Discovering the Sky at Longest wavelengths

DAIA

SULFRO

LUWISA

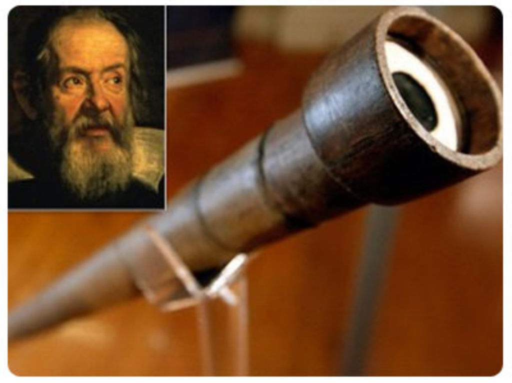
DSL: the joint Sino-European team

1. *HONG Xiaoyu, AN Tao, Willem Baan et al*., ShAO/CAS, China
2. *YAN Jingye, ZHENG Jianhua, CHEN Ding et al*., NSSC/CAS, China
3. WU Xiangping, *CHEN Xuelei, LI Di, YAN Yihua, HUANG Maohai, CHEN Linjie et al*., NAOC/CAS, China
4. *Albert-Jan Boonstra, Michael Garrett et al*., ASTRON, NL
5. *Leonid Gurvits*, JIVE & TU Delft, NL
6. *Heino Falcke, Marc Klein-Wolt et al*., Radboud University, NL
7. *Leon Koopmans*, Groningen University, NL
8. *Mark Bentum*, Twente University, NL
9. *Baptiste Cecconi, Philippe Zarka*, Observatoire de Paris, France
10. *Reza Ansari*, Université Paris Sud & LAL, France
11. *Andrea Ferrara*, SNS, Pisa, Italy
12. *Hanna Rothkaehl*, Space Research Center, Poland
13. *Jan Bergman*, Institute of Space Physics, Uppsala, Sweden
14. *Graham Woan*, University of Glasgow, UK

plus supporting scientists and engineers (100+) from 17 countries

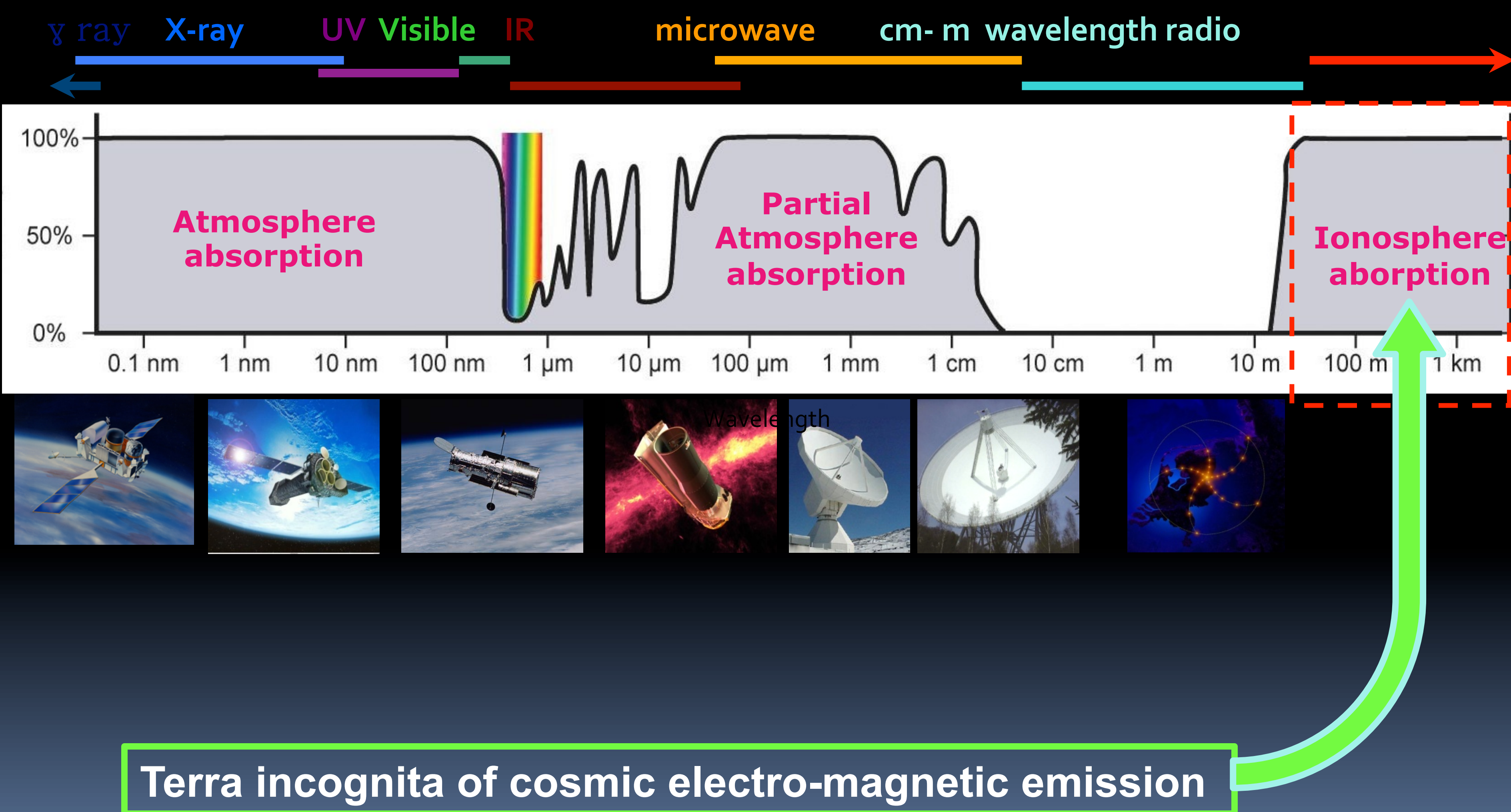
Two revolutions in astronomy

- Introduction of a telescope, Galileo Galilei, 1609



- Multi-wavelength astronomy, end of XIX century
  - UV – 1890s
  - Radio (meters wavelengths and shorter) – 1930s
  - X-rays – 1940s
  - IR and sub-mm – 1950s
  - Gamma-rays – 1960s
- The last remaining unopened window at decameter and longer wavelengths (frequencies below ~30 MHz)
- Our intention is to conclude the second revolution!

Why ULWA (radio!) in Space?



Ultra-Long-Wavelength studies/initiatives

- 1964: S. 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,…)
- 1999-2012: Boonstra, Falcke et al., several studies of orbital and Moon-based ULWA missions

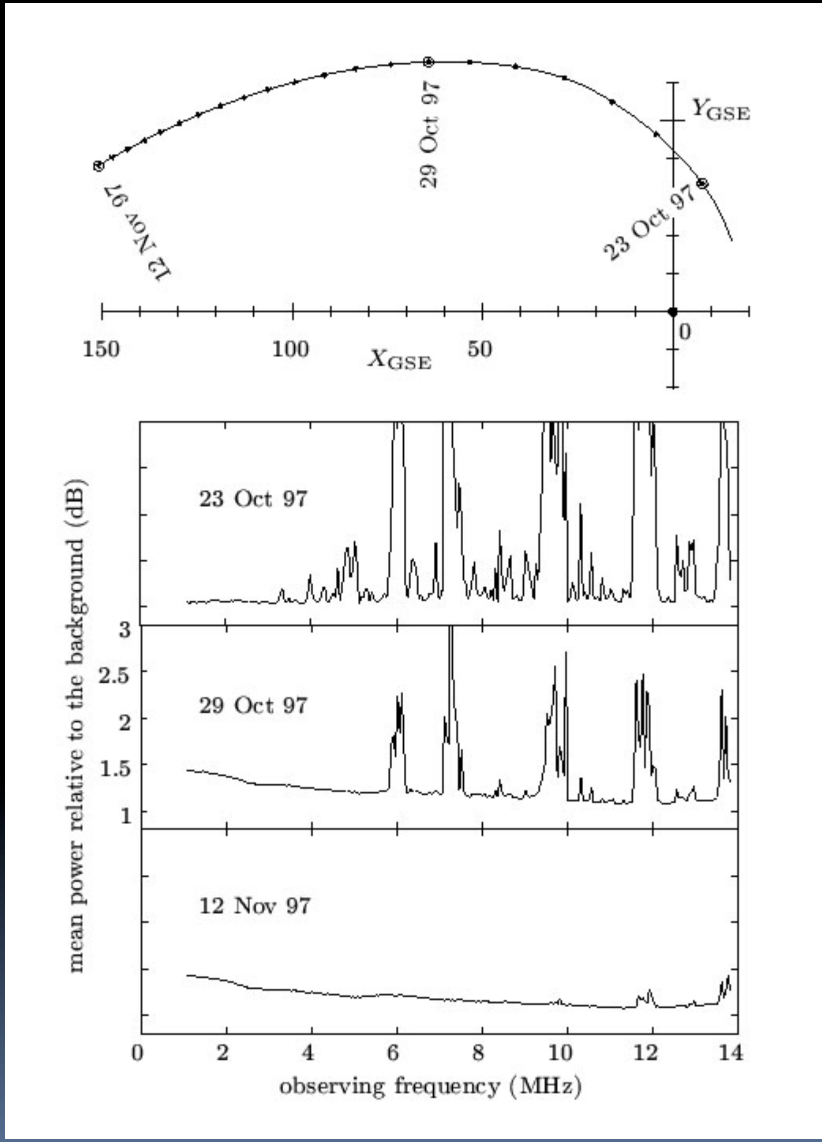
DSL major specifications

- Wavelength/frequency range:
  - *mandatory: 300 – 10 m 1 – 30 MHz*
  - *desirable: 1 km – 10 m 300 kHz – 30 MHz*
  - *optional: 3 km – <10 m 100 kHz – >30 MHz*

- Imaging capability:
  - *mandatory: Dynamic Range (DR) 300:1*
  - *desirable: DR 1000:1 (or confusion-limited)*
  - *optional: DR>3000:1 (or confusion-limited)*

- Spectral resolution, $f/\Delta f \geq 250$

Terrestrial interference

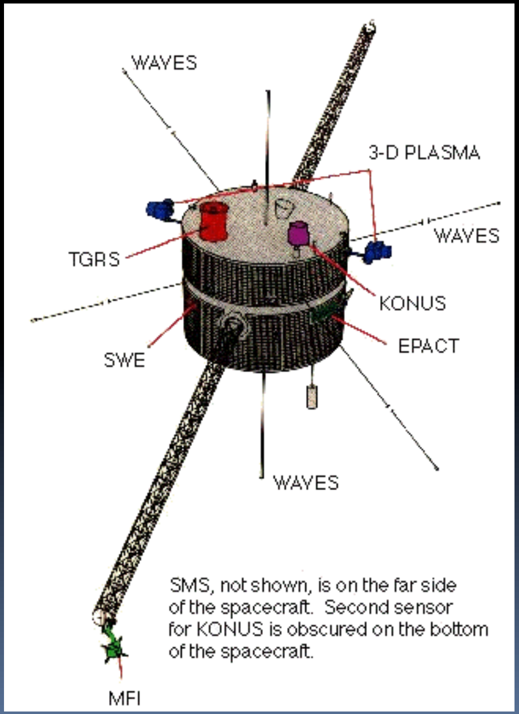


Typical human-made interference received by the WAVES instrument on Wind, averaged over 24 hours. Orbital dimensions in Earth radii.

40 Earth radii

93 Earth radii

157 Earth radii



…and if you don't trust this plot, watch "Contact" the movie, the first 1 min.

