Toward Moon-based Very Long-Wavelength Astronomy Facility: *science drives and technological challenges*

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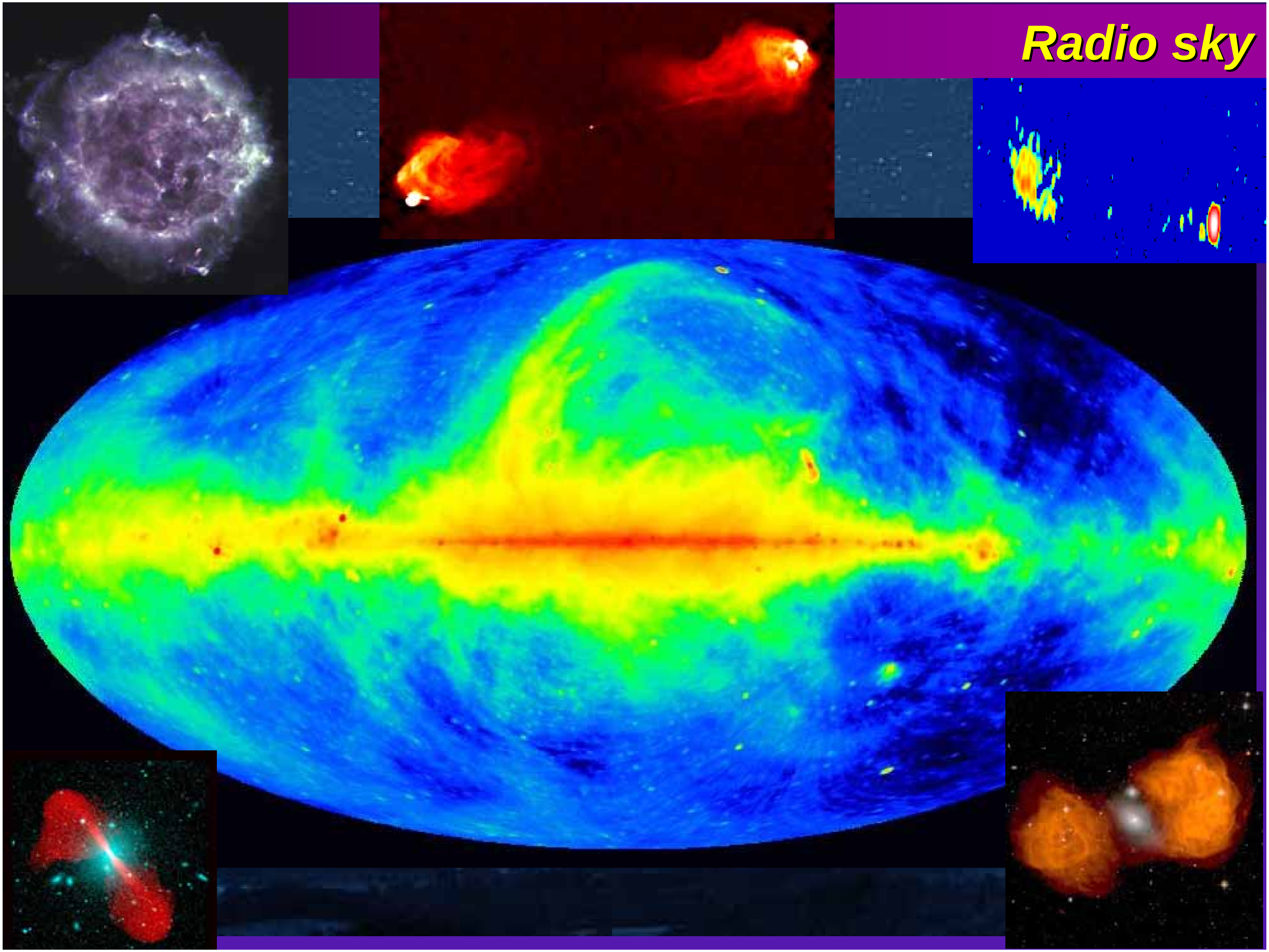
Why Radio Astronomy on the Moon?

