines the signals from many thousands of simple antennas.

The general design the telescope consists of 3 structures. Each structure has a radial shape: a number of eight 45 degrees spaced tracks allows antennas to be easily moved and accurately positioned. The distance between two consecutive antennas on each track is *d*. The total number of antennas on one track is six. Thus each structure would appear to be formed from six concentric rings, each circle having eight antennas equally spaced. The total number of antennas is 144.

We considered a few such locations in Romania and one of the most suitable one is near Campulung Muscel, Arges district. We have considered a location close to the city, where the total area where such a detector could be deployed is of about

0.16 km^2. The geographic position already limits the construction of the detector: it allows a distance between rings of only 34 m.

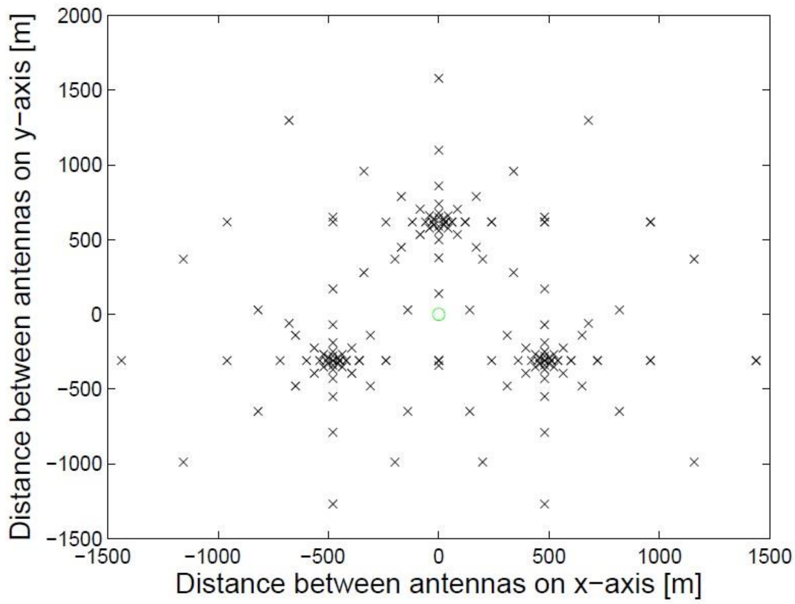

Fig. 1 – Geometry of the observatory.

3. OBSERVATORY PERFORMANCES

To exemplify the observatory performances were chosen as primary antennas dipoles of length 1 m. Dipoles are cheap, easy to use. Moreover, in order to increase the sensitivity in all directions 3 perpendicular dipoles can be mounted on the same pole. Here the efficiency η of one antenna was considered 0.7. All antennas are placed 1.2 m above ground. Given the total number of antennas, the total number of baselines is 7875 for this radio interferometer.

The receiving detection chain is formed by the antenna (noise temperature 35K) fed by a waveguide (2dB loss), followed by a low noise amplifier (20dB gain and 14dB noise factor). We also included the losses from the cable that connects the amplifier to the recording computer. The figures were taken from [11]. The bandwidth was set to $0.1\times f_0$, where f_0 is the resonant frequency of the dipoles.

One of the greatest advantages of phased arrays of antennas is that the phases of each antenna can be selected such as the main beam of the array to have its maximum oriented toward the transient radio source one wants to measure. This introduces an extra degree of freedom in the construction of the detector.

To exemplify the performances of the observatory a number of radio sources were considered (presented in Table 1). Centaurus A will be used for calibrations [12] so the phase of each antenna was chosen such as the maximum direction of the beam is oriented towards Centaurus A.

Table 1

Radio sources

Source	**Right Ascension**	**Declination**
Centaurus A	13h 25.5m	–43° 01’
Crab Nebula	05h 34m 31.97s	+22° 39’ 52.1’’
Vela Pulsar	08h 35m 20.65s	–45°10’35.15’’

According to [14], the minimum beam solid angle was determined to be $\Omega_A = 0.0021$ rad^2. The source Centaurus A has a 14.5621 arcmin angular extent on the sky so this will represent a resolved source. The minimum beam solid angle (thus highest directivity of the array) is achieved for multiple pairs of *n* and *d*. However, the best resolution of $7.41 \cdot 10^{-4}$ deg. is obtained when $d = 95.38$ m and $n = 7.42$. If the parameter *d* becomes 30.7 m the resolution increases to 0.0024 rad.

The second radio source considered is Crab Nebula [15, 16]. The minimum beam solid angle is $\Omega_A = 0.0033$ rad^2 (thus this is also a resolved source). This value corresponds to $n = 7.42$ and is achieved for $d = 30.7$ m. The resolution becomes 0.0024 rad.

The last source is the pulsar Vela. Highest directivity of 0.0018 rad^2 is obtained when *d* is either 53.84 m or 2 m.