RAE-2 occultation of Earth

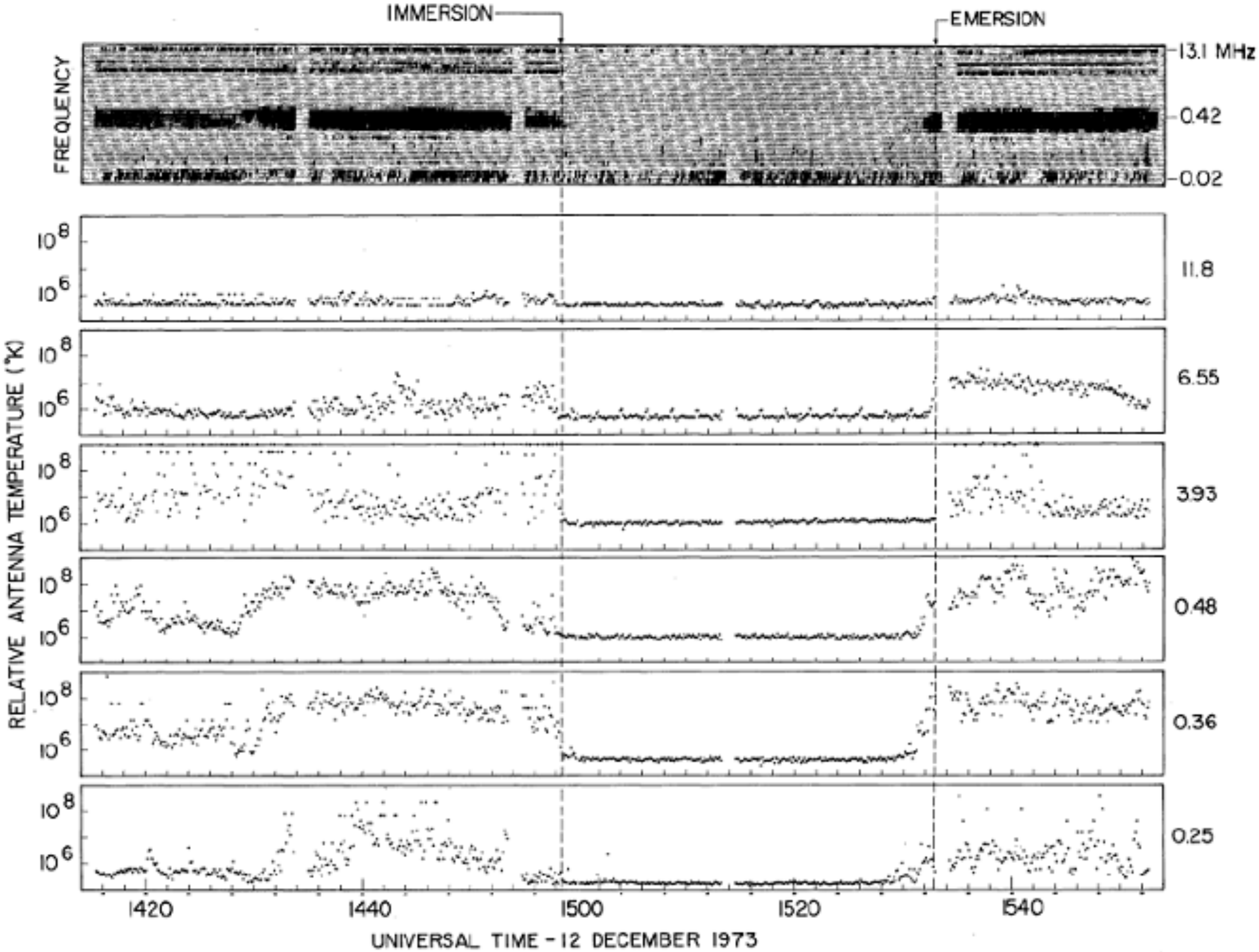
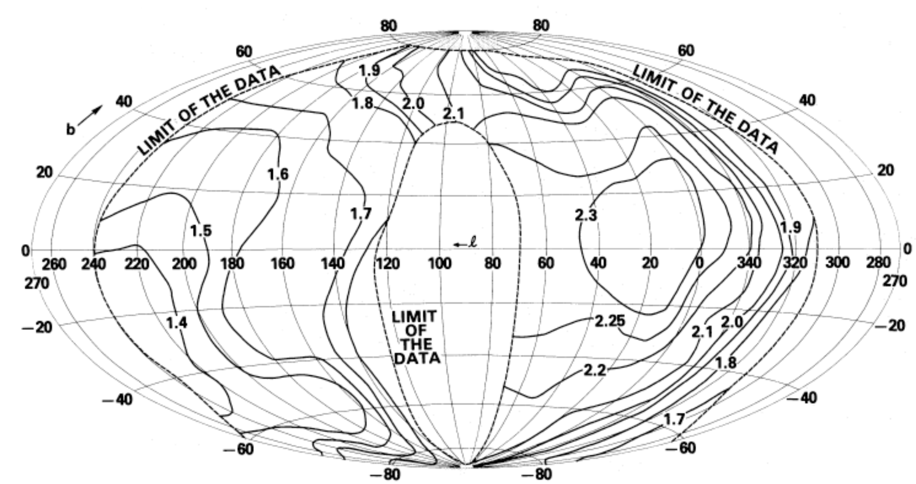


Fig. 5. Example of a lunar occultation of the Earth as observed with the upper-*V* burst receiver. The top frame is a computer-generated dynamic spectrum; the other plots display intensity vs. time variations at frequencies where terrestrial noise levels are often observed. The 80-s data gaps which occur every 20m 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

System temperature … dominated by sky emission

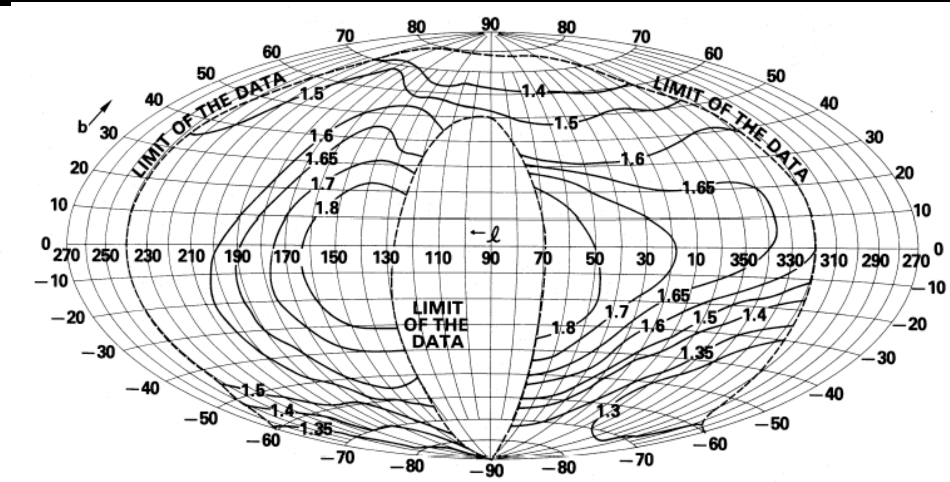
T_{sys}	freq (MHz)	
3.3×10^5	10	galactic synchrotron emission
2.6×10^6	5	
2.0×10^7	1	
2.6×10^7	0.5	free-free absorption
5.2×10^6	0.25	

RAE-2 observations,
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

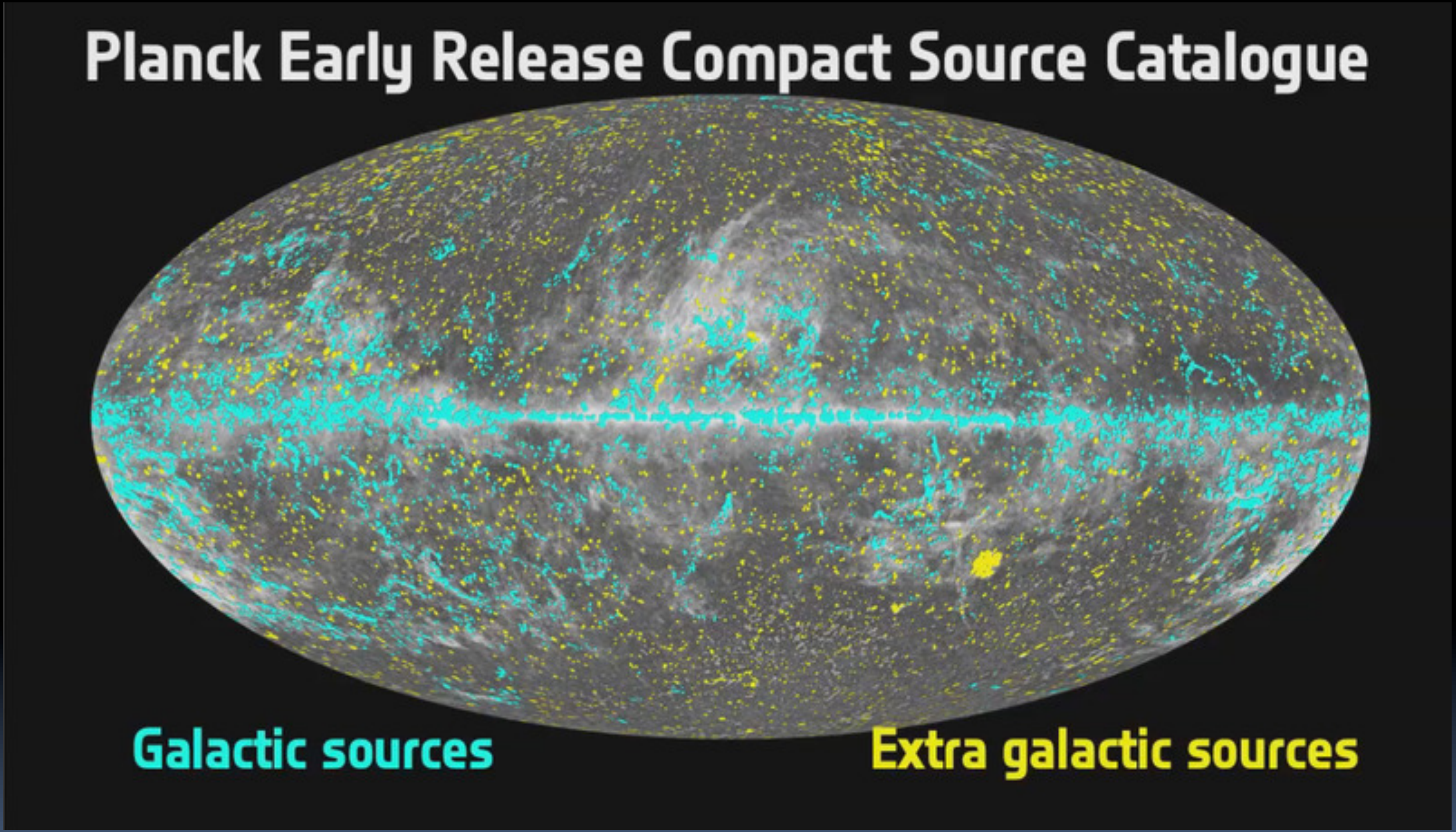
FIG. 8.—Contour map in galactic coordinates of the nonthermal emission observed by *RAE 2* at 1.31 MHz

DSL objectives

- ***<u>Prime</u>:*** pioneering studies in the hitherto unexplored window of the cosmic EM spectrum
  - Full sky continuum survey of discrete sources:
    - *Ultra-steep spectrum extragalactic sources*
    - *Pulsars*
    - *Transients (galactic and extragalactic)*
  - Full sky map of (galactic) continuum diffuse emission
  - Search for signatures of Dark Ages
  - Recombination radio lines (of “macro-atoms”)?
  - Search for “exo-Jupiters”
  - Solar-terrestrial physics
  - Radio-showers from high-energy particles (and neutrinos) interacting with Moon