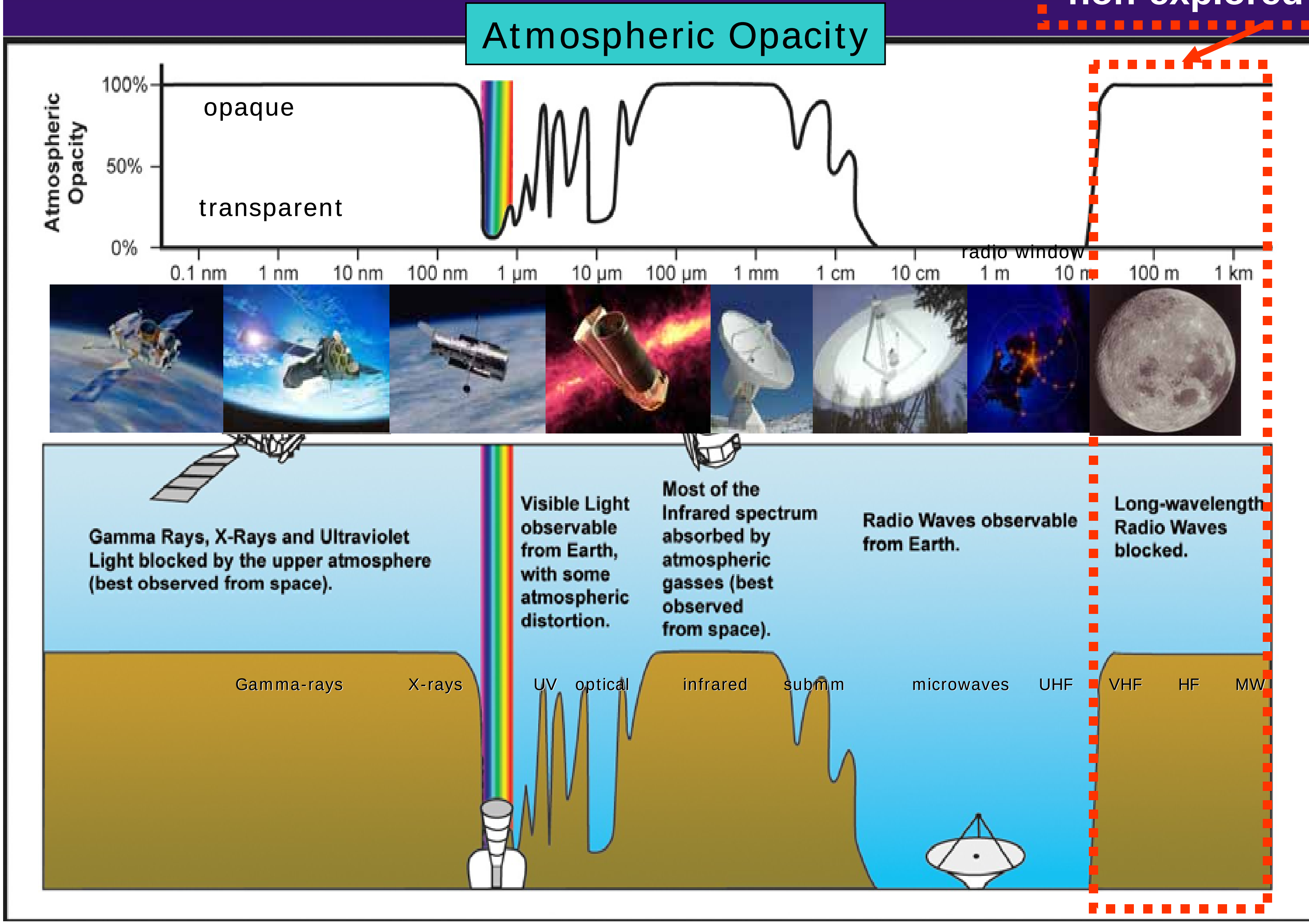
- **Radio Astronomy: a fore-front of science and technology progress over the last 75 years**
- **Technology: radio astronomy principles and innovations are part of our daily live (radio/TV, communications, wireless, GPS, medical diagnostics and therapy, etc.…)**
- **Science: Five Nobel Prizes in 45 years**
  - ***Big Bang (Cosmic Microwave Background) and Dark Matter & Dark Energy***
  - ***Gravitational Waves***
  - ***Exotic States of Matter (Black Holes & Neutron Stars)***
- **Radio astronomy everywhere on Earth – Moon is no exception**

Radio sky



Astronomical Exploration of the EM Spectrum

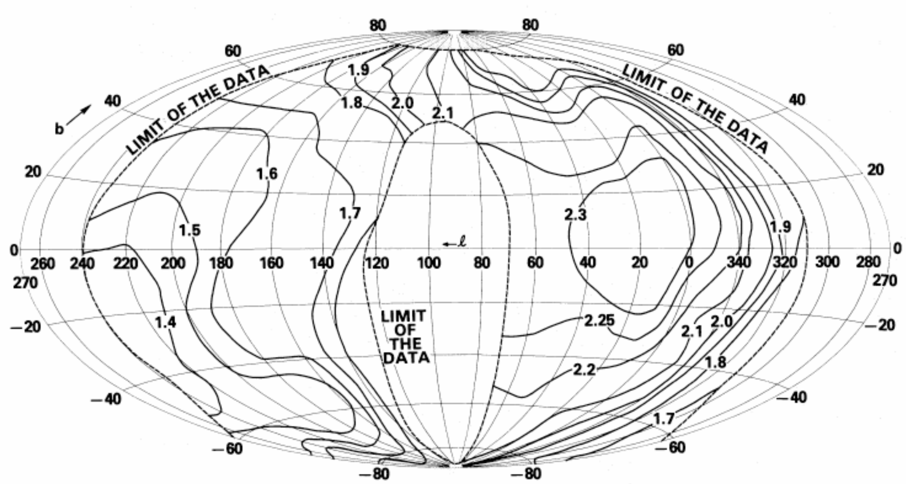
The last non-explored window



Sky at Long Wavelengths: current status

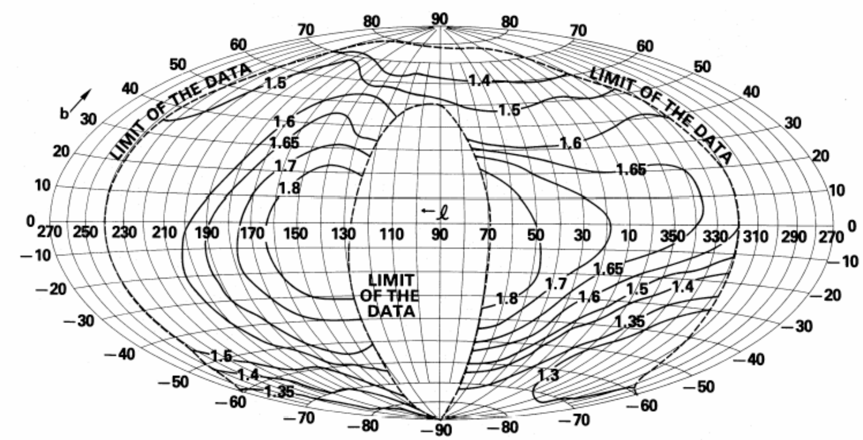
Extremely poor resolution, strong diffuse Galactic emission

