# Lunar Radio Detection of Ultra-High-Energy Particles

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# Abstract

Ultra-high-energy cosmic rays, and their expected counterpart neutrinos, are the most energetic particles in nature, and their origin remains unknown. The detection of these particles is key to identifying their origin, but is complicated by their low flux, which necessitates the use of extremely large detectors. The largest potential aperture for detecting the most energetic of these particles is offered by the lunar radio technique, which makes use of the Moon as a detector, using ground-based radio telescopes to search for nanosecond-scale radio pulses from particles interacting in the lunar regolith, and it is this technique that is the subject of this thesis.

In this thesis I present a description of the most sensitive lunar radio experiment to date, conducted in 2010 with the Parkes radio telescope as part of the LUNASKA project, including a comprehensive test of the purpose-built Bedlam backend used in this experiment. The signal-processing strategy is explored in great detail, with an extensive discussion of the statistics of stochastic signals, and an optimal strategy is described which compensates both for known effects such as ionospheric dispersion and for previously-unidentified effects such as phase ambiguity from frequency downconversion. A series of cuts is outlined which successfully removes all anthropogenic radio interference, the first time this has been accomplished for a lunar radio experiment without the benefit of a coincidence filter operating between multiple channels. After these cuts, no radio pulses are observed; this null detection allows limits to be placed on the fluxes of ultra-high-energy cosmic rays and neutrinos.

To place this experiment in context, I perform a review of the null detections published for previous lunar radio experiments, including detailed analyses of their experimental techniques, based on the rigorous treatment applied in the above work. In several cases, I find previously-unidentified problems which significantly limit the sensitivity of previous experiments. Finally, I improve on existing analytic models for calculating the sensitivity of lunar radio experiments to ultra-high-energy cosmic rays and neutrinos, allowing a comparison with a range of possible future experiments, and comment on future prospects for this technique.

# Declaration

I, Justin Derek Bray, certify that this work contains no material which has been accepted for the award of any other degree or diploma in any university or other tertiary institution in my name and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide.

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# Acronyms

| | |
|---|---|
| **ADC** | Analog-to-Digital Converter |
| **ADU** | Analog-to-Digital Unit(s) |
| **AEST** | Australian Eastern Standard Time |
| **AGN** | Active Galactic Nucleus/Nuclei |
| **ANITA** | ANtarctic Impulsive Transient Antenna |
| **ARA** | Askaryan Radio Array |
| **ASKAP** | Australian Square Kilometre Array Pathfinder |
| **ATCA** | Australia Telescope Compact Array |
| **CMB** | Cosmic Microwave Background |
| **CODE** | Centre for Orbit Determination in Europe |
| **CR** | Cosmic Ray |
| **CROME** | Cosmic Ray Observation by Microwave Emission |
| **EVLA** | Expanded Very Large Array |
| **FIR** | Finite Impulse Response |
| **FORTE** | Fast On-orbit Recording of Transient Events |
| **FWHM** | Full Width at Half Maximum |
| **GLUE** | Goldstone Lunar Ultra-high-energy neutrino Experiment |
| **GNSS** | Global Navigation Satellite System |
| **GPS** | Global Positioning System |
| **GRB** | Gamma-Ray Burst |
| **GZK** | Greisen-Zatsepin-Kuz'min |
| **HBA** | High-Band Antenna |
| **IF** | Intermediate Frequency |
| **INL** | Integral Non-Linearity |
| **IONEX** | IONosphere map EXchange |
| **JEM-EUSO** | Japanese Experiment Module — Extreme Universe Space Observatory |

| | |
|---|---|
| **LCP** | Left Circularly Polarised |
| **LO** | Local Oscillator |
| **LOFAR** | LOw Frequency ARray |
| **LPM** | Landau-Pomeranchuk-Migdal |
| **LUNASKA** | Lunar Ultra-high-energy Neutrino Astrophysics with the Square Kilometre Array |
| **MLT** | Magnetic Local Time |
| **MWA** | Murchison Widefield Array |
| **PAF** | Phased Array Feed |
| **RCP** | Right Circularly Polarised |
| **RESUN** | Radio EVLA Search for Ultra-high-energy Neutrinos |
| **RF** | Radio Frequency |
| **RFI** | Radio-Frequency Interference |
| **RICE** | Radio Ice Cherenkov Experiment |
| **RMS** | Root Mean Square |
| **SEFD** | System Equivalent Flux Density |
| **SKA** | Square Kilometre Array |
| **SNR** | Signal-to-Noise Ratio |
| **STEC** | Slant Total Electron Content |
| **TEC** | Total Electron Content |
| **TECU** | Total Electron Content Unit(s) |
| **UHE** | Ultra-High Energy |
| **UHECR** | Ultra-High-Energy Cosmic Ray |
| **UT** | Universal Time |
| **VCV** | Véron-Cetty & Véron |
| **VLA** | Very Large Array |
| **VLBI** | Very Long Baseline Interferometry |
| **VTEC** | Vertical Total Electron Content |
| **WGS84** | World Geodetic System 1984 |
| **WSRT** | Westerbork Synthesis Radio Telescope |