- **<u>Above all</u>**, a lesson of science history:
  - Discovery of unknown

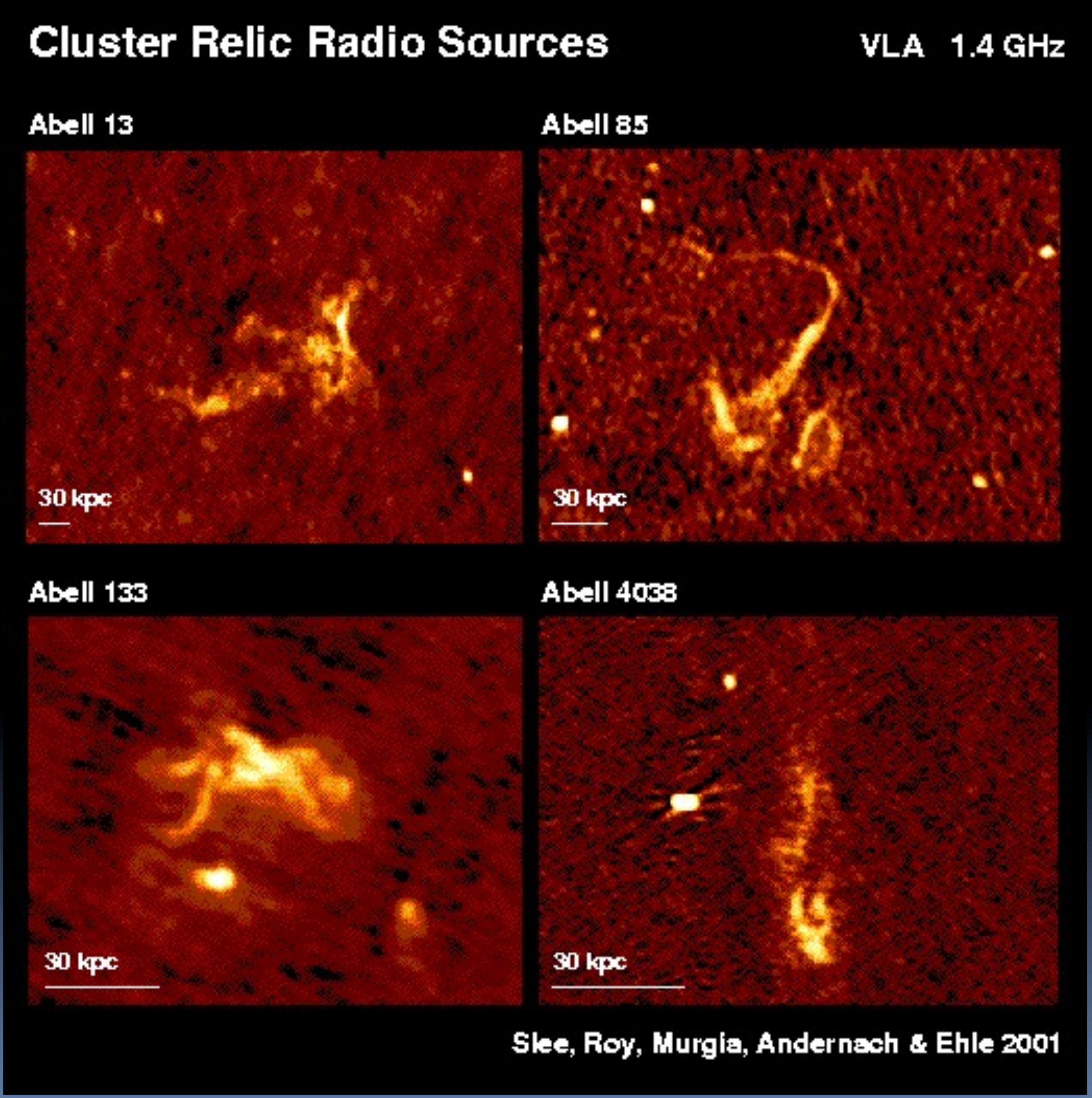
Survey of discrete continuum sources



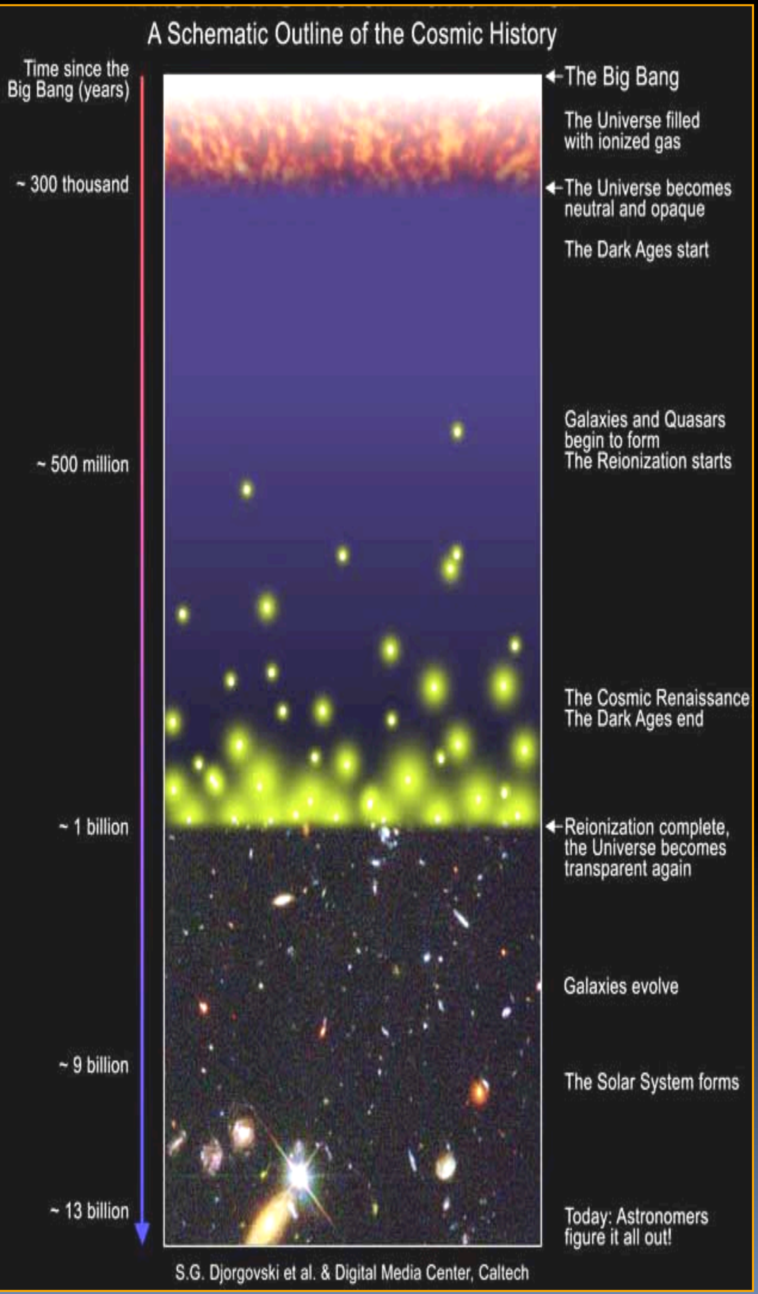
- Classification/statistics (*log*N-*log*S) of sources at frequencies <10 MHz
- Their spectral properties (synchrotron selfabsorption, evolution)

Fossil extragalactic radio sources

- When quasars die, they leave relic plasma.
- The plasma forms buoyant steep-spectrum bubbles.
- They may be revived and refreshed at outer shocks produced in large scale structure formation of the universe and cluster mergers (Ensslin et al. 1998; Ensslin & Brüggen 2002).
- ULWA is the most efficient domain for their studies

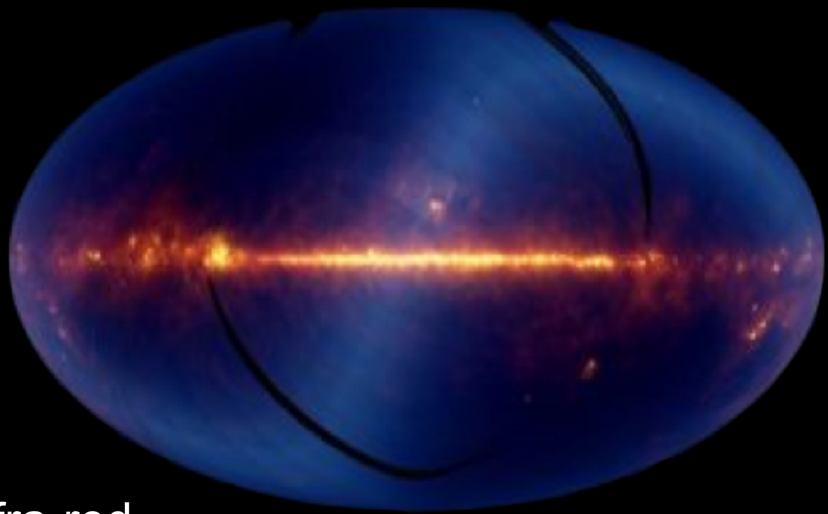


Evolution of the Universe (as guessed today)

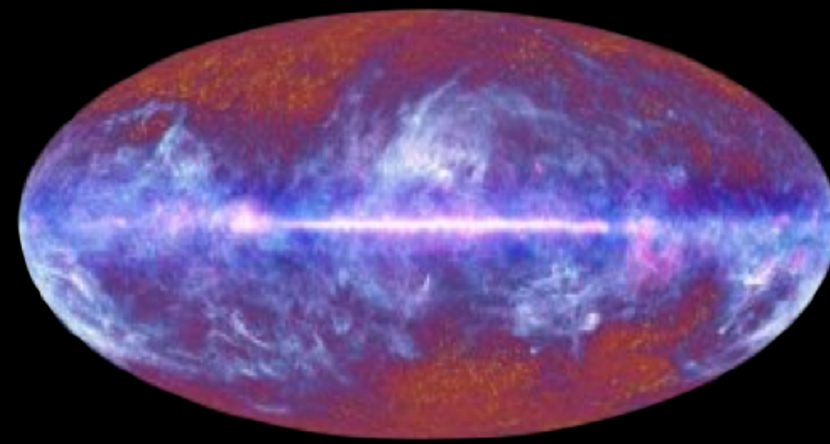


- Dark Ages: $z \sim 30–200$; IGM thermal evolution
- First Stars: $z \sim 20–25$?; heat/ionize the IGM via UV emission
- First Black Holes: $z \sim 15–10$?; heat the IGM via X-ray emission
- A Quiet Era: $z \sim 10–12$; may require *fine tuning*
- Reionization: $12 <\sim z < 6$ (SDSS Gunn-Peterson; WMAP, LOFAR, MWA, LWA)

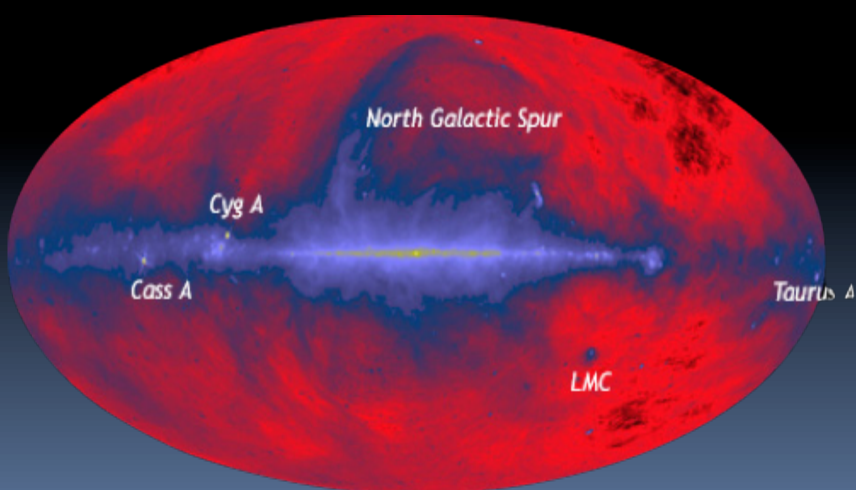
Milky Way in all "colours" – magnetism



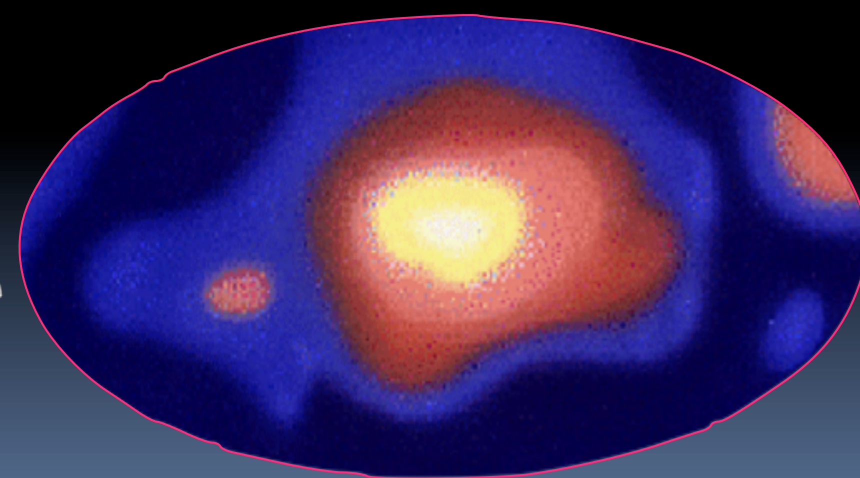
Infra-red



cm wavelengths



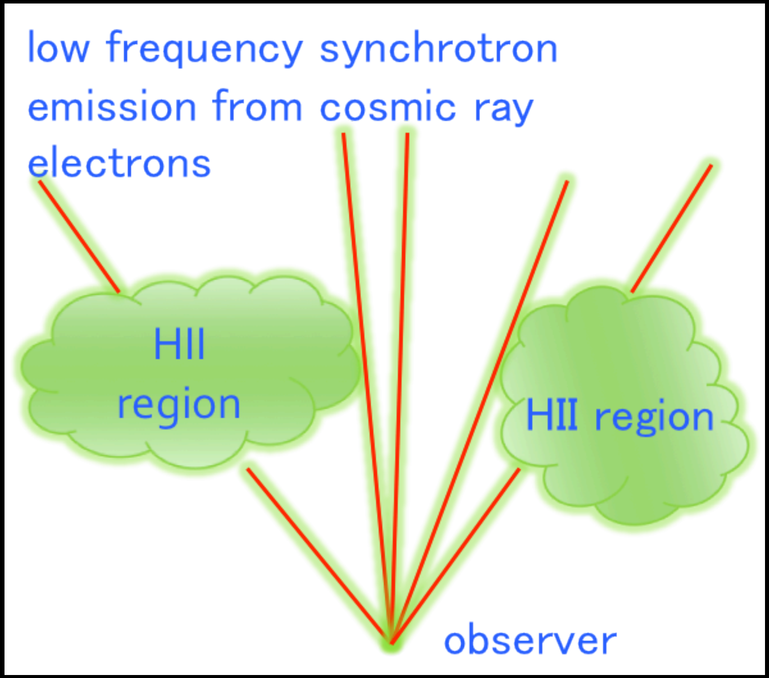
75 cm



hypothetic decameters

Interstellar Medium and Origin of Cosmic Ray

With absorption by interstellar free electrons can probe WIM structure



HII region is opaque to low frequency (a few MHz) synchrotron emission from cosmic ray electrons. So, observing the HII region enables determination of cosmic ray in that short l.o.s., helps address the quest on the origin of cosmic ray.