RAE-2 observations at
1.3 and 4.7 MHz,
Novaco & Brown 1978



CONTOURS ARE IN UNITS OF 10^6K

FIG. 5.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 4.70 MHz

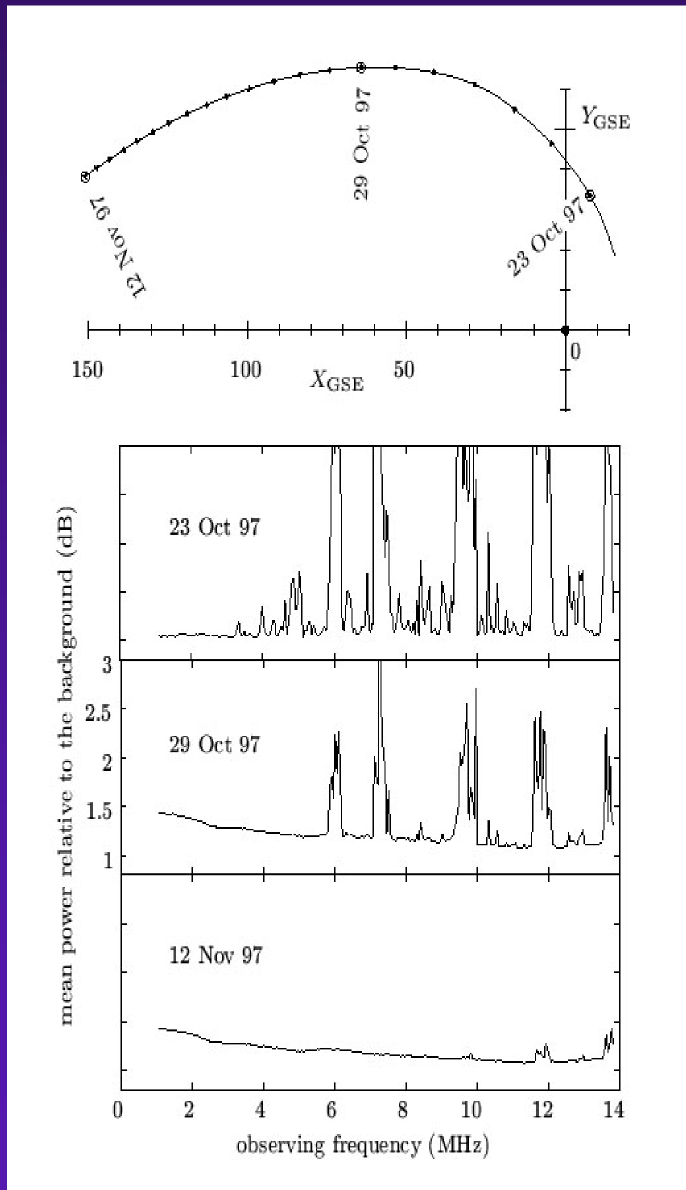


CONTOURS ARE IN UNITS OF 10^7K

FIG. 8.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 1.31 MHz

slide from G. Woan

Why Moon? Terrestrial Radio Interference

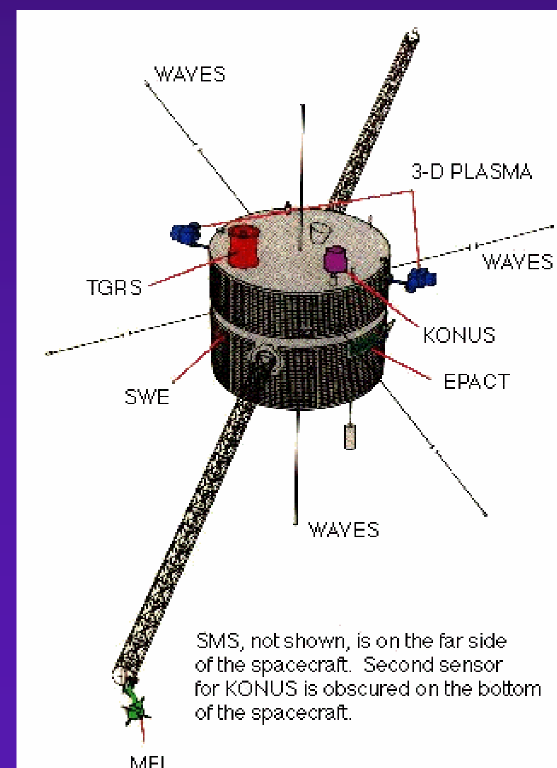


Typical anthropogenic interference received by the WAVES instrument on Wind, averaged over 24 hours. Orbital dimensions in Earth radii.

