PROCEEDINGS OF SCIENCE

PoS(ARENA2022)029

A continuously-operating standalone radio cosmic ray detection system at the OVRO-LWA

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The new cosmic ray detection system at the Owens Valley Radio Observatory Long Wavelength array expands on methods introduced in a previous demonstration to use radio signals alone to trigger data capture, reject radio frequency interference, and reconstruct the air shower properties: energy, arrival direction, and $X_{\max}$. The Owens Valley Radio Observatory- Long Wavelength Array (OVRO-LWA) in Eastern California is currently completing an expansion to 352 dual-polarization antennas and new signal processing infrastructure. The upgraded array will operate a full-duty-cycle cosmic ray detector simultaneously with a variety of radio astronomy observations. In order to detect cosmic rays in the presence of radio frequency interference, initial event classification and RFI rejection is performed on Field Programmable Gate Array boards which each process a sampled voltage timeseries from both polarizations of a subarray of thirty-two antennas. Each board uses dedicated RFI veto antennas outside the air shower radio footprint to reject RFI events. I will present the trigger design, RFI flagging strategy, and a progress update from early commissioning. When fully commissioned, the OVRO-LWA will offer a new estimate of cosmic ray composition at the upper energy limit of Galactic accelerators by observing thousands of cosmic rays per year at energies 10^{17}–10^{18} eV and reconstructing air showers with a typical $X_{\max}$ precision better than 20 g/cm^2 per air shower.

9th International Workshop on Acoustic and Radio EeV Neutrino Detection Activities - ARENA2022
7-10 June 2022
Santiago de Compostela, Spain

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1. Motivation

Disentangling the origins of cosmic rays at the Galactic to extragalactic transition will require precise composition measurements for a large number of air showers. Cosmic ray searches at arrays built for radio astronomy interferometric imaging are an important approach for improving the statistics on mass composition measurements around the Galactic to extragalactic transition [1],[2].

A radio-only self trigger reduces the cost of large cosmic ray searches and reduces complicated selection effects, but requires a strategy for rejecting radio frequency interference (RFI). Here we present an overview of the radio-only trigger and RFI rejection approach at the the Owens Valley Radio Observatory Long Wavelength Array (OVRO-LWA).

2. The Owens Valley Radio Observatory Long Wavelength Array

OVRO-LWA is an array of dual polarization dipoles in eastern California that pursues science goals including studying extrasolar space weather, cosmic dawn, and solar flares, as well as cosmic ray science. The array is currently undergoing an upgrade to 352 dual polarization dipole antennas with a maximum separation of 2.4 km. After the upgrade, the sensitivity of the antennas will be dominated by Galactic background noise from 12–85 MHz. The upgrade includes all new digital signal processing electronics, which created the opportunity to add a cosmic ray detection system that searches for air showers continuously, alongside the other types of astronomy observation.

The Owens Valley Radio observatory is in a sparsely-populated region of Eastern California, in a narrow valley between two tall mountain ranges, which help block radio frequency interference from major cities. The array layout is optimized for interferometric imaging, with a densely packed core array surrounded by a sparse array. Signals from all antennas are continuously digitally sampled in a centrally-located electronics shelter which contains the computing cluster for the astronomy correlator, as well as a dedicated computer for processing cosmic ray data. The analog signals are transmitted to this central electronics shelter using a combination of coax and fiber, and then are digitized after passing through analog filters (see Figure 1).

Prior to the upgrade, [3] demonstrated the potential to use the OVRO-LWA as a cosmic ray detector, by detecting 10 cosmic rays in 40 hours with a dedicated observing session, using only the central portion of the array. For this demonstration, the field programmable gate arrays (FPGAs) were reprogrammed with single-purpose firmware to conduct the cosmic ray search. As part of the upgrade, we implement entirely new firmware and software to enable a continuous search for air showers. When cosmic ray candidates are detected, a snapshot of data will be saved for the entire array, not only the antennas that triggered the data readout.

