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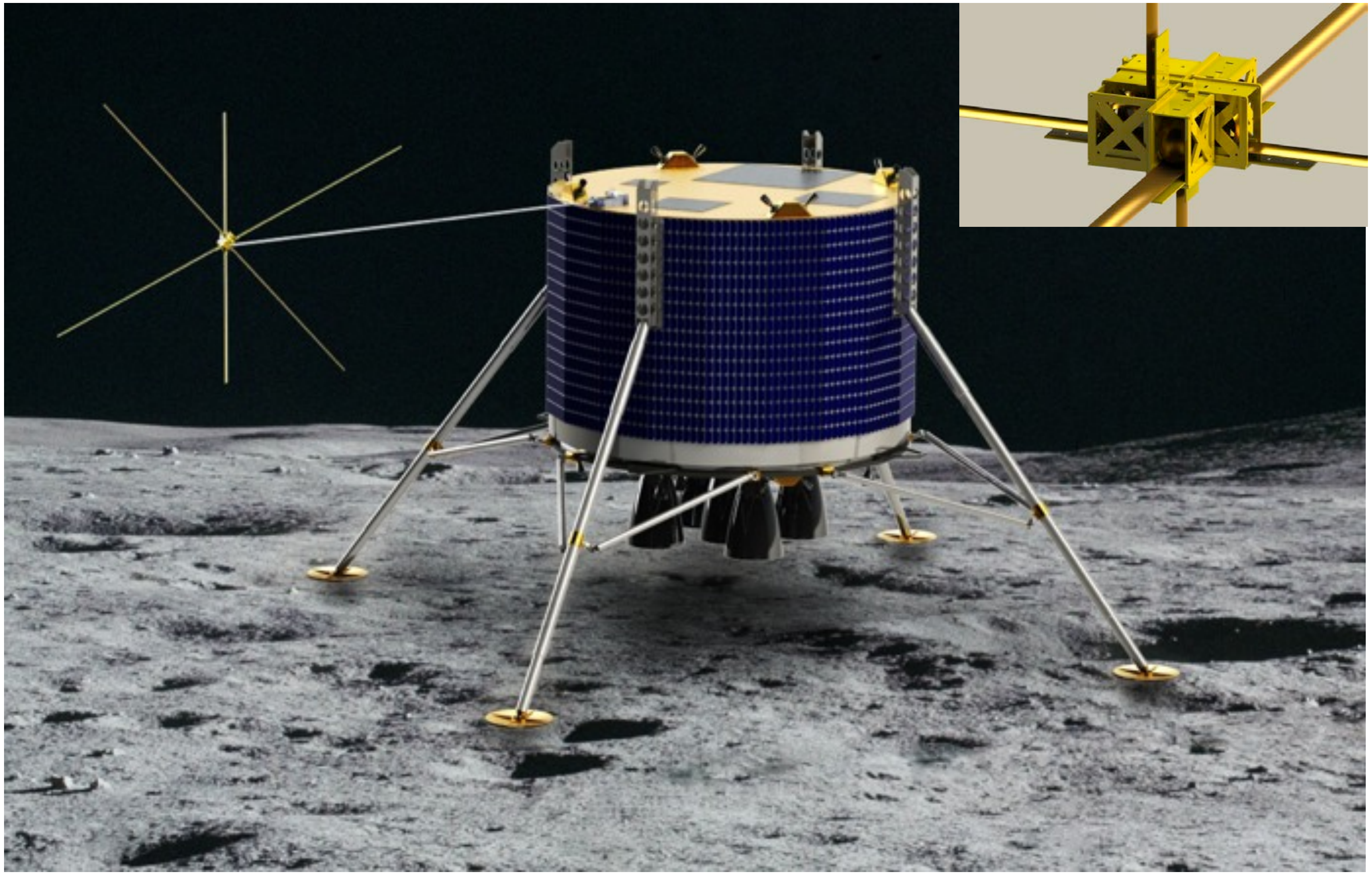
The Lunar Radio Experiment (LRX)



Léon Koopmans
(Kapteyn Astronomical Institute)

Lunar Radio experiment

The team:

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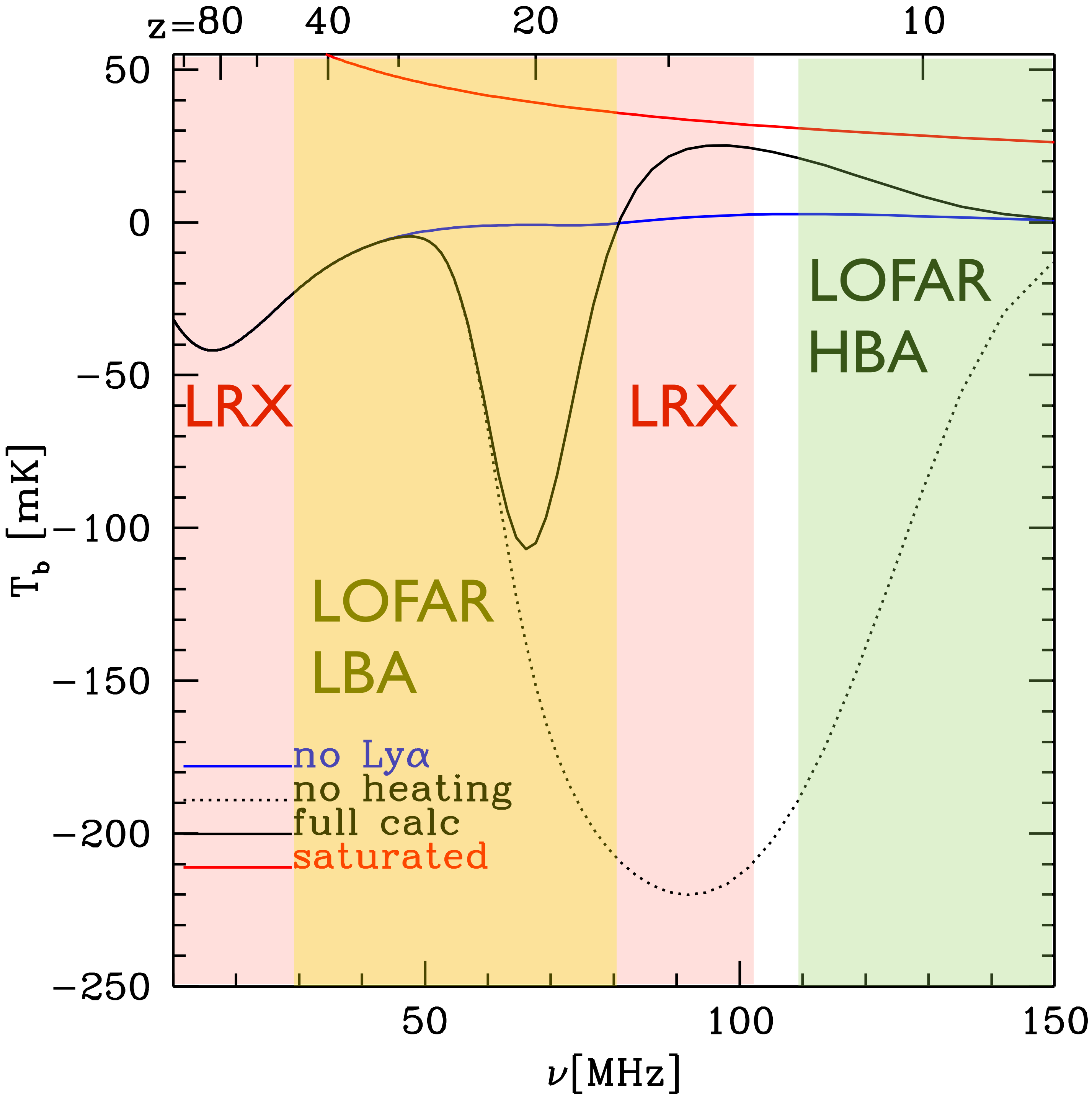
This talk heavily borrows from a talk given by Marc Klein-Wolt

The Global Signal of Neutral Hydrogen

Name	Freq. Range	Instrument
LOFAR-LBA	30-80 MHz	Ground Interf.
LEDA	20-80 MHz	Ground Interf.
EDGES	90-205 MHz	Single Dipole
CORE/ZEBRA/SARAS	50-250 MHz	Log-spiral/Single-Dual Dipole
BIGHORNS	MHz?	Log-spiral
DARE	40-120 MHz	Moon-orbiting Two Dipoles
SURO	0.1-70 MHz	Space Interf.
LRX	0.005-100 MHz	Lunar-lander + Tripole

The Global Signal of Neutral Hydrogen seen by the Lunar Radio Experiment



Adapted from Pritchard

The physical processes during the Dark Ages, Cosmic Dawn and EoR are poorly known.

Whereas LOFAR-HBA can study the EoR, the Cosmic Dawn can only be studied with the LOFAR-LBA or other instruments

LRX covers the entire redshift range of the Cosmic Dawn and Dark Ages.

Issue	Earth LOFAR-LBA LOCOS	Moon LRX	Pros for going to Moon
Sensitivity	Thermal level can be reached	Thermal levels can be reached	Little, except below ionospheric cutoff around 5 MHz
Di/tripole time dependent gain variations	Slow variations with temperature and humidity.	Relatively stable, but relatively unimportant in signal detection.	Moon is more stable, but effect is minimal.
Ionosphere Refraction/ diffraction	Refraction, diffraction and absorption	Negligible	No significant effects of the ionosphere
Radio Frequency Interference	Severe, but manageable above 30 MHz with high time/freq. resolution in (semi)remote areas. Self-RFI might be issue.	Very low levels, but possibly -80dB needed around z=80. Self-RFI has to be suppressed.	Far less RFI on the moon, if shielded from the Earth. High time-freq. resolution might be critical (1s-1kHz).
Sky*Beam model variations	Causes frequency variations in the dynamic spectrum. Mitigated through combination with interferometry.	Use sky models extrapolated to low frequencies. Moon environment might change the beam.	No interferometric cross-checks, but time-variations are minimal on south pole, because the sky rotates slowly in the beam.
Bandpass gain variations	Noise loads required, but receiver noise (after LNA) might be the limiting factor for LOFAR.	Noise loads required. Understanding of receiver noise is also required.	Similar as on Earth.

European Lunar Lander

"Lunar Lander is a robotic explorer that will demonstrate key European technologies and conduct science experiments. The mission is a forerunner to future human and robotic exploration of the Moon and Mars. It will establish European expertise to allow strong international partnerships in exploration."