40 Earth radii

93 Earth radii

157 Earth radii



G. Woan from ESA study SCI(97)2

RAE-2 lunar occultation of Earth

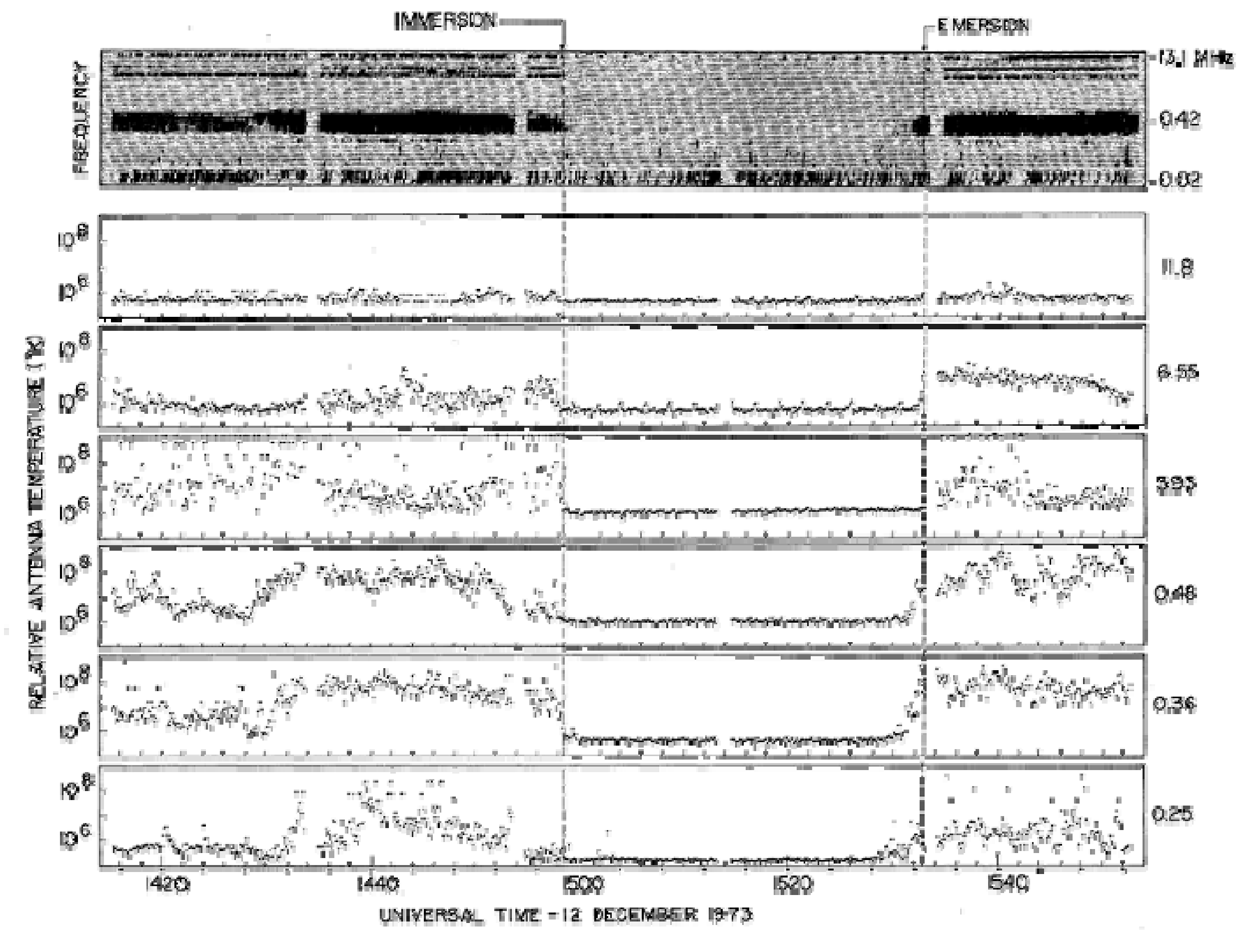
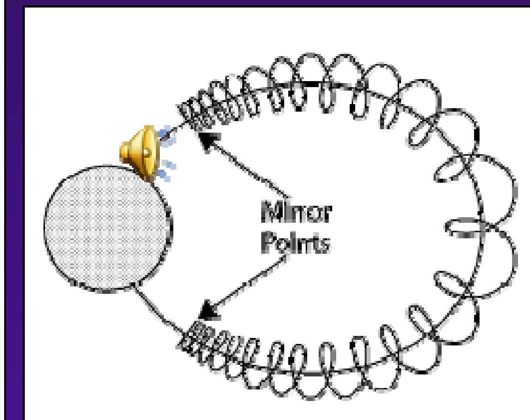


Fig. 5. Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. tim variations at frequencies where terrestrial noise levels are often observed. The 89-s data gaps which occur every 20 m are at times when in-flight calibrations occur. The short noise puls observed every 144 s at the highest frequencies during the occultation period are due to weak interference from the Ryle-Vonberg receiver local oscillator on occasions when both that receive and the burst receiver are tuned to the same frequency



G. Woan et al. from ESA study SCI(97)2

Good “news”: the Moon is a radio-protected zone!

- **The far side of the moon is declared as a radio protected site within the ITU Radio Regulations**
  - *•The IT Radio Regulations are an international treaty within the UN.*
  - *•Details are specified in a published ITU Recommendation (this is a non-mandatory recommendation, but is typically adhered to).*

⇒ **Radio astronomy on the Moon has been a long-standing goal, protected by international treaties!**

⇒ **Steps need to be taken to protect the pristine and clean nature of the moon.**

⇒ **Lunar communication on the far side needs to be radio quiet.**

ARTICLE 22
(ITU Radio Regulations)
Space services
Section V – Radio astronomy in the shielded zone of the Moon

22.22 **§ 8 1) In the shielded zone of the Moon[31] emissions causing harmful inter-ference to radio astronomy observations[32] and to other users of passive services shall be prohibited in the entire frequency spectrum except in the following bands:**

22.23 ***a)*** **the frequency bands allocated to the space research service using active sensors;**

22.24 ***b)*** **the frequency bands allocated to the space operation service, the Earth exploration-satellite service using active sensors, and the radiolocation service using stations on spaceborne platforms, which are required for the support of space research, as well as for radiocommunications and space research transmissions within the lunar shielded zone.**

