ICRC'07

Mérida, México

Developments in Nanosecond Pulse Detection Methods & Technology

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Abstract: A promising method for the detection of UHE neutrinos is the Lunar Cherenkov technique, which utilises Earth-based radio telescopes to detect the coherent Cherenkov radiation emitted when a UHE neutrino interacts in the outer layers of the Moon. The LUNASKA project aims to overcome the technological limitations of past experiments to utilise the next generation of radio telescopes in the search for these elusive particles. To take advantage of broad-bandwidth data from potentially thousands of antenna requires advances in signal processing technology. Here we describe recent developments in this field and their application in the search for UHE neutrinos, from a preliminary experiment using the first stage of an upgrade to the Australia Telescope Compact Array, to possibilities for fully utilising the completed Square Kilometre Array.

Introduction

The origin of the most energetic particles observed in nature, the ultra high energy (UHE) cosmic Rays (CR), which have energies extending up to at least 2×10^{20} eV, is currently unknown. Finding the origin of these particles will have important astrophysical implications, however direct detection of UHE neutrinos is very difficult due to their extremely small interaction cross-sections. Instead, they may be detected indirectly via observation of the Askar'yan effect [1] in the lunar regolith. Askar'yan first predicted coherent Cherenkov emission in dielectric media at radio and microwave frequencies. Using the moon as a large volume neutrino detector, coherent radio Cherenkov emission from neutrino-induced electromagnetic cascades in the lunar regolith can be observed with ground based telescopes. This method was first proposed by Dagkesamanskii and Zheleznykh (1989) [3] and first applied by Hankins, Ekers and O'Sullivan (1996) [5] using the Parkes radio telescope.

Lunar Cherenkov radiation is a linearly polarised, broadband continuous emission. The spectrum of coherent Cherenkov emission rises approximately linearly with frequency until a peak value is reached. The peak frequency is determined by decoherence and/or attenuation in the regolith, and can vary between approximately 5 GHz for near-surface showers viewed at the Cherenkov angle down to a few hundred MHz for showers deep in the regolith and/or viewed far from the Cherenkov angle. The dependence of the peak frequency on shower geometry makes the choice of an optimum observation frequency non trivial [6].

Detection Issues

Lunar Cherenkov emission produces an extremely narrow pulse (sub-nanosecond duration). These pulses travel through the ionosphere and experience a frequency dependent time delay resulting in pulse dispersion similar to the dispersion experienced by pulsars traveling through the inter-stellar medium. Therefore lunar Cherenkov pulses received on an Earth based radio telescope will be dispersed by the ionosphere and further broadened by receiver band limiting.

Ionospheric pulse dispersion must be corrected in real time to maximise the received signal to noise ratio and subsequent chances of pulse detection.
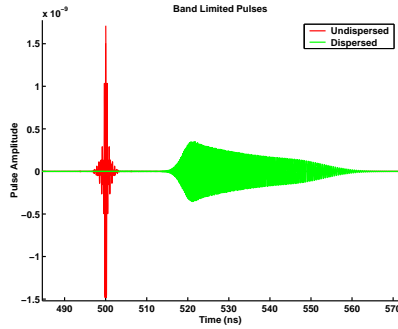
Figure 1: Pulse dispersed over 50ns (corresponding to solar maximum) and bandlimited between 1.2-1.8 GHz.

Coherent pulse de-dispersion requires an accurate knowledge of the ionospheric dispersion characteristic which can be parameterised by the instantaneous ionospheric Total Electron Content (TEC). The TEC produces a frequency dependent delay in the received signal via Equation 1

$$\Delta t = 1.34 \times 10^{-7} \times TEC \times \nu^{-2} \qquad (1)$$

where Δt is in seconds, TEC is in electrons per m^2 and the frequency terms are in Hz.

