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A Cosmic Ray Trigger for LOFAR

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We present the development and first results of an independent cosmic ray trigger for the multiple dipole antenna radiotelescope LOFAR (LOw Frequency ARray). LOPES (LOfar PrototypE Station), at the KASCADE (KArlsruhe Shower Core and Array DEtector) site in Germany, has been initiated as a test case for LOFAR, and designed to detect air showers through their coherent radiation pulses upon external triggers by particle detectors. To fully exploit the capabilities in detecting CRs with the final LOFAR telescope, however, an independent, radio-only trigger is needed. We are searching for pulse coincidences in the antenna digital data stream. The limiting factor for applying real-time detection is the capacity of digital processing of the $8 \cdot 10^7$ samples per second per antenna. Here, we discuss constraints on basic criteria for the detection, like number of antennas, pulse height, pulse width, direction, distance of shower maximum and polarisation. We also present the first results of the application of such a trigger, and discuss optimization of the different parameters.

1. Introduction

A Dutch consortium, headed by ASTRON (The Netherlands Foundation for Research in Astronomy), is building a new radio telescope which is based on an array consisting of simple dipole antennas (see Figure 1a) with bandwiths of 30 to 80 MHz and 120 to 240 MHz. This telescope is called LOFAR (Low Frequency ARray), and will consist of a core of a few square kilometers (3 200 antennas), and 61 outer stations with a diameter of 100–200 m (100 detectors) each, spread out over an area 150 km in diameter in total (see Figure 1b). The total bandwidth from 30 to 240 MHz is covered by two different antenna types. The *low frequency antennas* are tuned to 30 to 80 MHz, the *high frequency antennas* to 120 to 240 MHz.

Of the five key projects, four propose to observe specific astronomical objects, and one addresses the study of Ultra High Energy Cosmic Rays (UHECR). In this latter project, we aim to detect air showers through radiosynchrotron radiation. The charged particles in the shower (mainly electrons and positrons) are deflected in the Earth's magnetic field and emit coherent geosynchrotron radiation [1, 2].

Currently, three test stations for LOFAR exist, two of which are optimized for cosmic ray air shower measurements in the radio regime from 40 to 80 MHz. LOPES [3], the LOfar PrototypE Station consists of 30 dipoles. For simultaneous data acquisition of particles and radio emission, LOPES is triggered by the KArlsruhe Shower Core and Array DEtector (KASCADE), situated at the Forschungzentrum Karlsruhe in Germany [4]. Since the beginning of 2004 we have recorded more than a million triggered events, more than a thousand of which are detected in radio. The second prototype is called LORUN (LOfar @ Radboud University Nijmegen) consisting of four crossed dipole antennas on top of the university building. LORUN is triggered by two particle detectors of the Nijmegen Area High School Array (NAHSA). The use of this prototype station lies mainly in the fields of outreach and education. The third test station is ITS (Initial Test Station), but currently no cosmic ray research has been carried out with this instrument.

From confirmed detections of cosmic ray air showers with LOPES [5], we have learned about basic properties of the antenna response to the radio signal. Based on this experience, we are developing a method to trigger the antennas without using particle detectors. In this way, all kinds of transient events in the radio data can be studied, and detecting air showers is not limited to the field of view and sensitivity of an external particle detector.

In this article we explain the self-trigger method and discuss its application for the LOFAR project.

2. Method

For the detection of Coscmic Rays (CR) with LOFAR dipole antennas, we develop an algorithm to find short pulses in the digitized data. The LOFAR design suggests to divide the trigger into three hardware levels:

In the first step, the signal will be monitored on a per-antenna level. A dedicated transient buffer board, consisting of Field Programmable Gate Arrays (FPGAs), performs real-time data analysis according to the algorithm

$$|x(t)| > \mu_n(t - t_1) + k\sigma_n(t - t_1), \tag{1}$$

where $x(t)$ is the received signal, and $\mu_n(t - t_1)$ is the time averaged signal, running over a time interval t_n (containing n samples) ending at time $t - t_1$. This is done to avoid 'contamination' of the average. $\sigma_n(t - t_1)$ is the standard deviation over the same sample block, and k is the threshold factor for the standard deviation. When the condition is fulfilled and the signal is above an overall power level, the station core processor is notified.

At station level, the core processor monitors the antenna messages. A station trigger is generated, when the

Figure 1. **A:** A prototype LOFAR antenna. The dipoles run down the black PVC tubes. **B:** LOFAR layout showing the core and logarithmically spaced remote stations on five spiral arms in the border region of the Netherlands and Germany.

number of antenna messages exceeds a decision limit n_a within a certain time window t_2, e.g. the light travel time between the antennas. When the decision for a trigger is made, the relevant part of the data buffer for all antennas in the station is downloaded and sent to the LOFAR core processor ($\sim$25 MB for 1 ms of data per antenna). Since the data production is not continuous the data transfer can be performed without disturbing the data acquisition of other observations.