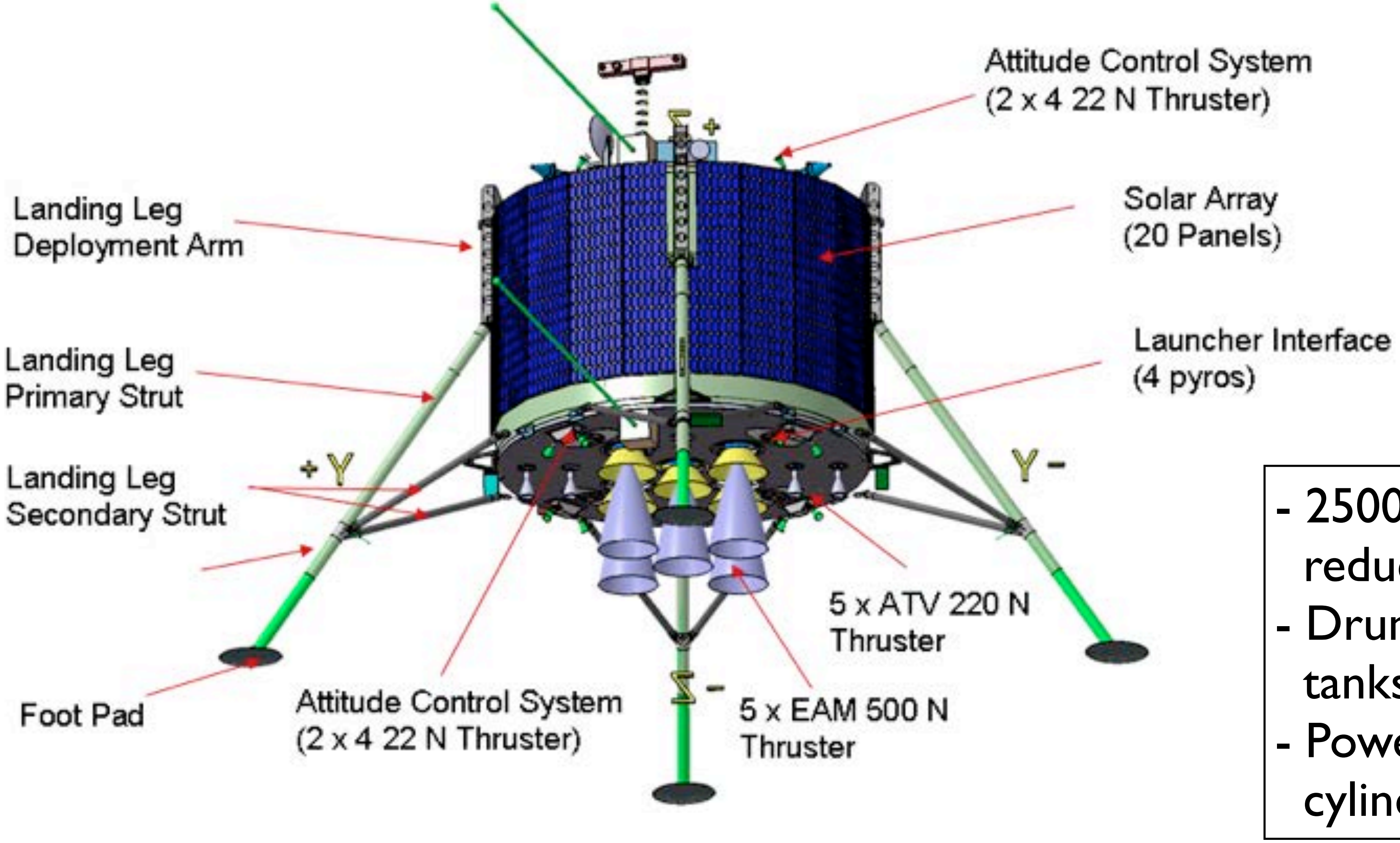
Main goals:

- Study and characterize dust and its impact on human exploration of the moon.
- Study plasma and electric field environment on the lunar surface
- Study resources (e.g. water, ice, nitrogen and metals), identifying their potential for use in future missions.
- Study visual data (via camera) from the south pole environment
- Radio Astronomy.

European Lunar Lander

Lunar Lander will be launched in 2018 from Europe's Spaceport in French Guiana on a Soyuz rocket. Total costs (R&D/Launch/Operations for 6 months: Costs: ~500 M€). Mostly pushed by Germany (70% costs so far). Fr/It/UK not yet behind it.

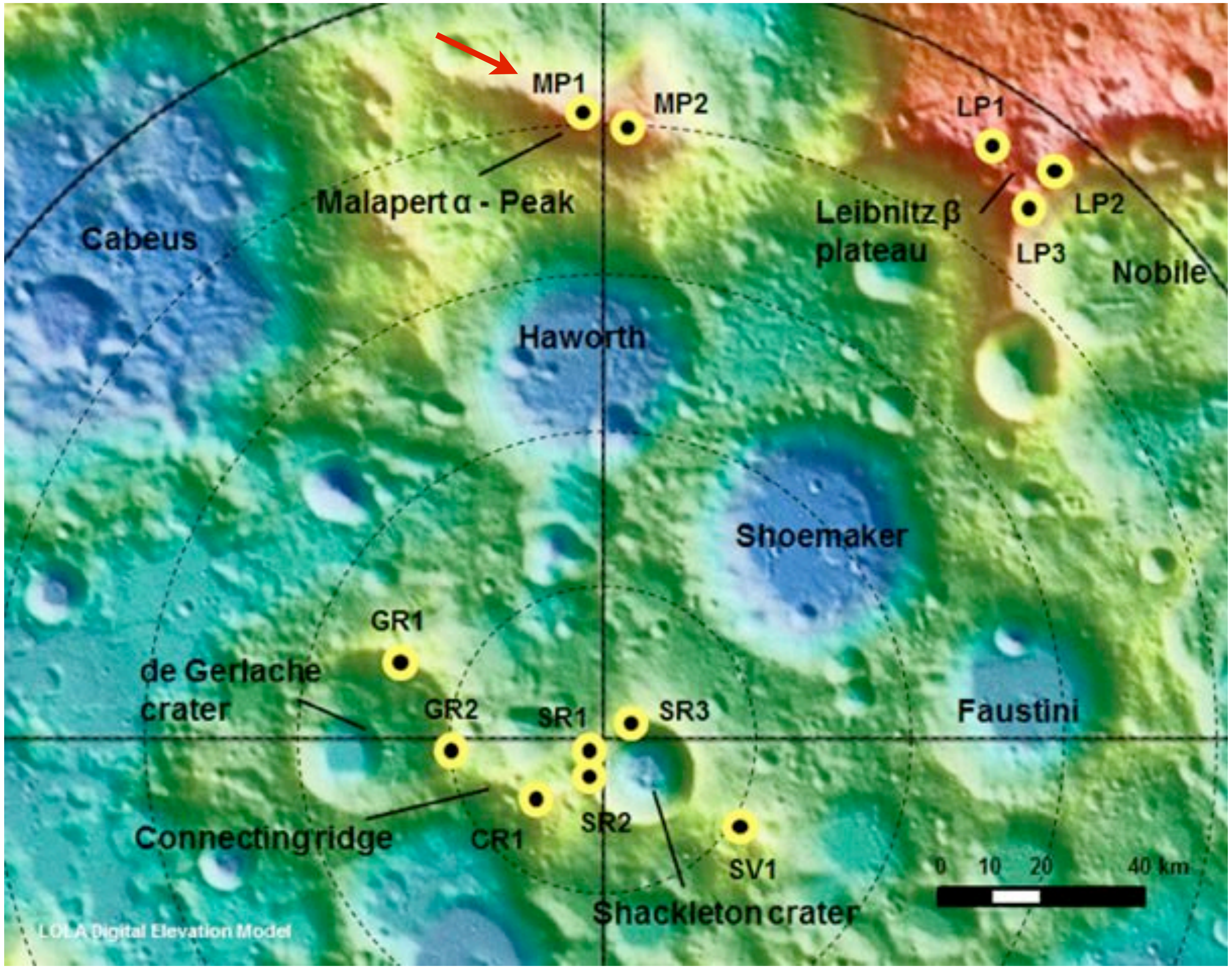
After insertion into a polar orbit, the Lander establishes a circular orbit 100 km up and waits for the correct phasing with respect to the Sun, Earth and Moon for the descent.



- 2500 kg on Soyuz launcher reduced to 800 kg on moon.
- Drum-shaped+4 propellant tanks
- Power from solar panels on cylindrical body

