Spectrum Management for Cislunar Space in the Era of Commercial Missions

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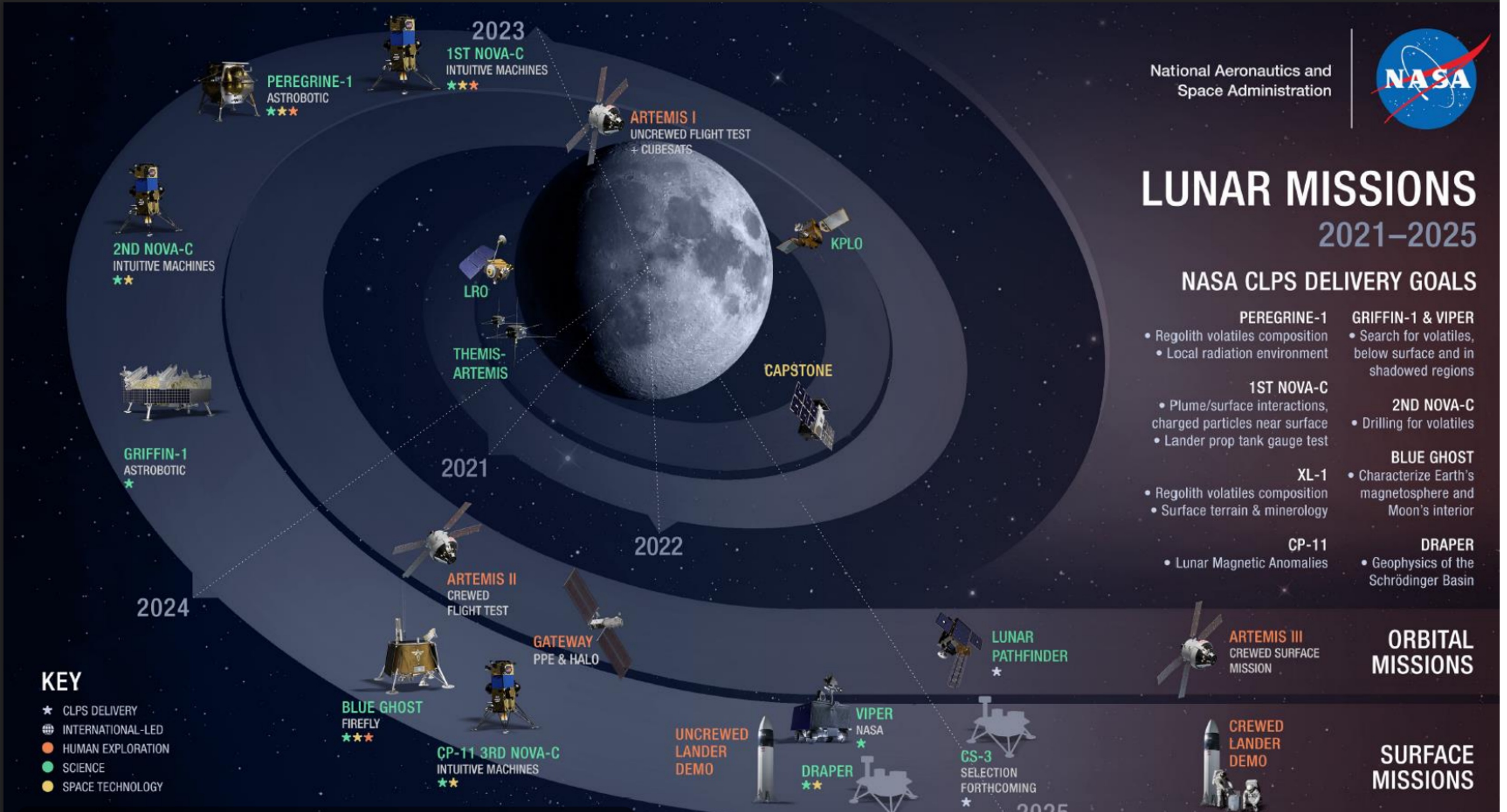
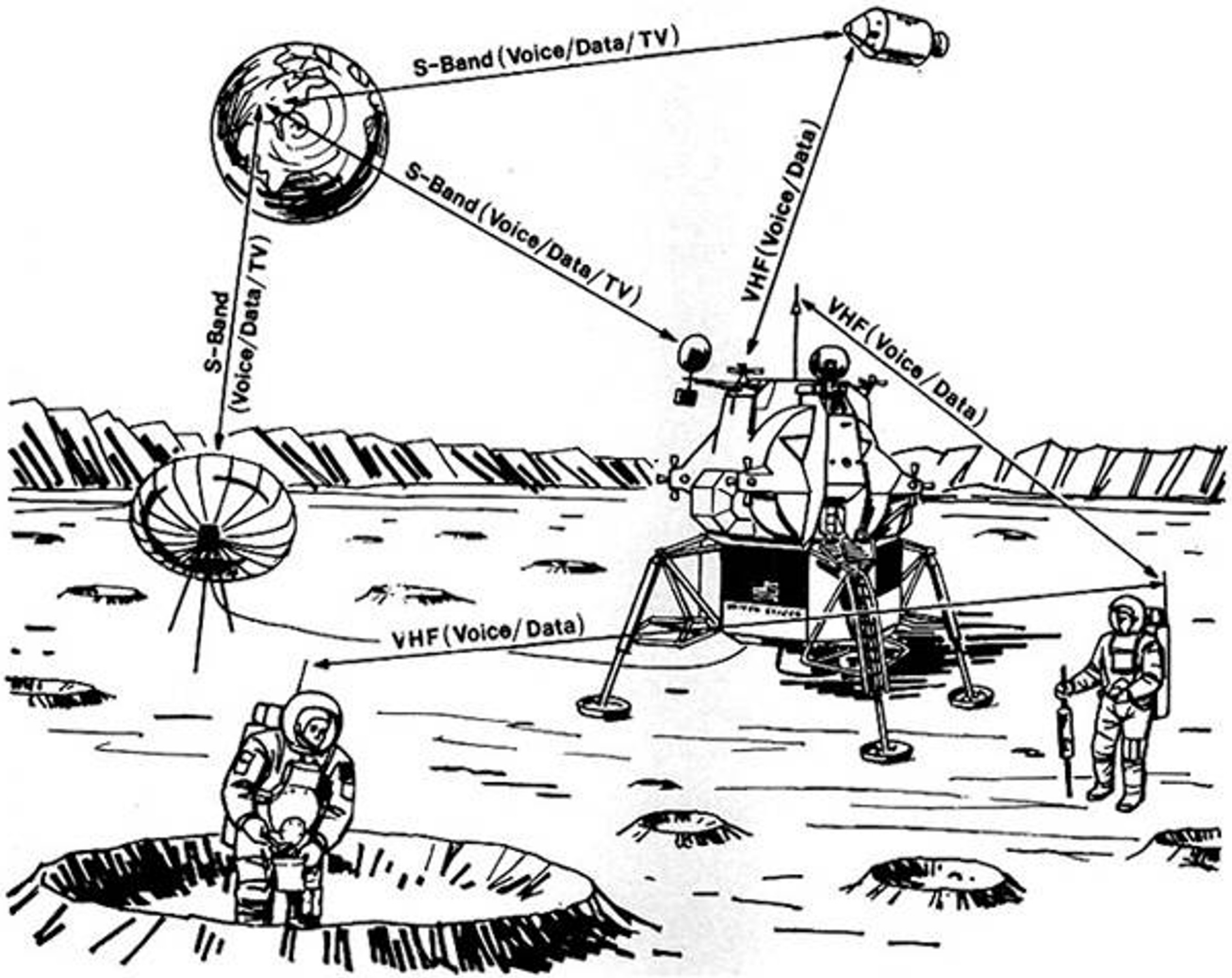
The interference problem



