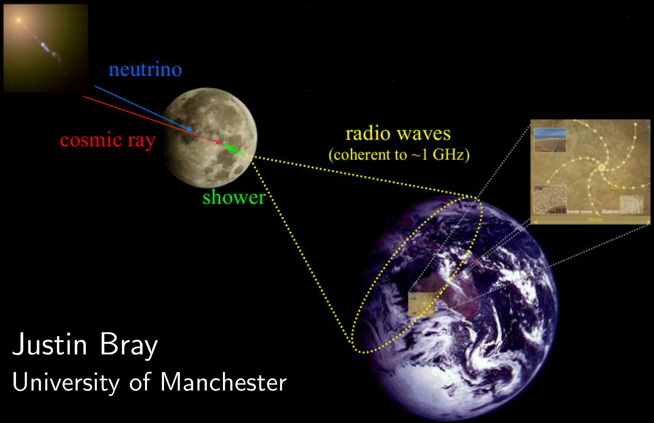
Sensitivity of lunar particle-detection experiments



Justin Bray
University of Manchester

Image credit: Ron Ekers

Contents

- Re-evaluation of radio sensitivity
- Anticoincidence rejection of interference
- Ionospheric dedispersion
- Cosmic-ray/neutrino sensitivity
- Jupiter!

Radio sensitivity

Table 1
Observation parameters for past and near-future lunar radio experiments.

	Pointing ($\times n_{\text{beams}}$)	ν (MHz)	$\Delta\nu$ (MHz)	$\mathcal{E}_{\text{min}}$ (μV/m/MHz)	$\mathcal{E}_{\text{max}}$	ζ (%)	t_{obs} (h)
Past experiments							
GLUE	Limb	2200	150	0.0221	0.3695	11	73.5
	Half-limb	2200	150	0.0500	0.2527	20	39.9
	Centre	2200	150	0.4737	0.2527	100	10.3
Kalyazin	Limb	2250	120	0.0235	–	7	31.3
LUNASKA ATCA	Limb	1500	600	0.0153	–	36	13.6
	Centre	1500	600	0.0207	–	100	12.6
NuMoon	Limb (×2)	141	55	0.1453	–	14	46.7
RESUN	Limb (×3)	1425	100	0.0549	–	100	200.0
LUNASKA Parkes	Limb (×2)	1350	300	0.0053	0.0241	16	127.2
	Half-limb	1350	300	0.0142	0.0489	15	99.4
Future experiments							
LOFAR	Face (×50)	166	48	0.0313	0.0768	100	183.3
Parkes PAF	Limb (×12)	1250	1100	0.0043	0.0303	100	170.0
AuScope	Centre	2300	200	0.0830	–	100	2900.0

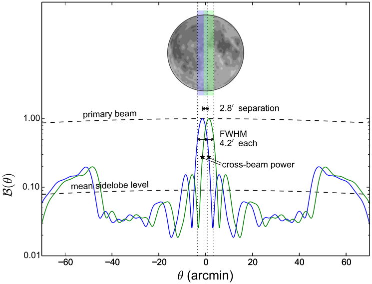
Bray, Astropart. Phys. 77, 1 (2016)

- ν, radio frequency
- ζ, limb coverage
- t_{obs}, observing time
- $\mathcal{E}_{\text{min}}$, min. pulse amp.
- $\mathcal{E}_{\text{max}}$, max. pulse amp.

Anticoincidence rejection of radio-frequency interference

NuMoon

Buitink et al., A&A 51, A47 (2010)

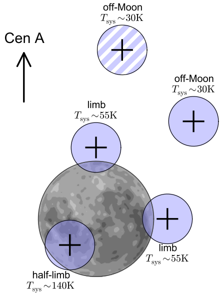


Bray, Astropart. Phys. 77, 1 (2016)

$$\mathcal{E}_{\mathrm{min}} = 0.136\ \mu\mathrm{V/m/MHz}$$
$$\mathcal{E}_{\mathrm{max}} = 0.165\ \mu\mathrm{V/m/MHz}$$

LUNASKA Parkes

Bray et al., Astropart. Phys. 65, 22 (2015)



Bray et al., Phys. Rev. D 91, 063002 (2015)

$$\mathcal{E}_{\mathrm{min}} = 0.0053\ \mu\mathrm{V/m/MHz}$$
$$\mathcal{E}_{\mathrm{max}} = 0.0241\ \mu\mathrm{V/m/MHz}$$