3. A Radio-only Self-trigger

The cosmic ray air shower search occurs on the eleven SNAP2 FPGA boards that process the output from the ADCs, operating in parallel with the filterbank firmware for the other astronomy applications. Figure 2 outlines the a flowchart of the trigger firmware. The SNAP2s buffer

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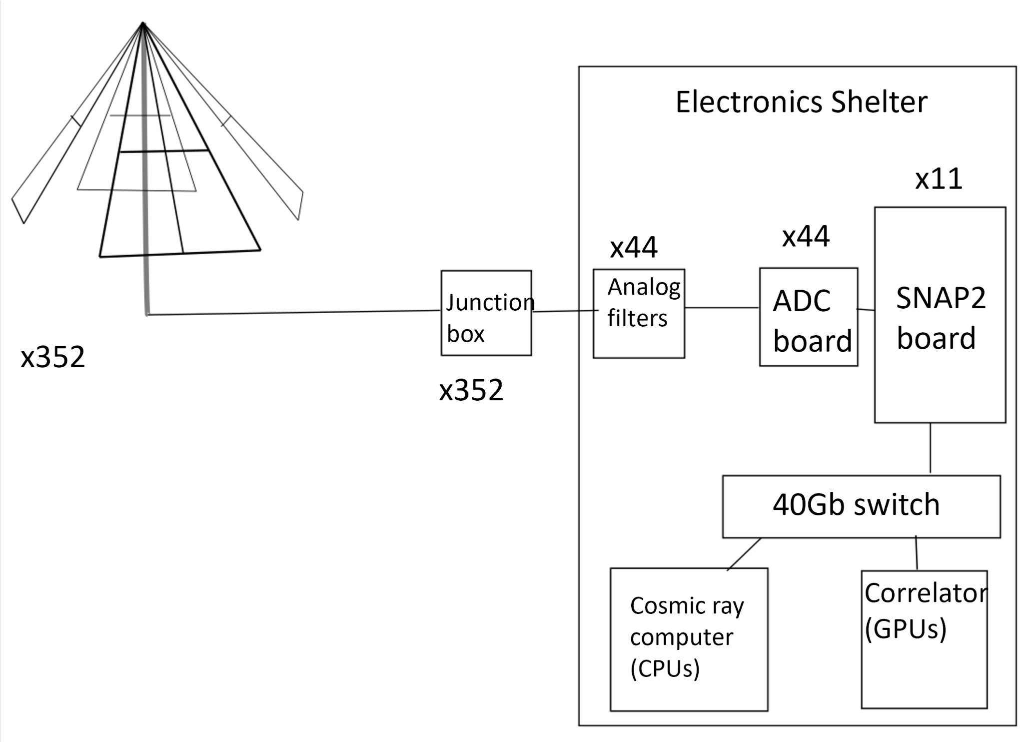

Figure 1: Flowchart of the signal path of the LWA. Signals from 352 dual polarization antennas are transmitted to a central location, where 44 analog circuit board filter 16 signals each before the signals are digitized by 44 ADC boards which sample 16 signals each. Eleven SNAP2 boards process the output of the ADCs, and the cosmic ray trigger logic runs on these boards. A 40Gb switch allows cosmic ray data to be transmitted to a separate computer from the correlator.

20 microseconds of the time series output by the ADCs, with 5-nanosecond time resolution, implemented as a circular buffer. In parallel with the buffer, the firmware searches for pulses above a threshold. Each SNAP2 searches both dipoles for 32 antennas (64 signals total). If pulses occur in the signals from more than a threshold number of antennas, within the light travel time between those antennas, then the detector logic outputs a trigger signal. The trigger can be cancelled by RFI rejection logic that will be described in the next section. If the trigger is not cancelled by the RFI blocker, then the board stops writing new data to the buffer and transmits the buffered timeseries over ethernet to a computer for the next stages of processing.

If the trigger condition is met for any SNAP2 board, all the SNAP2 boards will read out their buffers, so that a snapshot is saved for the entire array, including the antennas whose signal did not meet the trigger condition. This will allow sub-threshold pulses to be used in the air shower reconstruction.

The readout deadtime is determined by how fast the receiving computer can process the ethernet packets, not by the maximum speed that the SNAP2 boards can transmit the data. To avoid overwhelming the receiving computer, readout time takes 920 microseconds, which causes a 4.6% dead time at the expected trigger rate.