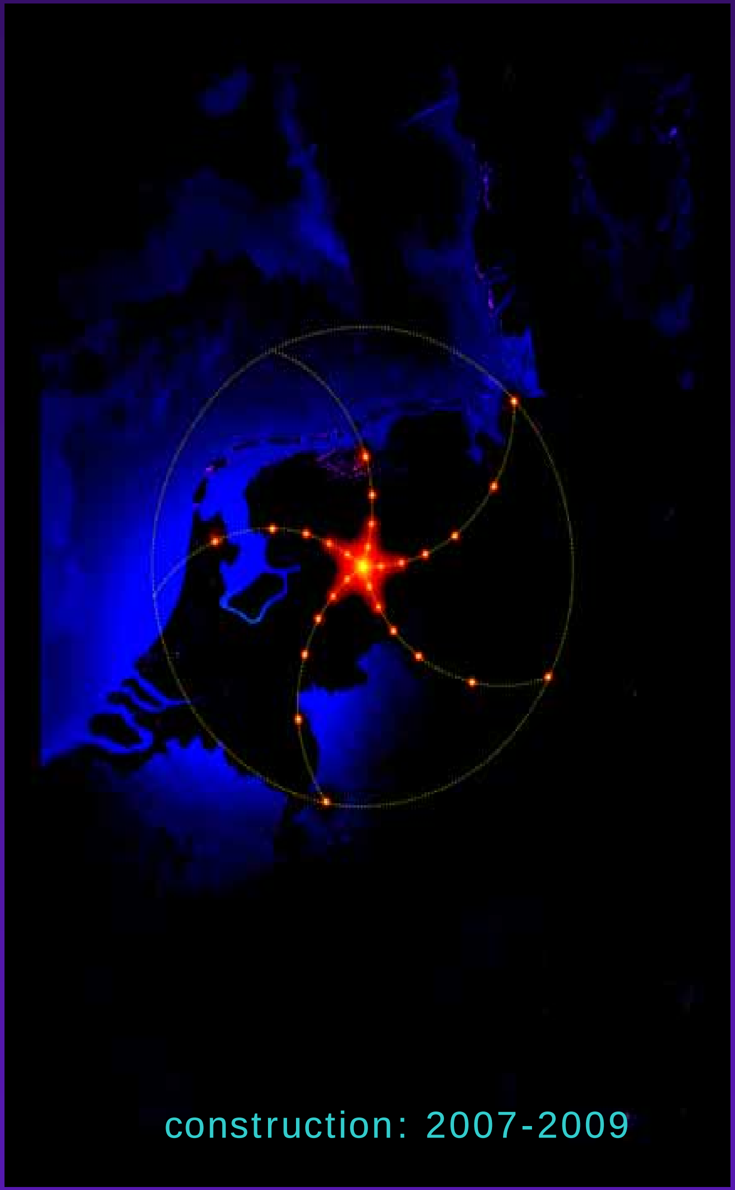
22.25 **2) In frequency bands in which emissions are not prohibited by Nos.** 22.22 **to** 22.24**, radio astronomy observations and passive space research in the shielded zone of the Moon may be protected from harmful interference by agreement between administrations concerned.**

22.22.1 **The shielded zone of the Moon comprises the area of the Moon’s surface and an adjacent volume of space which are shielded from emissions originating within a distance of 100 000 km from the centre of the Earth.**

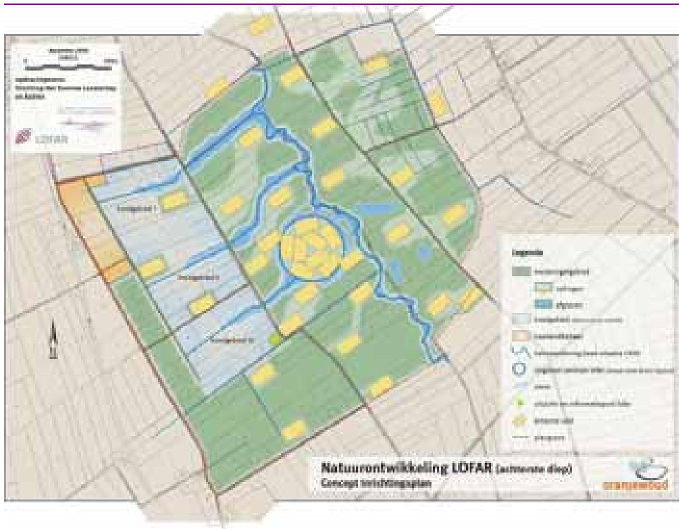
32 22.22.2 **The level of harmful interference is determined by agreement between the administrations concerned, with the guidance of the relevant ITU-R Recommendations.**

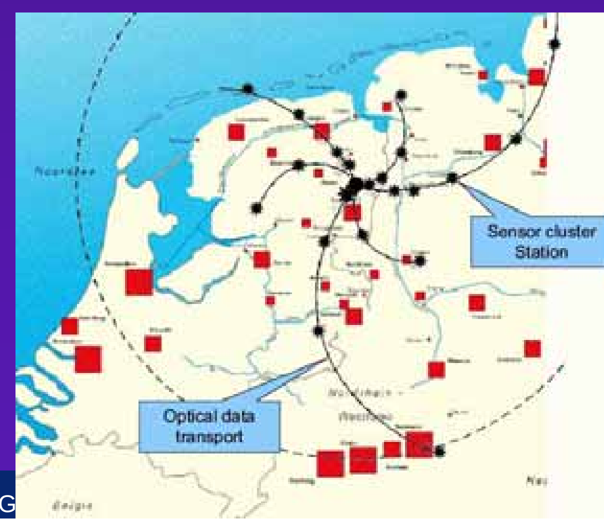
LOFAR – the next generation radio telescope

- **Telescope the size of the Netherlands plus neighbouring countries**
- **Frequencies: 30 - 240 MHz**
- **Replace a few big expensive antennas by many cheap ones**
  - ***100 stations of 100 dipole antennas + extra sensors (geo+meteo)***
- **No moving parts: purely electronic antenna beam steering**
  - ***IBM Blue Gene/P supercomputer "synthesizes" a giant dish***
- **Two orders of magnitude improvement in resolution and sensitivity**
- **Science applications: Big bang, astro-particles and the unknown**
- **Operations: from 2009**



LOFAR: roll-out!