European Lunar Lander

Potential landing sites w/i 5 degrees from the Lunar South pole

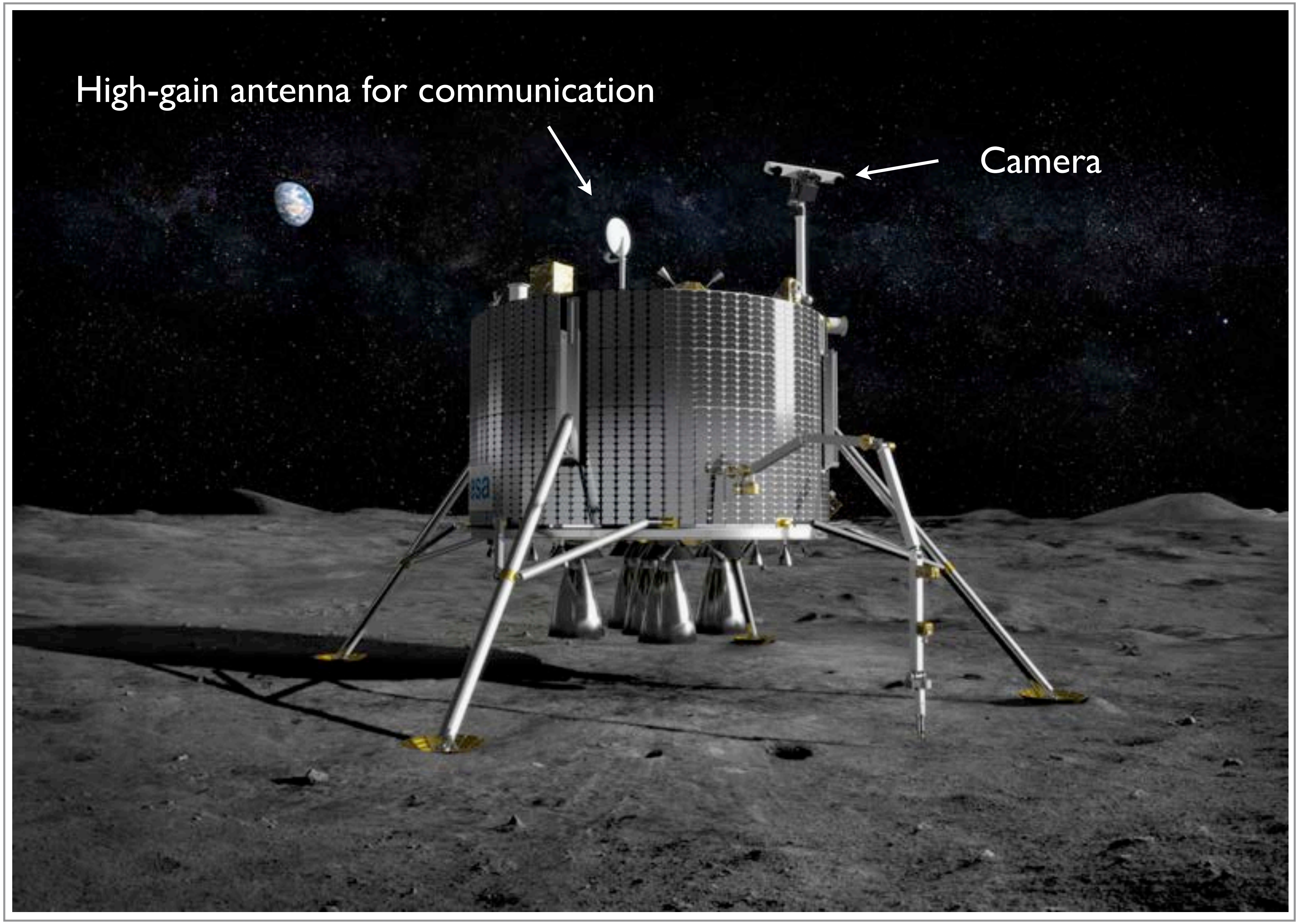


The South Pole has been identified as a possible future location for a human outpost and the poles are the new frontiers for lunar exploration missions.

Lunar Lander relies exclusively on solar power to operate its instruments, so maximizing its exposure to the Sun is vital. Unlike Earth, which turns on its axis every 24 hours, the Moon takes about 30 days to make a complete rotation. This means that days and nights on the Moon last two weeks.

Once the landing site comes into view, it scans the surface with a laser for hazards such as slopes, boulders, craters and shadows. If the site seems too dangerous, it can decide to target a safer zone.

European Lunar Lander


High-gain antenna for communication

Camera

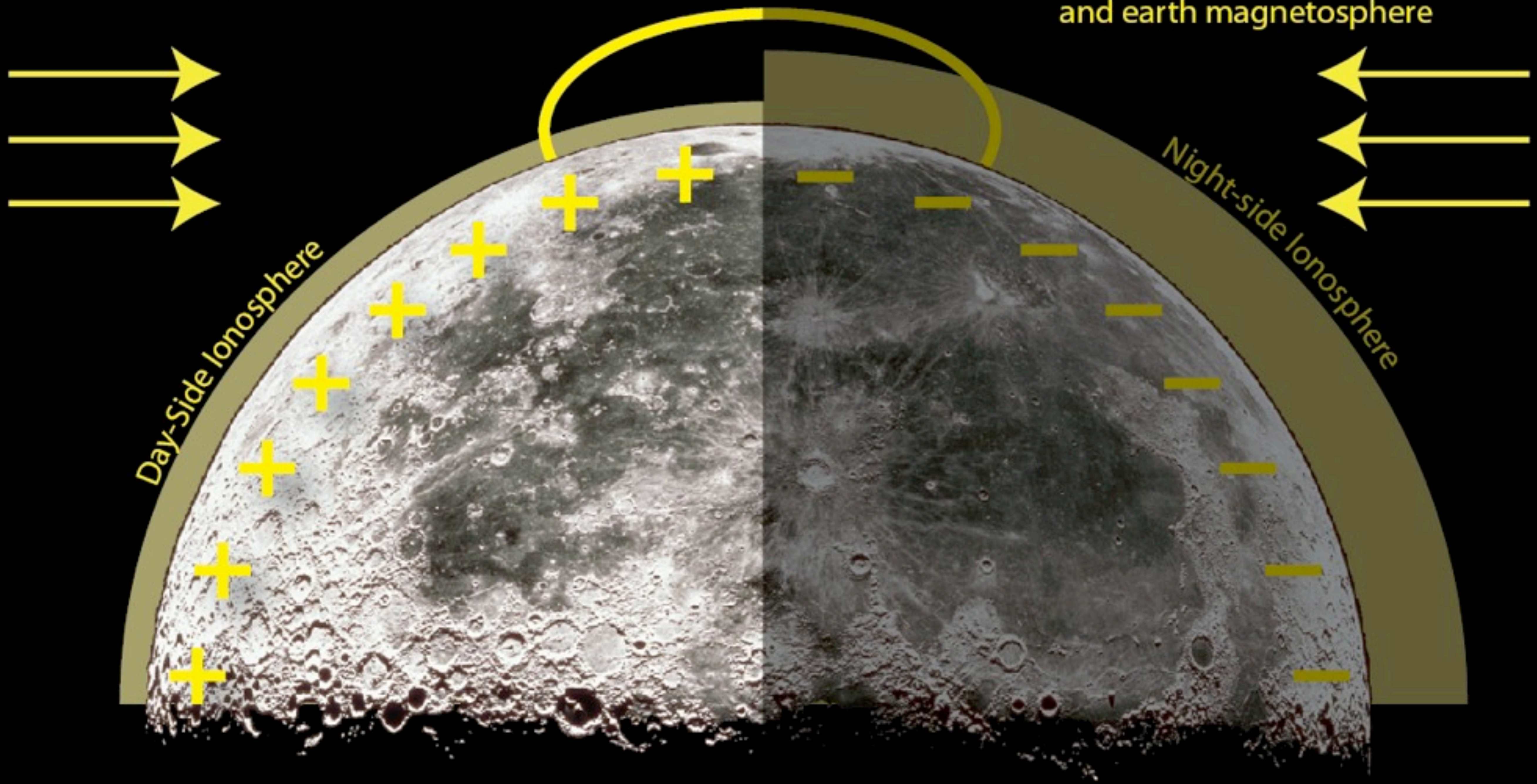
Day

Night

Solar UV radiation

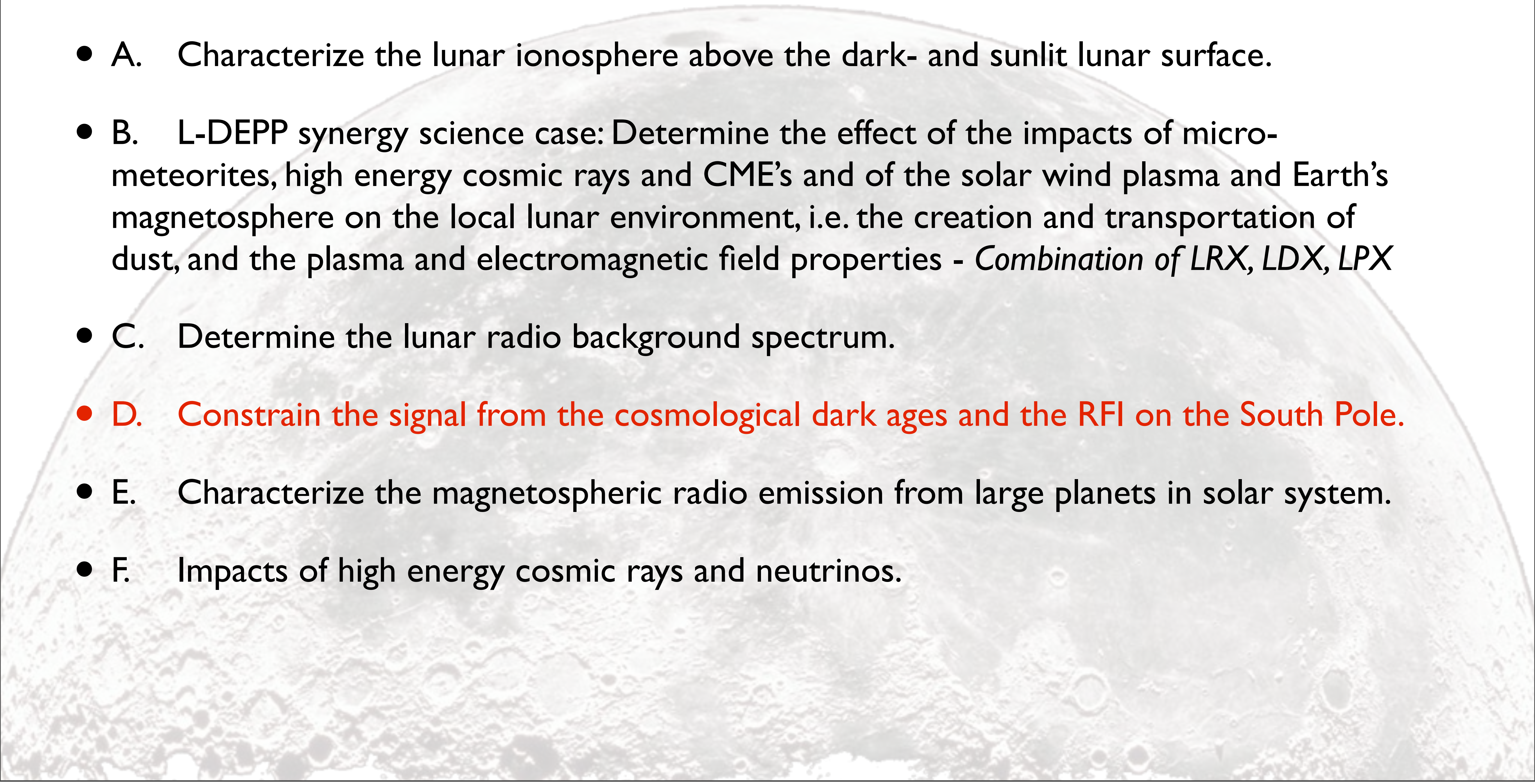
Electric field near the poles

Plasma electrons in the solar wind
and earth magnetosphere



Day and night difference on a lunar polar location: solar UV radiation causes the lunar surface to be positively charged on the day-side (a few Volts, extending up to ~1meter in height), on the night-side the interaction with plasma electrons (from the solar wind and the earth's magnetosphere) causes the surface to become negative (~100V, extending up to ~1 km). This causes a strong electric field on the south and north pole. In addition the moon is constanty exposed to micrometeorites and cosmic rays.

LRX Objectives



- A. Characterize the lunar ionosphere above the dark- and sunlit lunar surface.
- B. L-DEPP synergy science case: Determine the effect of the impacts of micro-meteorites, high energy cosmic rays and CME’s and of the solar wind plasma and Earth’s magnetosphere on the local lunar environment, i.e. the creation and transportation of dust, and the plasma and electromagnetic field properties - *Combination of LRX, LDX, LPX*
- C. Determine the lunar radio background spectrum.
- D. Constrain the signal from the cosmological dark ages and the RFI on the South Pole.
- E. Characterize the magnetospheric radio emission from large planets in solar system.
- F. Impacts of high energy cosmic rays and neutrinos.

