

Lunar Radio Detection of Ultra-High-Energy Particles

Justin Derek Bray



School of Chemistry & Physics,
University of Adelaide

August 2013

Contents

Contents	i
List of Tables	v
List of Figures	vii
Abstract	ix
Declaration	xi
Acknowledgements	xiii
Acronyms	xv
1 Introduction	1
1.1 Outline of this Thesis	1
1.2 Ultra-High-Energy Particles	2
1.2.1 Production	3
1.2.2 Propagation	4
1.2.3 Directionality	5
1.2.4 Spectrum and Composition	8
1.2.5 Neutrino Flavour	10
1.2.6 Fundamental Physics	10
1.3 Detection Techniques	11
1.3.1 Particle Cascades	11
1.3.2 The Askaryan Effect	14
1.3.3 Lunar Radio Detection	16
1.3.4 The LUNASKA Project	17
2 Noise Statistics in the Parkes Bedlam Backend	19
Statement of Authorship	20
Preface	21
Abstract	22
2.1 Introduction	22
2.2 Frequency Mixing	24
2.2.1 Origin of the Phase Ambiguity	24

2.2.2	Phase Searching and the Signal Envelope	25
2.2.3	Phase Ambiguity from Aliasing	27
2.3	Excursion Rates	28
2.3.1	Raw Signal	29
2.3.2	Interpolated Signal	29
2.3.2.1	White Noise	31
2.3.3	Signal Envelope	31
2.3.4	Interpolated Signal Envelope	32
2.3.4.1	White Noise	34
2.4	Monte Carlo Simulation	34
2.4.1	Uncorrelated Noise	35
2.4.2	Correlated Noise	35
2.5	Experimental Test with the Parkes Bedlam Backend	37
2.5.1	The Parkes Bedlam Backend	37
2.5.2	Experiment	39
2.5.3	Excursion Rates	41
2.5.4	Non-Linearity	44
2.5.5	Hardware Error Rate	47
2.6	Conclusion	48
	Acknowledgements	48
3	A Lunar Radio Experiment with the Parkes Telescope	49
	Statement of Authorship	50
	Preface	53
	Abstract	56
3.1	Introduction	56
3.2	Experiment Design	59
3.2.1	Pointing Strategy	61
3.2.2	Receiver Linearity	65
3.2.3	System Dispersion	65
3.3	Calibration	68
3.3.1	Bandpass Calibration	68
3.3.2	Absolute Flux Calibration	71
3.3.3	Overall Sensitivity	74
3.4	Ionospheric Dispersion	77
3.4.1	GPS Electron Content Measurements	78
3.4.2	Ionosonde Electron Content Measurements	84
3.5	Signal Optimisation	86
3.5.1	Bandpass Optimisation	86
3.5.2	Dedispersion	89
3.5.2.1	Filter Design	92
3.5.3	Pulse Phase	94
3.5.4	Interpolation	96
3.5.5	Signal Recovery	97

3.6	Observations and Analysis	99
3.6.1	Processing	102
3.6.2	Removal of RFI	106
3.6.2.1	Bit Errors	112
3.6.2.2	Atmospheric Cascades	112
3.6.3	Threshold	115
3.6.3.1	Effective Observing Time	117
3.7	Results	117
3.7.1	Small-Scale Lunar Surface Roughness	119
3.7.2	Diffuse Neutrino Sensitivity	121
3.7.3	Directional Neutrino Sensitivity	127
3.7.3.1	Centaurus A	128
3.7.3.2	Gamma-Ray Bursts	131
3.8	Conclusion and Summary	132
3.8.1	Considerations for Future Experiments	132
	Acknowledgements	135
4	The Sensitivity of Lunar Radio Experiments	137
	Statement of Authorship	138
	Preface	139
	Abstract	140
4.1	Introduction	140
4.2	Sensitivity to Coherent Radio Pulses	141
4.2.1	Amplitude Recovery Efficiency	143
4.2.2	Combining Channels	144
4.3	Past and Future Lunar Radio Experiments	146
4.3.1	Parkes	147
4.3.2	GLUE	149
4.3.3	Kalyazin	153
4.3.4	LUNASKA ATCA	154
4.3.5	NuMoon	155
4.3.6	RESUN	160
4.3.7	LaLuna	161
4.3.8	LUNASKA Parkes	161
4.3.9	LOFAR	163
4.3.10	Parkes PAF	166
4.3.11	AuScope	167
4.4	Sensitivity to Ultra-High-Energy Particles	169
4.4.1	Neutrinos	171
4.4.1.1	Comparison of Analytic and Simulation Results	172
4.4.1.2	Comparison of Different Experiments	174
4.4.2	Cosmic Rays	176
4.5	Discussion	180
	Acknowledgements	181

5	Conclusion and Future Prospects	183
5.1	Theoretical Work	183
5.1.1	Small-Scale Lunar Surface Roughness	183
5.1.2	Neutrino Cross-Section	184
5.2	Near-Future Experiments	185
5.2.1	Sensitivity to Neutrinos	187
5.2.2	Sensitivity to Cosmic Rays	189
5.2.3	Cost-Effectiveness	189
5.3	The More Distant Future	191
A	Rice's Formula for the Excursion Rate	193
B	The Optimality of a Matched Filter	197
B.1	Uncorrelated Noise	197
B.2	Correlated Noise	199
C	Interpolation of Nyquist-sampled Signals	201
D	Simulation of Amplitude Recovery Efficiency	205
E	Analytic Calculation of Particle Aperture	209
E.1	Neutrinos	210
E.2	Cosmic Rays	212
	Bibliography	215