The same network of antennas must be used to detect cosmic rays. We simulated the radio emission [17] from 6000 showers generated by primary particle of energies 10^{18} eV, $10^{18.5}$ eV and 10^{19} eV, coming from all directions and arriving randomly on points of the radio array. To allow reconstruction of the properties of the primary particle it was imposed that a number of 10 antennas to detect a radio signal with a signal to noise ratio (SNR) higher than 10. For best performances the *n* parameter should be 1.6. The distances between rings should be ~30 m [18].

3.1. ORIENTATION OF THE ANTENNAS

The next step was to determine if the orientation and polarization of the antennas influence the results. Hence we have used as an observation source Centaurus A. We have considered that the dipoles are parallel to the Oy and Ox axis. The amplitude excitation of each element is equal and there exists a progressive phase excitation between the elements.

For a planar array and for far-field observations, it is useful to define the beam solid angle [19] by:

$$\Omega_A = \Theta_h \Psi_h\,, \tag{1}$$

where Θ_h is the elevation plane half-power beamwidth and Ψ_h is the half power beamwidth in the plane that is perpendicular to the $\Phi = \Phi_0$, Φ_0 being the declination of Centaurus A:

$$\Theta_h = \sqrt{\frac{1}{\cos^2\theta_0\left(\Theta_{x0}^{-2}\cos^2\Phi_0 + \Theta_{y0}^{-2}\sin^2\Phi_0\right)}} \tag{2}$$

$$\Psi_h = \sqrt{\frac{1}{\left(\Theta_{x0}^{-2}\sin^2\Phi_0 + \Theta_{y0}^{-2}\cos^2\Phi_0\right)}}\,. \tag{3}$$

In a first case we considered the antennas to be positioned parallel to the *y*-axis. The minimum beam solid angle was calculated to be $\Omega_A = 0.0013\,\mathrm{rad}^2$. The best resolution is 0.00054 rad^2 obtained for the pairs n = 6.7 and d = 19.23 m or n = 6.1 and d = 21.53 m (Fig. 2).

The second case is when antennas are parallel to the x-axis. The minimum beam solid angle was calculated as $\Omega_A = 0.0021\,\mathrm{rad}^2$. The best resolution is 0.00054 obtained for n = 6.7 and d = 33.07.

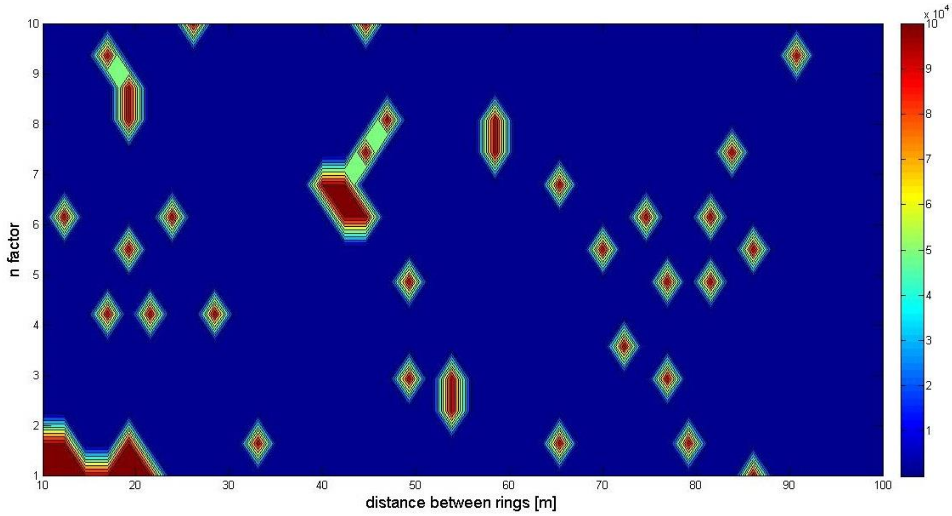

Fig. 2 – Beam solid angle when scanning Centaurus A with dipoles parallel with the *y*-axis. Color red marks the highest values while blue the smallest.

3.2. THE IMAGING CAPABILITIES

The final step was to determine the imaging capabilities of our system. First we will analyze the field of view (FOV).

The *Full Width Half Maximum* (FWHM) is determined by [20]:

$$\mathrm{FWHM} = a_1 \frac{\lambda}{D}, \tag{4}$$

where $a_1 = 1.42$, λ is the wavelength and D is the distance between antennas.

The FOV is calculated as:

$$\mathrm{FOV} = \pi \left(\frac{\mathrm{FWHM}}{2} \right)^2 . \tag{5}$$

For the observatory we determined a FOV of $1.70939536 \times 10^{-05}$ rad^2 in both cases of dipoles parallel to the O*x*- and O*y*-axis.