Science Cases

Science Case	Experiment	Description
Plasma	Plasma	Study the impact of dust and magnetized plasmas on the Lunar ionosphere (synergy science case)
Riometer	Riometer	Study of the Lunar ionosphere
RadioAstro	Dark	Constrain the Dark Ages signal @ 30 MHz
	Impact	Measure and localize the impacts of cosmic rays and micro-meteorites
	HISS	Study of the temporal lunar surface radio background i.e. static discharges and cosmic ray induced noise
	PROPA	Propagation of radio waves along the lunar surface
	PGPR	Passive ground penetrating radar study sub-surface properties using cosmic ray impacts
	SOWI	Study of the Solar activity (CME, Solar Wind)
	SPECTRA	Determining the lunar radio background spectrum
	RadioAstro	Study of the Auroral emission from Jupiter and Saturn

Requirements

Science Case	Freq Range	Band Width	Sample Rate (MHz)	Operating time (s) per day	Daily data Volume (bit)	Ang. res.	ADC (Dyn Range in dB)	Mode
Plasma	100 Hz-50 KHz	50 kHz	7.5	15000	$1.35*10^9$	90°	MF:12 bit(36) HF: 12 bit(36)	Nominal
Plasma	100 Hz-50 KHz	50 kHz	7.5	10	$9.0*10^7$	90°	MF:12 bit(36) HF: 12 bit(36)	Burst
RIOMETER	5 kHz - 3MHz	3 MHz	250	30000	$7.2*10^7$	90°	MF: 12 bit(36) HF: 4 bit(12)	Nominal
RIOMETER	5 kHz - 3MHz	3 MHz	250	10	$2.4*10^8$	90°	MF:12 bit(36) HF: 4 bit(12)	Burst
RadioAstro	10 kHz - 100 MHz	100 MHz	200	60000	$4.8*10^8$	1°	MF: 8 bit(24) HF: 8 bit(24)	Nominal
RadioAstro	10 kHz - 100 MHz	100 MHz	200	5	$8.0*10^8$	1°	MF: 8 bit(24) HF: 8 bit(24)	Burst

Requirement	Description	Compliant
Frequency range	5 kHz - 100 MHz	Y
Bandwidth	50 kHz - 100 MHz	Y
Angular resolution	DOA: ~1° - 90°	Y
Sensitivity - I	Limited by noise levels: typically 2x10^7 Jy, and 4x10^3 Jy for an integration time of 60 min (@10 MHz, 10 kHz bandwidth)	Y/N; DARK requires stable conditions and low RFI
Sensitivity - II: reduce the noise to allow for higher sensitivity	LNA noise power shall be 5 dB lower then noise power from galactic background; Cross polarization shall be less then 20 dB; limit Lander EMC noise by using boom	Y/N; EMC needs to be confirmed
Sensitivity - III: weakest sources require large RFI attenuation	Obs. during no Earth an Sun visibility	Y/N
Omnidirectional FOV, and allow for beamforming, DOA and broad band sensitivity	Active Tripole antenna	Y
Max. Dynamic range: MF: 36 dB, HF: 36 dB	Requires a 12 bit ADC @MF and @HF	Y/N; 12 bit space qualified ADC required
Max. Sample Rate: 250 MHz	250 MHz FPGA	Y/N; 250 MHz space qualified FPGA
Max Daily data volume: 1.35*10^9 bit	Requires storage capacity of: 30 GB, and data transfer rate of: 4 Mb/s	Y

LRX Function tree

FFT (waveform)

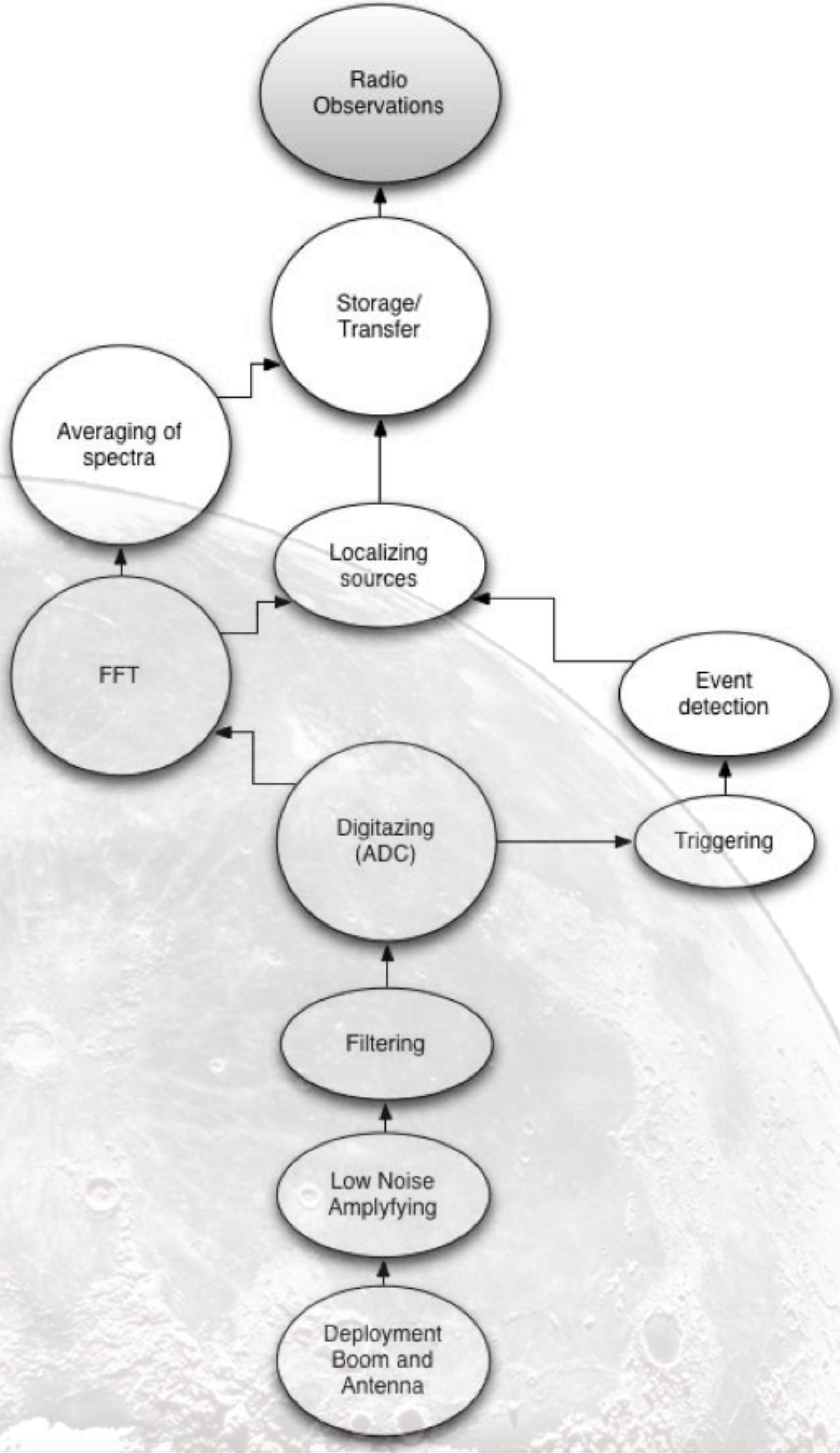
Digitizing (time-series)

Filtering + Amplification

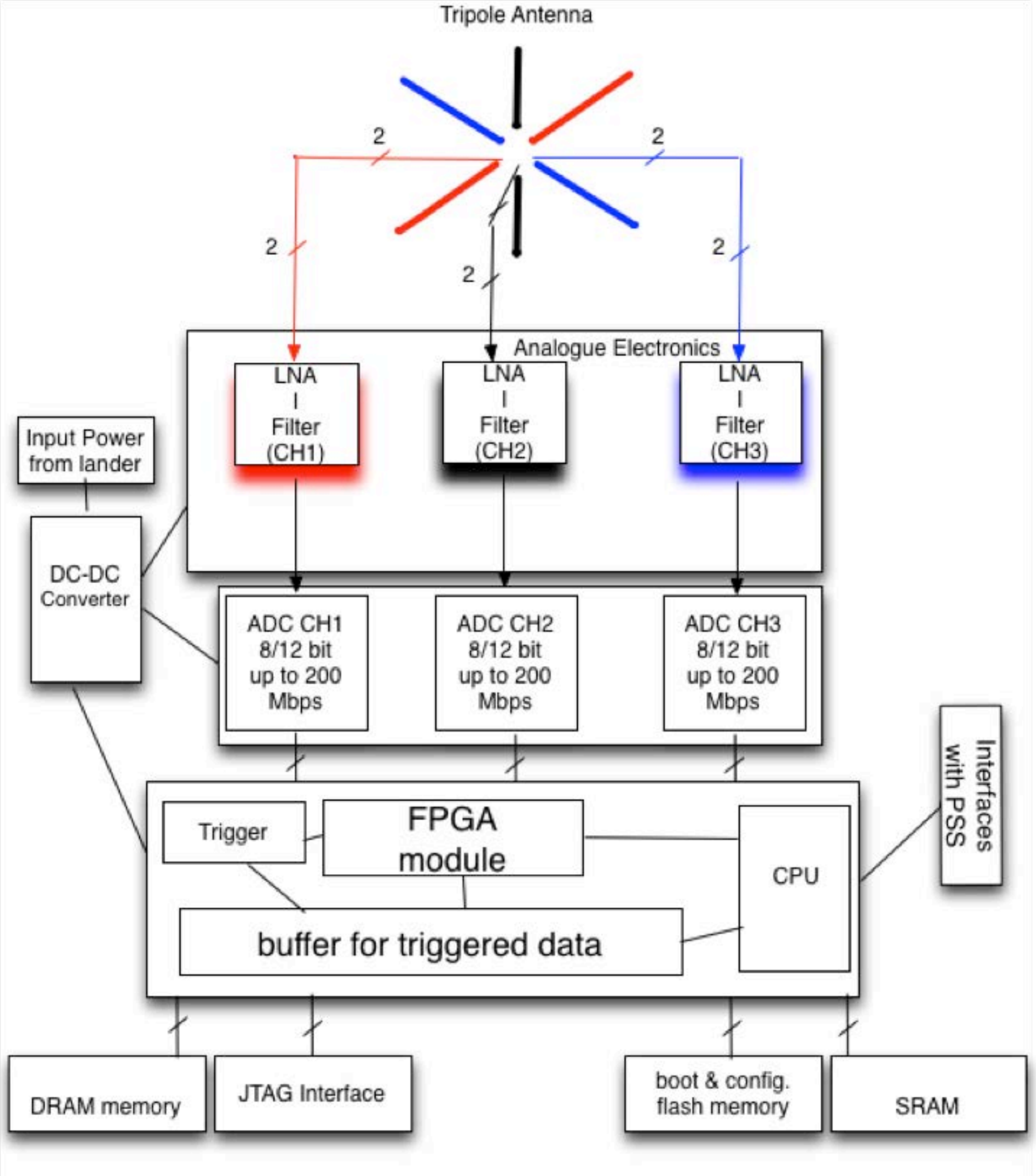
Voltage

Potential difference

Radio Wave



LRX Data Flow



- 2 freq. bands: MF:5kHz-3MHz, HF: 1-100 MHz
- Design allows for: Beam-forming, DOA techniques (goniopolarimetry), spectral averaging
- 3 modes: nominal (5 min averages), burst (1 sec average), power-save mode (lower sampling rate)
- 2 triggers: spectral trigger and waveform trigger: re-analysis of buffer data
- Average power: 9-12 W, Peak pow: 20W
- Average data rate: 0.1 Gbyte/day (nominal) 0.05 Gbyte/day
- *Noise load needed?*

