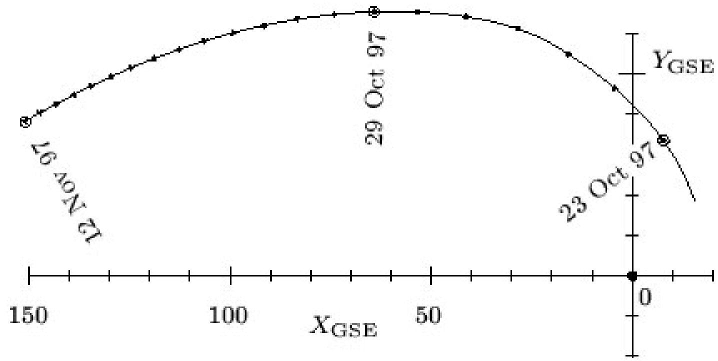
Radio astronomy from space

Graham Woan
University of Glasgow

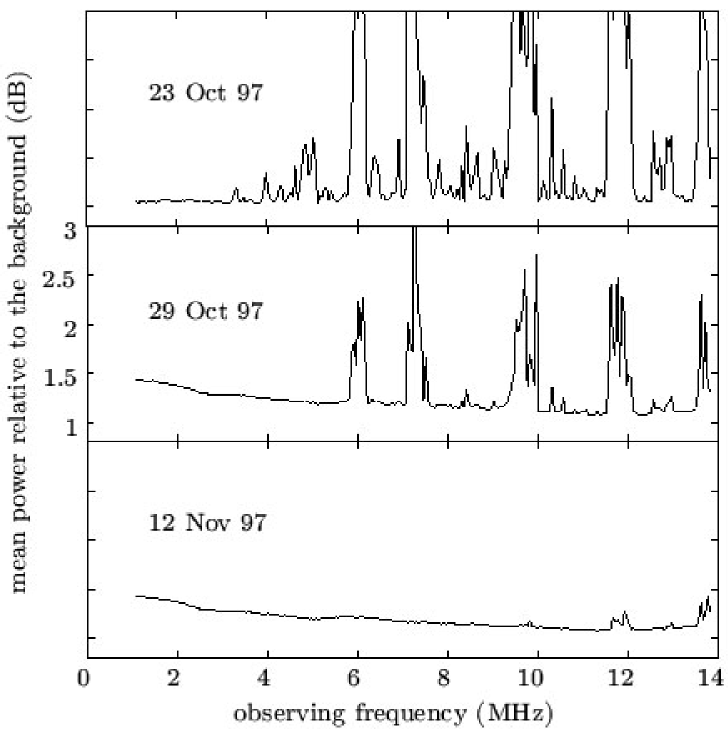
investigations

- Timeline
  - 1964 Gorgolewski identifies the far side of the Moon as a good site for VLF radio interferometry (Lunar International Laboratory Panel)
  - 1968 RAE-1 VLF Earth satellite (0.2-9.2 MHz)
  - 1973 RAE-2 VLF Moon satellite (0.02-13.1 MHz)
  - 1983 VLF radio observatory on the Moon proposed by Douglas & Smith in *Lunar Bases and Space Activities of the 21 Century*
  - 1988 Workshop: Burns et al., *A Lunar Far-Side Very Low Frequency array* (NASA)
  - 1992 Design study: *Astronomical Lunar Low Frequency Array* (Hughes Aircraft Co.)
  - 1993 Design study: Mendell et al., *International Lunar Farside Observatory and Science Station* (ISU)
  - 1997 Design study: Bely et al., *Very Low Frequency Array on the Lunar Far Side* (ESA)
  - 1998 MIDEX proposal: Jones et al., *Astronomical Low Frequency Array - ALFA* (JPL, NRL, GSFC,...)
  - 2003 GSFC workshop for the *Solar Imaging Radio Array* (*SIRA*)

terrestrial interference



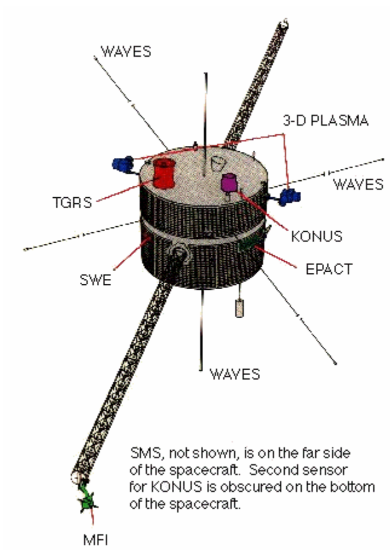
Typical man-made interference received by the WAVES instrument on Wind, averaged over 24 hours. Orbital dimensions in Earth radii.



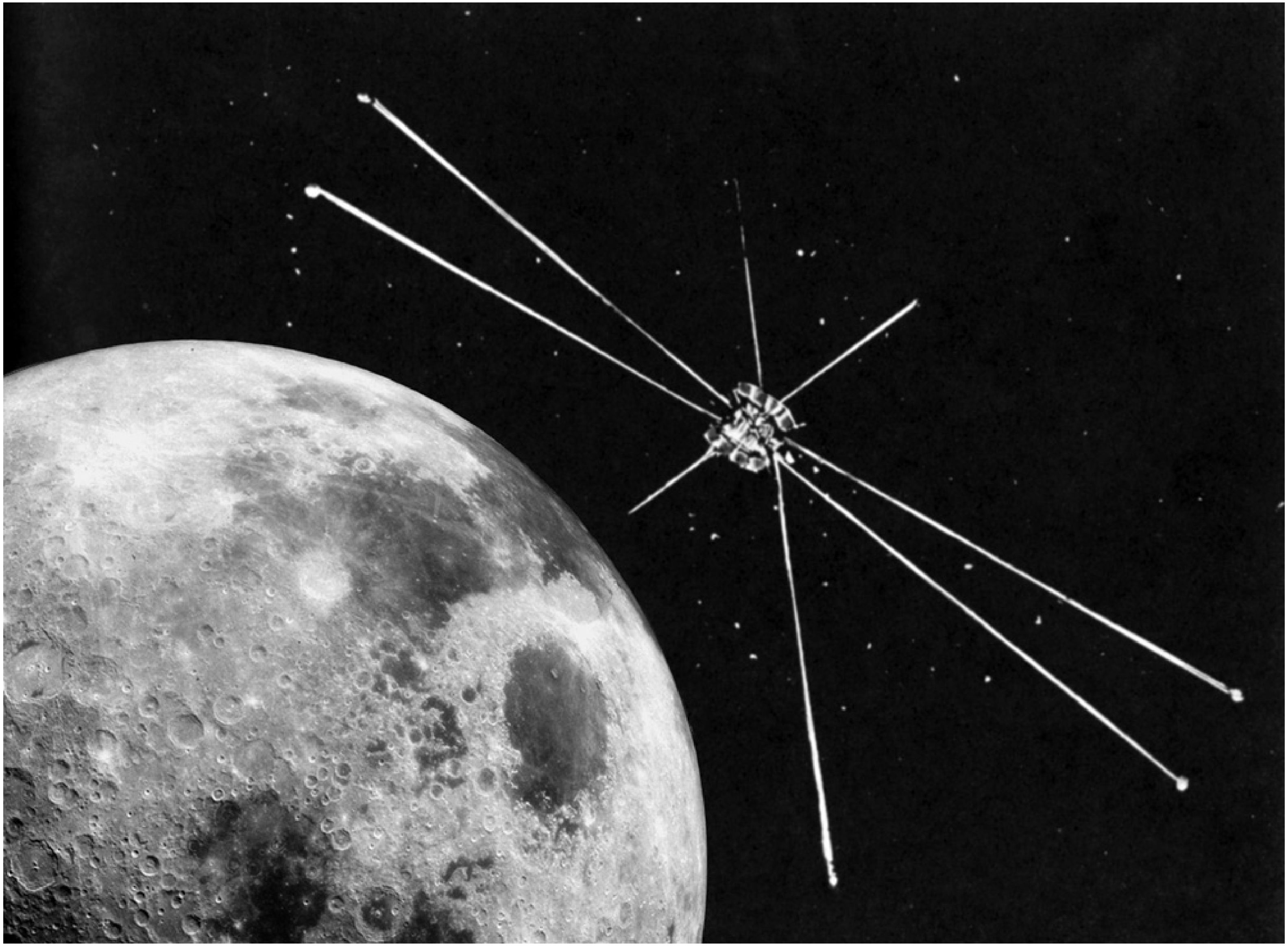
40 Earth radii

93 Earth radii

157 Earth radii



RAE-2 (1973)