The resolution of the array is given by [19]:

$$\delta = a_2 \frac{\lambda}{L}, \tag{6}$$

where $a_2 = 0.8$ and L denotes the longest baseline. The value 0.8 is the approximately value used for the LOFAR system [19]. The resolution for both orientation of the dipoles is 0.00054575 rad^2 .

The system's noise temperature is given by:

$$T_{sys} = T_{sky} + T_{instr}, \tag{7}$$

where T_{sky} is the noise temperature coming from radio emission from the sky:

$$T_{sky} = T_{s0} \lambda^{2.55}, \tag{8}$$

where $T_{s0} = 60 \pm 20$ K for Galactic latitudes between 10 and 90 degrees and here λ_n represents the dimensionless wavelength expressed in meters. The noise temperature will vary between 7783 K and 8024 K.

The effective area of a single dipole is:

$$A_{eff,dipole} = \frac{\lambda^2}{\Omega_{\mathrm{dipole}}}, \tag{9}$$

where λ denotes the wavelength and Ω_{dipole} the effective solid angle covered by the beam. This factor is equal to 4 for a dipole of half wavelength spaced dense array, which is what we have used. Since the effectie area per dipole is constrained by the available space (such as the presence of the nearby antennas) one should use [19]:

$$A_{eff} = \min\left\{\frac{\lambda^3}{3}, A_{\text{available}}\right\}. \tag{10}$$

The effective area of the detector is then the summation of the effective areas of the composing dipoles and it is equal to 147.625 m^2.

The System Equivalent Flux Density (or system sensitivity) is defined as [19]:

$$S_{sys} = \frac{2\eta k}{A_{eff}} T_{sys}. \tag{11}$$

where η is the free space impedance, *k* is Boltzmann's constant. Results show a sensitivity of 5.488 μJy when T_{s0}=40K and a sensitivity of 5.6585 μJy when T_{s0} = 80 K.

The point-source sensitivity of a two-element interferometer can be determined from the radiometer equation for a total-power receiver on a single antenna. If we consider an interferometer with two identical elements, each of which also has a square-law detector, observing a point source, the effective collecting area of the two-element interferometer equals the effective collecting area of each element [20]. The observatory presented here has *N* = 144 antennas so it contains $\frac{N(N-1)}{2} = 10296$ independent two-element interferometers. The point-source sensitivity is:

$$\sigma_S = \frac{2kT_{sys}}{A_{eff}\left(\frac{N(N-1)}{2} f\tau\right)^{1/2}}, \tag{12}$$

where f is the operating frequency of 148 MHz and $\tau = \frac{L\vec{s}}{c}$ is the geometric delay (*L* is the longest baseline, $\vec{s}$ is the unit vector and *c* the speed of light). The point source sensitivity is 25.68626 mJy.

The sensitivity of the radio telescope was calculated with:

$$S = \frac{1.45 T_{sys}}{\eta S_{tot}\sqrt{N(N-1)\tau\Delta f}}, \tag{13}$$

where τ represents the measurement time expressed in hours (here equal to 4), S_{tot} the radio interferometer area, *N* – the number of antennas, Δf the considered bandwidth expressed in kHz and T_{sys} the system temperature. If the distance between the rings of antennas is 95.38m the sensitivity was determined to be 10.02μJy. If the distance decreases to 30.7m, the sensitivity increases at 1.06μJy.

The maximum baseline was also determined: it is 854.15 m (if the total area is 0.16 km^2) and increases to 2.6 km when d = 95.38 m.

4. CONCLUSIONS

In this work was presented an initial analysis of a simple radio interferometer to possibly be constructed in Romania. Due to the modular construction it should be easily integrated in the LOFAR system.

The main scientific projects are: low frequency surveys of the radio sky (centered around 148 MHz), radio transients and pulsars, ultra-high energy cosmic rays.

The construction is modular (presented in Fig. 1) and consists of 3 ringed structures. For best performances the n parameter should be 1.6. The distances between rings should be ~ 30 m for a sensitivity of ~ 1 μJy (4 hours integration time). The resolution is ~ 152 arcsec and the field of view is 6.4 square degrees.

Although in practice only two-dimensional patterns can be measures, we reconstructed the three-dimensional pattern of our observatory. It can be seen that physically placing the elements to be parallel to the Ox and Oy axis, the characteristics of the array do not change. Numerically they yield identical patterns, but their mathematical forms differ.

When compared to other radio interferometer (*e.g.* LOFAR in Netherlands), the resolution is about 4 times higher (at ~ 150 MHz) when the baseline is more than two times larger [21]. The figures for sensitivity compare well when the number of antennas is adjusted (and so is the total area).

Results show a system sensitivity of 5.488 μJy for the interferometric system and a point source sensitivity of 25.68626 mJy.

The cost of such a project is expected to be around 2 million Euros in hardware only. However, we expect other outcomes then scientifically such as: national publicity, the observatory to serve as a teaching instrument etc.

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