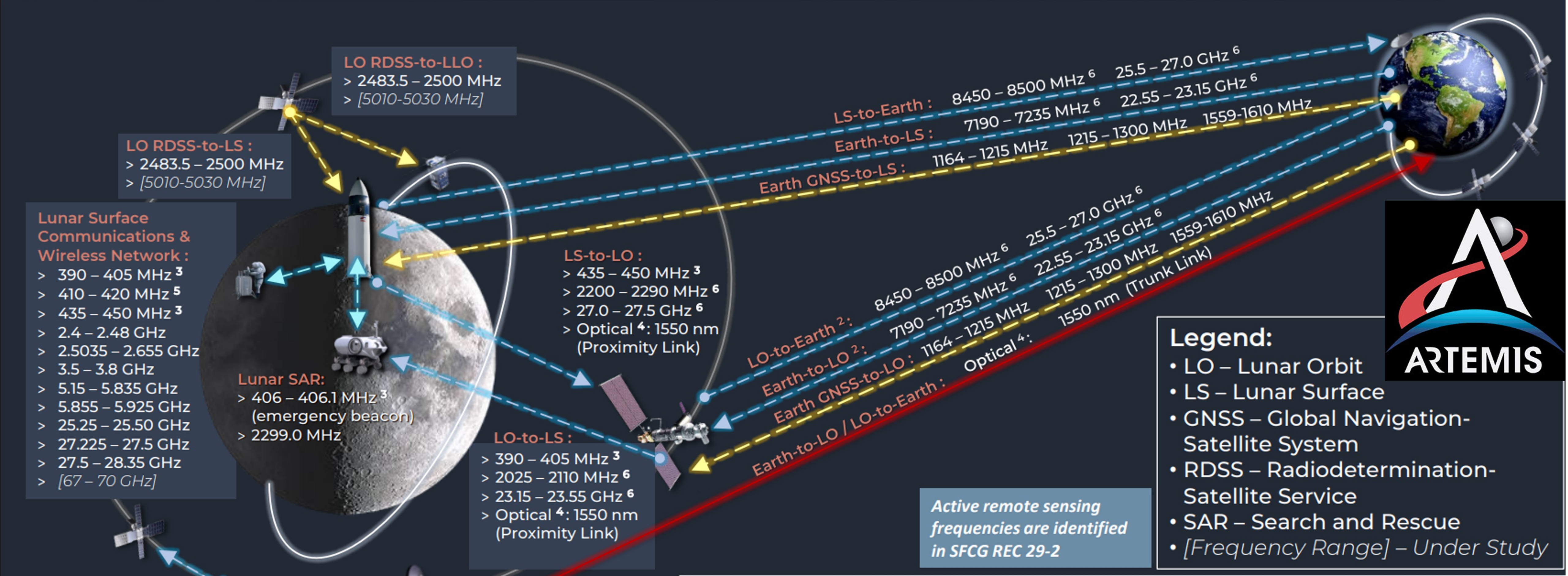
Source: J. Kearns, "Lunar Discovery and Exploration Program Update," NASA Science Mission Directorate, 2023.

