PROCEEDINGS OF SCIENCE

Radio Interferometry applied to air showers recorded by the Auger Engineering Radio Array

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A new radio interferometric technique was recently developed that takes into account time lags caused by the three-dimensional dependency of the refractive index in the atmosphere. It enables us to track the extensive air shower while it propagates through the atmosphere. Using this technique, properties of the air shower can be estimated, like the depth of maximum and the axis of propagation. In order to apply this method, strict constraints on the time-synchronisation between radio antennas in an array must be satisfied. In this contribution, we show that the Auger Engineering Radio Array can meet these timing criteria by operating a time reference beacon. We will show how this enables us to reconstruct air shower properties using the radio interferometric technique.

38th International Cosmic Ray Conference (ICRC2023)
26 July – 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)380

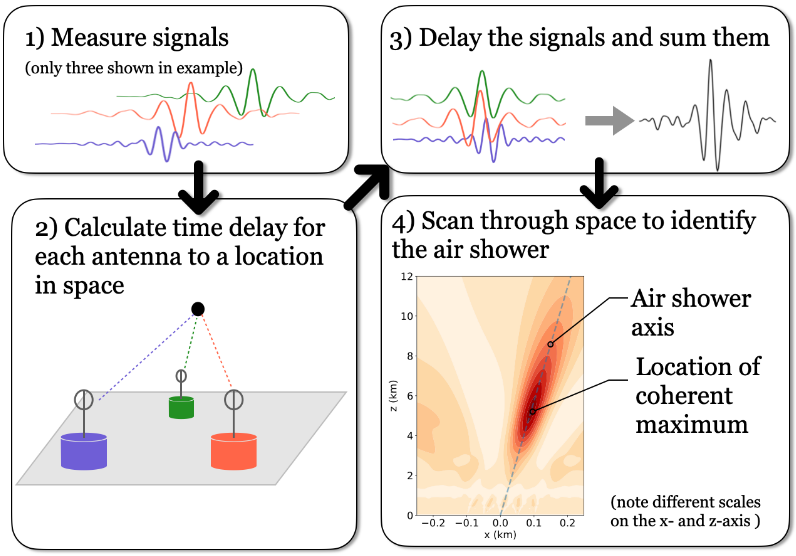

Figure 1: Steps involved in scanning space for coherency by performing interferometry on radio signals from extensive air showers. Panel 4) has been modified from [1].

1. Introduction

Cosmic-ray induced extensive air showers emit impulsive radio signals, which are observed by the Auger Engineering Radio Array (AERA) [3] in the frequency range of 30 – 80 MHz. Following the success of interferometry in radio astronomy, it is natural to wonder if interferometry can also be used in the radio observations of air showers. There have been several attempts to use radio interferometry for the observation and reconstruction of extensive air showers [4–6]. Recently, it was shown on simulations how interferometry can be used to reconstruct the air shower axis and depth of shower maximum (X_{max})[1] and the applicability to the auger radio detectors was investigated in [2]. In Figure 1, we summarise the steps involved in applying radio interferometry to air showers following this approach. For this method to work, individual detector stations need to be synchronised with an accuracy of the order of a nanosecond. At AERA there is dedicated hardware installed to reach this kind of accuracy making it suitable to test extensive air shower reconstruction using interferometry.

2. Setup

The Auger Engineering Radio Array is embedded in the Pierre Auger Observatory[7] in Malargüe Argentina and it contains 153 radio detector stations distributed over an area of 17 km^2. During its lifetime, starting in 2010, it has been extended and modified in three phases, each phase came with its own version of hardware and specific grid layout, as is shown in Figure 2.

Each radio detector station in AERA is equipped with a GPS receiver, providing information of its location and time. Using this system, a synchronisation between all the stations in the array can be achieved with an accuracy of roughly tens of nanoseconds. To obtain more accurate synchronisation an external transmitter is used, which we call a beacon[8]. It is installed on the nearest