As Cherenkov radio pulses are much shorter in time than any signals normally encountered in radio astronomy, real time de-dispersion and detection requires broadband technology and innovations to the current instrumentation. Our experiment utilises the Australia Telescope Compact Array radio telescope which currently has 600 MHz bandwidth at 1.5 GHz but is being upgraded to cover 1-3 GHz. Due to data storage limitations, the only way to exploit these new bandwidths is to implement real time detection algorithms. This requires innovations in hardware design to perform signal processing with nanosecond timing accuracy. New radio instruments planned, such as the Square Kilometre Array (SKA) could provide huge advances in collecting area and technology for the method of lunar Cherenkov UHE neutrino detection.

An array of small dishes is the optimum radio instrument for this experiment. If the dish size is kept small enough (20m at 1.4 GHz), all of the moon will be seen by the array's primary beam.

Increased sensitivity from using larger dishes is off-set by decreased coverage of the Moon due to the smaller beam size, and thus a reduced effective aperture. Using multiple smaller dishes allows the same sensitivity without loss of coverage, provided their separation is such that the thermal lunar emission, which tends to dominate the system temperature, is incoherent between antenna. Signals can also be added coherently to form multiple beams around the limb of the moon, where the event rate is maximised, and the array geometry can be exploited for RFI discrimination based on the signal direction of arrival.

Current Experiment with the ATCA

Our current experiement uses the Australia Telescope Compact Array with a 600 MHz bandwidth. The 600 MHz signal is taken from a maintenance point in the antenna, therefore obtaining this bandwidth requires the development of customised detection hardware which must operate with nanosecond timing accuracy. Ionospheric pulse dispersion must also be corrected in real time to maximise the received signal to noise ratio and subsequent chances of pulse detection [5]. For this stage of our experiment, we have developed analog de-dispersion filters and an FPGA based trigger system to detect events in real time and transmit event data to the site control room via an Ethernet link.

Field Programmable Gate Arrays (FPGAs) are reprogrammable semiconductor devices, composed of Configurable Logic Blocks (CLBs), which can perform simple logic tasks as well as more complicated mathematical and signal processing algorithms. Their reconfigurable logic blocks also provide the ability to optimise hardware interconnections for each specific algorithm implemented. Modern FPGAs can operate at clock frequencies of around 500 MHz and have signal processing capabilities that far exceed anything previously available for optimised real time operation. This high speed operation and optimised processing power make FPGAs an ideal technology to perform real time signal processing and pulse detection.

The preliminary ATCA experiment makes use of an FPGA based sampler board for event trigger-

ing. Future experiments with the ATCA, will make use of larger FPGA boards to perform real time de-dispersion 4 however for this stage of the experiment, signal de-dispersion is performed in analog microwave filters with a fixed dispersion characteristic. These filters were designed using a new method of planar microwave filter design based on inverse scattering [8]. This results in filters with a continuously changing profile, in this case a microstrip line with continuously varying width. The width modulations on the microstrip line produce cascades of reflections which sum to produce the desired frequency response. For the lunar Cherenkov detection experiment the desired frequency response has a group delay which is quadratically chirped according to Equation 1. As the microwave de-dispersion filters have a fixed de-dispersion characteristic, an estimate had to be obtained for the TEC which would minimise the errors introduced by temporal ionospheric fluctuations.

Temporal fluctuations in the ionosphere experience a strong diurnal cycle and are also dependent on the season of the year, phase of the current (11 year) solar cycle and the geometric latitude of observation. Observations were planned during nighttime hours to minimize these fluctuations and as we are currently at solar minimum, it was assumed that the electron density for our observations could be estimated based on recorded electron density measurements from the appropriate season last year. This estimate was produced by analysis of Vertical TEC (VTEC) data maps which were derived from GPS dual frequency signals and are available online from NASA's Crustal Dynamics Data Information System (CDDIS) [7].