Ultra-High Energy CR & Neutrinos

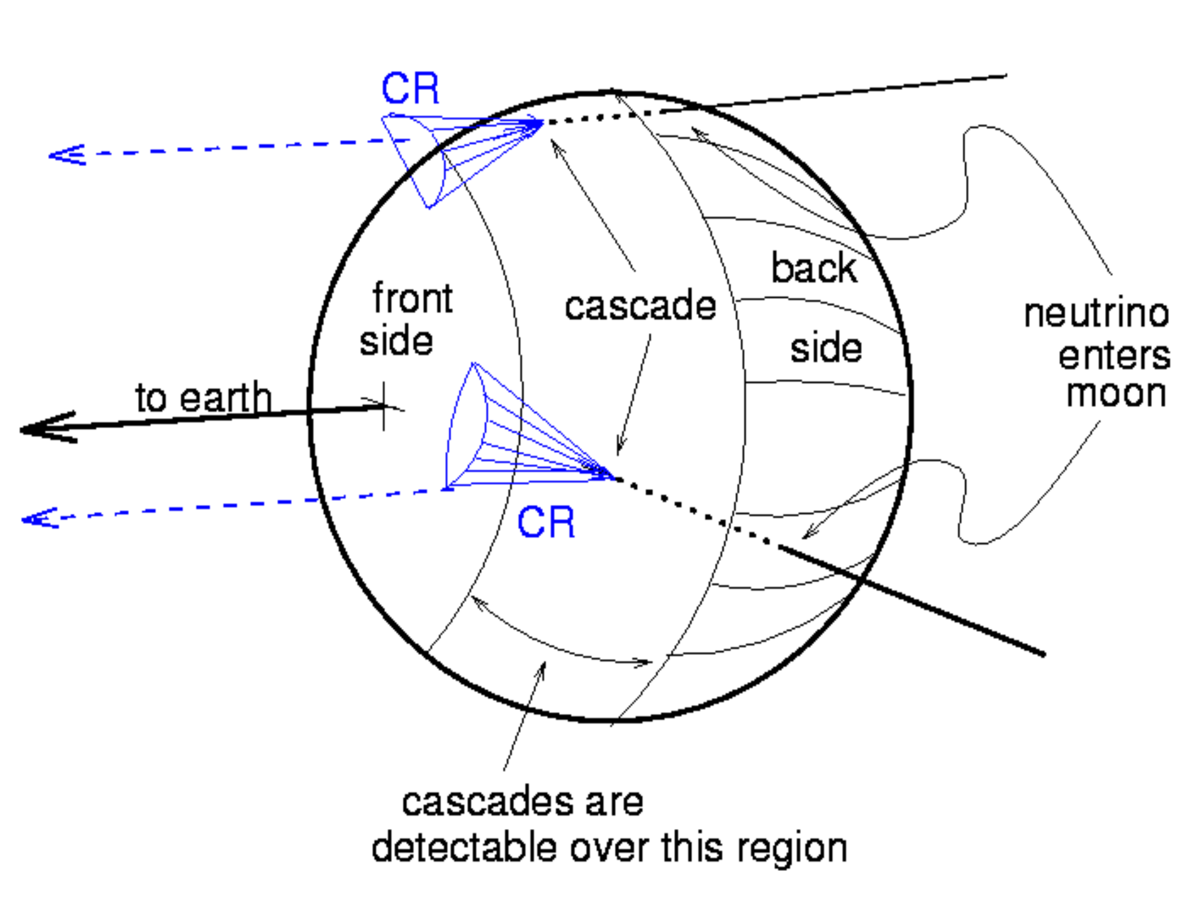
- **Astroparticle physics crown jewels**: Ultra-high energy elementary particles with energies a billion times higher than at CERN!
- They are rare and one needs a large detector volume …
- Particles hitting the Moon produce detectable **radio Cherenkov** emission.

⇒ The **Moon is by far the largest particle detector** available for astroparticle physics!

⇒ Best data from radio obs.

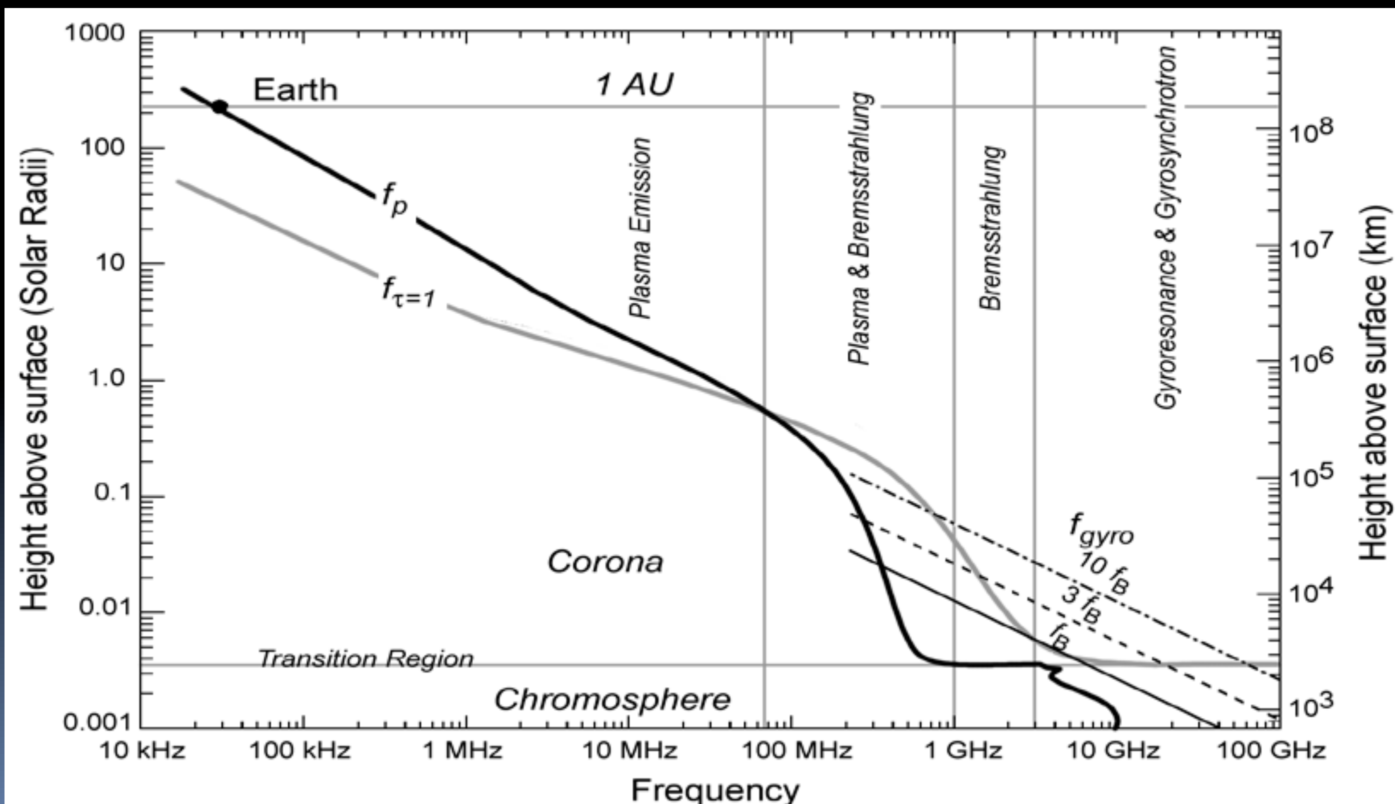
⇒ We need to understand the Moon …

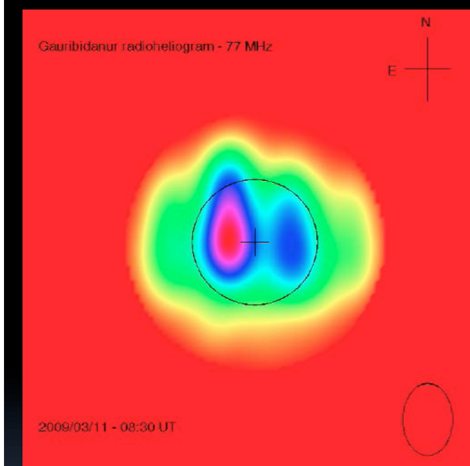
Radio emission from neutrinos hitting the Moon



Heliophysics

- Imaging Solar activity at lower frequencies <10 MHz), resolution >10 pixels
- Imaging Type II (slow) & III (rapid) bursts
- Optional: imaging & tracking of CMEs beyond Earth distance
- Coupling of different solar processes



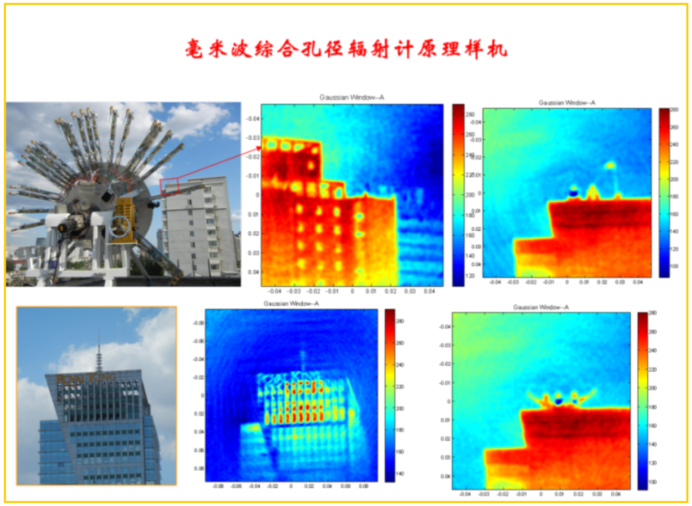


Ground-based image at 77 MHz

Outline

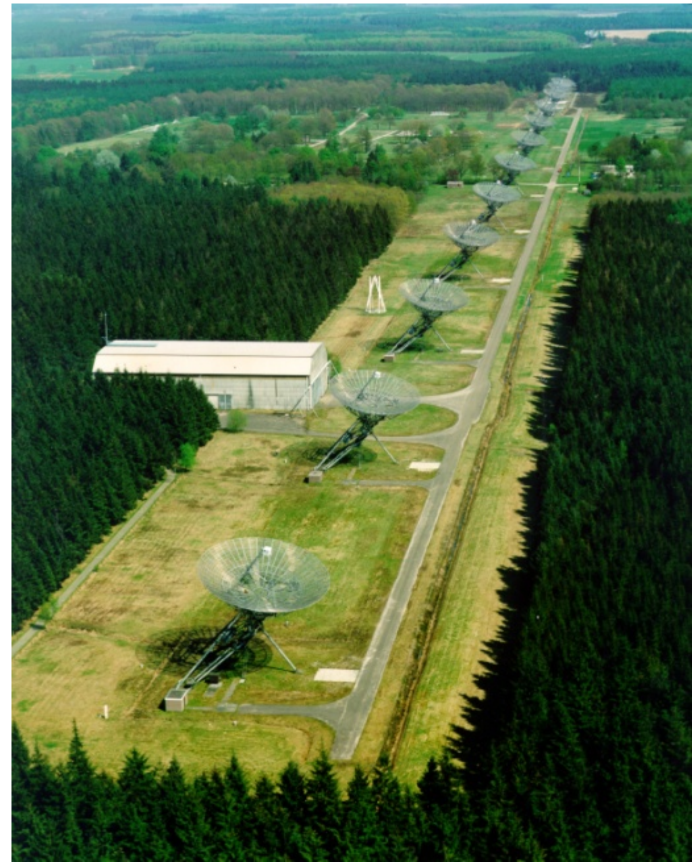
- Science objectives
- Suggested payload
- Mission concept
- Heritage from previous studies/missions
- Summary

Suggested Payload
Interferometric Array onboard nano-sat flying formation



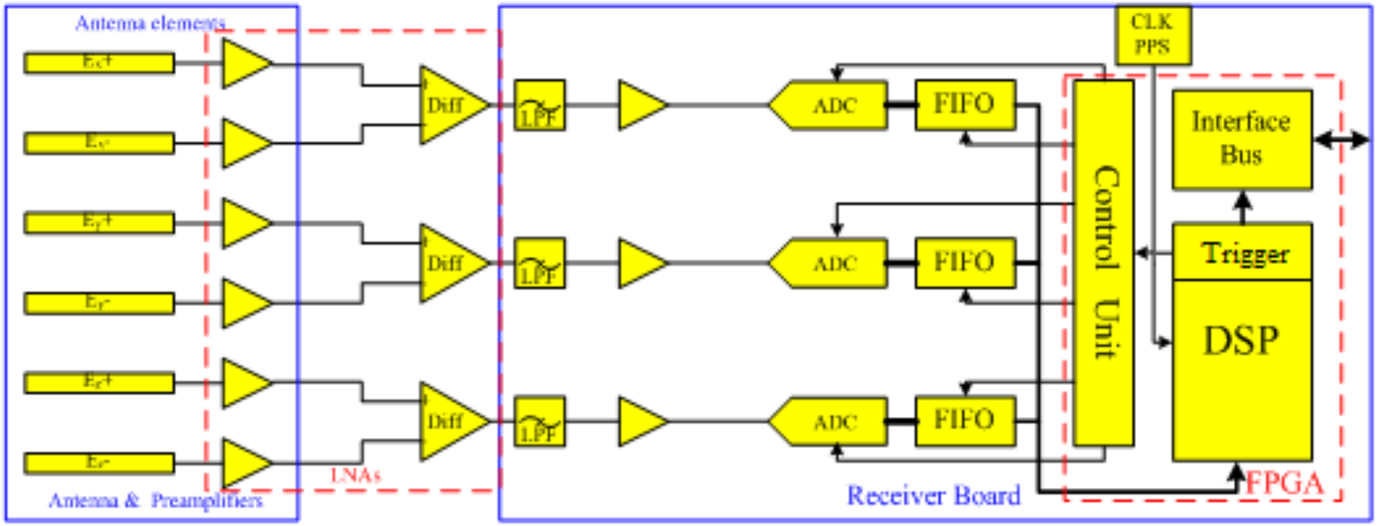
From space to Earth surface (GIMS/NSSC, CAS)