RAE-2 occultation of Earth

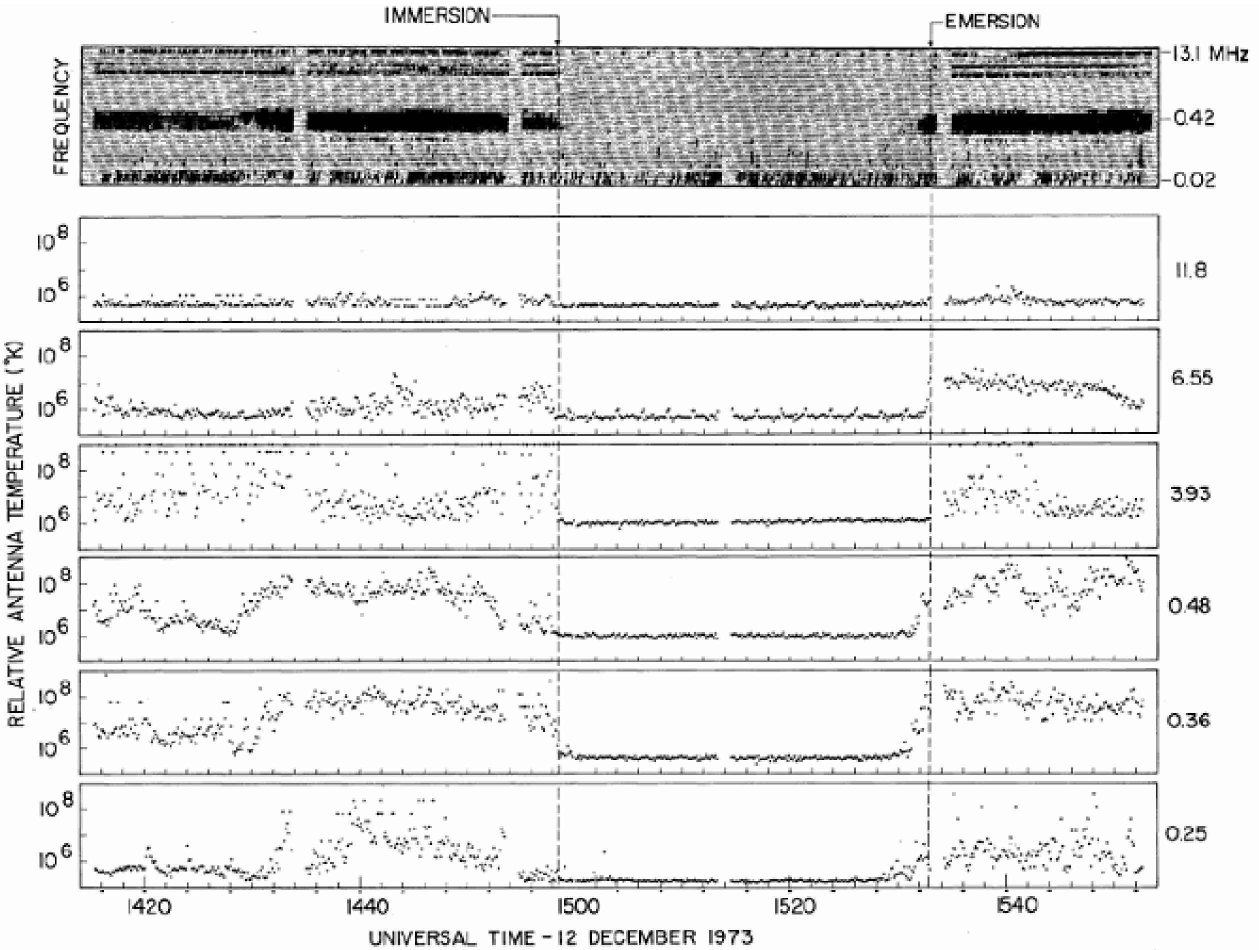


Fig. 5. Example of a lunar occultation of the Earth as observed with the upper-V burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur every 20 m are at times when in-flight calibrations occur. The short noise pulses 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 receiver and the burst receiver are tuned to the same frequency

RAE-2 occultation of a solar storm

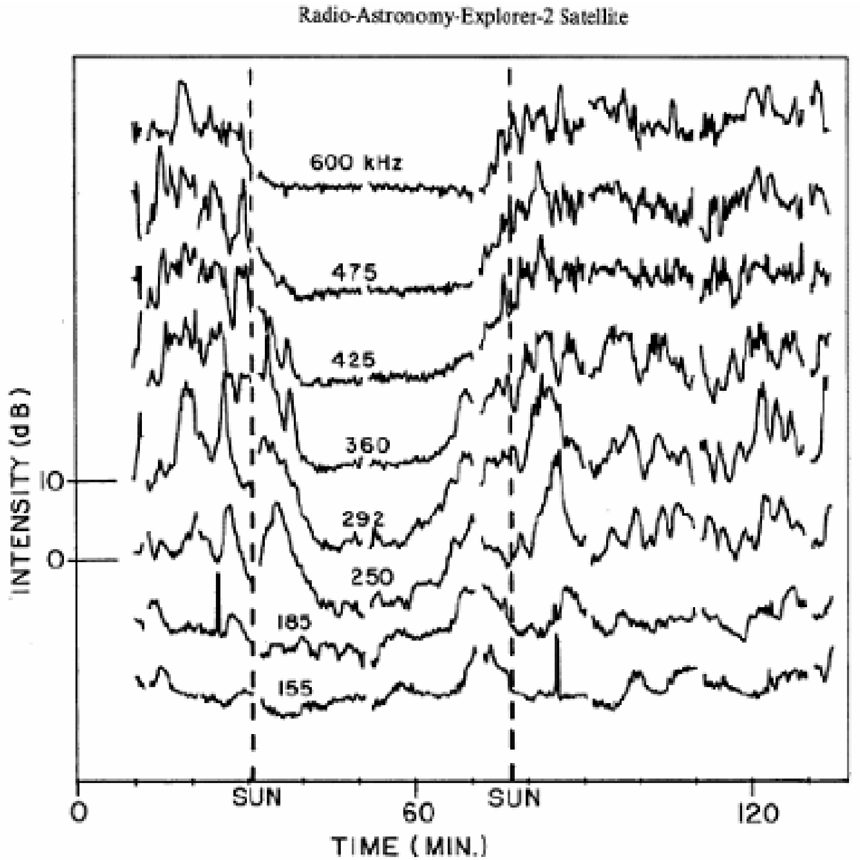
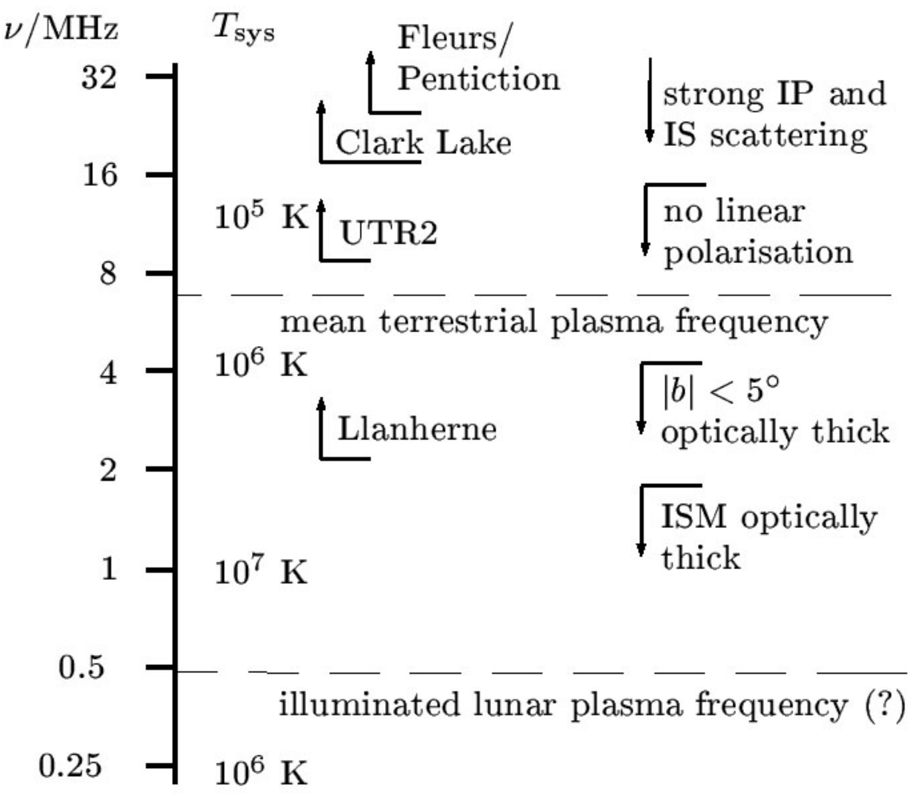
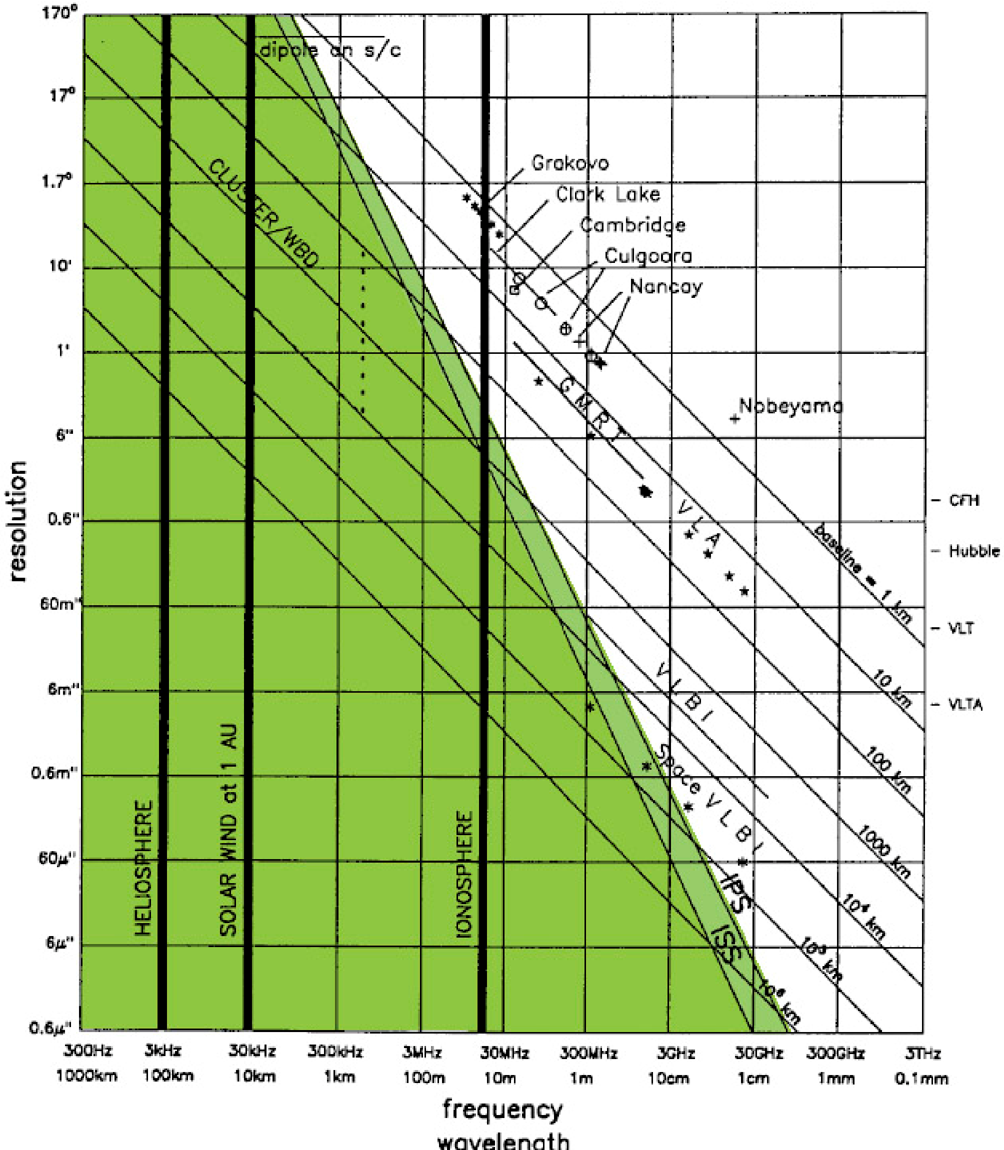