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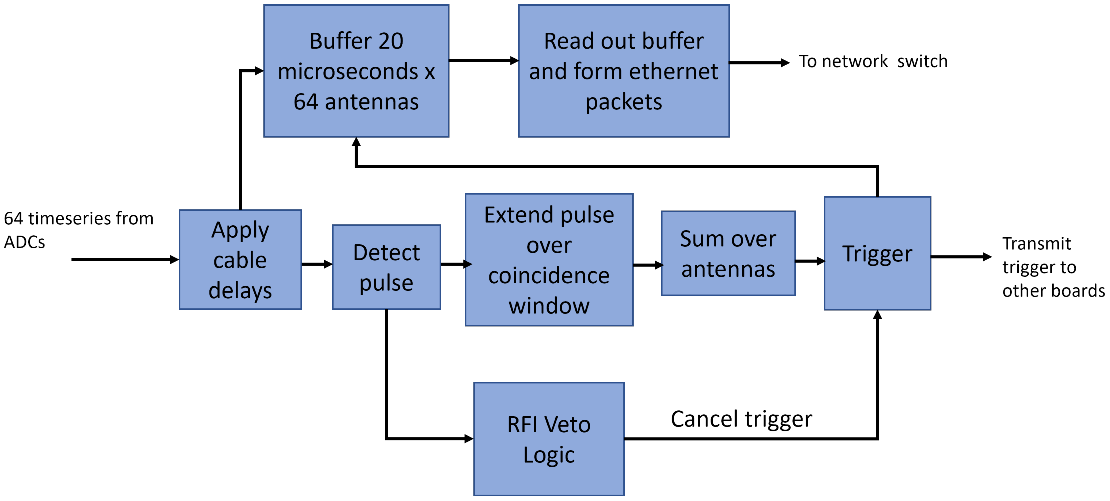

Figure 2: Flowchart summarizing the trigger logic for the cosmic ray radio-only trigger. This process is implemented in firmware running on the SNAP2 FGPA boards.

4. Rejecting Radio Frequency Interference

To operate a radio-only self trigger in the presence of radio frequency interference (RFI), a first stage of RFI rejection must occur on the FPGAs. The first stage of RFI rejection on the FPGAs must ensure that the trigger rate stays low enough to avoid saturating the ethernet network used for data readout, and to keep the dead time small. Later stages of RFI rejection will occur in CPUs after the snapshots of data have been transmitted off the FPGAs.

Since cosmic ray air showers are beamed, we plan to use distant antennas to veto RFI. Figure 3 shows the array layout, color-coded according to which of the 11 SNAP2 FPGA boards will process data from each antenna. The grouping of antennas to FPGAs does not affect any other science purposes of the OVRO-LWA other than the cosmic ray detector, and so the groupings were optimized for cosmic ray detection.

For antennas in the core array, neighboring antennas are grouped to the same FPGAs. This arrangement increases the probability that an air shower will illuminate enough antennas within the same FPGA to meet the trigger condition. Each FPGA will also process a few distant antennas, separated by a sufficient distance that most cosmic ray air showers in the energy range of interest would not illuminate the distant antennas on both sides of the array. Within each FPGA, when the trigger condition is met in the core antennas, the trigger is canceled if an above-threshold signal is also detected by a threshold number of the distant veto antennas. If the trigger is not vetoed, then the buffered snapshot of data is transmitted off the FPGAs.

Further stages of RFI rejection will take place after snapshots of buffered data are transmitted from the whole array to one receiving computer. The approach is similar to the method successfully applied by [3]. First, the pulse search will be repeated on the raw time series, obtaining the peak power, arrival time, and an estimate of the noise power. The arrival times of the pulses will be used for an initial fit of a wavefront model. If this fit fails, the event is likely a thermal noise coincidence and will be discarded. If the fit succeeds, the best fit arrival direction will be used to discard events that come from specific directions of known RFI sources. RFI from airplanes will

