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TEC, Trigger and Check, preparing LOFAR for Lunar observations

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Abstract. One of the main ways to use radio to detect Ultra High Energy Neutrinos and Cosmic Rays is the Lunar Askaryan technique, that uses the Moon as a target and searches for nanosecond pulses with large radio telescopes. To use low frequency aperture arrays, such as LOFAR and the SKA, pose new challenges and possibilities in detection techniques of short radio pulses and to measure the Total Electron Content (TEC). As a prepatory work, we have used other measurements that use similar techniques, or that can answer a specific question, with the LOFAR radio telescope. This contribution reports on our work on triggering on short radio signals, post-event imaging of radio signals from buffered data and methods to determine the TEC-value.

1 Introduction

One of the ways to determine the flux and direction of ultra high energy (UHE; $> 10^{18}$ eV) cosmic particles (cosmic rays and neutrinos) is to point a large radio telescope to the Moon to search for nanosecond pulses induced by lunar showers from these particles following the Askaryan effect [1]. Previous measurements with radio telescopes such as Parkes [2–4] and WSRT [5, 6] have developed these techniques and set limits to the flux of these particles. However, it requires even larger telescopes, such as the SKA [7] or FAST, to be sensitive to the known cosmic ray flux. To set better limits and to test the techniques used for a distributed telescope such as the SKA, we are working on a method to search for ultra high energy cosmic particles with LOFAR, within the NuMoon project. The proceedings by T. Winchen gives an introduction to this subject and deals with re-obtaining a high time resolution signal to search for these pulses. This proceeding reports on two other challenges faced in this project: The influence on the ionosphere and the verification of observed pulses.

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2 LOFAR

LOFAR [8] is a low frequency radio telescope that consists of stations with fields with antennas distributed on relative distances of 10s of meters up to 100s of kilometers. The antennas of each field are combined to form one or more beams on the sky with a size of a few degrees. NuMoon observations cover 110-190 MHz. By combining the beams of the inner 24 stations, the moon can be covered with 50 beams to search for nanosecond signals induced by lunar showers from ultra high energy cosmic particles. In addition, the data from each antenna is stored in a ring buffer for 5 seconds. If a trigger is received within this time, the data can be read out to disk for further analysis.

2.1 Ionospheric corrections

The first challenge is the correction of the ionosphere. The free electrons in the ionosphere cause a dispersion in the arrival time of the signal of different frequencies, with the relation

$$\tau[ns] = k\,\mathrm{STEC}/\nu^2 = 1.34 \cdot \mathrm{STEC}/\nu^2 \quad \text{with} \quad \mathrm{STEC} = \int n_e(s)ds \tag{1}$$

with ν the observing frequency in GHz. In this STEC is the Slanted Total Electron Content following the integrated electron density along a slanted path in TEC units (TECU) of 10^{16} electrons / m^2. This dispersion causes the signal to be spread out over 10s of nanoseconds [Fig. (1)]. lowering the peak amplitude. This effect needs to be corrected, to be able to detect pulses induced by cosmic particles. A second effect is Faraday rotation, in which the polarisation angle of a polarised source changes over frequency according to

$$\beta = \mathrm{RM}\lambda^2 \tag{2}$$

where λ is the wavelength in meters and the rotation measure

$$\mathrm{RM} = \frac{e^3}{2\pi m_e^2 \epsilon_0 c^3} \int_0^d n_e(s) B_{||}(s) ds, \tag{3}$$

in which $B_{||}$ is the magnetic field parallel to the line of sight, e the charge of an electron, c the speed of light in vacuum, m_e the mass of an electron and ϵ_0 is the vacuum permittivity, all in SI units. The Faraday rotation is easy to measure at low frequencies. If the magnetic field is known, this gives a measurement of the TEC value. [9] give a comparison in the measured RM variation of pulsars, as observed by LOFAR, with predicted values based on TEC and B values. This method may be used by observing pulsars in parallel or using the polarized rim of the Moon in online or offline analysis [10], and using the known B field to predict TEC values. With astronomical measurements differential[1] Faraday Rotation and differential TEC can be obtained with high precision, but the uncertainty in the differential magnetic field makes it difficult to obtain the absolute TEC value. An alternative approach is to use GPS data directly. The current maps are only available days later and have a temporal resolution of 2 hours and a spatial resolution of 2.5 x 2.5 degrees, but for the trigger real-time data is required. However, the Space Radio-Diagnostics Research Centre of the University of Warmia and Mazury and the UPC-IonSAT research group of the Technical University of Catalonia are currently developing algorithms to provide real-time high resolution TEC maps, specifically for the ILT (International LOFAR Telescope), using 119 Euref Permanent Network stations [11–13]. In the result, near real-time and high-spatial resolution maps are obtained at 15 minutes in temporal resolution and 0.5 degree in latitudinal and longitudinal spatial resolution, (Fig. (2)), with the possibility of obtaining