Fig. 6. Example of a lunar occultation of a solar storm (from Fainberg, 1974). The emission level scale derived from RAE-1 solar data (Fainberg and Stone, 1974) would predict that no clear occultation event should be observed below about 200 kHz since the apparent source size would exceed the size of the lunar disk as observed by RAE-2

propagation effects



interplanetary & interstellar scattering



From Bougeret 1996

- Very approximately, for strong scattering below 30 MHz, expected angular broadening is (in arcmins)

$$\text{IPM}: \quad \theta_s \approx 100/(P\nu_{\text{MHz}})^2$$

$$\text{ISM}: \quad \theta_s \approx 22/\nu_{\text{MHz}}^2,$$

where P is the closest approach to the Sun of the line-of-sight (in AU).

- The corresponding temporal broadening is very severe:

$$\text{IPM}: \quad \Delta\tau_b \approx 0.1\nu_{\text{MHz}}^{-4} \text{ seconds}$$

$$\text{ISM}: \quad \Delta\tau_b \approx 2\times10^8\nu_{\text{MHz}}^{-4} \text{ seconds.}$$

free-free absorption

- The interstellar medium becomes increasingly optically thick with wavelength due to free-free absorption in the warm component, turnover frequency:

$$\nu_{\mathrm{T}} = 5.21 \times 10^{-7} T_e^{-0.64} (\int n_e^2 \mathrm{d}x)^{0.48} \ \text{GHz}$$

With x in pc. For electron temperatures of 10^4 K and n_e of ~3×10^4 m^{-3}, the depth of view is approximately

$$l \approx (34 \nu_{\mathrm{MHz}})^{2.1} \ \text{parsec.}$$

- So the whole sky (even out of the plane) is cloudy below 1-2 MHz, though there will breaks in the clouds
- Bad for extragalactic studies, but good for ISM studies