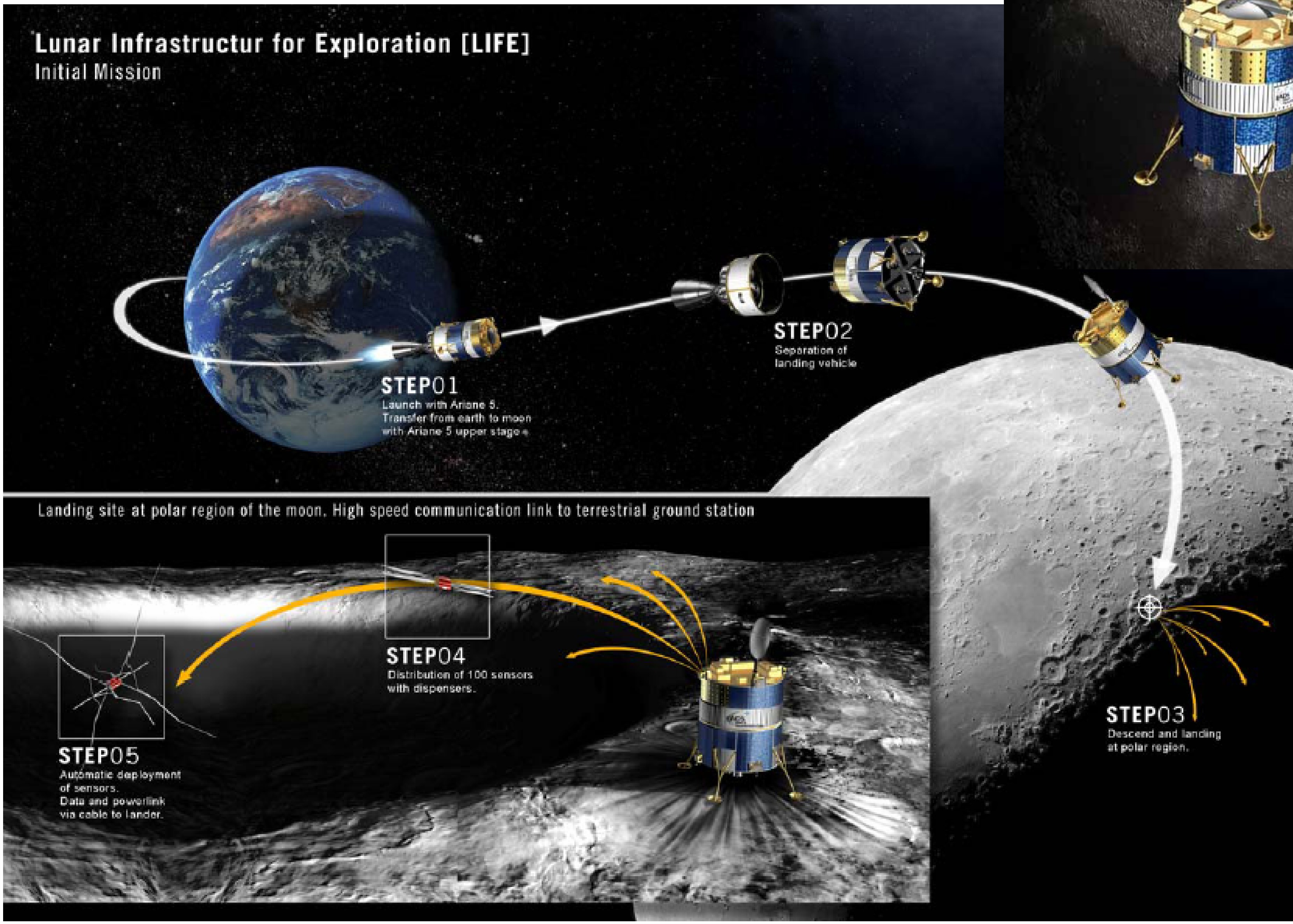




Moon-based VLWA Facility: stepping stones

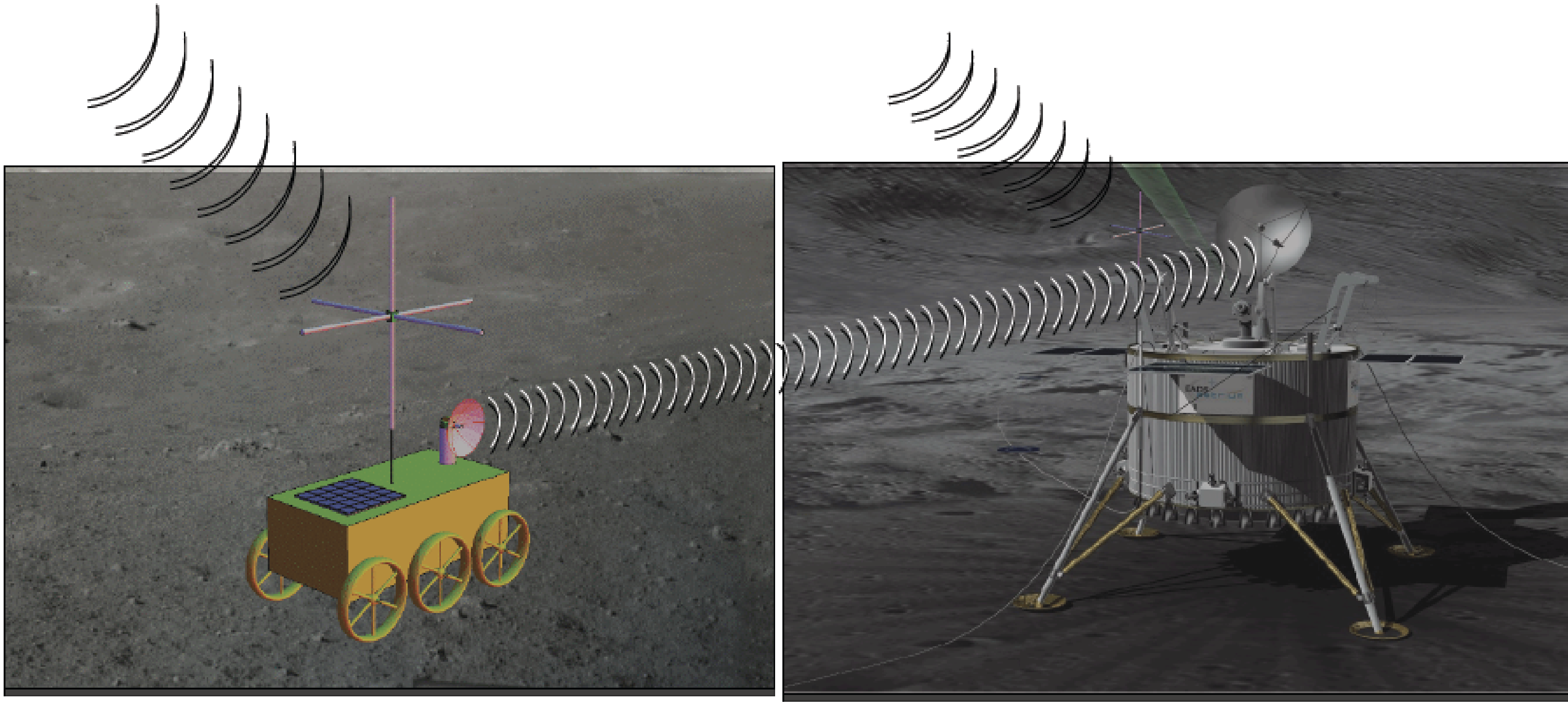
- LRX – Lunar Radio Explorer**:**
  - 2 dipoles, **100m-10km, protoype**
  - **Interferometry demonstration, southern sky survey, astronomical site-testing**
- Lunar LOFAR**:**
  - 33 -100 dipoles**, 30-100 km, serious imaging**
  - **Imaging surveys, foreground studies, 3D imaging of local bubble around solar system, transients**
- LDAM – Lunar Dark Ages Mapper:
  - $10^{3\text{-}5.5}$ dipoles**, 10 km², >100 km, centrally concentrated**
  - **Origin of Universe**

Lunar Infrastructure for Exploration (LIFE)



H. Müller, EADS, International Symposium on Lunar Infrastructure for Exploration (LIFE), Bremen, 2005

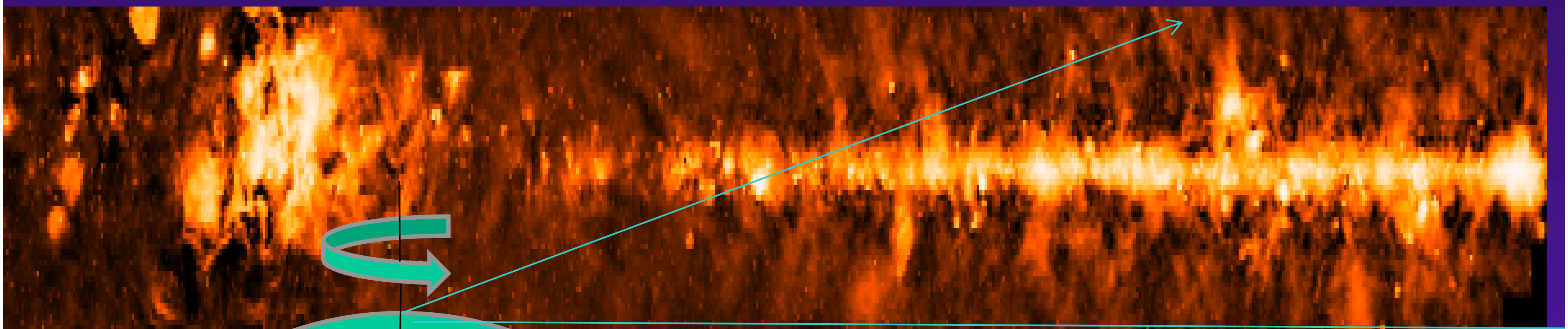
LRX – Basic Design

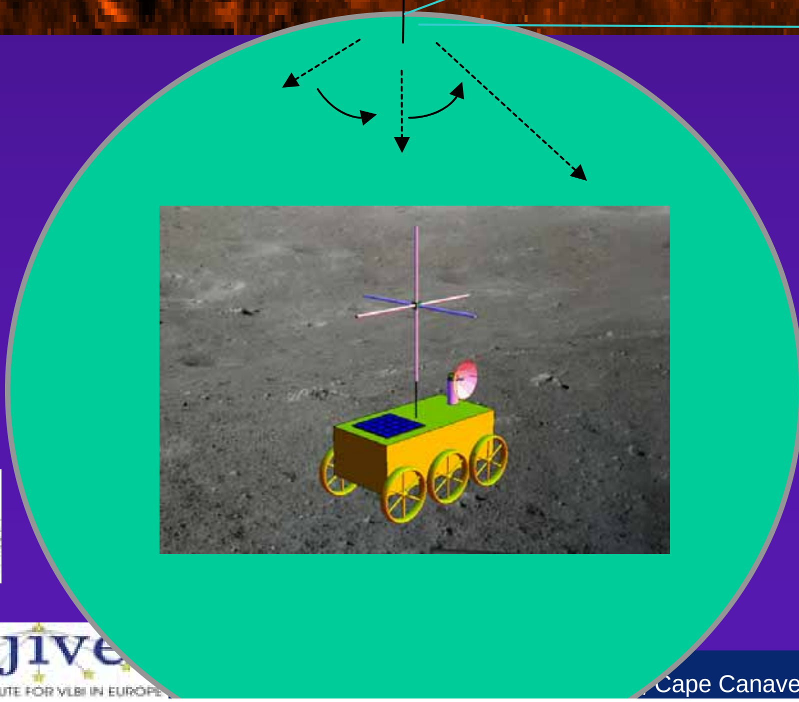


One Module: Mass ~2 kg, Power 7.5 W, Data rate: 1 Mbit/s (M:M) 2 kb/s (M:E)
(Some of these numbers are scalable with observing bandwidth)