Anticoincidence rejection of radio-frequency interference

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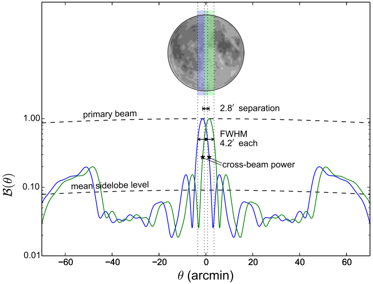
Buitink et al., A&A 51, A47 (2010)



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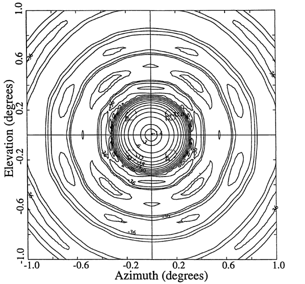

Figure 2—Beam pattern for the central feed of the array. Contours are every 3 dB. The peak value is −1·59 dB relative to a uniformly illuminated aperture, corresponding to an efficiency of 69·3%. Cross-polar lobes, which are shown dotted, peak at −39·6 dB relative to peak co-polar.

Staveley-Smith et al., PASA 13, 243 (1996)

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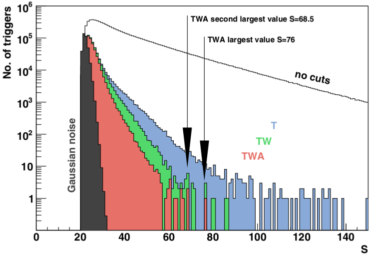
Anticoincidence rejection of radio-frequency interference

NuMoon

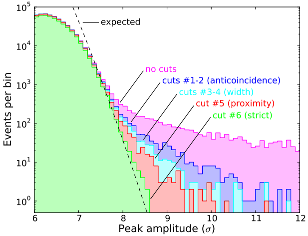


Buitink et al., A&A 521, A47 (2010)

$$\mathcal{E}_{\rm min} = 0.145\ \mu\text{V/m/MHz}$$
$$\mathcal{E}_{\rm max} = \infty\ \mu\text{V/m/MHz}$$

(anticoincidence non-essential)

LUNASKA Parkes



Bray et al., Astropart. Phys. 65, 22 (2015)

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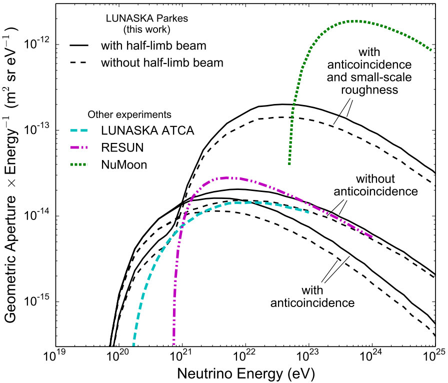
$$\mathcal{E}_{\rm max} = 0.0241\ \mu\text{V/m/MHz}$$

(anticoincidence essential)

Anticoincidence rejection of radio-frequency interference

LUNASKA Parkes aperture

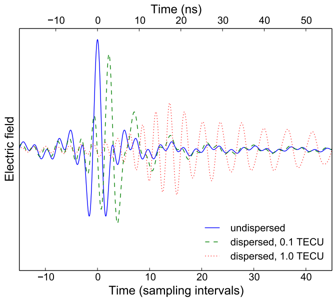


Bray et al., Phys. Rev. D 91, 063002 (2015)

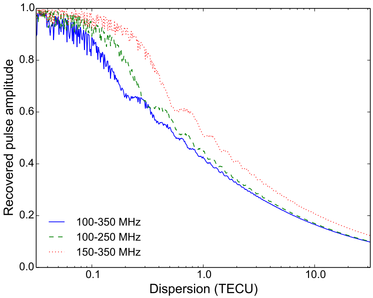
Aperture loss only significant at higher energies, this time.

For future experiments (LOFAR, SKA, etc.), the anticoincidence scheme should be chosen carefully.

Ionospheric dispersion & dedispersion



Bray et al., ICRC 2015, Proc. Sci. 597 (2015)

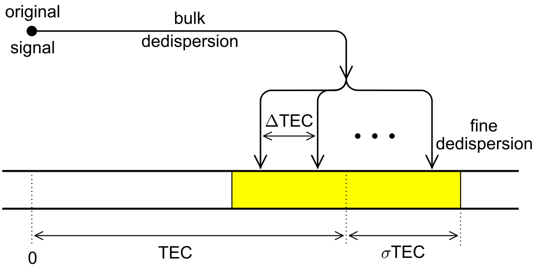


Bray et al., ICRC 2015, Proc. Sci. 597 (2015)

Dispersion extends pulse in time, proportional to ionospheric TEC (total electron content).