system temperature

… dominated by galactic emission

T_{sys}	freq (MHz)
3.3×10^5	10
2.6×10^6	5
2.0×10^7	1
2.6×10^7	0.5
5.2×10^6	0.25

galactic synchrotron emission

free-free absorption

RAE-2 observations,
Novaco & Brown 1978

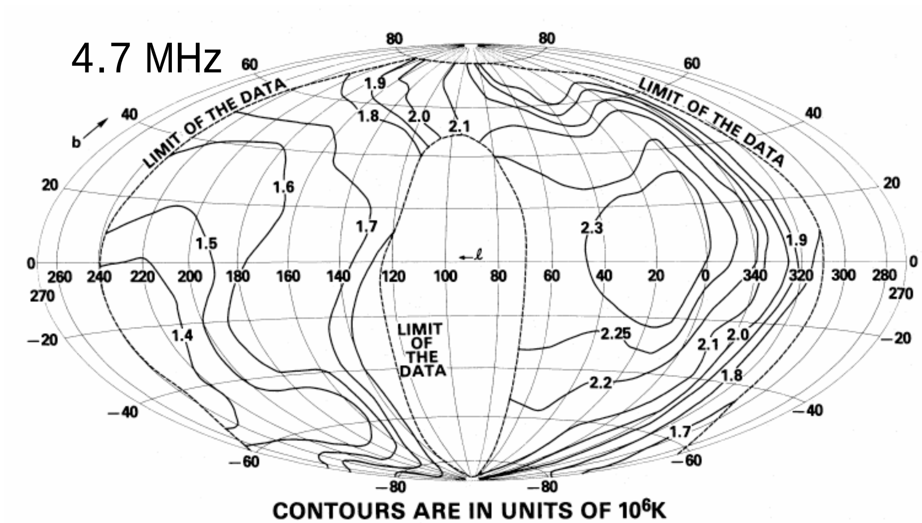


FIG. 5.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 4.70 MHz

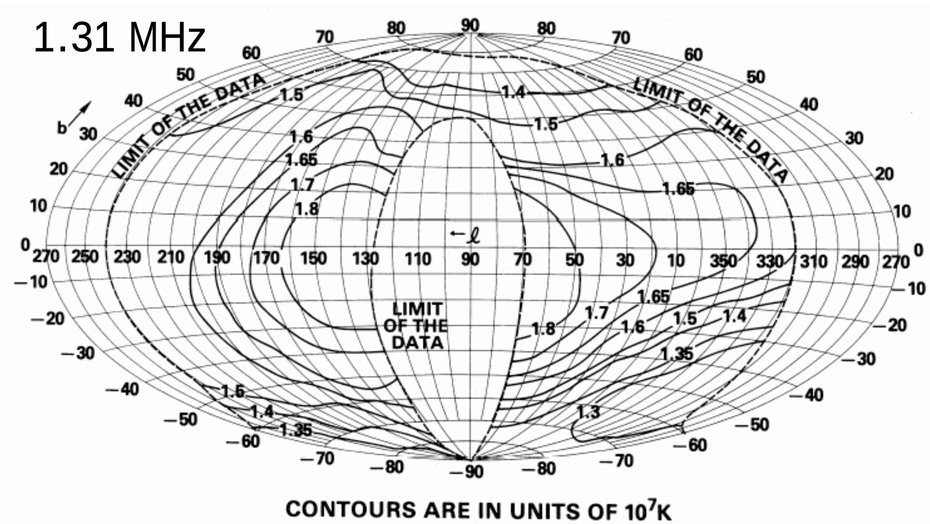
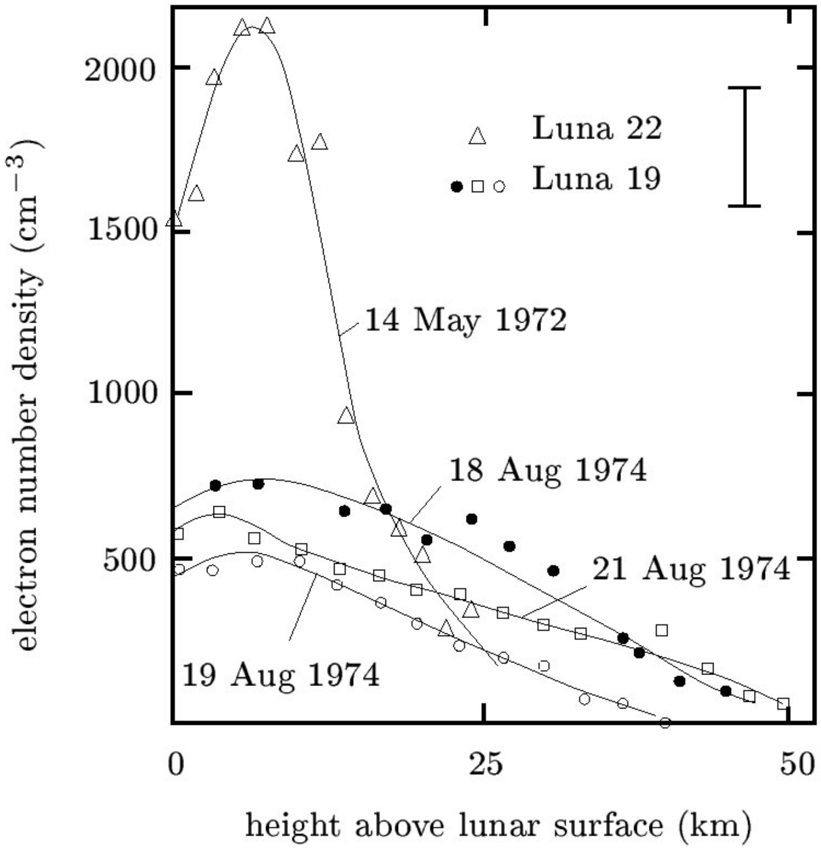


FIG. 8.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 1.31 MHz

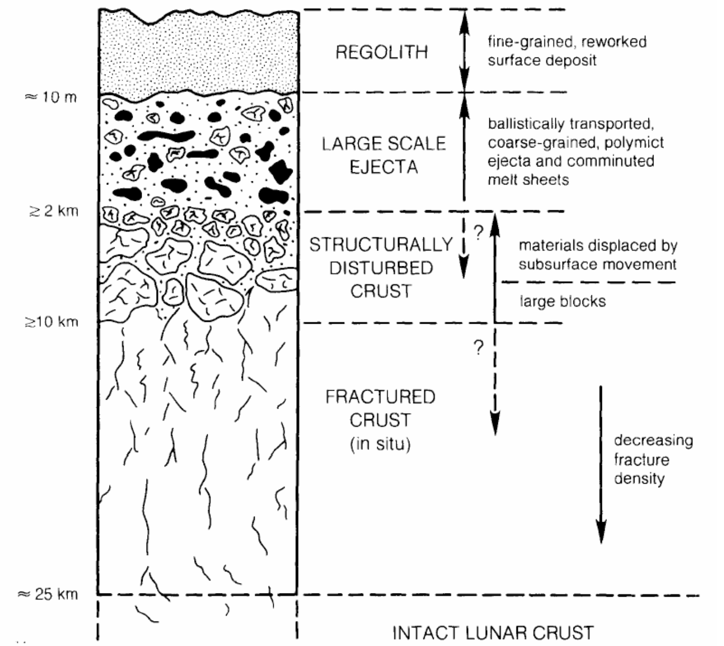
lunar exosphere

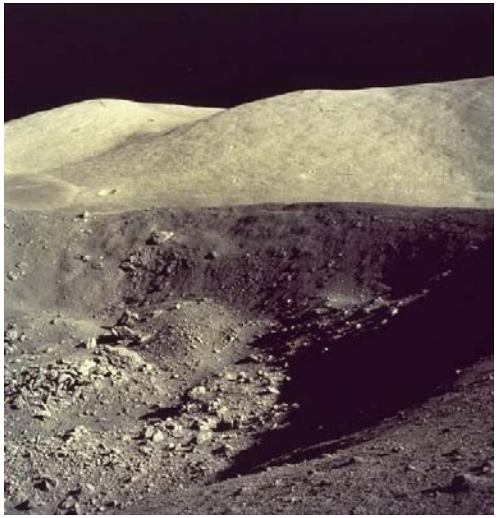


- Dual-frequency Luna spacecraft measurements give reasonably good evidence that an ionised layer, several kilometres thick, builds up on the illuminated side of the Moon (Vyshlov 1976)
- Max illuminated plasma frequency of ~0.5 MHz
- No layer seen during the lunar night

lunar regolith

- Regolith electrical properties from Apollo missions:
  - electrical conductivity ~10^{-14} /Ohm/m at d.c.
  - loss tangent ~0.001 to 0.1 at VLF frequencies
  - relative permittivity ~6
- Conductivity low enough to allow dipoles to be placed on the regolith without degrading beam pattern too severely.
- But:
  - dipole antenna pattern has largest lobe on the lunar side
  - skin depth of between 1 and 100λ (30 km at 1 MHz)
  - possible trouble for subsurface reflections (from mascons etc)





diffractive screening

Radio propagation around the Moon,
with subsurface penetration and a lunar density model

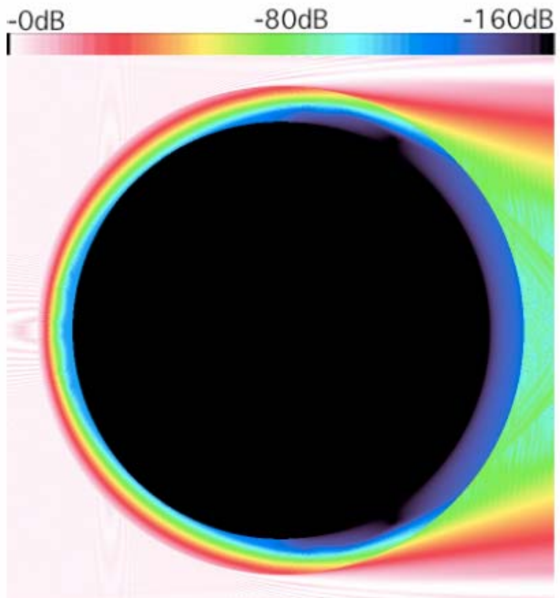


Figure 3.13: Energy density distribution around the Moon with a continuous 10-km (30-kHz) plane wave incident from the left.

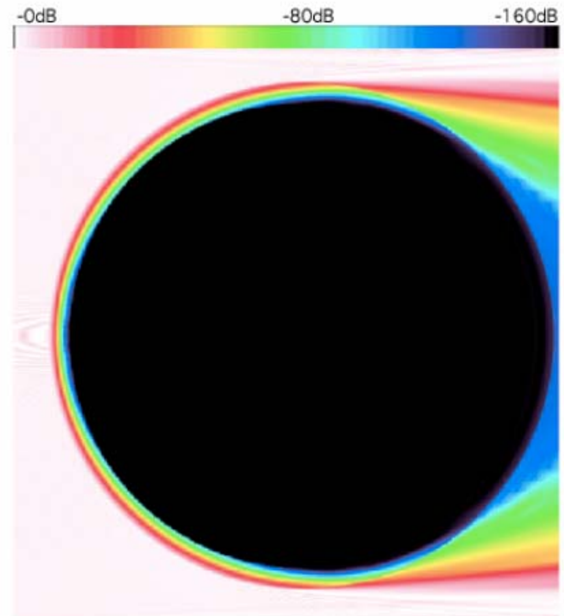
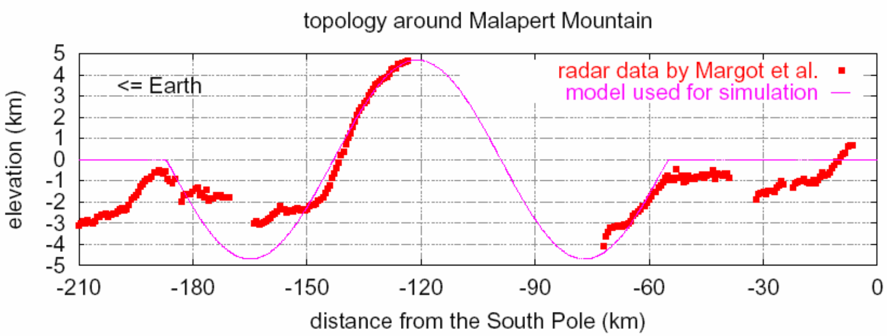


Figure 3.14: Energy density distribution around the Moon with a continuous 5-km (60-kHz) plane wave incident from the left.