Finally, at full LOFAR level, the obtained event is roughly analyzed to obtain estimates for shower properties like direction of arrival, lateral particle distribution, and primary energy. If the event is found to be a 'random' occurence it is deleted, else it is transferred to the data center at the Radboud University Nijmegen, where further offline analysis is performed. We estimate to receive up to a few GB of data per day.

3. Parameter optimization

The above trigger introduces a handful parameters to adjust. First of all, we have to rely on absolute gain calibration of a single antenna element to set a minimum absolute signal height for the peak search algorithm. This level also sets a lower limit on the minimum cosmic ray energy that can be detected at single antenna level. Since no absolute calibration is available yet for LOPES or LOFAR, we will not discuss this parameter here.

To test dependencies on the other parameters, a collection of bright events was used, which is a subset of the selection by A. Horneffer [3]. Steps 1 and 2 of the trigger algorithm were run over 156 event files, using various combinations of parameters. Because the exact time of the occurence of a cosmic ray pulse is known, the returned triggers could be marked 'correct' or 'incorrect'.

Changing n_a between 4 and 7 (out of 8 available dipole signals) does not influence the amount of correct detections much. Changing the value for t_2 also hardly has an effect on the trigger quality; a value of 0.63 μs, slightly larger than the light travel time through the detector, does the trick quite well, and this value has been used throughout.

The block size t_n and threshold value k are probably the most important selector for the type of event one wants to trigger on: larger block sizes will trigger broader events, higher threshold values will produce less

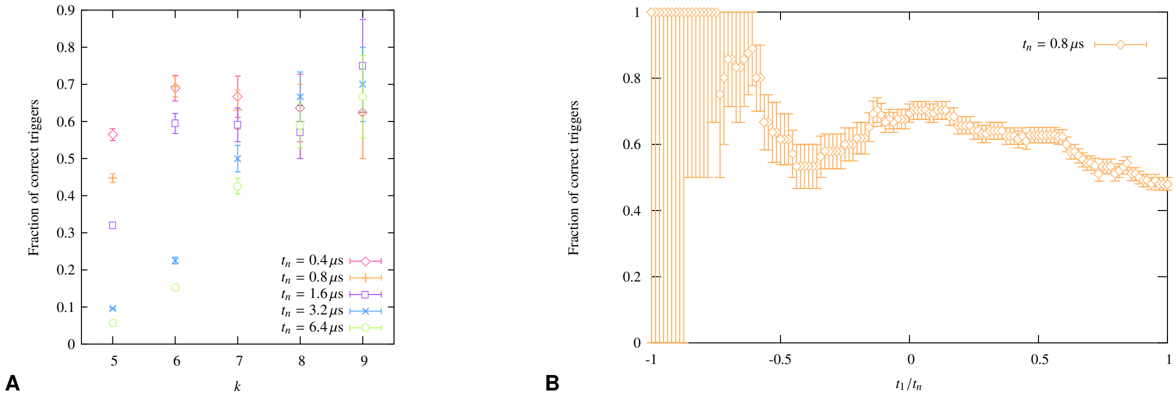

Figure 2. **A:** Trigger performance for the discussed trigger algorithm for various values of k and t_n. In this plot, $t_1 = 0$, $t_2 = 63\,\mu$s, and $n_a = 5$. The error bars are a measure for the absolute number of detected events: the longer the error bars, the smaller the number of events. **B:** Trigger performance for the discussed trigger algorithm for various values of t_1. In this plot, $t_n = 0.8\,\mu$s, $k = 6.0$, $t_2 = 63\,\mu$s, and $n_a = 5$. t_1 is expressed in units of t_n.

triggers in general. In Figure 2a, we tested the performance of our algorithm for certain values of k and t_n. This performance ratio, given on the vertical axis, is the fraction of correctly delivered triggers over the total amount of triggers. The error bars also provide some information on the total amount of triggers given: the longer the bars, the lower the number of triggers. Therefore, good data points lie in the top of the diagram and have a small error bar. From the diagram, it is clear that the performance ratio greatly varies with the parameters, and one can say that a combination of $k = 6$, $t_n = 0.8\,\mu$s gives best results.

The time shift t_1 also turns out to be an important marker. For $t_n = 0.8\,\mu$s, $k = 6$, and $n_a = 5$, Figure 2b gives the trigger performance for various values of t_1 between t_n (corresponding to a trigger at the beginning of the sampled average) and $-t_n$ (a trigger t_n after the last sample of the average). A value of $t_1 = 0$, putting the trigger at the end of the sampled average, gives best results.

4. Conclusions

For the brightest events ($E > 10^{17}$ eV), the proposed trigger seems to work reasonably well. One has to keep in mind, of course, that the data set over which it was tested is not extensive, and that the final setup will be different from the one currently in use. For example, in the final LOFAR setup there will be a lot less radio noise than in LOPES. Further testing on more (LOPES) data will hopefully provide more insight. But only after the first dipoles of LOFAR itself will have been set up, we will know whether our results prove to be valid.

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