Reduces pulse amplitude. Worse for lower frequencies and wider bandwidths.

Ionospheric dispersion & dedispersion

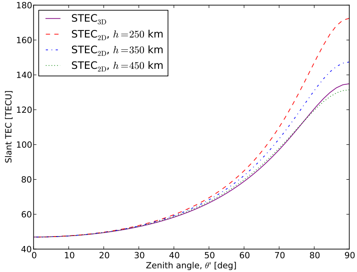


HECP group, SKA-lunar ECP (2015)

Use multiple dedispersion trials.

May dominate computing budget;
depends on TEC precision, $\propto \sigma\text{TEC}^2$.

Ionospheric dispersion & dedispersion



Martin, Bray & Scaife, MNRAS 459, 3525 (2016)

Dependence on TEC rather than dTEC/dx; different from astronomical imaging.

Derived TEC from thin-layer GPS model is inaccurate, depending on assumed altitude.

Ideally, avoid thin-layer step:

- GPS line-of-sight measurements?
- lunar Faraday rotation?
- pulsar Faraday rotation?

Sensitivity to cosmic rays and neutrinos

Analytic neutrino aperture:

- Gayley, Mutel & Jaeger, ApJ 706, 1556 (2009)

Analytic cosmic-ray aperture:

- Jeong, Reno & Sarcevic, Astropart. Phys. 35, 383 (2012)

Some amendments to both:

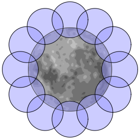
- Bray, Astropart. Phys. 77, 1 (2016), App. B

Near-future experiments

van Haarlem et al., A&A 556, A2 (2013)
Singh et al., NIMA 664, 171 (2012)

LOFAR, 200 h:

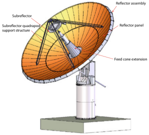
- beamformed aperture arrays
- 110–190 MHz
- anticoincidence



Bray et al., AIPCS 1535, 21 (2013)

Parkes PAF (Phased Array Feed), 200 h:

- improvement over multibeam receiver
- 0.7–1.8 GHz
- anticoincidence



$\times 3$

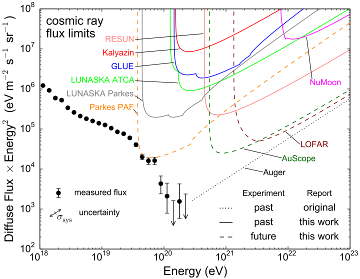
Lovell et al., J. Geod. 87, 527 (2013)

AuScope, 2900 h:

- three 12 m dishes
- 2.2–2.4 GHz
- coincidence

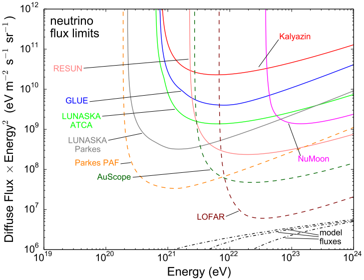
Sensitivity to cosmic rays and neutrinos

cosmic rays



Possibility of cosmic-ray detection with Parkes PAF.

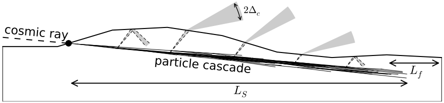
neutrinos



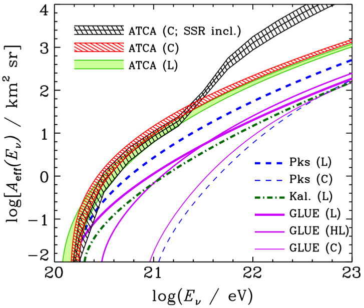
LOFAR able to test some top-down neutrino models.

Lunardini & Sabancilar, Phys. Rev. D 86, 085008 (2012)

Small-scale surface roughness



Roughness on scales smaller than shower causes emission to be scattered.



James et al., Phys. Rev. D 81, 042003 (2010)

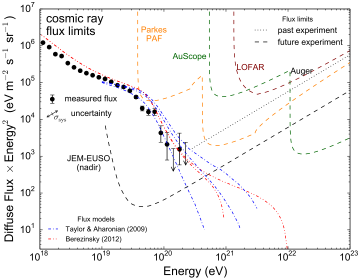
Increases aperture at higher energies.