H. Falcke

LRX – "Lunar Radio Explorer" Moon-Rotation Synthesis



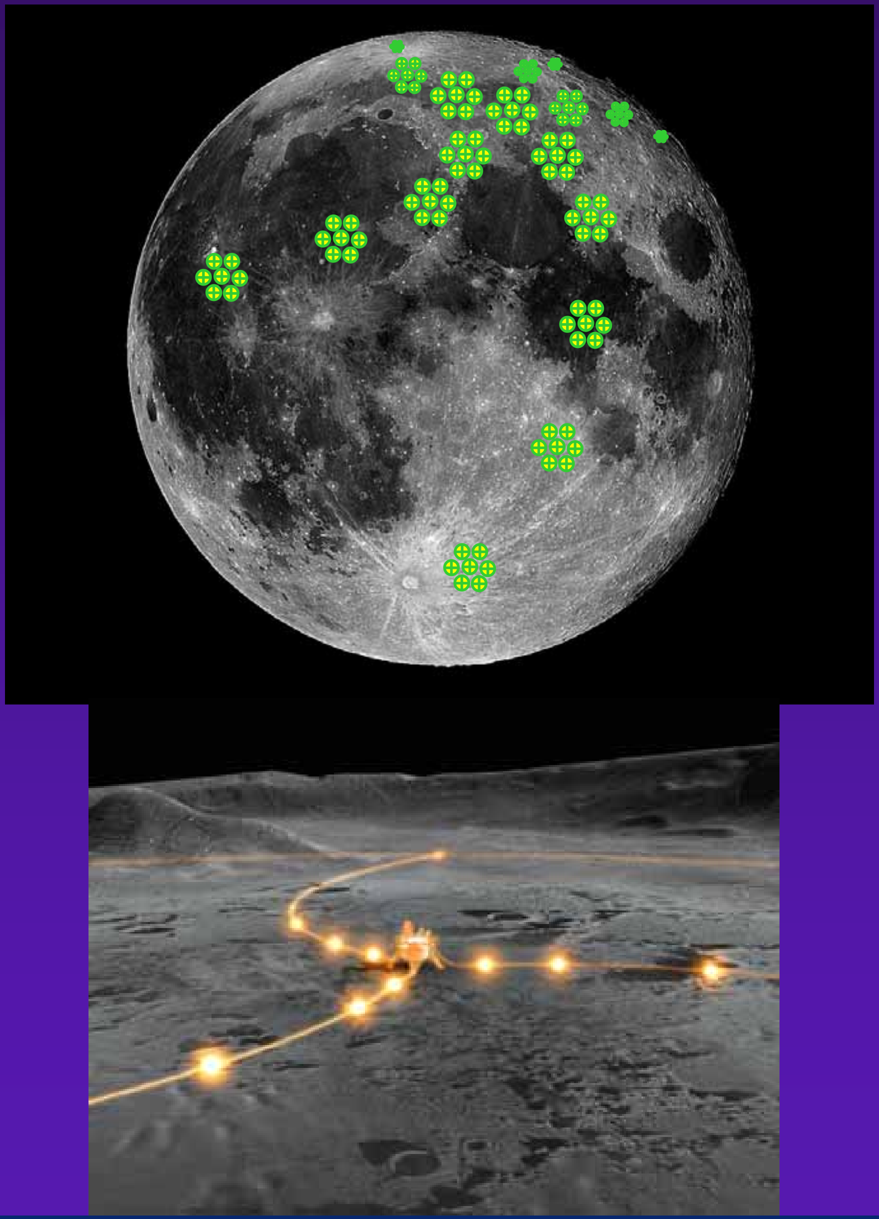


10 MHz:

Baseline	Resolution
100m	**17°**
300 m	**6°**
1km	**1.5°**
3 km	**0.6°**
10 km	**10'**

Lunar LOFAR: distributed array of radio sensors

- **First prototype phase:**
  - *•Antennas, power, computer, communication, dispatcher*
  - *•Weight ~ 1t (payload)*
  - *•Needs one Ariane V launch*
- **Start with ~100 tripoles**
- **Collecting area:**
  - *•A_{eff}~ 0.125 km^2 @ 3MHz (17 football fields ~400 m dish)*
- **Separation D = 1 km**
  - *•Resolution ~1.6° (10 MHz)*
- **Expand with additional mission(s)**
- **Importance of a demonstrator – modeling underway (PhD project)**



VLWA on the Moon: where to go from here

- **Early steps of Lunar exploration MUST have a component of high scientific impact**
- **Moon-based Very Long Wavelength Astronomy (VLWA) facility – top-notch science, affordable price**
- **Demonstrators are important – can be suitable for “light” landers of the coming decade (e.g. Chang’E-2)**
- **Synergies with major Earth-based and orbital astronomy facilities (e.g. LOFAR, ALMA, SKA, JWST, ELT, XEUS, etc.) must be exploited**