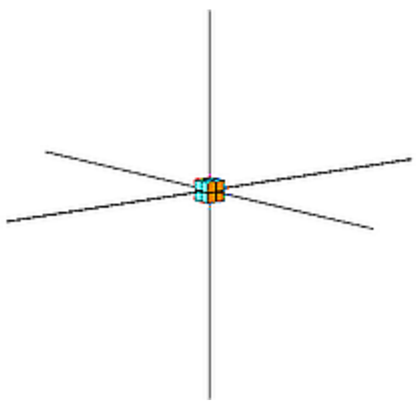
From space to Earth surface (SMOS/ESA)



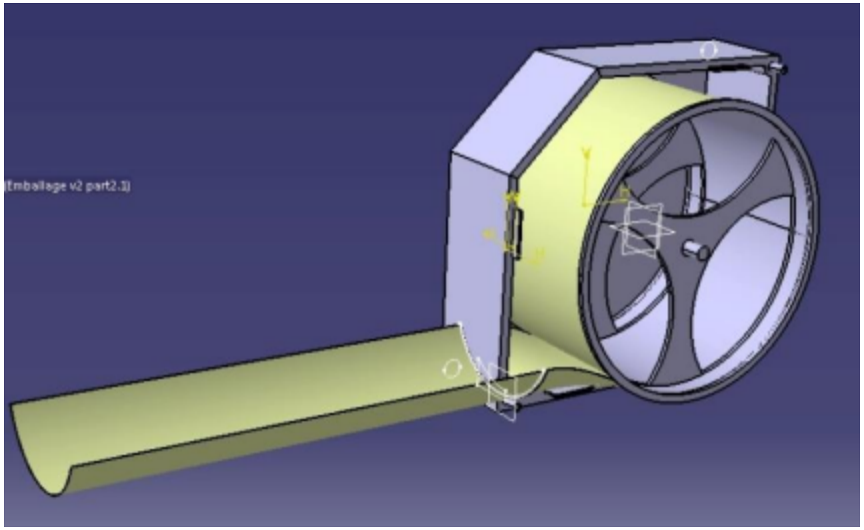
From Earth surface to space (WSRT, NL)

Payload onboard single nano-sat

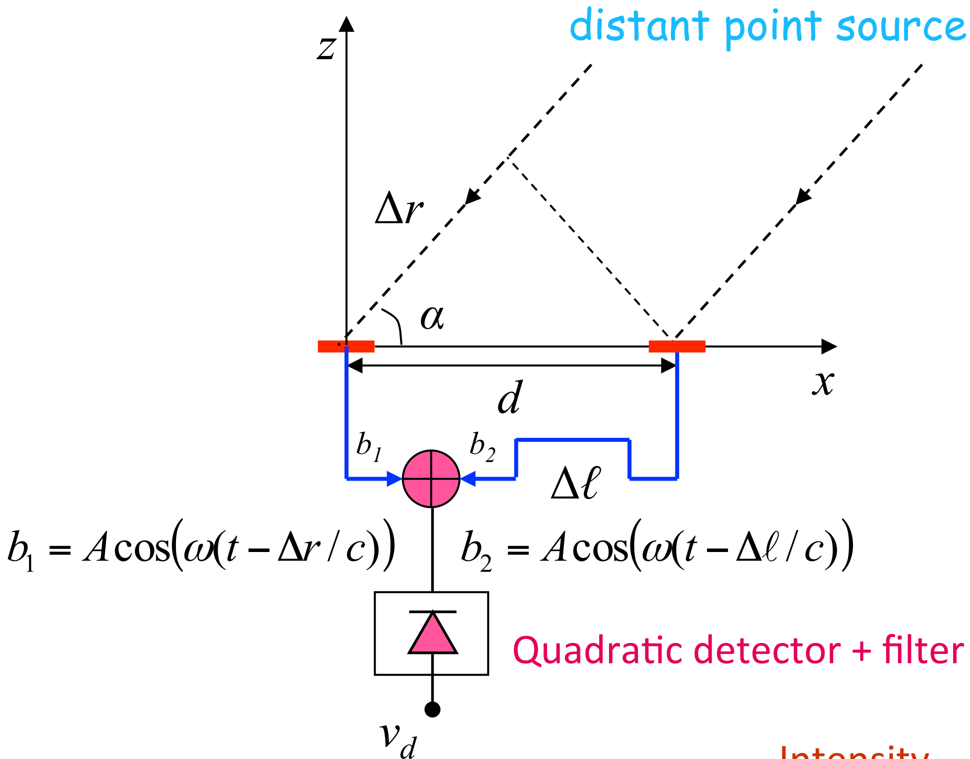


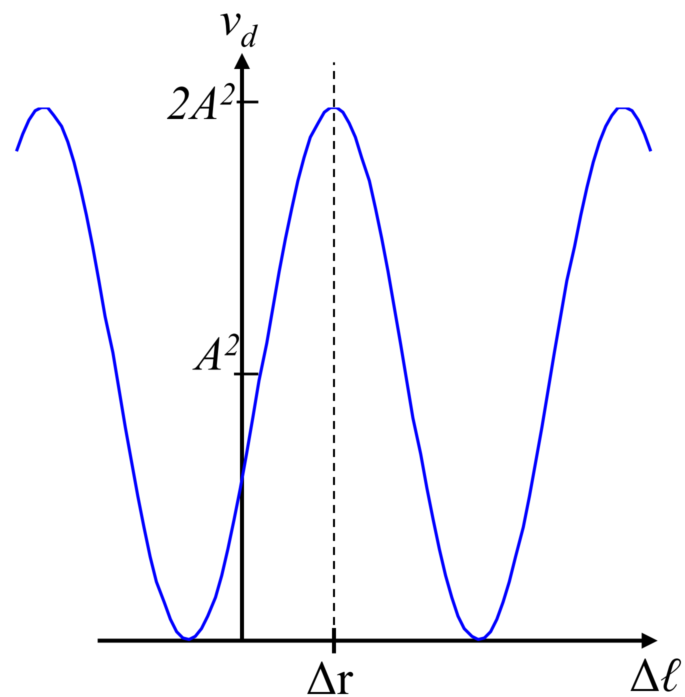


Element antenna



The payload: Interferometer



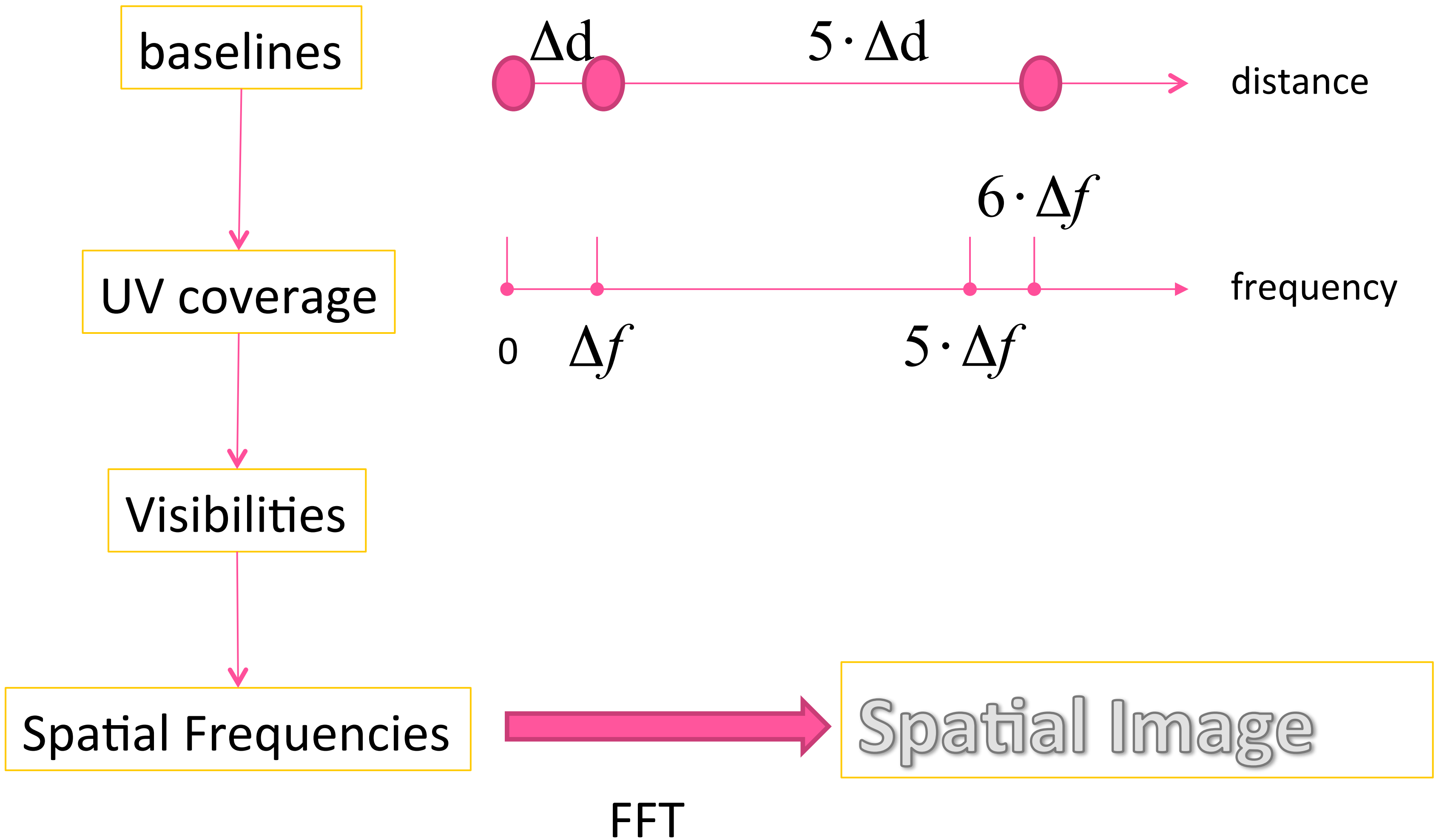


Intensity

$$v_d \propto \left\langle (b_1 + b_2)^2 \right\rangle = \left\langle b_1^2 \right\rangle + \left\langle b_2^2 \right\rangle + 2\left\langle b_1 b_2 \right\rangle \Rightarrow v_d \propto A^2 + A^2 \cos 2\pi(\Delta r / \lambda - \Delta \ell / \lambda)$$

Cross-correlation

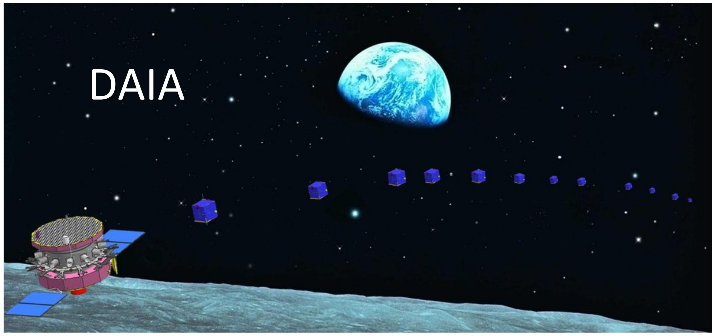
Principles of the Imaging Interferometer

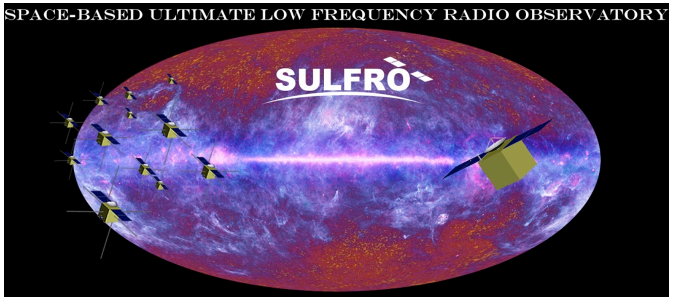


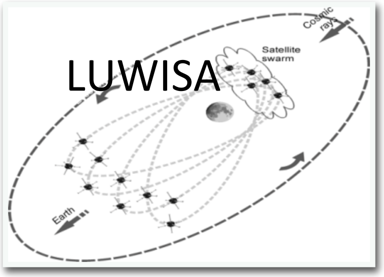
Array design = Optimize the UV coverage

3 concepts for CAS-ESA joint mission

- DAIA: Decametres Astronomy Interferometric Array
- SULFRO: Space-based Ultimately-Low Frequency Radio Observatory
- LUWISA: Lunar Ultra-long Wavelength Imaging and Survey Array