LRX Operations

Experiment	LRX OPERATIONS RELATED TO LOCAL CONDITIONS						
	DAWN	DUSK	DAY	NIGHT	EARTH VISIBLE	JUPITER/ SATURN	MODE
RIOMETER	X	X	X	-	X	X	NOMINAL
PLASMA	X	X	X	-	X	X	BURST
RADIOASTRO	X	X	X	-	X	X	NOMINAL/ BURST
DARK	X	X	-	X	-	-	NOMINAL/ Power Save
IMPACT	X	X	X	-	X	-	BURST
HISS	X	X	X	-	X	X	BURST
PROPA	X	X	X	-	X	X	NOMINAL
PGPR	X	X	X	-	X	X	BURST
SOWI	-	-	X	-	-	-	BURST
SPECTRA	X	X	X	-	X	X	NOMINAL

LRX Design

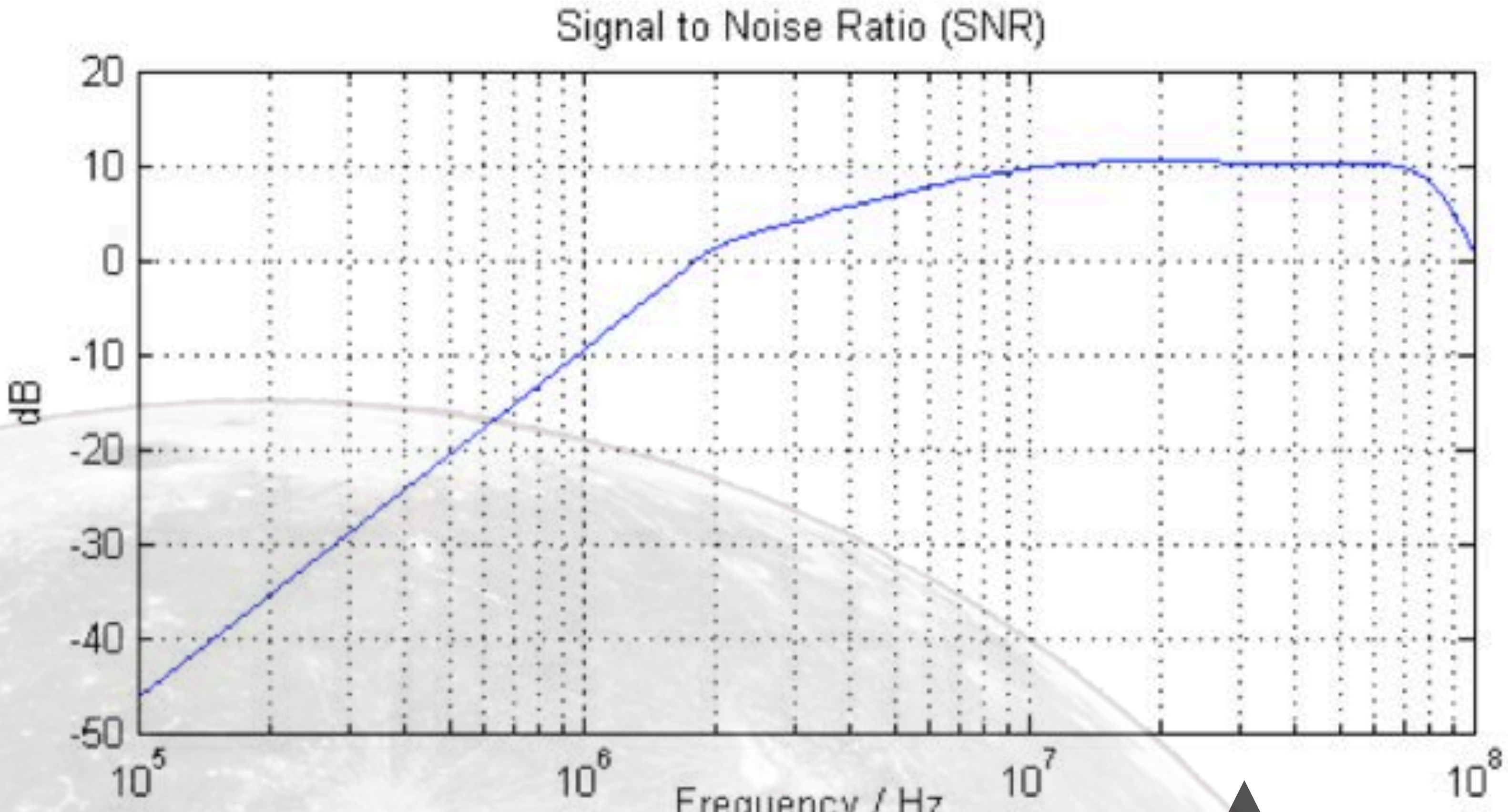
LRX front-end

- 2.5 m tip-to-tip, on a boom
- Tape measure mechanism, prototype build and tested at the Radboud Uni. Nijmegen
- Copper-Beryllium antenna arms
- Ultem 1000 (polymer) for housing

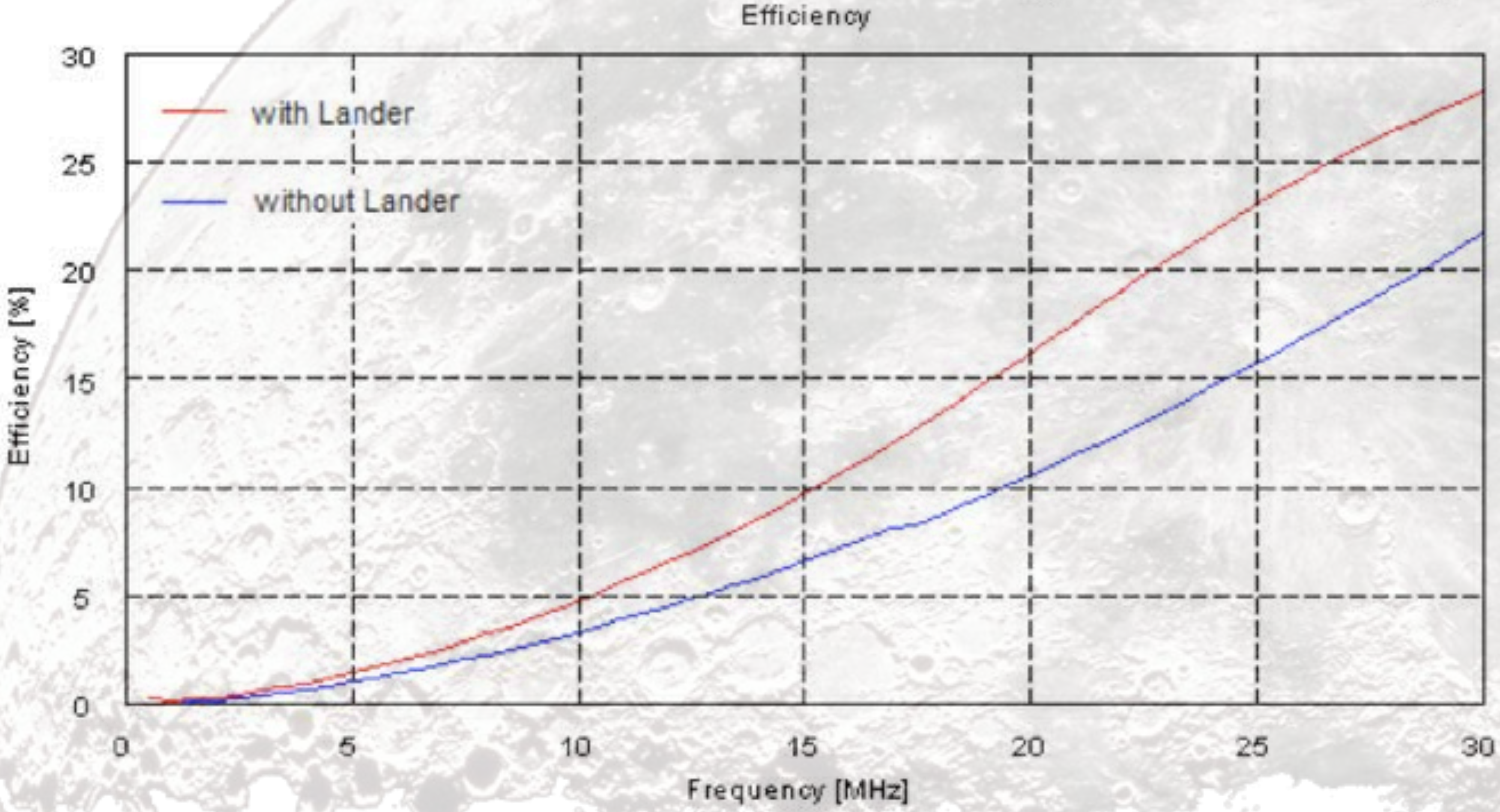
LRX characteristics

Tripole concept based on:

- less sensitive for Lander potential
- 2D beam-pattern (gain)
- Radiation Efficiency
- Polarization
- SRN (after LNA) (sensitivity)
- DOA capabilities
- Deployment



30 MHz



Positive effect of the Lander!