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[1] Between two different positions 1-1000 km apart

even higher temporal resolution. The biggest challenge here is still to get to an absolute TEC value, as there is a bias due to the ambiguous 2π phase shifts, as well as the slant to vertical TEC conversion, because of the unknown height of the ionosphere (see e.g.[14]). The lower uncharged atmosphere influences the signal only by a frequency independent delay. Therefore, its expected influence on the peak height of the signal, as well as on GPS-driven TEC measurements is negligible.

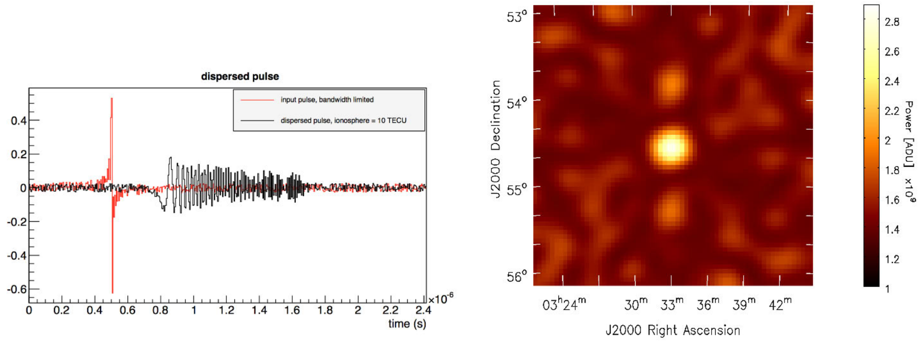

Figure 1. Left: Input pulse in red, dispersed pulse in black, with an ionospheric ionisation of 10 TECU., Right: Sky image from 6 LOFAR core stations of a dedispersed pulse of pulsar B0329+54 from TBB data obtained from triggering in real-time on beam formed data.

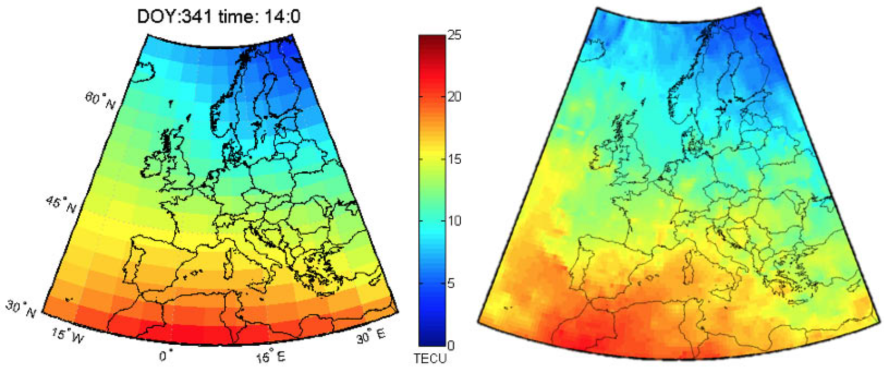

Figure 2. A comparison between the IGS global ionospheric maps [15] - on the left vs rapid ILT dedicated maps - on the right.

2.2 Pulse verification

The second challenge is the verification of pulses. For this we intend to read out the buffers from individual antennas. With this data we can check that it was not a single antenna or station creating the signal and check that the real direction is indeed coming from the Moon and not an off-beam satellite or terrestrial signal. We can further perform a better TEC correction to the pulse, and see for example if a 2x TEC value (as would be from a reflected signal) will give an even stronger signal. The technique of triggering the buffers and analysing the data was earlier performed in an astronomical context [16], to search for fast radio transients, such as pulsar pulses and the new class of fast radio bursts [17]. In this context a pulse of pulsar B0329+54 was localised [Fig. (1)], a strange signal was identified as an off-beam solar flare, and a signal was identified as coming from a single antenna.

3 Conclusion

The detection of ultra high energy cosmic particles, using the Askaryan techniques, remains challenging for telescopes such as LOFAR and SKA. But with the LOFAR observations and tests described here we are two steps closer to run successful observation in this or the next decade.

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