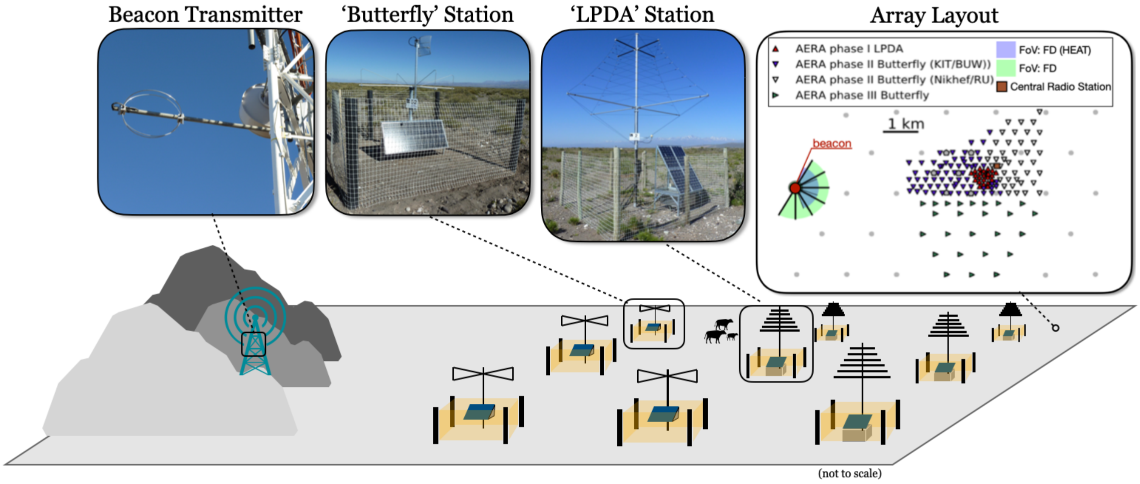

Figure 2: Schematic of the Auger Engineering Radio Array and its beacon for time synchronisation.

communication tower, located next to the building that houses the nearest fluorescence telescopes. The beacon emits continuously at four fixed frequencies a sinusoidal signal within the 30 – 80 MHz band. Each time AERA is read out, the beacon signals are present in the measurement. The locations of all stations and the beacon have been measured with differential GPS within 10 cm. From these locations the exact time difference that arises from propagating[1] the beacon signal to the detector stations can be estimated. By correcting the observed time differences to the expected time differences, an accuracy of two nanoseconds (or better) [9] is achieved for the synchronisation. The multiple beacon frequencies are needed to resolve periodic solutions for the timing correction that could arise from using a single frequency, i.e. the periodicity of the four summed sinusoids is much larger than the expected timing errors arising from the GPS time accuracy.

3. Data Analysis

The combination of the accurate synchronisation of AERA and an existing, well understood, data set, gives us the possibility to validate the interferometric reconstruction against other methods. In this contribution, we will be showing a single example of an interferometric reconstruction on an extensive air shower and in an upcoming publication an analysis on a larger set will be presented. We select the event that we will study to have signals observed in a large number (19) of radio detector stations and an accurate depth of shower maximum $X_{\max}$ reconstruction by another method. As a verification method for the $X_{\max}$ reconstruction we use a method that compares the observed fluence in the radio signal to the fluence that is obtained from a set of simulated air showers [12, 13]. For this particular event the uncertainty on the $X_{\max}$ of the verification method is estimated to be $11\,\mathrm{g\,cm^{-2}}$.

In Figure 3 we show the steps that are involved in reconstructing the air shower properties. We start the reconstruction with an initial shower axis obtained from the standard reconstruction of air

[1]This assumes that we also know the speed of propagation, which is given by $\frac{c}{n}$, with c the speed of light and n the effective refractive index over the path propagation.