Mass Budget

component	Subcomponent	Mass (gr)	margin	total
Antenna	Antenna Arms (6)	120	10%	132
	Antenna Housing (6)	150	10%	165
	Thermal Knifes (3)	30	10%	33
	LNA	50	10%	55
Boom	Boom	500	20%	600
Receiver	FPGA, ADCs. etc	300	20%	360
Total				1345

The digital receiver as presented here will fit either on 2 A5 boards, i.e. 210x149 mm with a thickness of 20 to 30 mm, or on 4 100x160mm boards with a thickness of 20 to 30 mm. In both cases they occupy a volume of about 2000 cm^3 and a mass per board of 200gr.

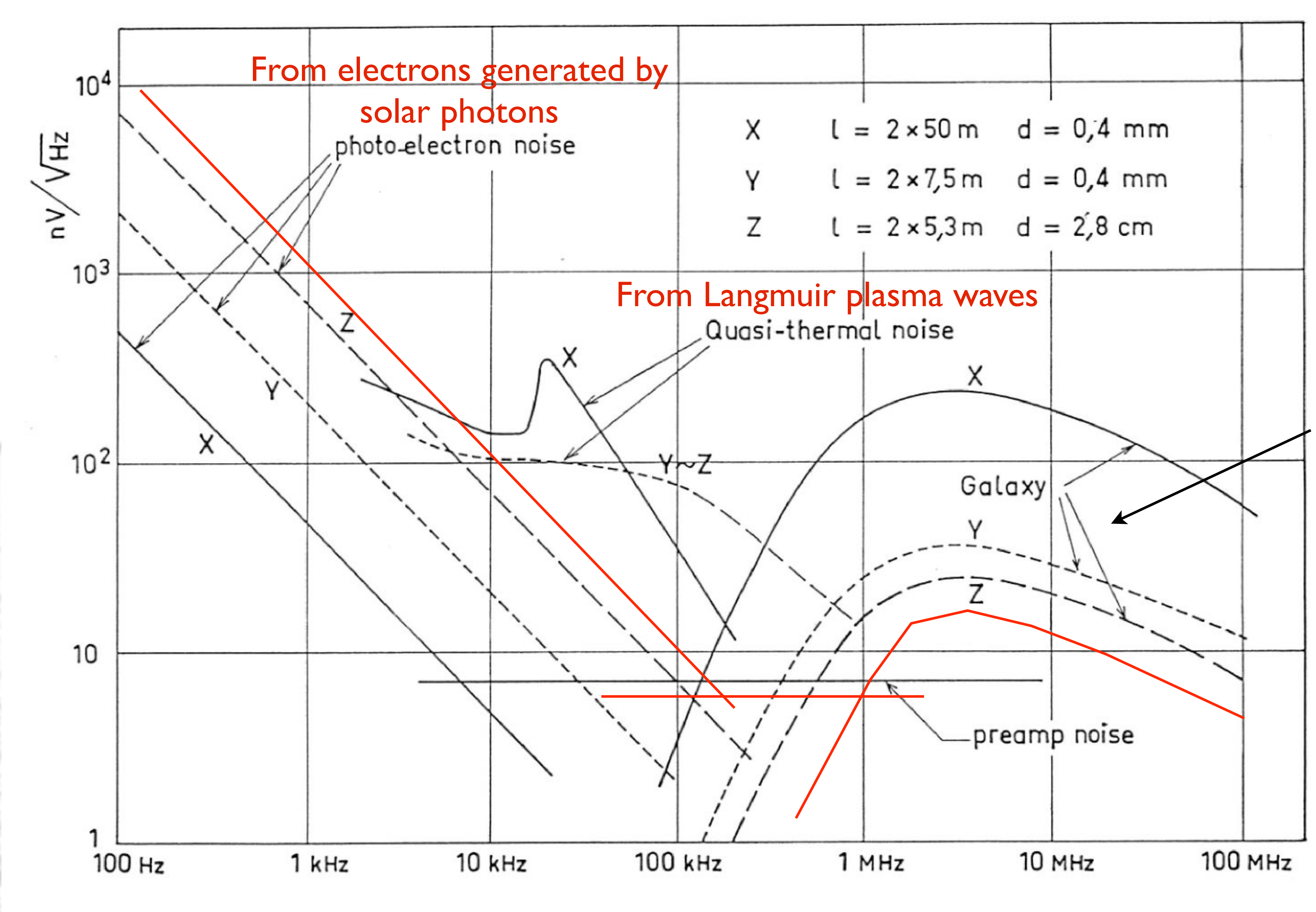
Critical components

Critical component	Limitation	Mitigation
FPGA	Limited by the speed and radiation and temperature	New design and development is required
LNA	The LNA is located at the center of the tripole outside the lander and electronics box and hence is subjected to large and extreme temperature variations. Current available LNAs operate between -50° and 125° C.	Either a new LNA has to be designed that is capable to operate at these extreme temperatures and cope with the radiation conditions at the moon, or a shielding and heating system must be put in place
ADC	No space qualified 200 Mbps, 12 bit and 8 bit ADC is available	New design and development is required

Expected sensitivity vs frequency

Dominant Noise:

The galactic background @ frequencies (≥ 1 MHz)
The receiver (LNA) noise ~ 100 kHz - 1 MHz
The quasi-thermal noise and
the photoelectron noise (depending
on local plasma conditions and illumination) @ frequencies (≤ 100 kHz)



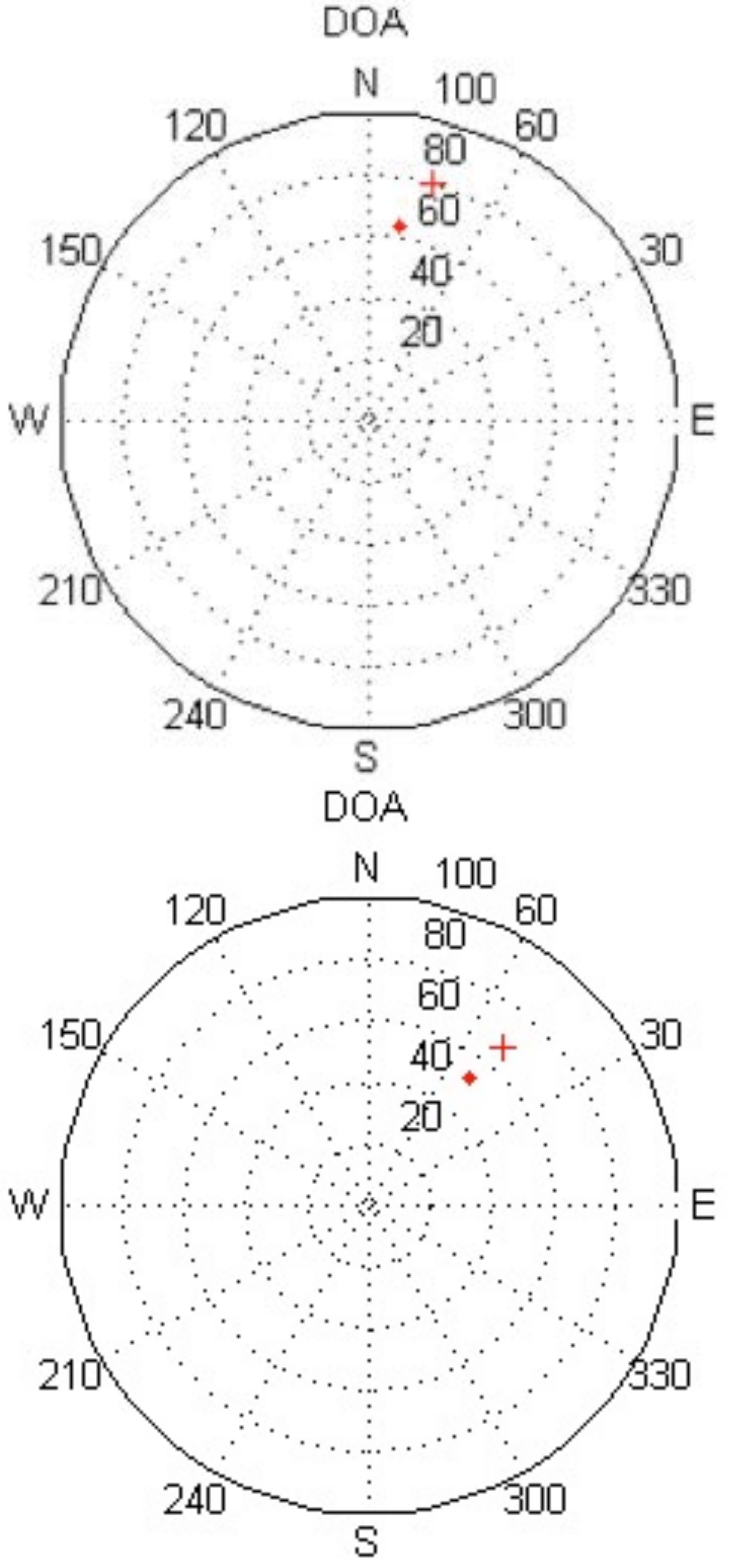
From electrons generated by solar photons