Communications CONOPs



Electromagnetic Spectrum for Lunar Region

Radio Frequency[1] and Optical



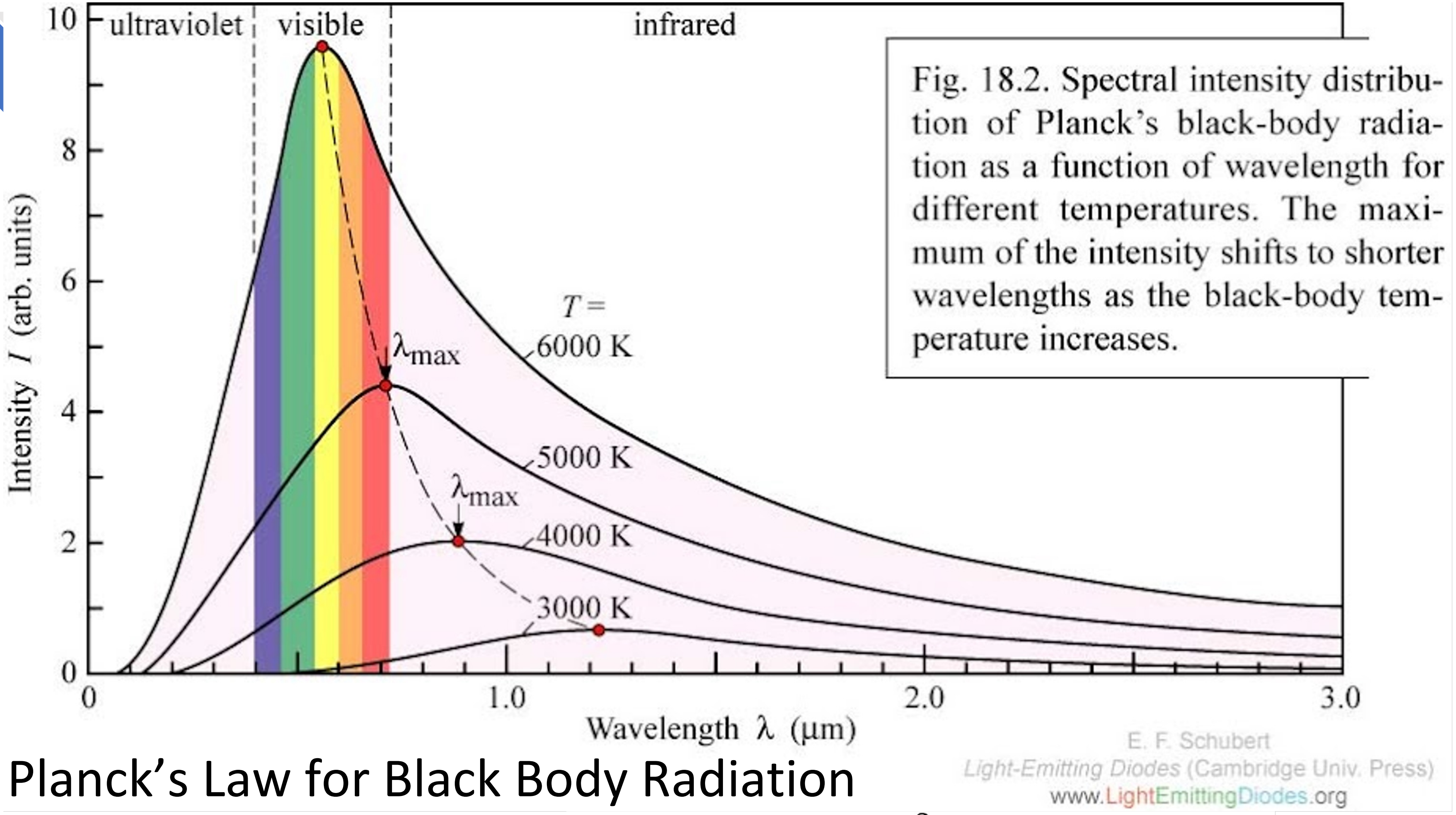
Legend:
- LO – Lunar Orbit
- LS – Lunar Surface
- GNSS – Global Navigation-Satellite System
- RDSS – Radiodetermination-Satellite Service
- SAR – Search and Rescue
- *[Frequency Range] – Under Study*