Takahashi and Woan

diffractive screening

Radio propagation at the Mapert Mountain (lunar south pole),
with subsurface penetration and a lunar density model



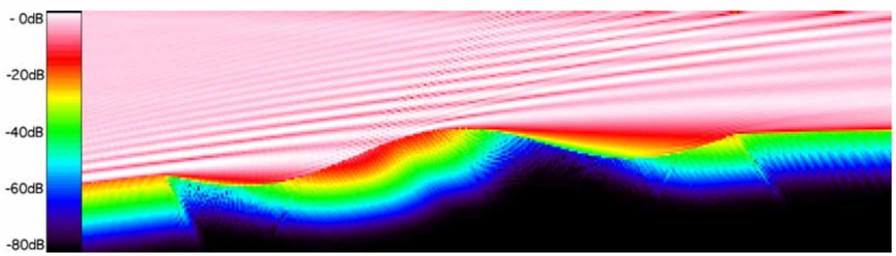


Figure 4.7: Energy density distribution for 0.5-MHz plane wave incident on Malapert Mountain from the direction of the Earth (left).

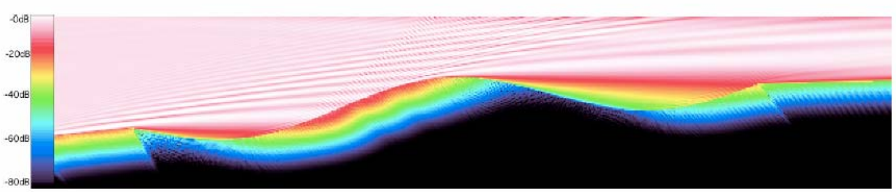
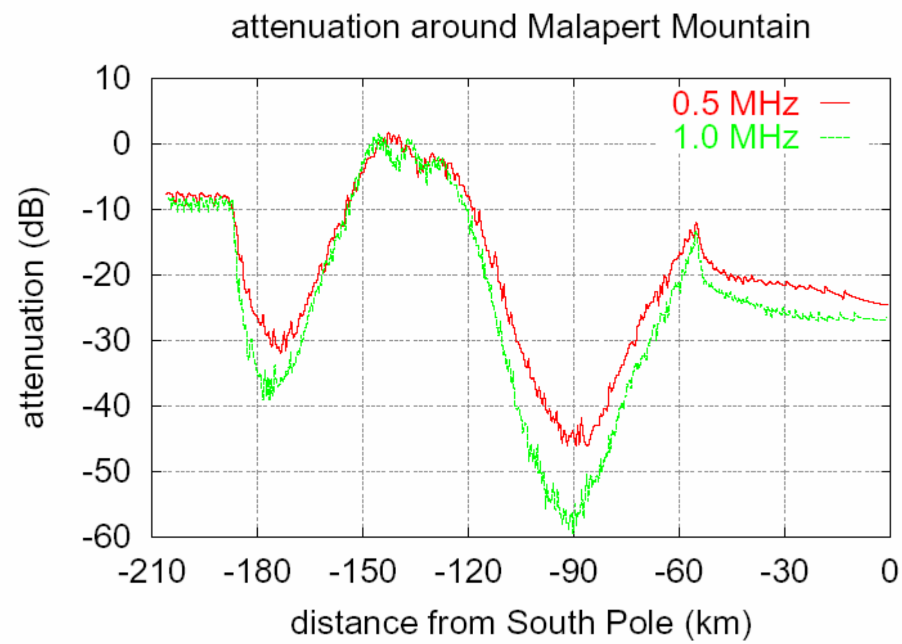
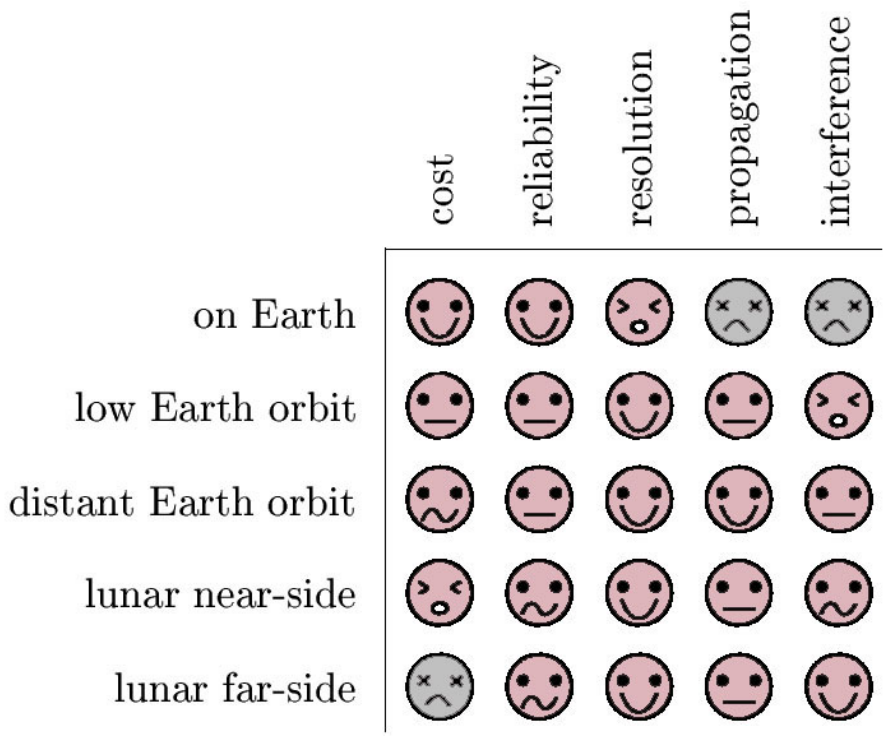


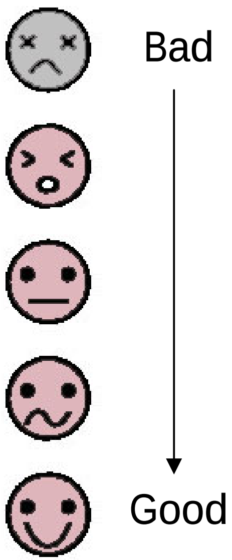
Figure 4.8: Energy density distribution for 1-MHz plane wave incident on Malapert Mountain from the direction of the Earth (left).

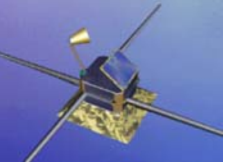


Takahashi and Woan

environments compared



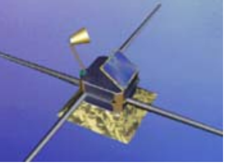




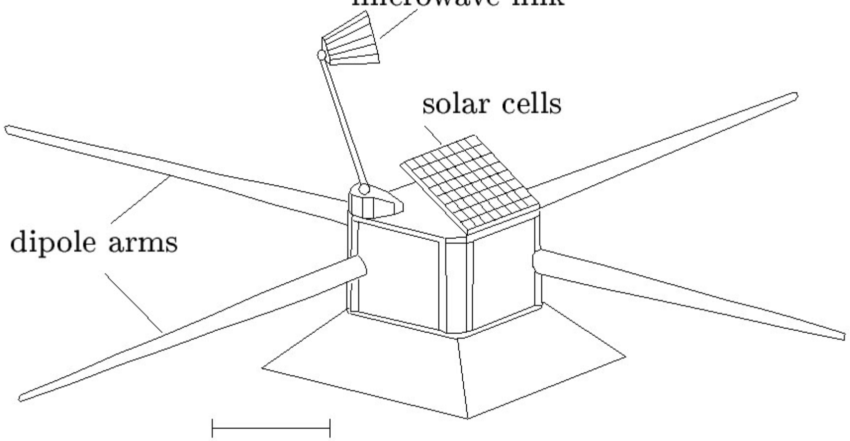
strawman mission ESA '97

- Baseline specifications for all-sky survey
  - map entire sky 500 kHz to 16 MHz in 100 kHz bands
  - minimum resolution of 0.5 degrees at 1 MHz
  - dual polarisation (though differential Faraday rotation is severe)
  - time to generate one map: 300 hours
  - sky coverage >60 percent