List of Tables

2.1	Non-linearity in each channel	46
3.1	Sources of variation in sensitivity	76
3.2	Sensitivity by beam and polarisation	77
3.3	Expected sensitivity improvement from bandpass optimisation	90
3.4	Simulated loss of signal strength	99
3.5	Details of observations	100
3.6	Events remaining after each set of anti-RFI cuts	111
3.7	Effective duration of observations	118
4.1	Observation parameters for lunar radio experiments	148
E.1	Constants used in analytic aperture calculation	210

List of Figures

1.1	Propagation distances for different ultra-high-energy particles	6
1.2	Arrival directions of ultra-high-energy cosmic rays	7
1.3	Cosmic ray and neutrino spectra	9
1.4	Neutrino-nucleon cross-section	12
1.5	Charged-current and neutral-current interactions	14
1.6	Illustration of the Askaryan effect	15
2.1	Effect of phase shifts on pulse profile	26
2.2	Phase shifts due to aliasing	28
2.3	Peak amplitude distribution for uncorrelated noise	36
2.4	Peak amplitude distribution for correlated noise	38
2.5	Signal path for noise test	39
2.6	Experimental pulse profiles	40
2.7	Power spectrum of experimental noise	41
2.8	Autocorrelation function of experimental noise	42
2.9	Peak amplitude distribution for experimental noise	43
2.10	Illustration of non-linear digitisation	45
3.1	Signal path for experiment	60
3.2	Inter-beam trigger logic	60
3.3	Layout of the multibeam receiver	62
3.4	Pointing configurations used in experiment	64
3.5	Test of receiver linearity	66
3.6	Test of system dispersion	67
3.7	Measured power spectra	69
3.8	Modeled brightness temperature of the Moon	71
3.9	Calibrated system temperature and flux density	73
3.10	Calibrated experimental sensitivity	75
3.11	Global distribution of ionospheric electron content	78
3.12	Historical ionospheric electron content over Parkes	79
3.13	Electron content from GPS and ionosonde data	81
3.14	Determination of ionospheric pierce point	82
3.15	Electron content of the plasmasphere	83
3.16	Dedispersion filter settings and target electron content	85
3.17	Bandpass optimisation	88

3.18	Performance characteristics of dedispersion filter	92
3.19	Effect of phase shifts on Askaryan pulse	95
3.20	Effect of signal reconstruction on experimental sensitivity	98
3.21	Distribution of real-time trigger rates	103
3.22	Distribution of event amplitudes in each observing run	104
3.23	Distribution of intervals between events	109
3.24	Distribution of event amplitudes after cuts	110
3.25	Quantification of the effect of small-scale surface roughness	120
3.26	Geometric neutrino aperture compared to other experiments	123
3.27	Geometric neutrino aperture by beam	124
3.28	Limits on the diffuse neutrino flux	125
3.29	Neutrino flux limits with small-scale surface roughness	126
3.30	Directional neutrino aperture around the Moon	128
3.31	Directional neutrino exposure on the sky	129
3.32	Limits on the directional neutrino flux from Centaurus A	130
4.1	Detection threshold for GLUE experiment	152
4.2	Beam shape for NuMoon experiment	158
4.3	Beam positions for LUNASKA Parkes experiment	162
4.4	Comparison of analytic and simulated neutrino apertures	172
4.5	Neutrino apertures	175
4.6	Neutrino flux limits	177
4.7	Cosmic ray apertures	178
4.8	Cosmic ray flux limits	179
5.1	Illustration of small-scale lunar surface roughness	184
5.2	Future neutrino flux limits	188
5.3	Future cosmic ray flux limits	190
A.1	Signal undergoing an excursion	194
B.1	Operation of pre-whitening and matched filters	200
C.1	Nyquist-sampling of a continuous signal	202
C.2	Interpolation of a Nyquist-sampled signal	203

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.

I give consent to this copy of my thesis, when deposited in the University Library, being made available for loan and photocopying, subject to the provisions of the Copyright Act 1968.

I acknowledge that copyright of published works contained within this thesis resides with the copyright holder(s) of those works.

I give permission for the digital version of my thesis to be made available on the web, via the University's digital research repository and the Library catalogue, and through web search engines.

Acknowledgements

My most sincere appreciation goes to my supervisors, Ray Protheroe and Ron Ekers, for their support and advice in seeing this work to its conclusion. Ray has now seen me through both Honours and Ph.D. projects, giving me both my first taste of astroparticle physics and the continued benefit of his experience in the field. Ron has similarly introduced me to the world of radio astronomy: his passion for the field has been inspiring, and his wealth of anecdotes occasionally enlightening.

It has been a pleasure to work with each and every member of the LUNASKA group, whose range of technical expertise made this work possible. Particular mention must be made of Clancy James, whose enthusiasm for this project originally enticed me into the field, and whose role I most closely filled on his departure; I can only hope that I have been a worthy successor.

My thanks go out to my family, for their love and support: whether nearby, or scattered across the country, or the globe, it is always a source of great comfort to know that they are there. Further thanks go to my friends, near and far, who have kept me sane; and, for my fellow students at the University of Adelaide and the Australia Telescope National Facility, also for commiserating with me in our shared trials and tribulations.

This research was supported by the Australian Research Council; it is a continual source of surprise and delight to me that such institutions of modern society have the curiosity or foresight to fund research into unresolved questions of basic science without an obvious material return on their investment. Finally, I would like to acknowledge my debt to the open-source software community: the tools that I use sit atop a stack of components that are freely available for everyone to use, improve, and share.

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