From Langmuir plasma waves

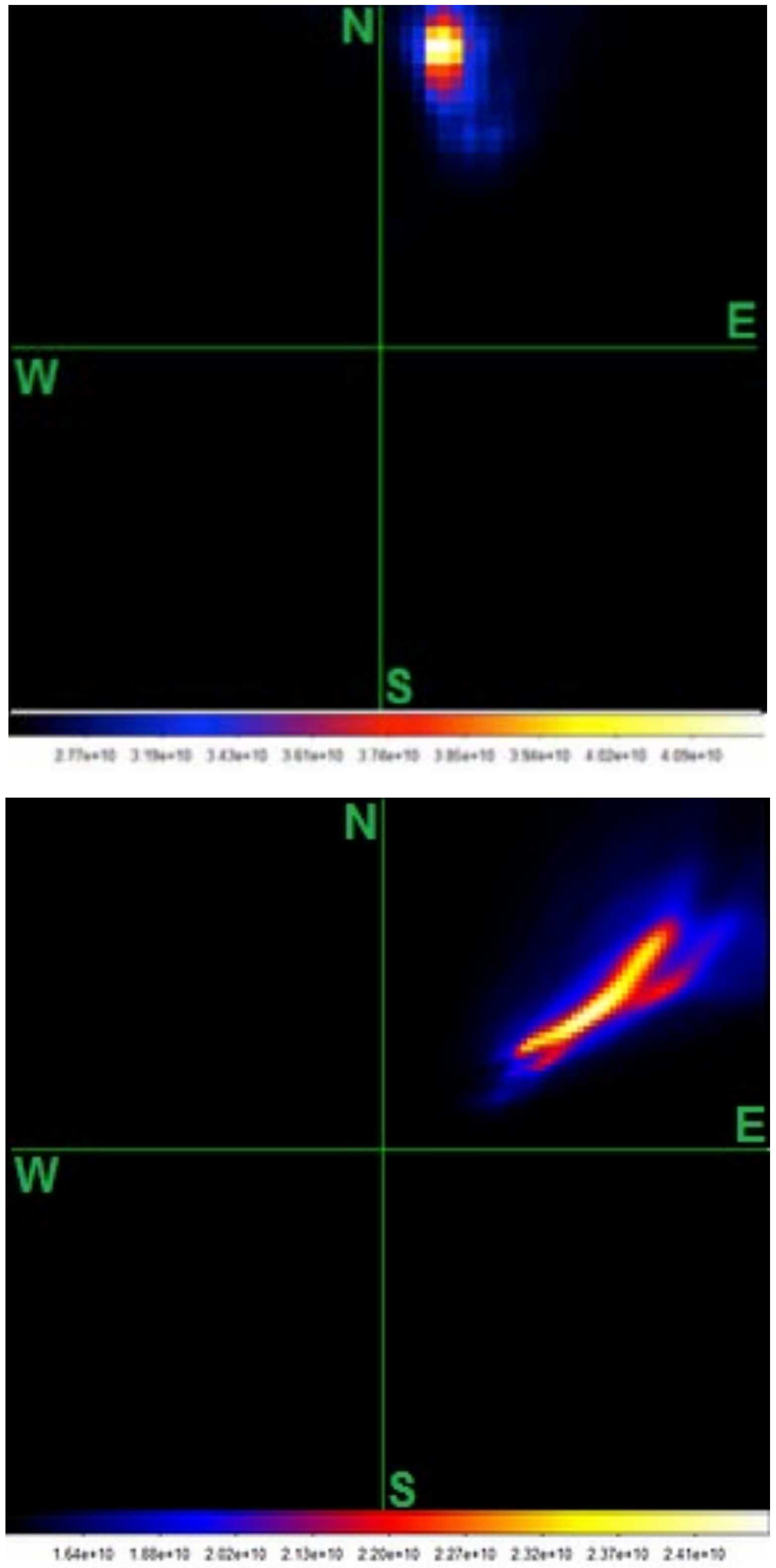
Typical levels for LRX antenna (2.5 m, 10 kHz, 100s)