- Baseline specifications for solar system astronomy
  - frequency range of 500 kHz to 2 MHz: 200 bands
  - frequency range of 2 MHz to 30 MHz: 300 bands
  - 1s resolution in L and R polarisations
  - 10 ms resolution at 20 fixed frequencies
  - sensitivity of 10^{-21} $W/m^2/Hz$

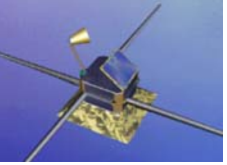


receiving element



- aluminium frame carbon fibre panels
- 2 m spring-loaded dipole booms
- silvered Teflon skirt
- 300 elements in total

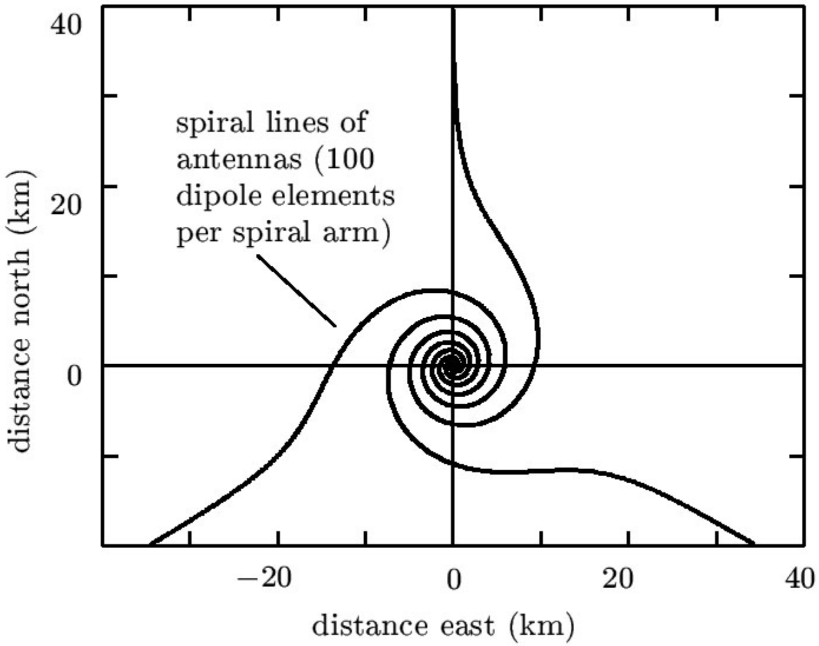
item	mass (kg)	power (W)
box	0.58	-
horn antenna and mechanism	0.50	-
battery	1.80	-
electronics	0.30	0.5
dipole	0.85	-
RF link	-	0.5
thermal control	0.16	1.0
solar panel	0.25	
contingency	0.43	
total	4.88	2

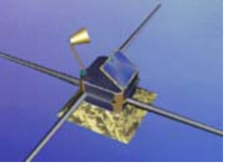


antenna arrangement

- Spiral structure maintains high filling factor (and therefore good temperature sensitivity) in inner region, without electrical overlap of dipoles at low frequencies

- Straight outer arms get high resolution for minimum arm length



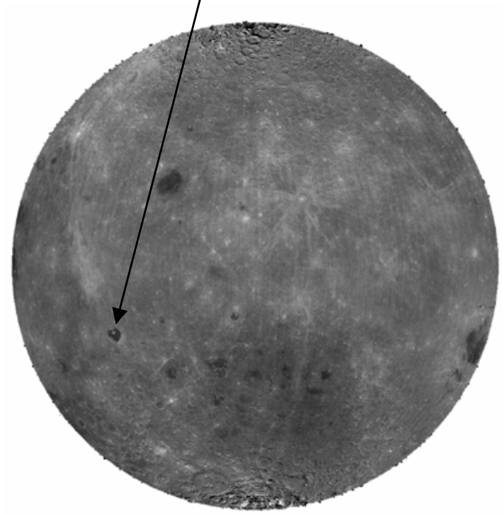


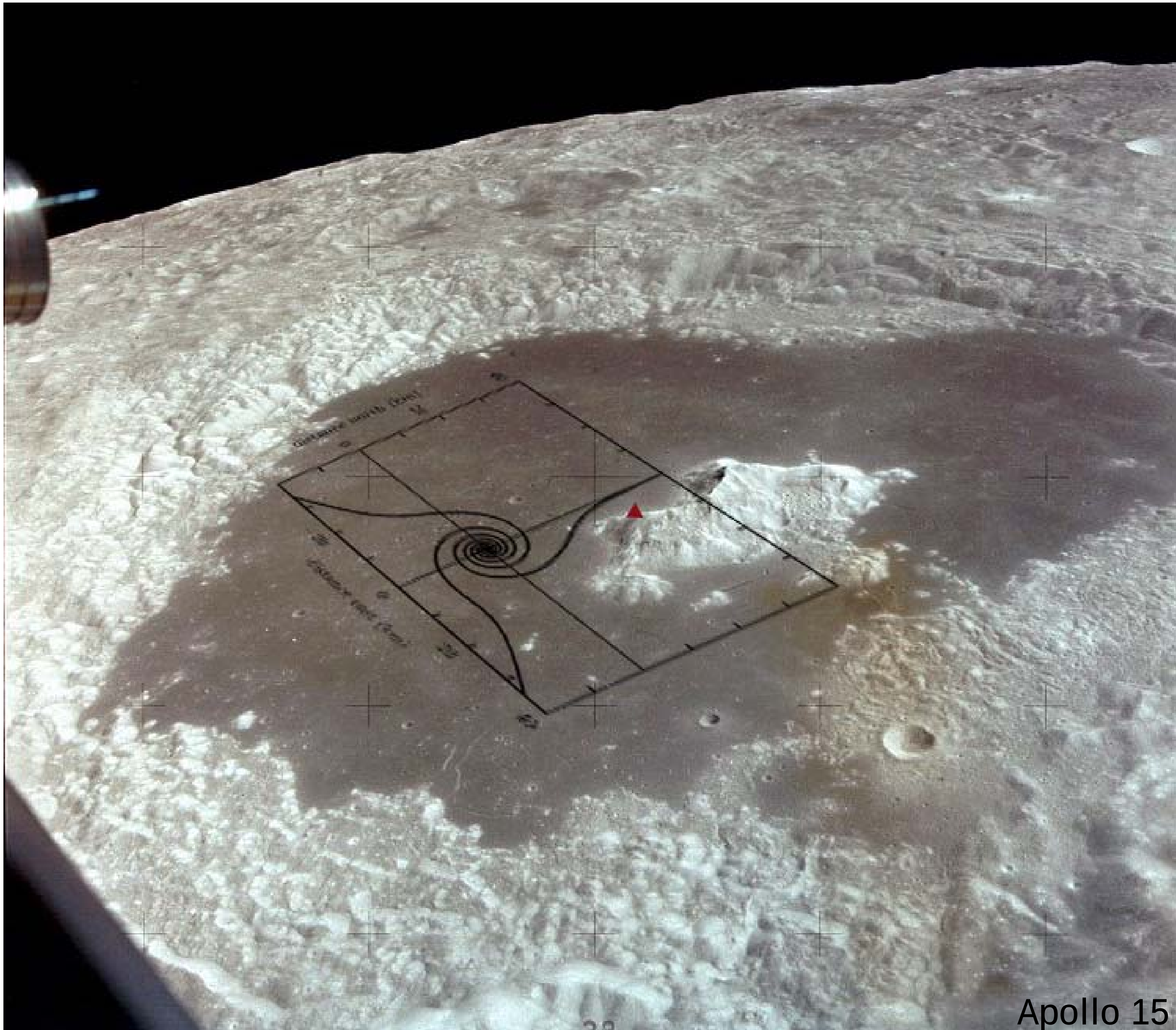
proposed site: Tsiolkovsky crater

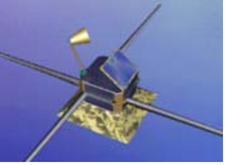
Tsiolkovsky crater

(100 km diameter)