Only one existing model, implemented here:

- James et al., Phys. Rev. D 81, 042003 (2010), App. B

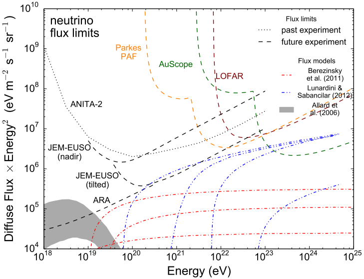
Sensitivity to cosmic rays and neutrinos

cosmic rays

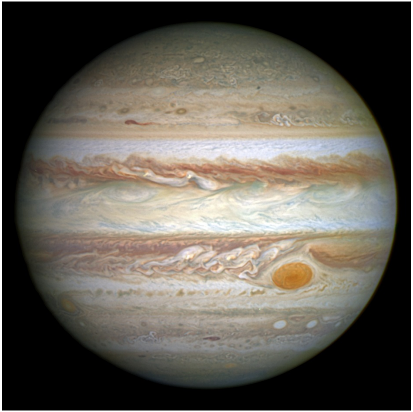


Increased exposure at higher energies.

neutrinos



All experiments able to test top-down models.

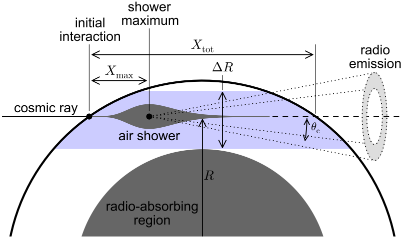


Rimmer, Stark & Helling, *"Jupiter as a Giant Cosmic Ray Detector"*, ApJL 146, 686 (2014)

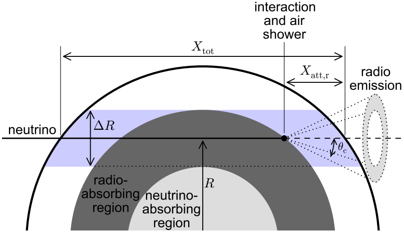
Privitera & Motloch, *"Solar System Objects as Cosmic Rays Detectors"*, ApJL 794, L15 (2014)

Bray & Nelles (2016), *"Minimal prospects for radio detection of extensive air showers in the atmosphere of Jupiter"*, ApJ accepted (2016), arXiv:1606.01291

cosmic rays



neutrinos



low-density H_2/He atmosphere, strong magnetic field

- large physical scales
- muon decay
- synchrotron suppression
- small Cherenkov angle

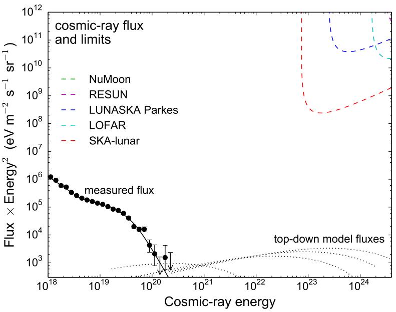
Joviomagnetic emission is weak, and narrowly beamed.

aperture $\sim 10^8$ km^2

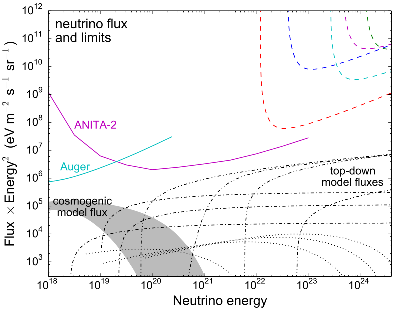
geometric aperture $\sim 10^3$ km^2 sr

threshold $\sim 10^{23}$ eV

cosmic rays



neutrinos



Prospective limits are very weak.

Conclusions

Near-future prospects:

- LOFAR: pathfinder for SKA experiment
- Parkes PAF (or similar): best prospect of cosmic-ray detection
- AuScope (or similar): easiest option

Experimental goals for SKA:

- more careful anticoincidence
- more precise dedispersion

Theoretical goals:

- figure out surface roughness effects
- forget about Jupiter

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Thank you.

Other references:

- Lunardini & Sabancilar, Phys. Rev. D 86, 085008 (2012)
- Berezinsky, Sabancilar & Vilenkin, Phys. Rev. D 84, 085006 (2011)
- Aloisio, Matarrese & Olinto, JCAP 8, 24 (2015)