Active remote sensing frequencies are identified in SFCG REC 29-2

Notes:
1. Consistent with the IOAG Architecture, NASA-SCaN Lunar Architecture, ICSIS and SFCG REC 32-2R5
2. SFCG REC 32-2R5 also contains amateur radio frequency allocations between the Earth and the Lunar region
3. Limited to outside of the Shielded Zone of the Moon (SZM)
4. Optical links are consistent with ITU-T Rec. G.694.1, and will complement, rather than replace, RF capabilities
5. 410-420 MHz spectrum used for EVA comm may occur in LO (e.g., from a spacecraft such as Orion or Gateway)
6. Per SFCG REC 41-1, lunar region links with occupied bandwidth < 6 MHz may use S-, X-, or Ka-band, while lunar region links with occupied bandwidth ≥ 6 MHz should use Ka-band only

An interference primer

Sources of Emission - Classical



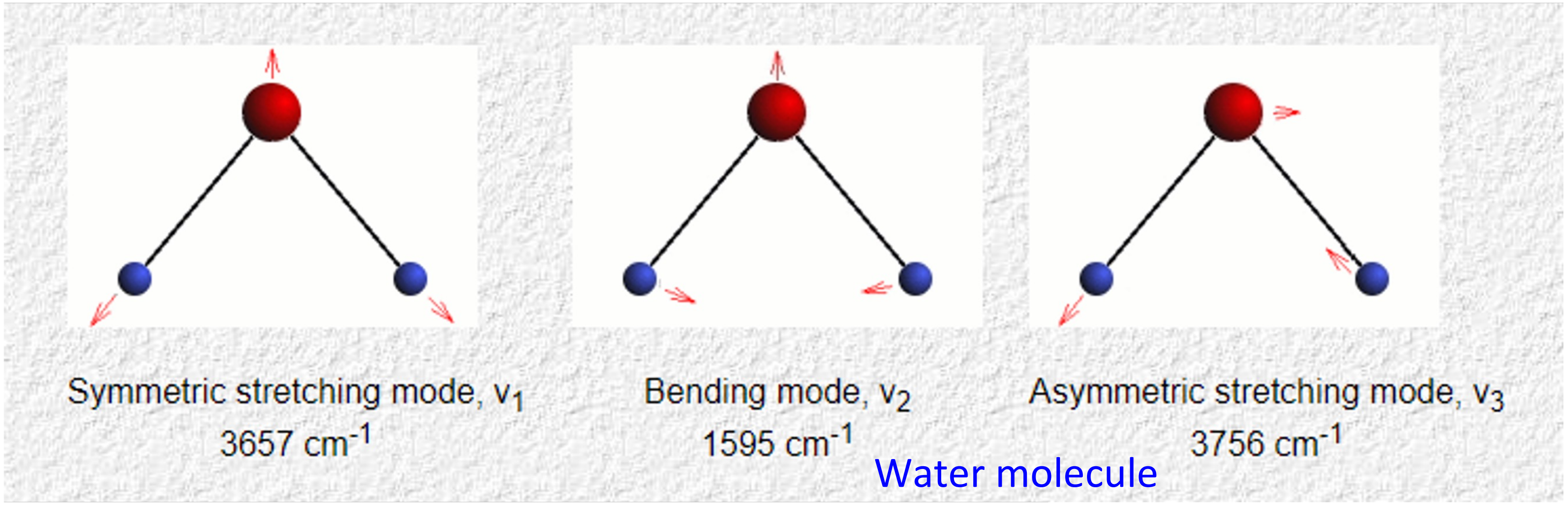
"Accelerating charges radiate" - Maxwell