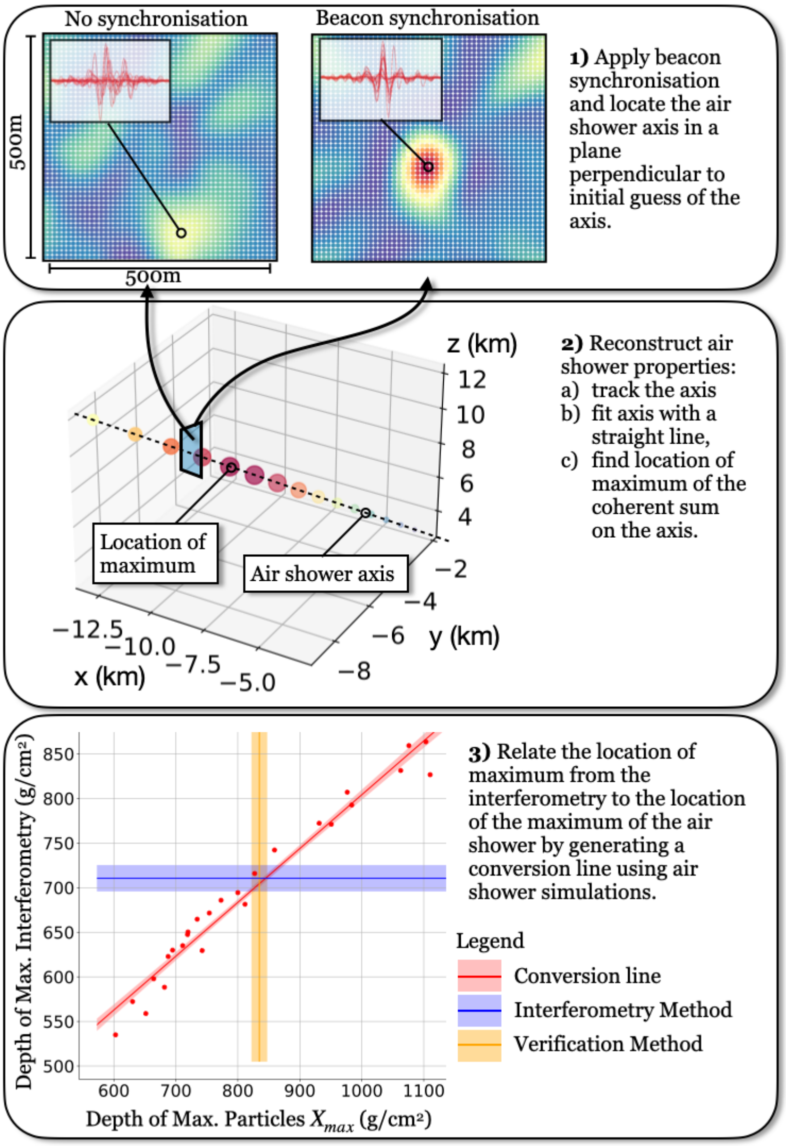

Figure 3: Reconstruction of the air shower axis and X_{max} (see text for detailed explanation).

showers with the surface detector of the observatory. We use this as an initial guess of the geometry and to define a grid of points in a plane perpendicular to this axis at an atmospheric slant depth of $X = 750\,\mathrm{g\,cm^{-2}}$. On this grid, we calculate the coherent intensity of the summed waveform (Figure 1) and the result is shown with and without beacon synchronisation in the top panel of Figure 3. The linear colour-scale indicates the intensity and has been fixed to the same range in both cases, a clear maximum is only found when the beacon synchronisation is applied, which illustrates the importance of this timing correction. We show all the individual, time delayed, waveforms that were summed at the location of the maximum intensity as insets in both panels. This visualises the coherency of the waveforms after applying the beacon timing corrections.

We repeat the calculation of the intensity in other planes along the initial axis, each separated by $50\,\mathrm{g\,cm^{-2}}$, and obtain the location of the maximum in each of the planes. This results in a set of points in the atmosphere, their location and intensity (both indicated by size and colour of the marker) are given in the middle panel of Figure 3 and are used to fit a straight line which is the reconstructed shower axis. This reconstructed axis deviates 0.3 ° from the direction reconstructed with the surface detector (SD), which is in the compatible with the estimated uncertainty of the SD-reconstruction.

Along this axis, we evaluate the intensity of the summed waveform in small steps of slant depth ($2\,\mathrm{g\,cm^{-2}}$) and obtain the slant depth of the maximum. We repeat the same procedure on a set of simulated air showers, with fixed geometry but with varying depths of shower maximum. We add measured background to the simulated signals from air showers and apply the detector response and standard air shower reconstruction [10, 11]. From this set of simulations, the relation between the maximum intensity and the depth of shower maximum is found. As expected, to first order, this is given by a linear relationship [1], so a first order polynomial is fitted to obtain the conversion. The result of this is shown in the bottom panel of Figure 3. Within uncertainties, the interferometry reconstruction intercepts the conversion line at the same location as the verification method, illustrating the agreement between both methods.

4. Conclusion

In this contribution we showed how interferometry can be used in the reconstruction of air shower properties on an air shower observed by the Auger Engineering Radio Array. Agreement is found with other reconstruction methods for both the direction of the shower axis and the depth of shower maximum. Only one, particularly well-measured, event was analysed here, but similar results were found on a larger events set. The study of these will be part of an upcoming publication. The uncertainty obtained on X_{max} for the example is estimated from the scatter around the conversion line and is about $25\,\mathrm{g\,cm^2}$, which is larger than what is typically expected from [1]. It is not fully understood what drives this uncertainty, but one reason might be the rather irregular structure of AERA; small changes in the footprint might result in different antennas present in the event. Studying the performance of the method on different event geometries will be part of a future analysis. The interferometry-based reconstruction is especially suitable for reconstructing the properties of inclined air showers. The radio detector [14] of AugerPrime [15], which is currently being deployed, and future observatories like GRAND[16] and GCOS[17] are designed to observe inclined air showers. Other methods of obtaining X_{max}, based upon the fluorescence light or the radio fluence, do not favour inclined geometries. However, it is of crucial importance to achieve similar, or better, synchronisation as in AERA for these very large arrays, which still is an unsolved challenge. If interferometry can be successfully implemented for AugerPrime, this will give us a unique opportunity to measure the electromagnetic energy, number of muons reaching the ground, and the depth of shower maximum of inclined air showers.