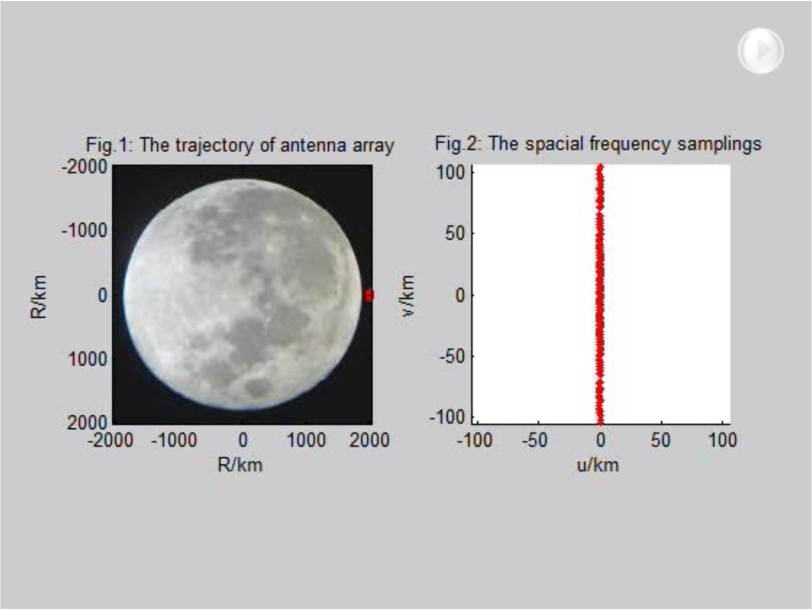






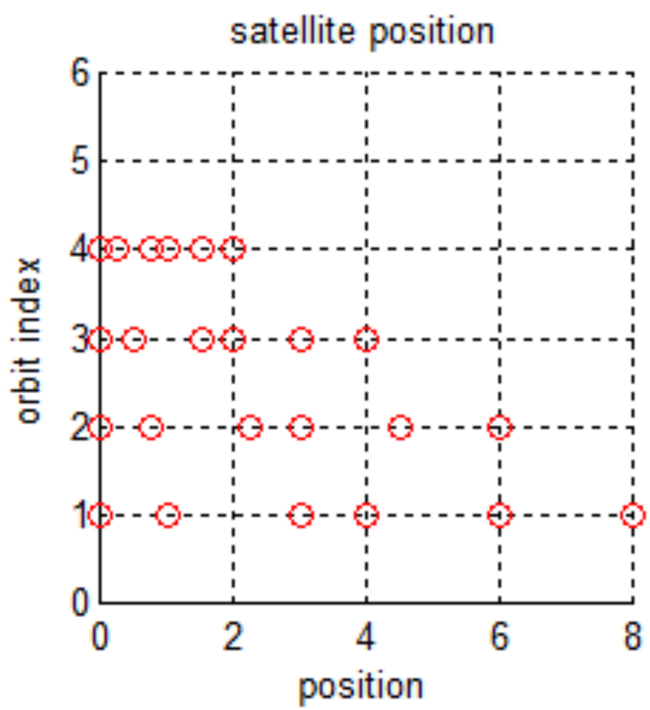
DSL array design *(based on the original DAIA concept)*

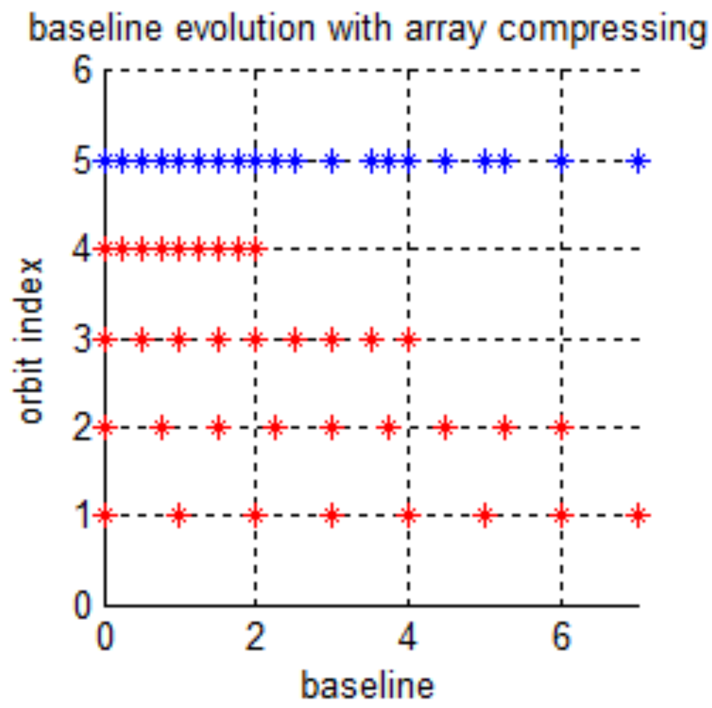
- **Linear array along the same orbit**
- **360°UV coverage every half orbit**
- **Baseline's length varies from orbit to orbit by maneuver**
- **Full UV coverage every 10 days**
- **UV coverage is configurable in orbit according to particular scientific goal**
- **Linear array simplifies the formation maintenance and maneuver**
- **30% of the life time is RFI FREE**



Example array: 1 4 10 22 24 35 39 52 63 71 74 78 79 **km**

Make full coverage in UV plane





Advantages:

✓ Imaging by FFT

✓Quick image refresh time

✓Image quality is improving orbit by orbit

From science to payload

- **Scientific input**： **Imaging + spectrum**
  - **0.5 ~ 30MHz band width**
  - **Spectral resolution: 10kHz?**
  - **Image of point sources**
  - **Image of large field of view**
- **Payload requirements**：

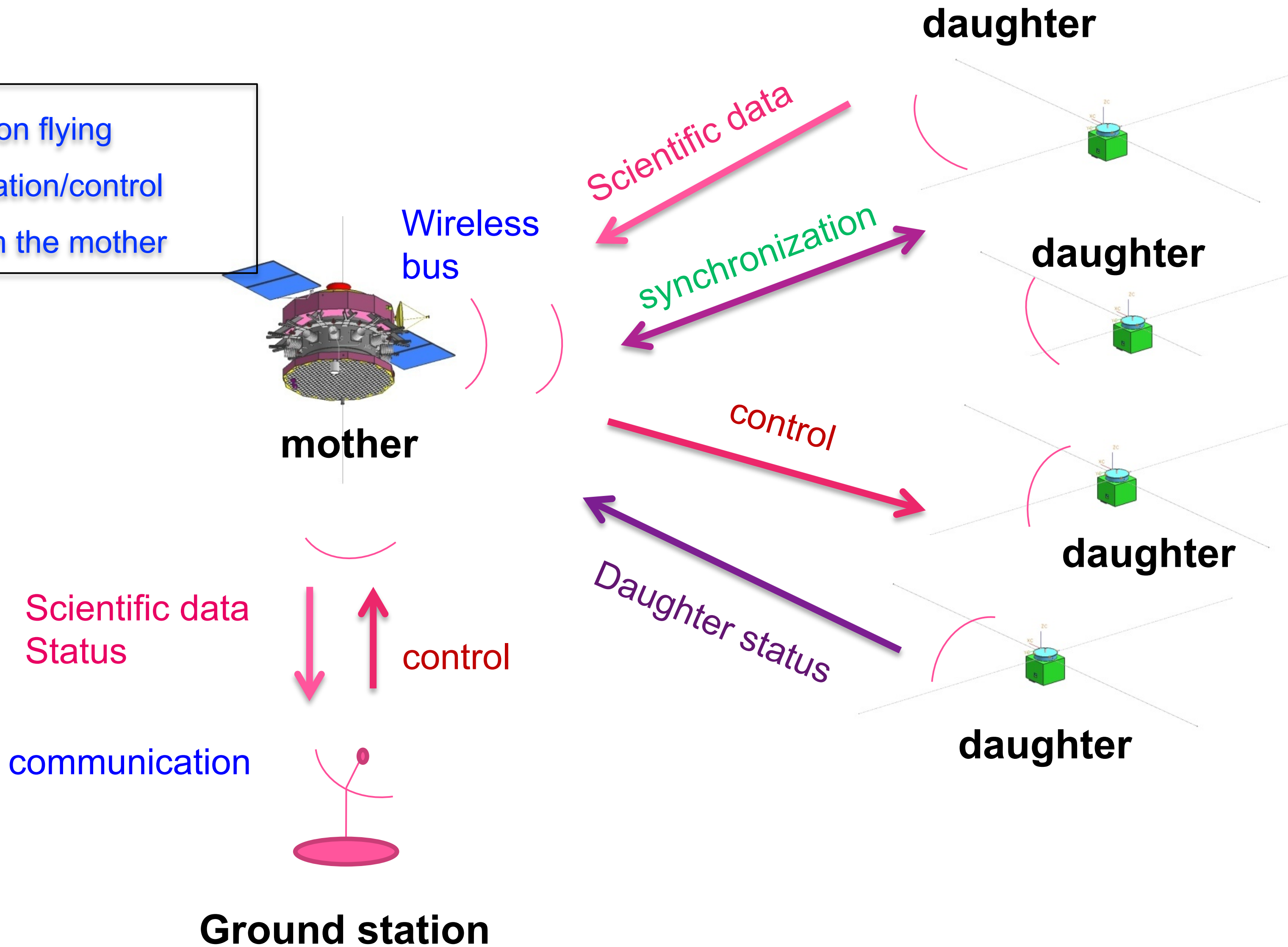
1. **Dense UV coverage and very long baselines**
2. **RFI free/mitigation**
3. **Wide band receiver chain**

Outline

- Science objectives
- Suggested payload
- Mission concept
- Heritage from previous studies/missions
- Summary

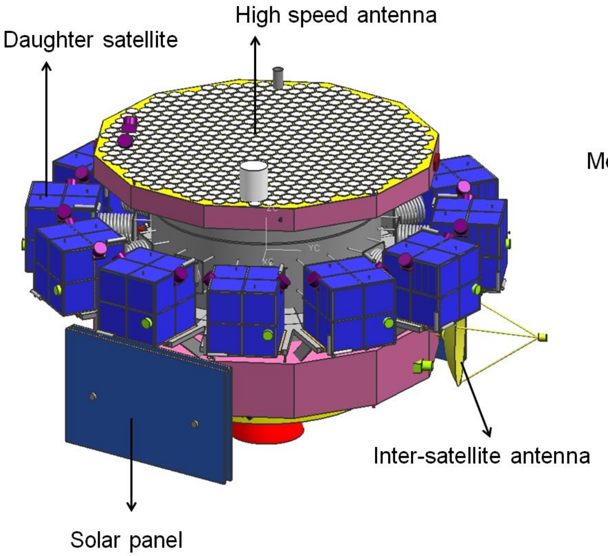
Top level configuration

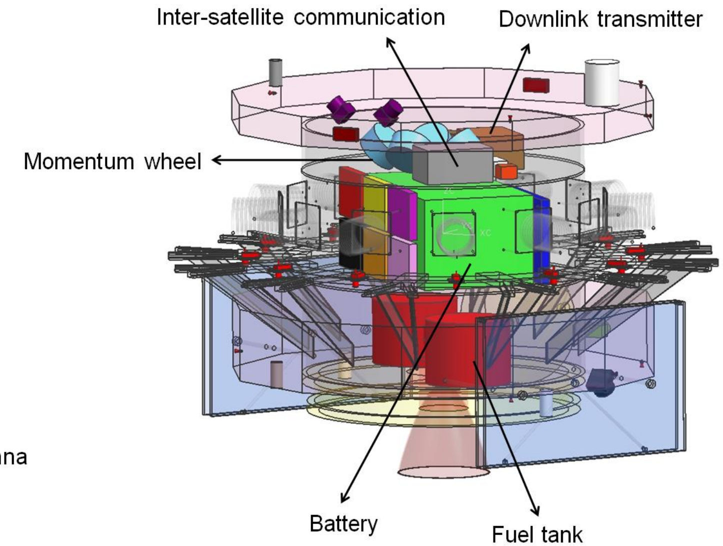
- Linear formation flying
- Central correlation/control
- Downlink from the mother



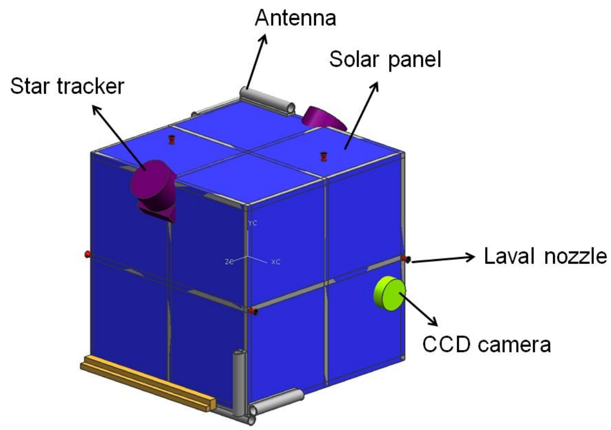
Satellite

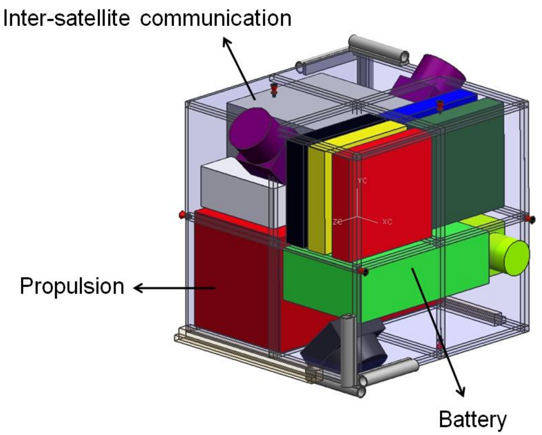
Mothership:



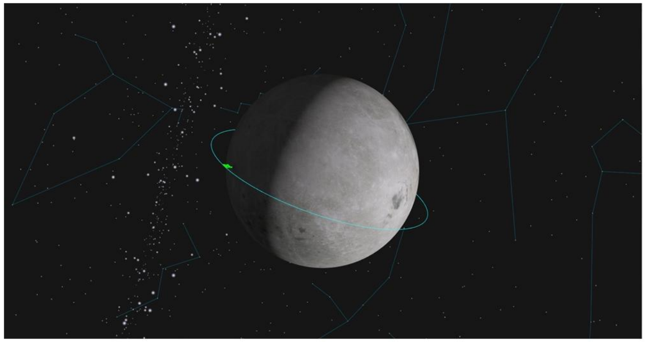


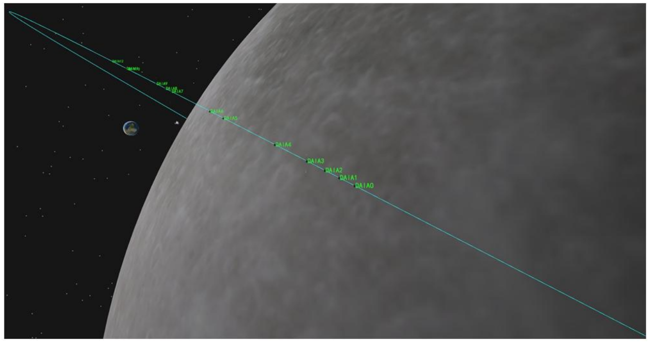
Daughter:



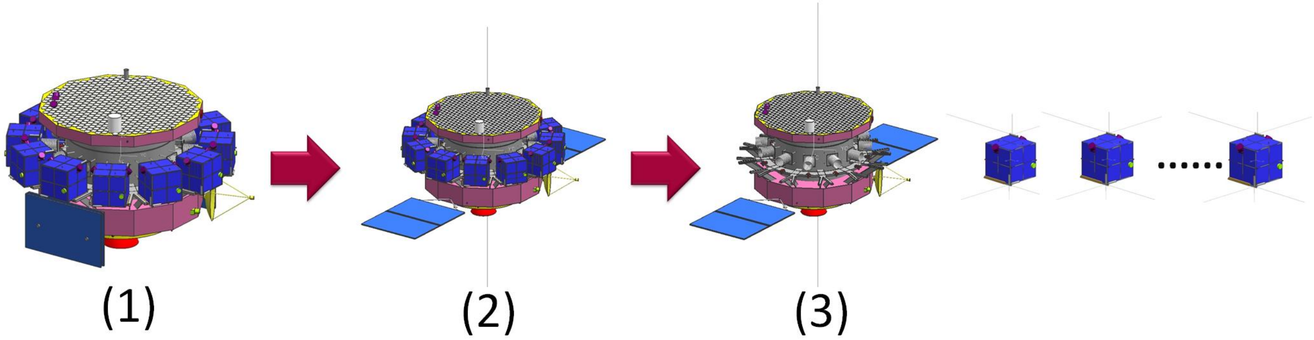


Mission Concept



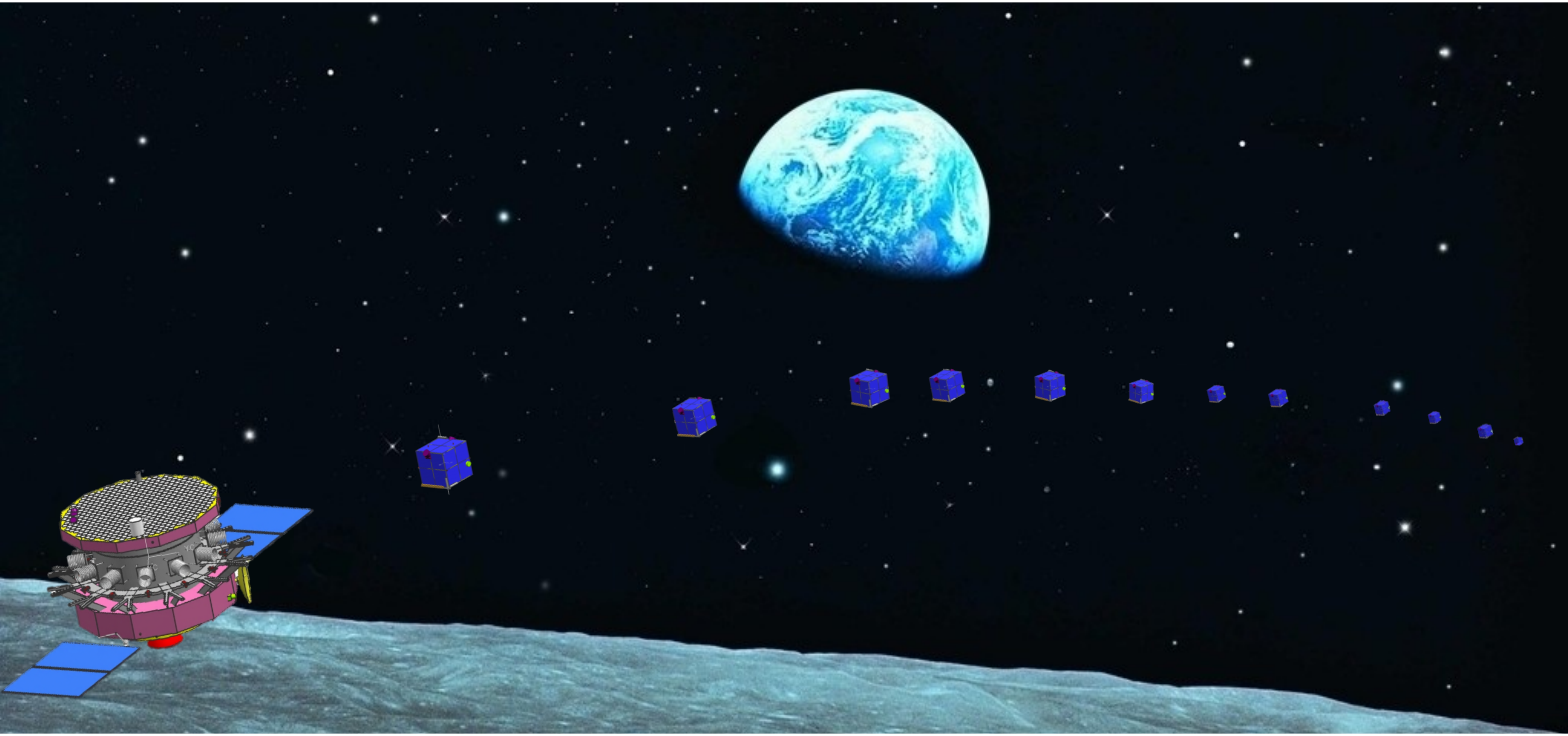


- 300km lunar orbit
- Linear formation flying.
- Active formation control
- Baselines coverage from 100km to 10m.

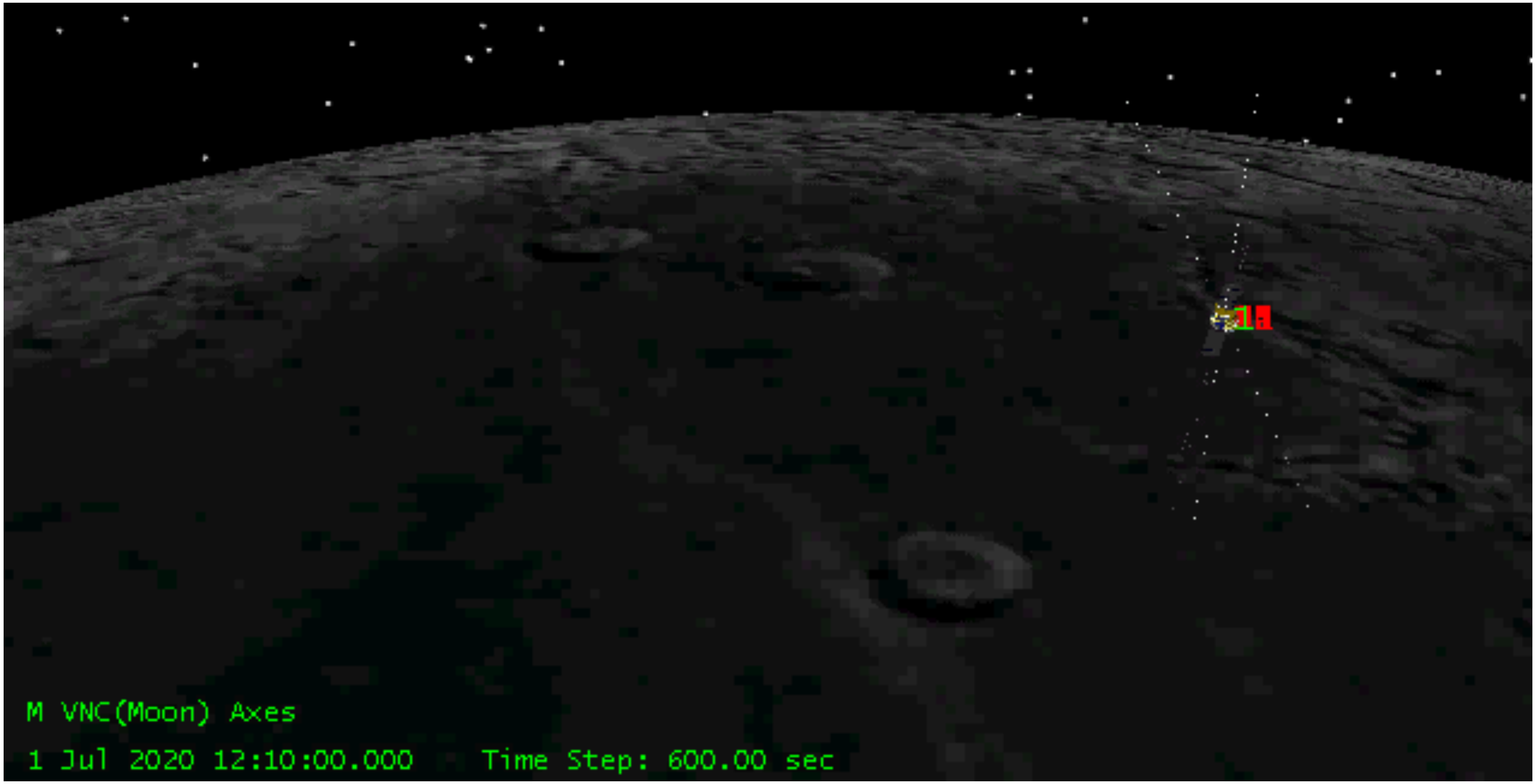


1. Satellites launch configuration.
2. Configuration in the transfer orbit from the Earth to the Moon.
3. Formation establishment.

Artistic impression of a lunar orbiting DSL concept



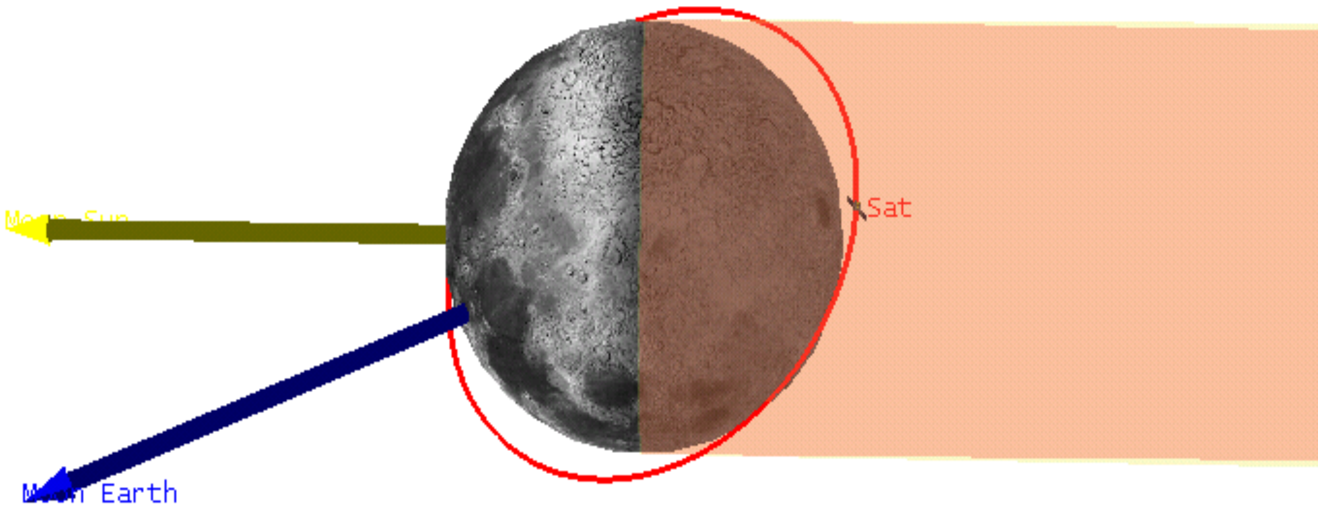
Mission concept



Baselines change from 100km to 10m within 5 days needs 15g cold gas for 12 satellites maneuver