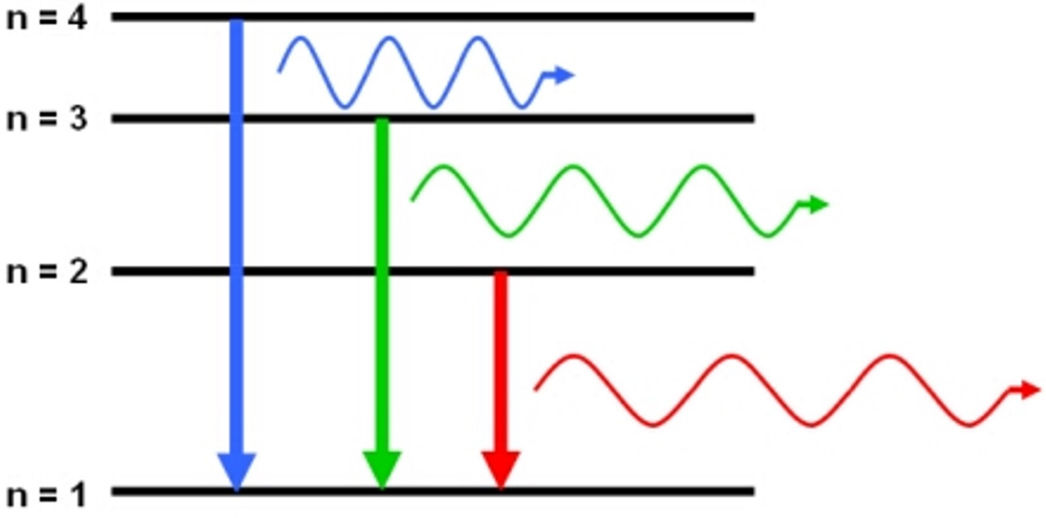
Continuous

Planck's Law for Black Body Radiation

$$B_\nu(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{\exp\left(\frac{h\nu}{k_B T}\right) - 1}$$