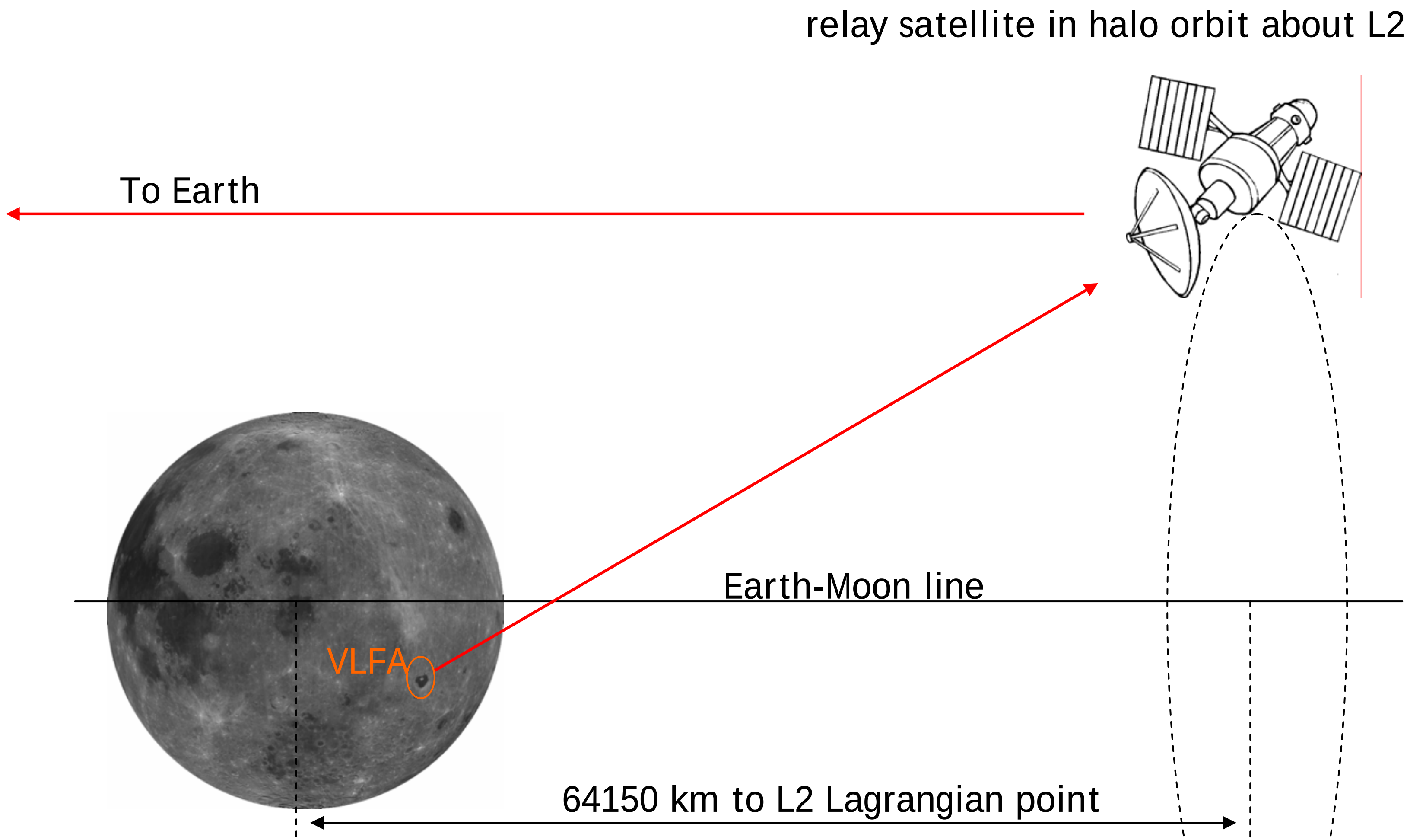
20°S 129°E



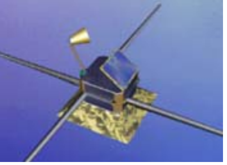




data processing and communication

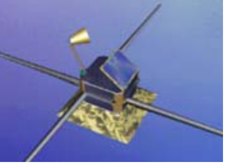


Data is correlated at the central VLFA station. This station communicates with Earth via an relay satellite in an L2 halo orbit.



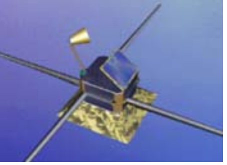
unresolved questions c1997

- What is the ionospheric environment of the Moon?
- What are the electrical properties of the regolith at the proposed site?
- What is the sub-surface structure of the Moon at the proposed site?
- What is the exact topology of the proposed site?
- What is the magnetic/plasma environment?
- What is the attenuation factor of the occulting Moon?



summary

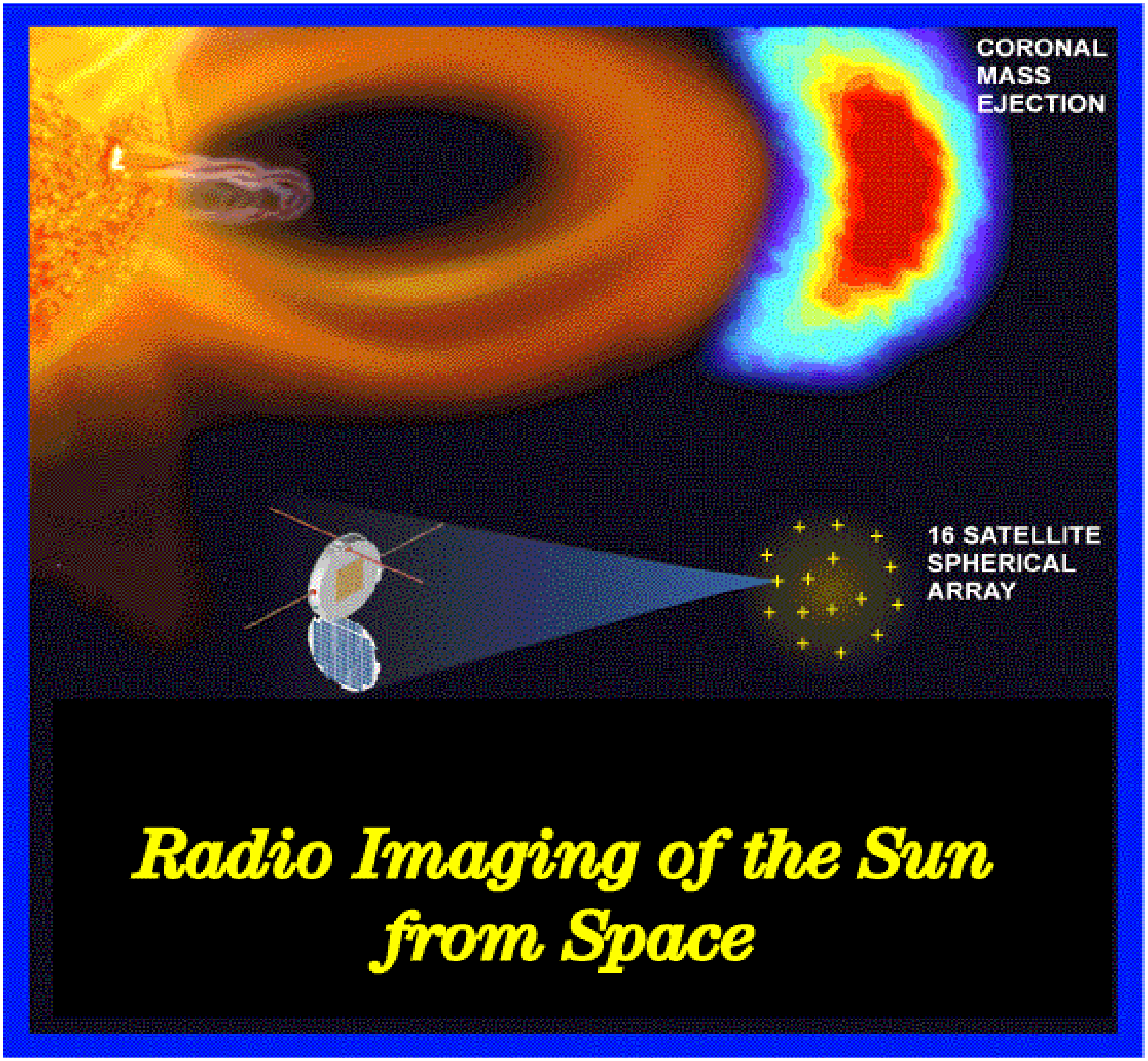
- Sky pathologies:
  - Background sky temperature is always high (~10^6 K)
  - The interstellar and interplanetary media broaden sources to about 1 degree at 1 MHz
  - Temporal broadening makes extrasolar transient work impossible (so no pulsars…)
  - Free-free absorption results in a uniformly foggy sky <1-2 MHz, but there are still things to see
  - Differential Faraday rotation limits polarisation studies
  - The lunar exosphere can (probably) be neglected if the Sun is well below the horizon