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Acknowledgments

The successful installation, commissioning, and operation of the Pierre Auger Observatory would not have been possible without the strong commitment and effort from the technical and administrative staff in Malargüe. We are very grateful to the following agencies and organizations for financial support:

Argentina – Comisión Nacional de Energía Atómica; Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT); Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET); Gobierno de la Provincia de Mendoza; Municipalidad de Malargüe; NDM Holdings and Valle Las Leñas; in gratitude for their continuing cooperation over land access; Australia – the Australian Research Council; Belgium – Fonds de la Recherche Scientifique (FNRS); Research Foundation Flanders (FWO); Brazil – Conselho Nacional de Desenvolvimento Científico e Tecnológico (CNPq); Financiadora de Estudos e Projetos (FINEP); Fundação de Amparo à Pesquisa do Estado de Rio de Janeiro (FAPERJ); São Paulo Research Foundation (FAPESP) Grants No. 2019/10151-2, No. 2010/07359-6 and No. 1999/05404-3; Ministério da Ciência, Tecnologia, Inovações e Comunicações (MCTIC); Czech Republic – Grant No. MSMT CR LTT18004, LM2015038, LM2018102, CZ.02.1.01/0.0/0.0/16_013/0001402, CZ.02.1.01/0.0/0.0/18_046/0016010 and CZ.02.1.01/0.0/0.0/17_049/0008422; France – Centre de Calcul IN2P3/CNRS; Centre National de la Recherche Scientifique (CNRS); Conseil Régional Ile-de-France; Département Physique Nucléaire et Corpusculaire (PNC-IN2P3/CNRS); Département Sciences de l'Univers (SDU-INSU/CNRS); Institut Lagrange de Paris (ILP) Grant No. LABEX ANR-10-LABX-63 within the Investissements d'Avenir Programme Grant No. ANR-11-IDEX-0004-02; Germany – Bundesministerium für Bildung und Forschung (BMBF); Deutsche Forschungsgemeinschaft (DFG); Finanzministerium Baden-Württemberg; Helmholtz Alliance for Astroparticle Physics (HAP); Helmholtz-Gemeinschaft Deutscher Forschungszentren (HGF); Ministerium für Kultur und Wissenschaft des Landes Nordrhein-Westfalen; Ministerium für Wissenschaft, Forschung und Kunst des Landes Baden-Württemberg; Italy – Istituto Nazionale di Fisica Nucleare (INFN); Istituto Nazionale di Astrofisica (INAF); Ministero dell'Universitá e della Ricerca (MUR); CETEMPS Center of Excellence; Ministero degli Affari Esteri (MAE), ICSC Centro Nazionale di Ricerca in High Performance Computing, Big Data and Quantum Computing, funded by European Union NextGenerationEU, reference code CN_00000013; México – Consejo Nacional de Ciencia y Tecnología (CONACYT) No. 167733; Universidad Nacional Autónoma de México (UNAM); PAPIIT DGAPA-UNAM; The Netherlands – Ministry of Education, Culture and Science; Netherlands Organisation for Scientific Research (NWO); Dutch national e-infrastructure with the support of SURF Cooperative; Poland – Ministry of Education and Science, grants No. DIR/WK/2018/11 and 2022/WK/12; National Science Centre, grants No. 2016/22/M/ST9/00198, 2016/23/B/ST9/01635, 2020/39/B/ST9/01398, and 2022/45/B/ST9/02163; Portugal – Portuguese national funds and FEDER funds within Programa Operacional Factores de Competitividade through Fundação para a Ciência e a Tecnologia (COMPETE); Romania – Ministry of Research, Innovation and Digitization, CNCS-UEFISCDI, contract no. 30N/2023 under Romanian National Core Program LAPLAS VII, grant no. PN 23 21 01 02 and project number PN-III-P1-1.1-TE-2021-0924/TE57/2022, within PNCDI III; Slovenia – Slovenian Research Agency, grants P1-0031, P1-0385, I0-0033, N1-0111; Spain – Ministerio de Economía, Industria y Competitividad (FPA2017-85114-P and PID2019-104676GB-C32), Xunta de Galicia (ED431C 2017/07), Junta de Andalucía (SOMM17/6104/UGR, P18-FR-4314) Feder Funds, RENATA Red Nacional Temática de Astropartículas (FPA2015-68783-REDT) and María de Maeztu Unit of Excellence (MDM-2016-0692); USA – Department of Energy, Contracts No. DE-AC02-07CH11359, No. DE-FR02-04ER41300, No. DE-FG02-99ER41107 and No. DE-SC0011689; National Science Foundation, Grant No. 0450696; The Grainger Foundation; Marie Curie-IRSES/EPLANET; European Particle Physics Latin American Network; and UNESCO.