Sources of emission - Quantum Lines

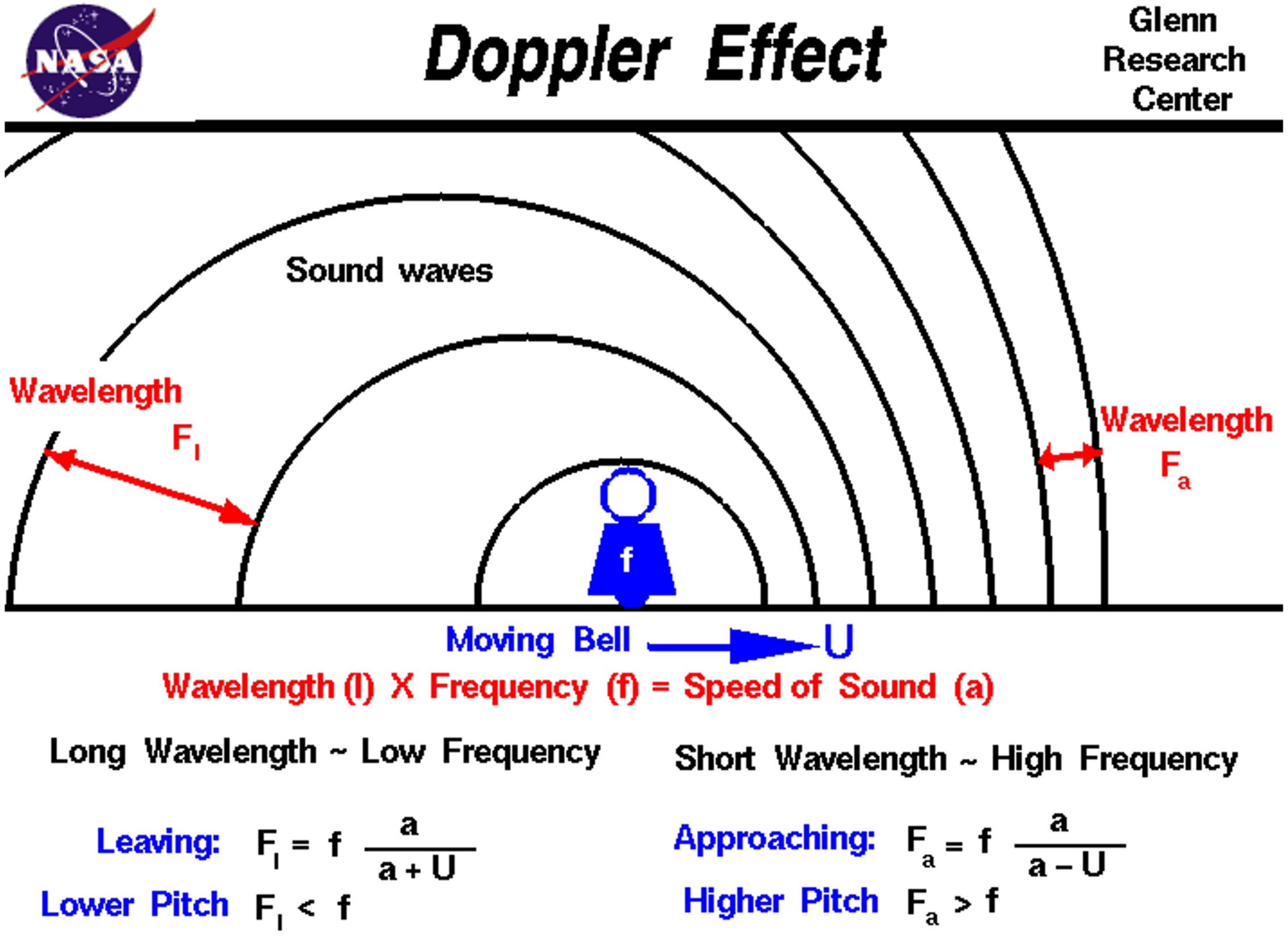


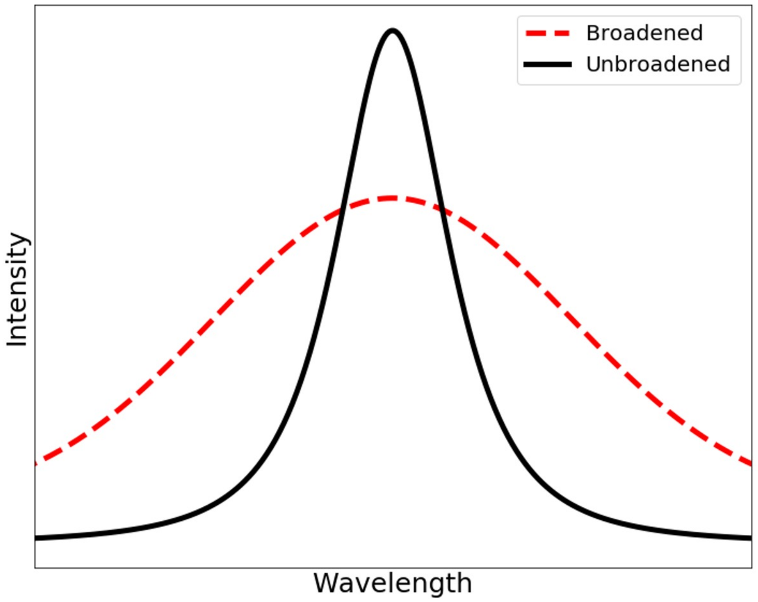


$$E_n = -\frac{m_e e^4}{2(4\pi\varepsilon_0)^2\hbar^2}\frac{1}{n^2}$$

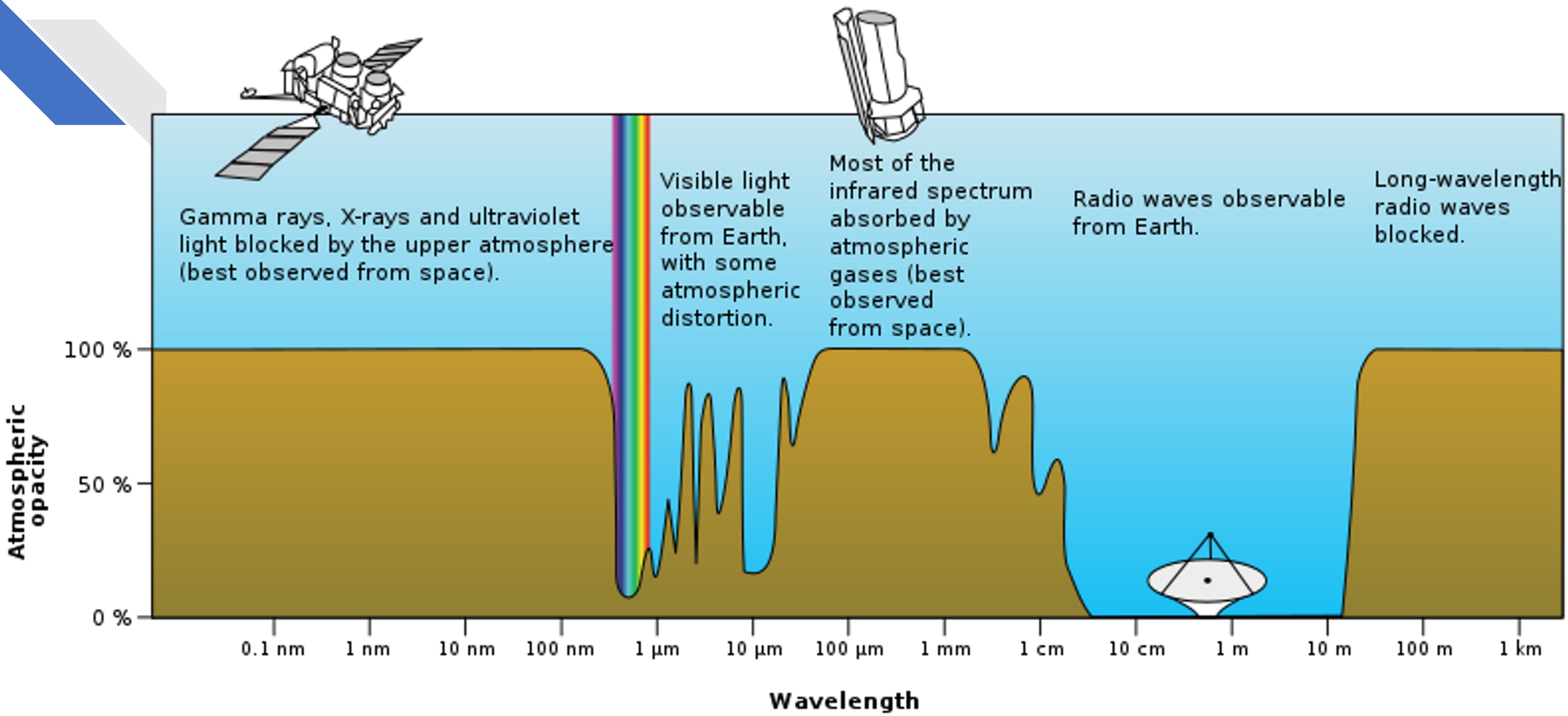
Principal Energy States in a Hydrogen Atom

The Science is EVERYWHERE!