summary

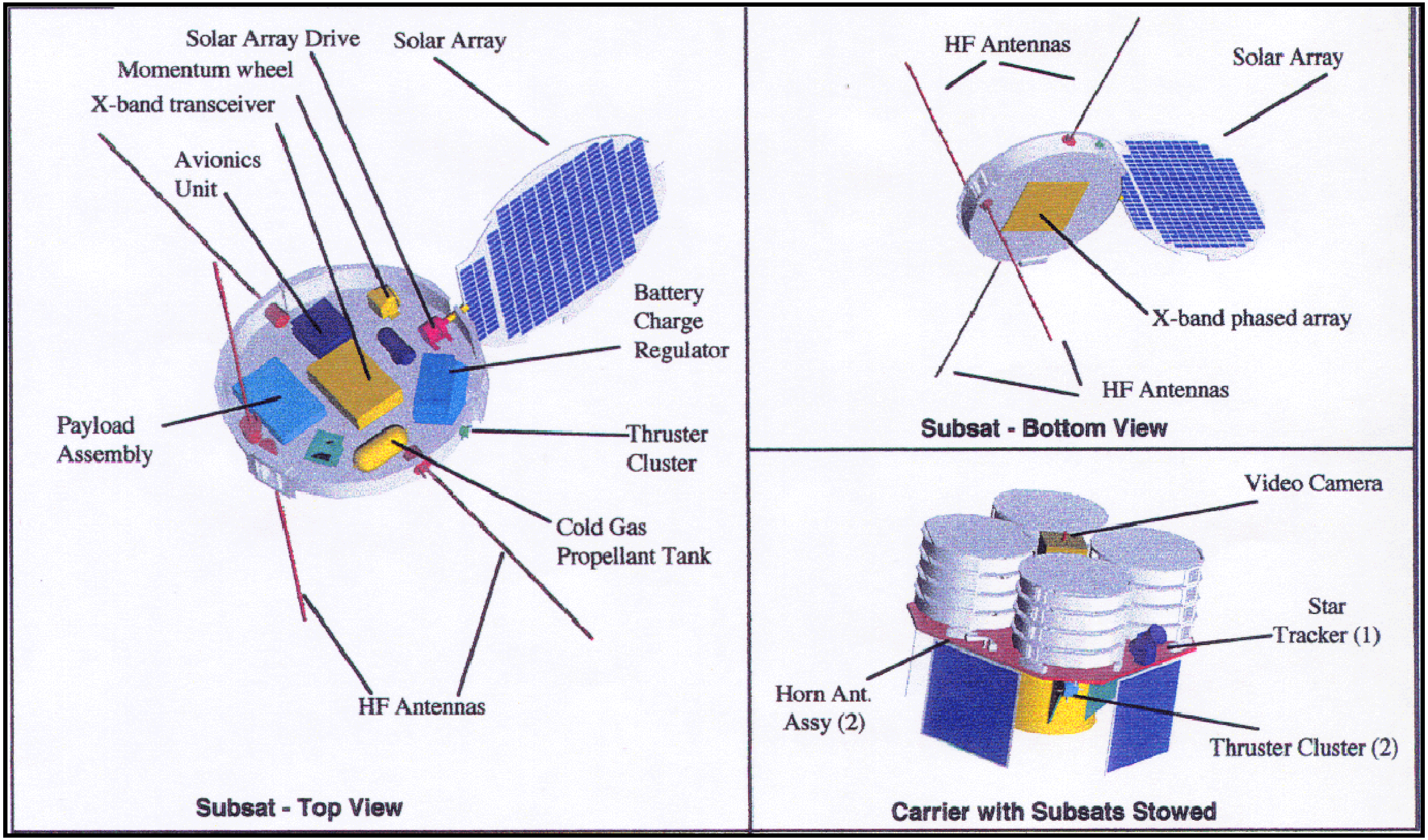
- Telescope design
  - 500 kHz to 16 MHz
  - Should be shielded from the Earth and the Sun (lunar limb or far side)
  - Use electrically-short crossed dipoles laid on the lunar regolith, but watch out for sub-surface reflections
  - ESA design had 300 dipole modules, arranged in a three-arm spiral to give a good filling factor over a range of frequencies but still able to deliver resolution at high frequencies…
  - … this has enough temperature sensitivity to map the sky to 0.25° in half a lunar day (bw 100 kHz)
  - Put the correlator on the Moon's surface and link it to Earth with an L2 halo relay satellite
  - Tsiolkovsky crater chosen for good sky coverage, good Earth shielding, and flat bottom with a central mound
  - Total mass (including central station and lander) ~2720 kg, within the capabilities of a single Ariane 5E launch
  - Estimated cost (1997)
    - Payload: 150 MAU (~150 million euro)
    - Mission (excluding lander and rover): 520 MAU

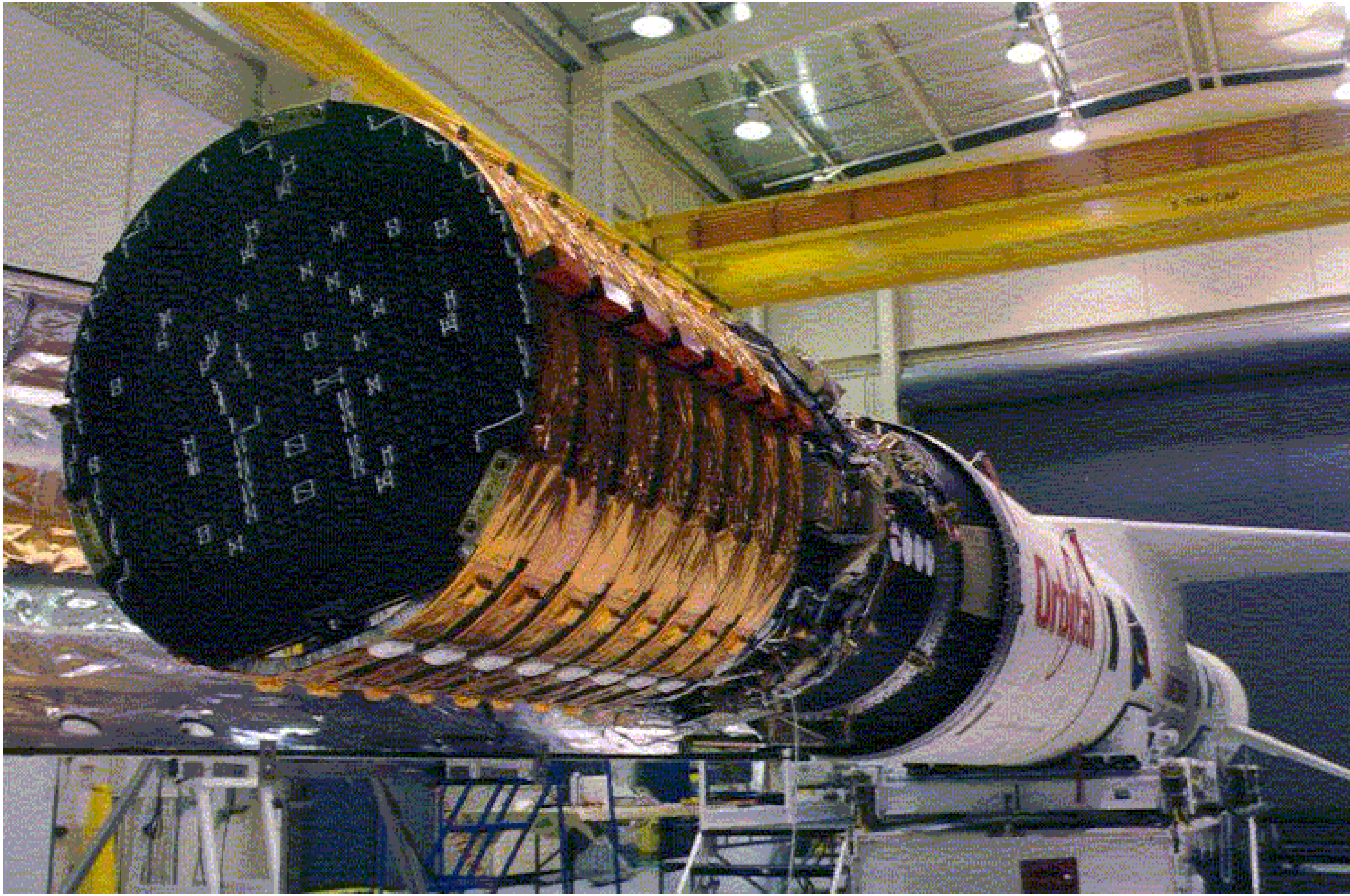
ALFA/SIRA



Astronomical
Low
Frequency
Array

ALFA microsats




Orbital