after Manning, 2000

DOA of EM Bursts



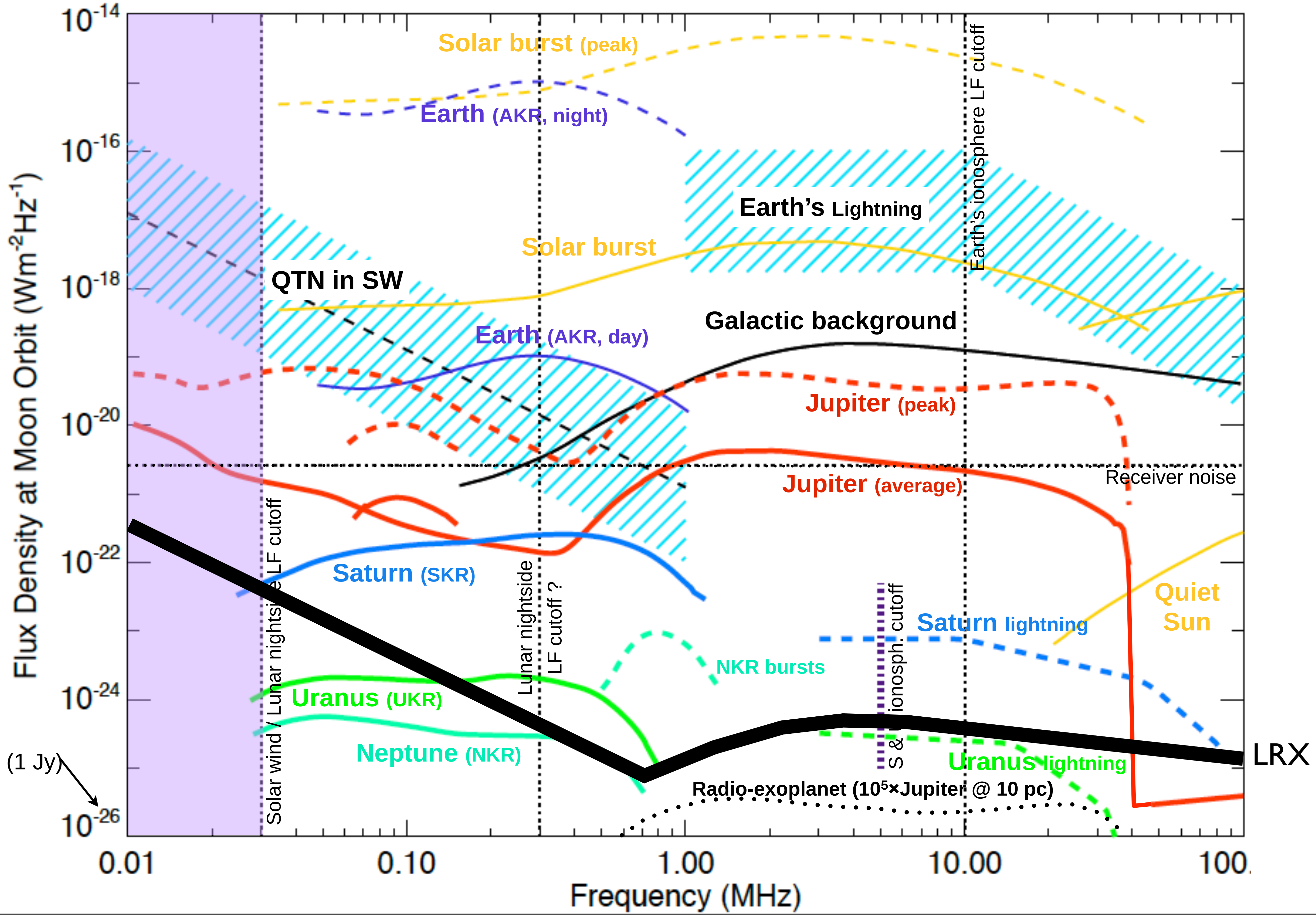
LRX prototype



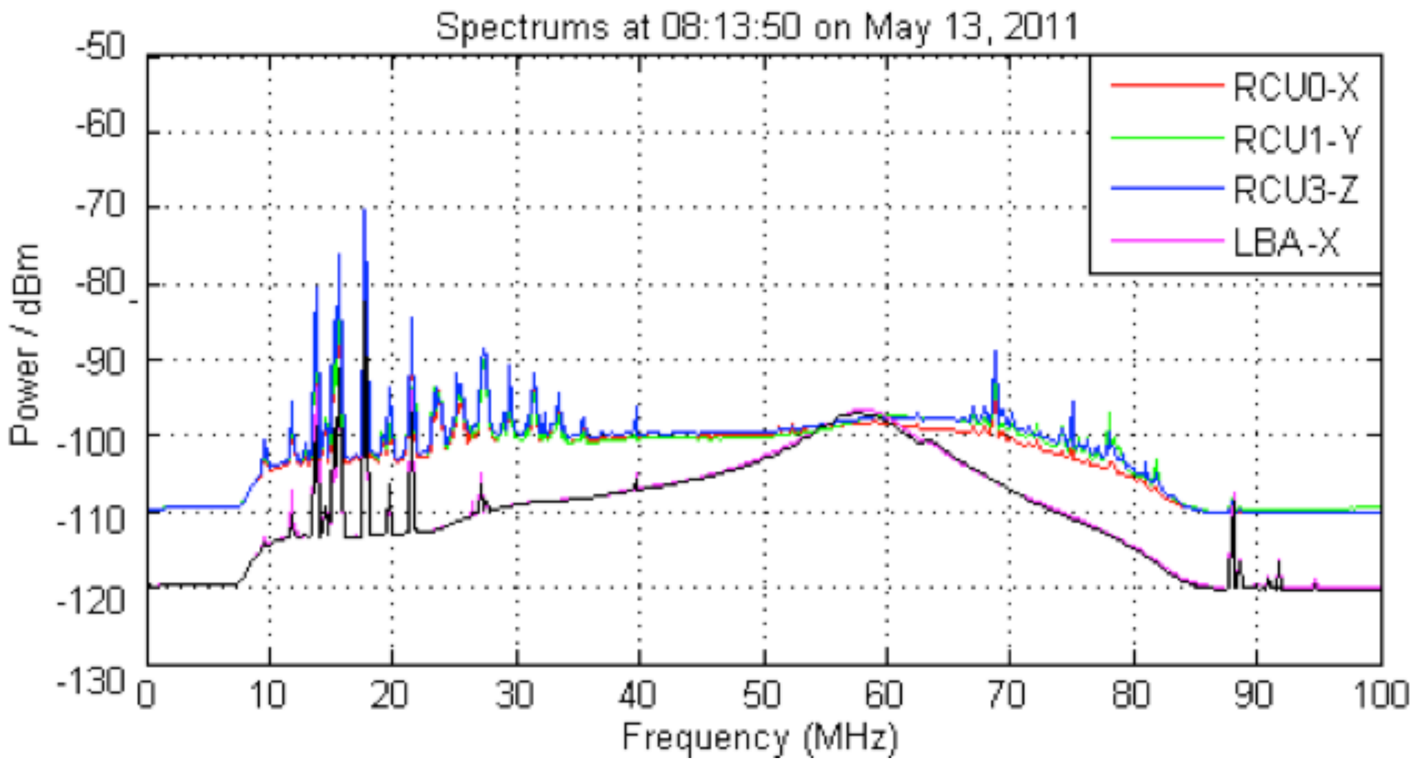
LOFAR

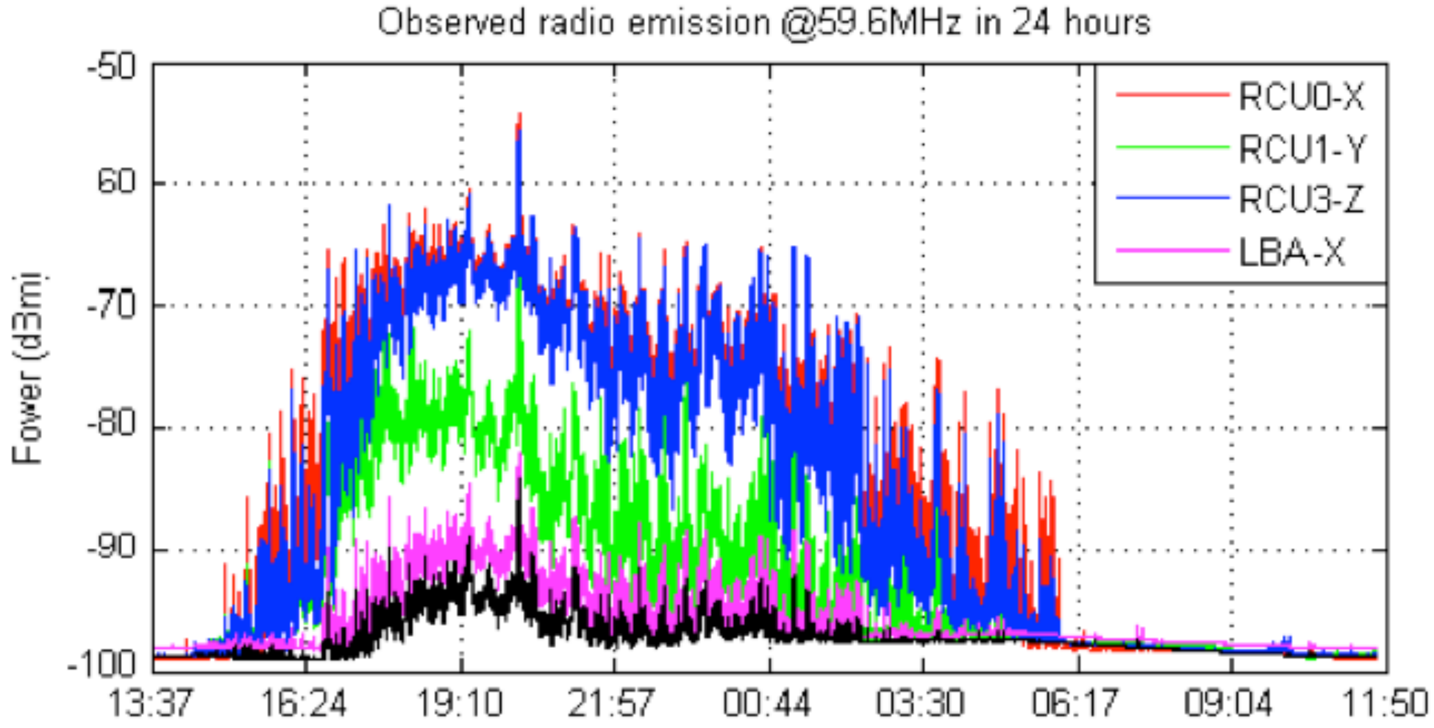
LRX Sensitivity

Zarka et al. 2012

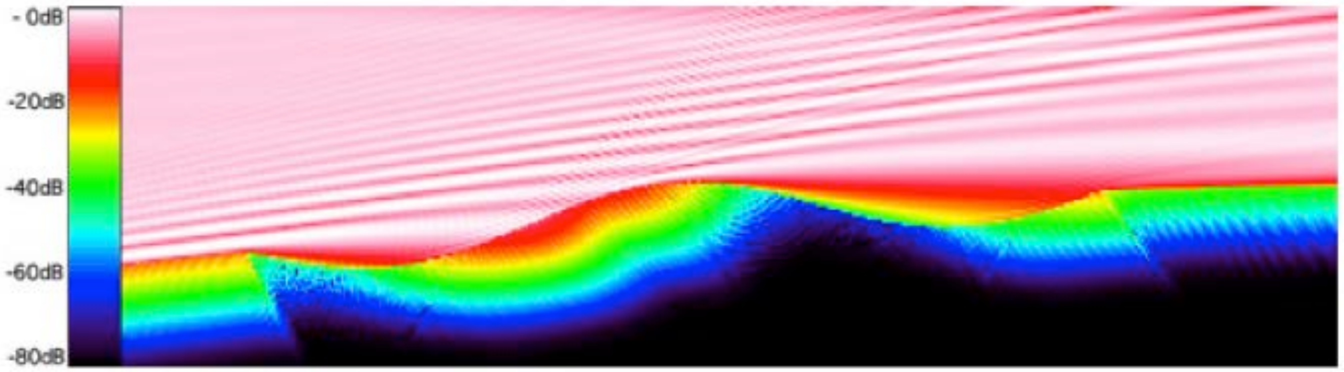


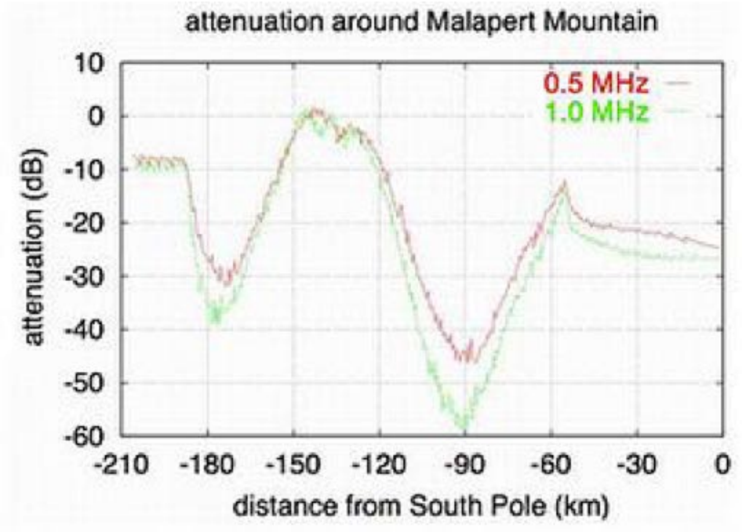
Comparison with LOFAR





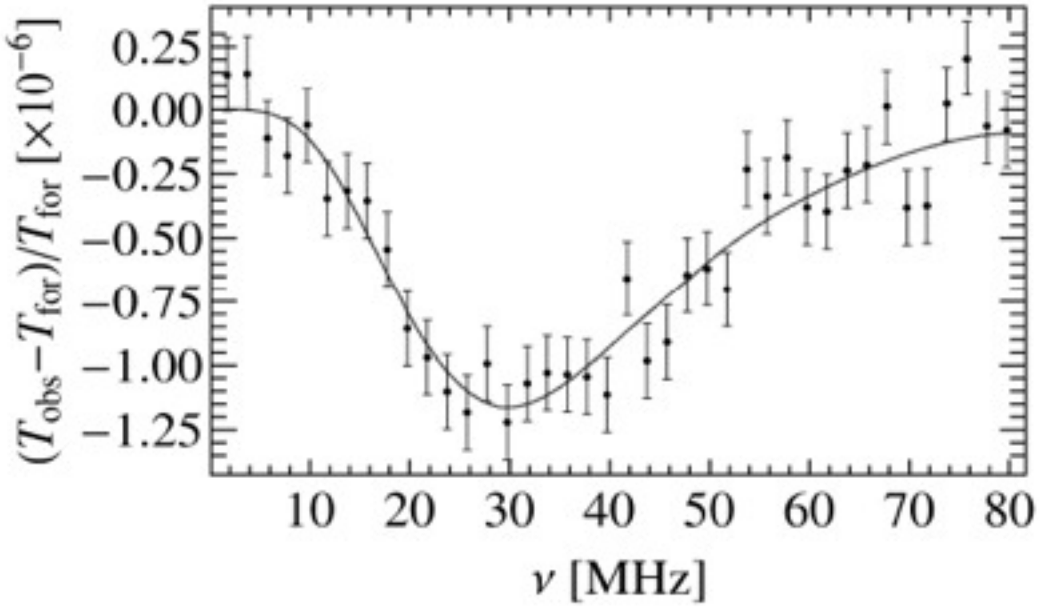
High-z 21-cm from South pole?

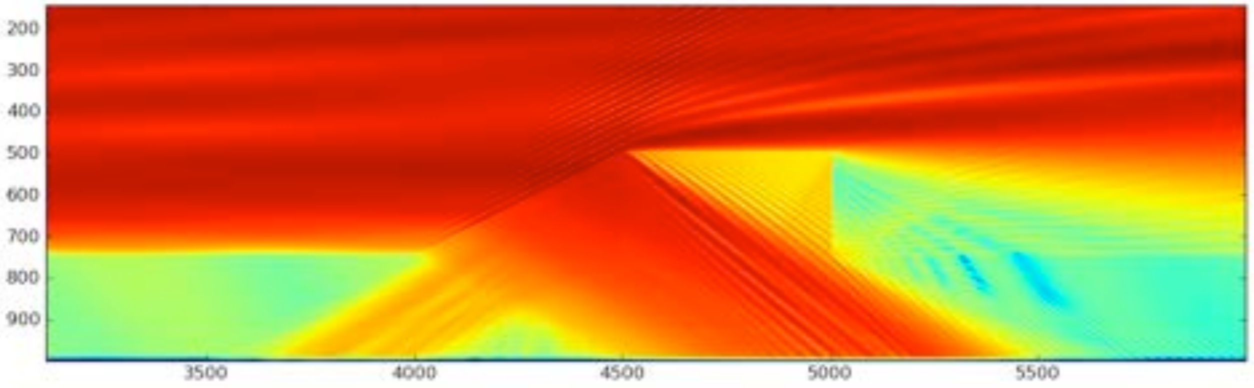




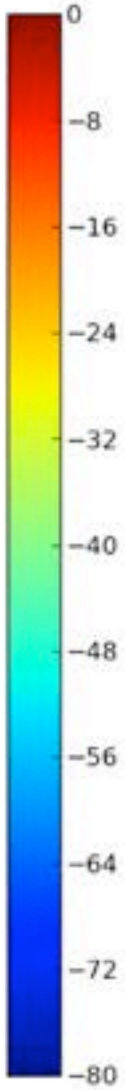
Takahashi, 2003

Jester & Falcke 2009: one dipole one year integration (@30 MHz), signal is 10^{-6} below Galactic Background





Preliminary results from RUN/RUG simulations: up to 40-50 dB attenuation behind mountain



Notes on RFI:

- Previous studies (simulations) show some locations with significant attenuation (up to 40 dB), but are at low frequencies, but Burns et al. 2012: up 80-90 dB is required.
- Preliminary results from our simulations show significant attenuation especially behind a mountain
- Refraction and diffraction effects are important, and detailed simulations or in-situ measurements are required: LRX can provide this!

Conclusions

- Astronomy from the moon: low-frequency radio telescope recognized as top priority (uniquely suited for the moon)
- Start in steps - one tripole antenna can do a lot:
  - Search for Epoch or Reionization / Dark Ages signal, determine RFI
  - Impacts from cosmic rays and meteorites
  - Site exploration: Ionosphere, Spectral and temporal noise, surface and dust effects
  - One scientist's noise is another one's signal: strong synergy with dust and plasma studies
- Ultimate goal: LOFAR-like radio interferometer on the moon to open last unexplored window to the universe: LRX is pathfinder mission!