Spectral Windows from Surface to Space



Frequency 3 THz 300 GHz 30 GHz 3 GHz 300 MHz

Types of Interference

1. Out Of Band Emissions

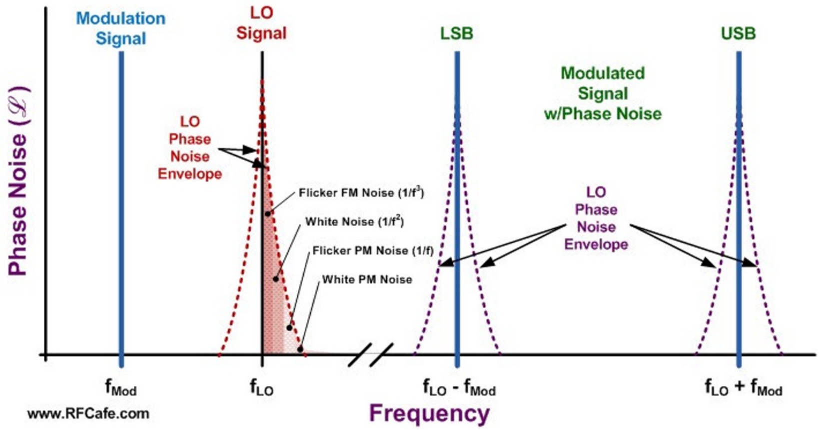
    Harmonics!

    Source: non-linearities of the components used in the RF chain

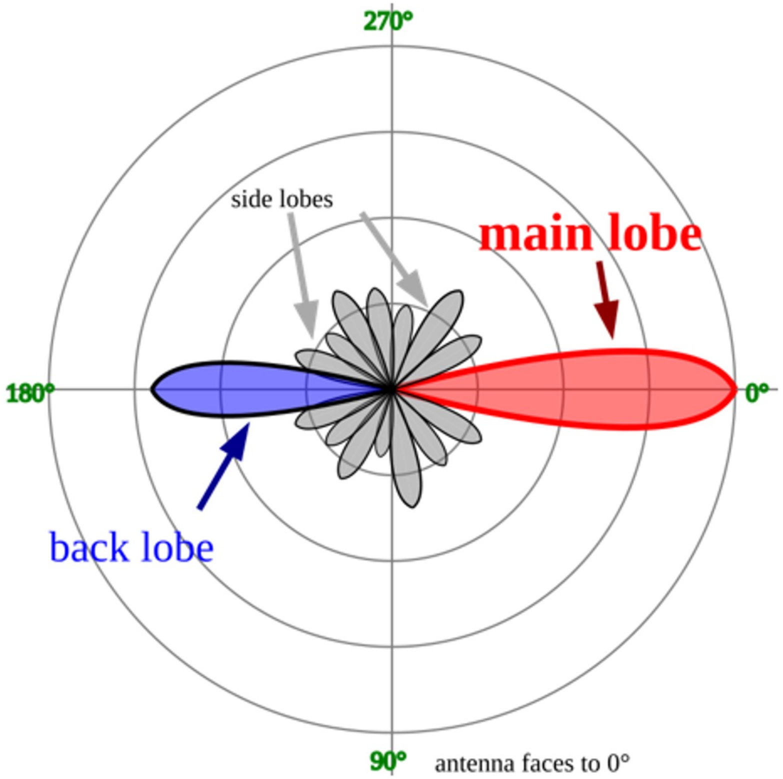
    (Let’s do some trigonometry…)

$$I = I_S\left(\exp\left(\frac{eV}{k_B T}\right) - 1\right)$$

2. Adjacent Band Emissions



Fundamental RFI problem:
Insidious Interference through the Side Lobes



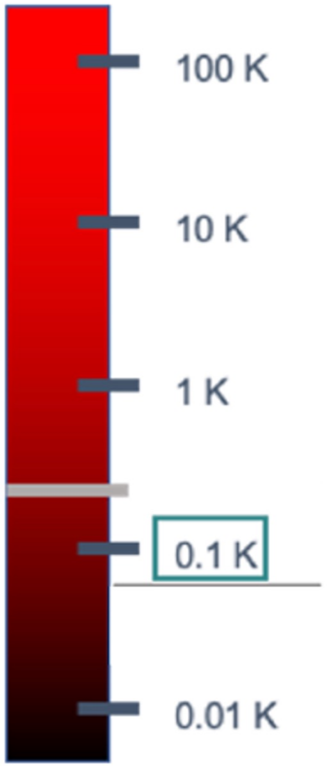
Source: Wikipedia

Obvious contamination	**Workable major concern** Forecasting model will reject corrupted data point due to self-consistency issues
Insidious contamination	**Area of concern** Corrupting signal is small enough to be realistic (not automatically rejected), but large enough to affect the data
Undetectable contamination	**Not a concern** Corrupting signal is too small and is indistinguishable from being absent