Our observations were during the nights of May 5, 6 and 7 2007. These dates were chosen to ensure that the moon was at high elevation (particularly during the night time hours of ionospheric stability) and the geometry is such that Cherenkov pulses from the moon line up with the galactic center. The corresponding CDDIS measurements for the month of May 2006 gave an average VTEC of 7.06 TECU over night-time hours (10pm-8am) with a standard deviation of 1.3 TECU. The filter design assumed a differential delay of 5 ns across the 1.2-1.8 GHz bandwidth, which was based on the average VTEC value, corrected for slant angle

through the ionosphere, and converted to a differential time delay. GPS data available post experiment revealed that the average VTEC for the nights of our observations was actually 7.01 TECU which gave an average differential delay of 4.39, with standard deviation 1.52, corrected for slant angle.

Our event trigger has been implemented in an FPGA based sampling board which was designed as part of the broadband upgrade planned for the compact array. The sampler board has two inputs, sampled at 2.048 G samples/s, which we are using to import two linear orthogonal polarisations of the 600 MHz RF signal. The sampled inputs are then multiplexed into parallel 512 MHz data streams for input into a Xilinx FPGA which performs pulse detection. Detection is performed via thresholding on both polarisation streams. The sampled data is buffered for 2 microseconds so that data surrounding candidate events can be sent back and recorded in the case of a detection.

Event data is transferred to a central processing site via a Gbit Ethernet connection for off-line processing. The de-dipsersion filters and CABB sampler boards were installed on three antennas so coincidence testing and direction of arrival discrimination can be performed during off-line processing. As each antenna triggers independently, trigger timing information and nanosecond synchronisation is essential for both of these processing stages.

Our current sampler boards do not have the capability of time stamping with nanosecond accuracy therefore alternative methods of time stamping had to be investigated. As the system temperature is dominated by thermal emission from the moon, the array operates in the intensity interferometer regime [2], and there is a small amount of correlation between the signal received at each antenna. This level of correlation can be exploited to determine relative timing between event buffers sent back from different antennas.

Future Experiments

Future improvements to the ATCA UHE neutrino detection experiment include using 5 antenna, performing coherent signal combination in on these antenna in real time to perform coincidence testing

and an increase to 2 GHz bandwidth. Real time coherent signal addition will be possible as part of an upgrade planned for the ATCA which will include the installation of powerful new FPGA based back-end receiver hardware. It will also be possible to implement real time de-dispersion algorithms in this hardware and, for this stage of the experiment, we have developed a technique for obtaining measurements of the ionospheric TEC which are both instantaneous and line-of-sight to the lunar observations. The ionospheric TEC can be deduced from Faraday Rotation measurements of a polarised source combined with geomagnetic field models, which are more stable than ionospheric models when the direction of signal propagation is parallel to the geomagnetic feild vector [4]. The Faraday Rotation induced in a radio wave is related to the ionospheric electron content via Equation 2

$$\Omega = 2.36 \times 10^4 \nu^{-2} N B \cos\theta \qquad (2)$$

where Ω is the rotation angle in radians, ν is the signal freqnecy in Hz, N is the electron density m^{-3}, B is the magnitude of the magnetic field vector in Wbm^{-2} and θ is the angle betwen the direction of propagation and the magnetic field vector. We propose to use this technique, with the polarised thermal radio emission from the lunar limb as our polarised source, to obtain instantaneous, line-of-sight TEC measurements. This makes the lunar Cherenkov technique extremely attractive for UHE cosmic ray and neutrino astronomy as it removes the need for searching in dispersion space.

The next phase in our experiment will involve the Square Kilometre Array (SKA). The SKA is a new generation radio telescope array which will be one hundred times more sensitive than the best present day instruments. The current designs proposed for the SKA consist of large numbers (on the order of 10^4) of small dishes (6-12m) to achieve a square km of collecting area in the 1-3 GHz range which is critical for UHE neutrino experiements. To gain the advantage of the large number of small dishes offered by the proposed SKA designs, signals have to be combined and analysed with nanosecond timing accuracy. This is equivalent to forming a phased array beam in real time using special purpose beam forming hardware. We will require enough beams to cover all the limb of the moon

and this will depend on frequency and resolution. However the effective aperture of the full sensitivity of the SKA will reach the flux level at which UHE neutrinos will be seen. (figure to come)

Acknowledgements

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