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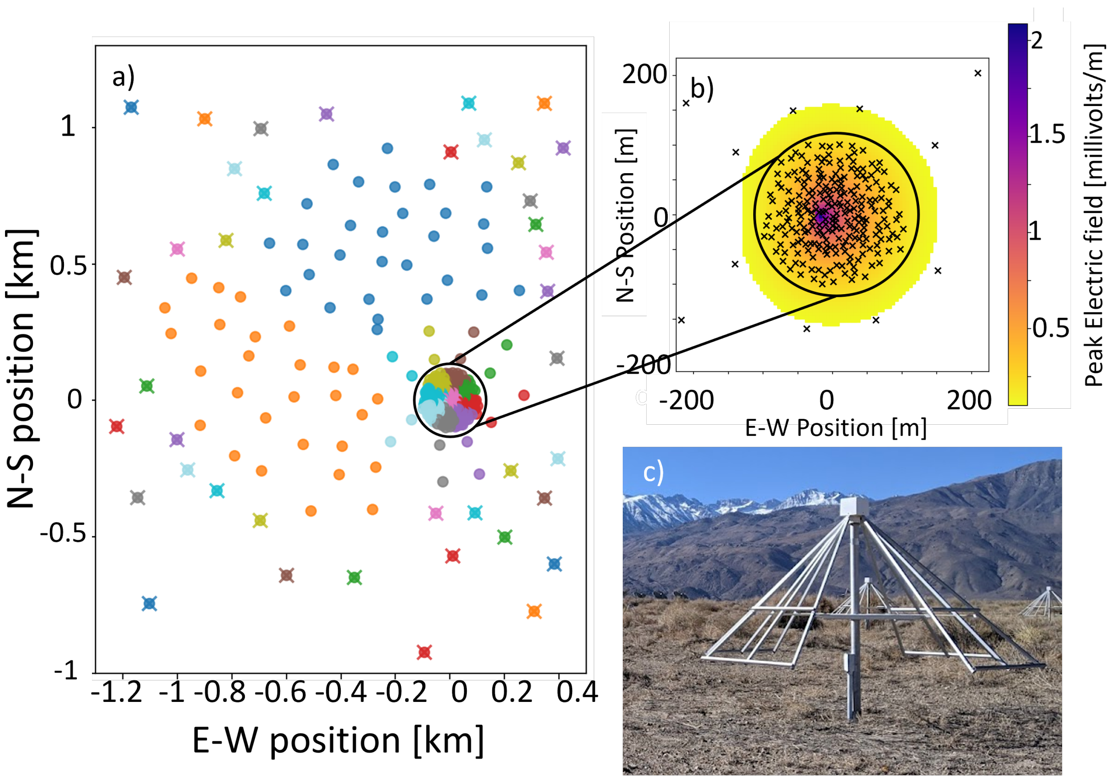

Figure 3: a) Layout of the OVRO-LWA antennas. Color indicates groups of antennas processed by each FPGA. Antennas that veto RFI are marked with Xs. b) Array layout in the core, overlaid with the peak electric field from a simulated air shower for a 10^{17} eV proton arriving from zenith. All antenna positions are marked with X in this panel (none are veto antennas). c) Image of an OVRO-LWA antenna.

be rejected by searching for clusters of events that trace flight paths. For the remaining candidates, we will compare the polarization and lateral power distribution to models of air shower footprints to identify the cosmic rays.

The most serious RFI for the previous OVRO-LWA cosmic ray search before the upgrade was impulsive transients from faulty power lines. Over the last few years, the worst of these sources have been identified and then repaired.

5. Near-future outlook

Construction of the OVRO-LWA is nearly complete, and commissioning will finish in early 2023. We plan to estimate energy and $X_{\max}$ for each air shower, in order to search for features in the composition spectrum across the Galactic to extragalactic transition. Simulations [4] suggest that we will be able to estimate $X_{\max}$ with precision better than 20 g/cm^2. When fully commissioned, the OVRO-LWA is expected to detect thousands of cosmic rays per year from 10^{17}–10^{18} eV.

The dense antenna layout of the core of the array makes the OVRO-LWA an interesting place to test new air shower reconstruction techniques, such as the interferometric technique outlined by [5].

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At the OVRO-LWA, access to the FPGA firmware and the raw ADC timeseries, makes a radio-only self-triggered cosmic ray detector possible in parallel with the other array activities.

Acknowledgements

This material is based in part upon work supported by the National Science Foundation under grant number AST-1828784, the Simons Foundation (668346, JPG), the Wilf Family Foundation and Mt. Cuba Astronomical Foundation. KP was supported by an NSF GRFP fellowship.

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