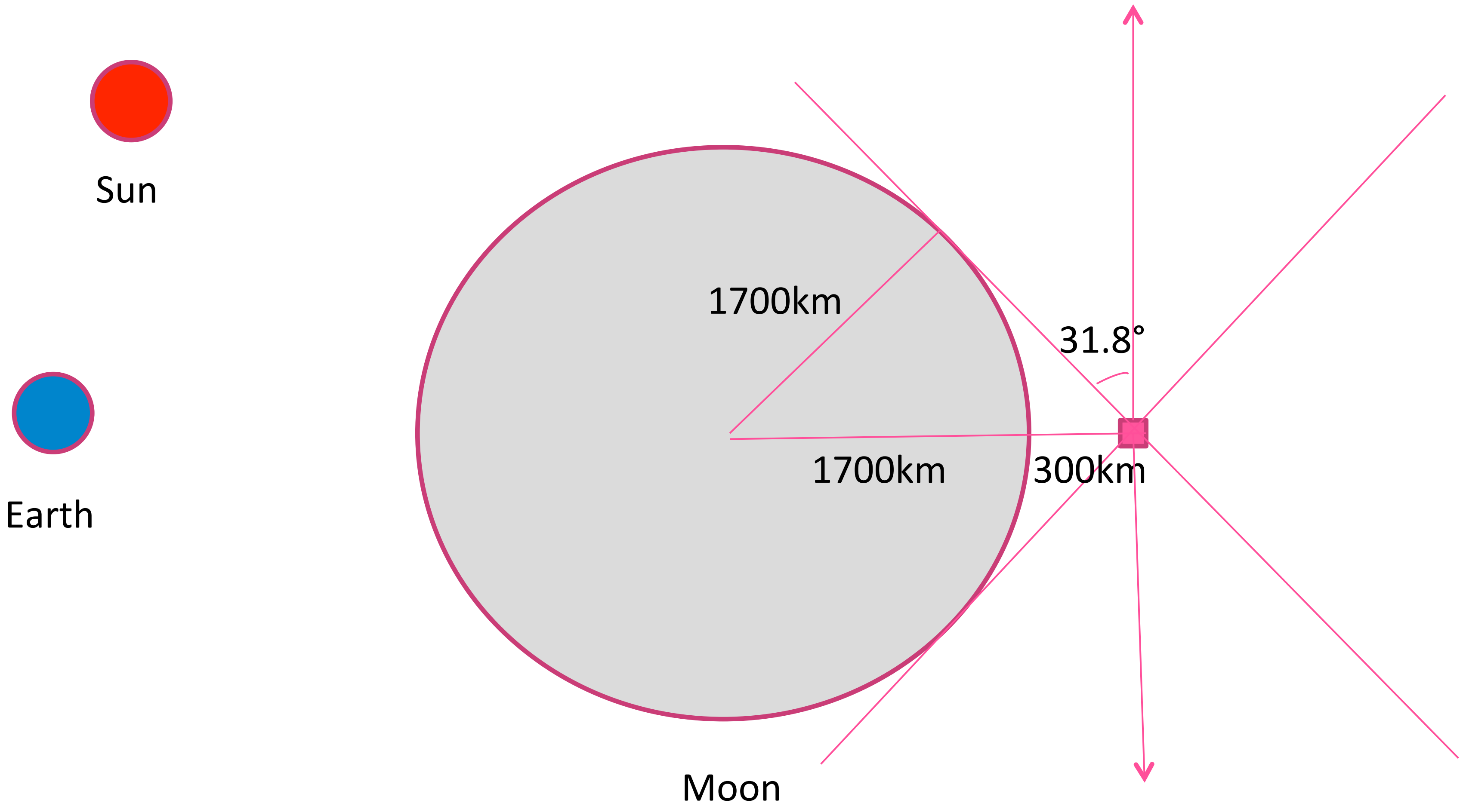
Target orbit analysis

- Perfect RFI free
- Perfect Solar interference free
- Quick imaging time



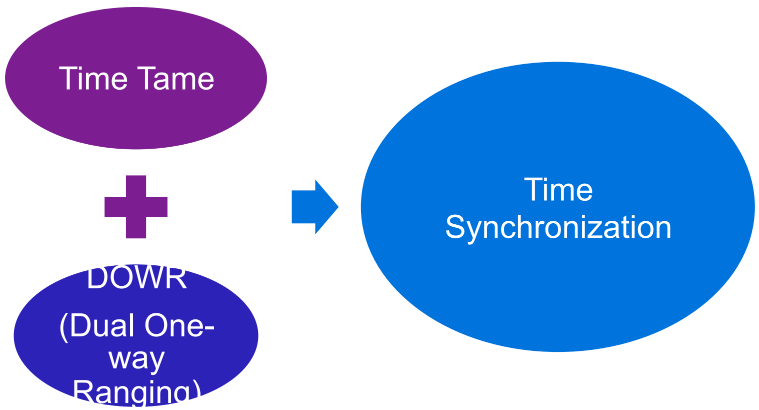
Orbit altitude: 300km
Sun/Earth free: 30%

Antenna field of view

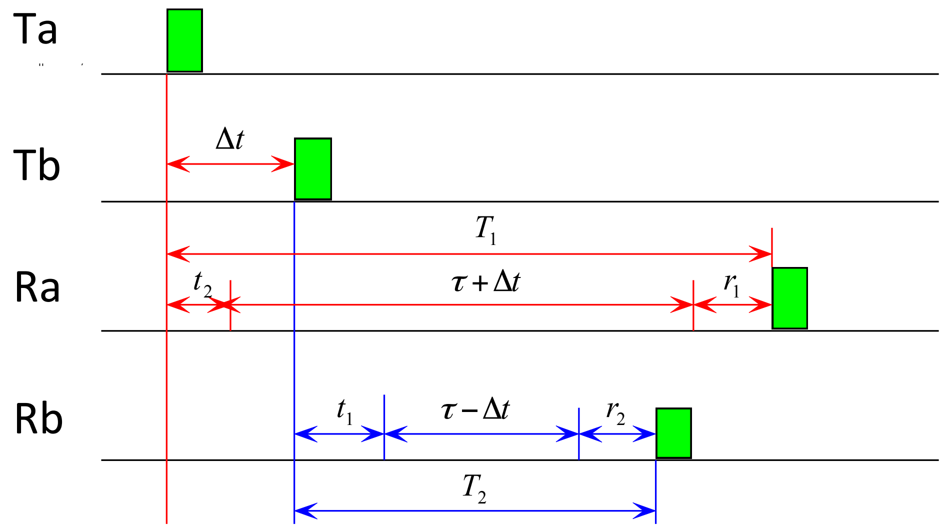


Communication, Ranging and Time Synchronization

Ranging Precision under Current Link Situation: 2cm



Time Synchronization

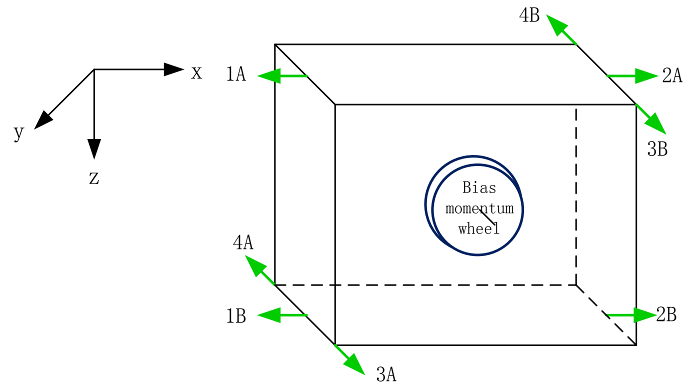


Dual One-way Ranging， DOR

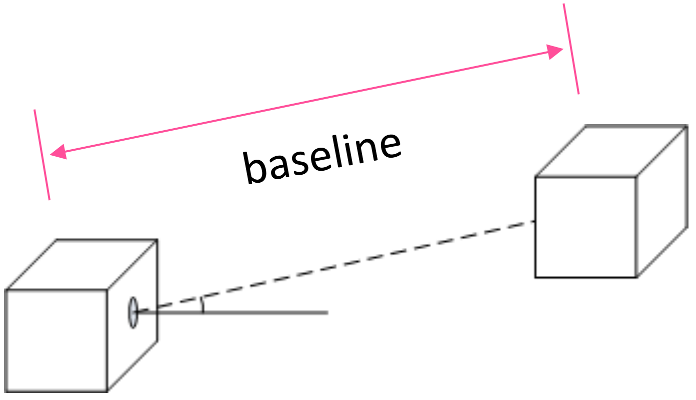
$$D = \frac{1}{2} \cdot [(T_1 + T_2) - (t_1 + t_2) - (r_1 + r_2)] \cdot c \qquad \Delta t = \frac{1}{2} \cdot [(T_1 - T_2) - (t_2 - t_1) - (r_1 - r_2)]$$

Attitude control and baseline determination

- Mother sat
  - 1 orbit control thruster, 12 attitude control thrusters and 4 momentum wheels.
- Daughter cubesat
  - 1 bias momentum wheel and 8 attitude control thruster.



Attitude control



baseline determination
CCD camera of 0.01°angular resolution

High speed downlink – no moving parts

Space engineering solution

Launch	• Launch into lunar orbit by LM-2D or Vega plus an upper stage
Wireless bus	• CCSDS Proximity-1 • SOIS
Relative distance	• Dual One-way Ranging, DOR
Time synchronization	• Dual time comparison
Relative positioning	• Relative distance • Relative spatial angle
Attitude measurement	• Star tracker
Payload	• Space-borne radio synthetic aperture radiometer with 12 nano-satellites

Preliminary specifications

Mission:

- **Orbit:** 300 km
- **Number of satellites:** 13 (1 mother + 12 daughters)
- **Mass:** 300kg
  Mother: 156kg
  Daughters: 12kg*12
- **Power:** 10W*12 + 80W
- **Downlink rate:** <1 Mbps (onboard correlation);
  optional ＞100 Mbps (raw data, via phased array antenna)
- **Life time:** 3 years

Payload

- **Frequency range:** 0.3 ÷ 30 MHz
- **Polarization:** 4 Stokes
- **Antenna:** Cross dipole, 2.5 m each stick
- **Interferometer baseline:** 10 m to 100 km
- **Angular resolution:** 6'@ 1 MHz, 12"@30 MHz
- **Visibilities:** ≈ 54K (half orbit), 59M (20 days)

Outline

- Science objectives
- Suggested payload
- Mission concept
- Heritage from previous studies/missions
- Summary

Mission studies and methodology heritage

- **Ultra-Long-Wavelength Astronomy in space: studies and proposals**
  - *DEX, Dark Ages eXplorer* proposal (2013 ESA)
  - *LRX Lunar Lander proposal* (2012 NOVA/ESA)
  - Multi-country *SURO* (ESA-M 2011) & *SURO-LC* (ESA-S 2012) proposals
  - *OLFAR* concept (2009-2014 STW, NL)
  - *DARIS* concept (2010 ESA, pre-phase A study)
  - *FIRST* Explorer (2009 ESA pre-study)
  - *Joint CAS-KNAW (NL) PhD project* on ULWA, 2007-2010
  - *CAS study* on VLWA observations, 2007
  - ESA VLF Study Team, *Very Low Frequency Array on the Lunar Far Side*, (Rep., ESA, 1997)
  - *ALFIS*, Nieuwenhuizen et al, Delft University (1992)

- **Low-frequency ground-based radio astronomy**
  - Long legacy or radio astronomy, inventing aperture synthesis, predicting & finding HI, etc.
  - LOFAR phased-array radio telescope: core in NL plus outer stations in Germany, UK, France, Sweden, Poland: frequencies 30-90 and 110-240 MHz
    - *operational since 2010*
  - NAOC low-frequency arrays

Payload science and engineering heritage

Instruments flown or flying (~1 kHz => ~ 10-20 MHz)

- Cassini/RPWS (OBSPM, IRFU)
- STEREO/Waves (OBSPM)
- WIND/Waves (OBSPM)
- Ulysses/URAP (OBSPM)
- MHz and sub-MHz receivers on Intercosmos missions (Poland)

Instruments in preparation:

- Solar Orbiter (OBSPM, IRFU)
- JUICE/RPWI (IRFU, OBSPM)
- Space-borne synthesis array for remote sensing, NSSC

Outline

- Science objectives
- Suggested payload
- Mission concept
- Heritage from previous studies/missions
- Summary

Concluding remarks

- Pioneering science (never before!) at affordable cost
- A “must” act: opening up the last unexplored window in Universe
  - *Let’s complete the second revolution in astronomy*
- Offers significant discovery potential
- A world-leading sci endeavour – no match by other space agencies
- The mission is highly compatible/synergistic with major radio astronomy projects in
  - *Europe (LOFAR, SKA)*
  - *China (FAST, SKA)*

Happy Wall in Copenhagen