Source: Beau Backus, JHU APL

T_B thresholds are approximate, not based on a specific analysis

Contaminating T_B



T_B: Brightness temperature

Various needs for electromagnetic spectrum

- Needing CPNT (Cislunar Positioning, Navigation and Timing)
  - Positioning: ISRU extraction, and mapping
  - Navigation: For landing of surface elements
  - Timing: For interferometric RA
- Ground penetrating RADAR
- Sounding of the lunar ionosphere
- Surface communications
- Data back-haul
- Unique radio environment for deeper astronomical observations!

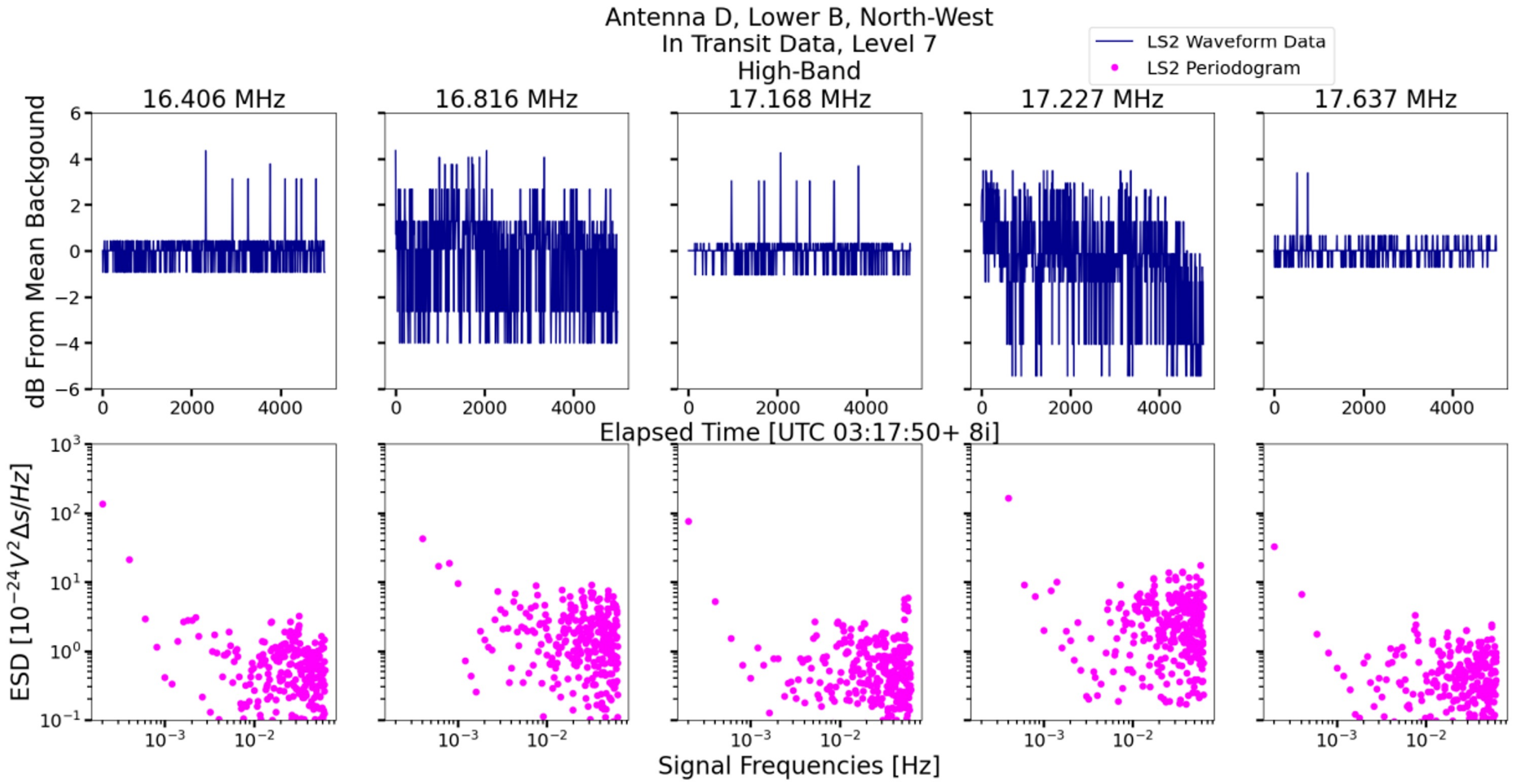


Figure 9: Spectra and periodograms for several frequency channels with candidate shortwave transmissions (technosignatures) for antenna D during the In-Transit observation day from the DSP. The top row shows the spectra in decibels relative to its own average value, while the bottom row shows the periodogram for each corresponding channel in the top row. The x-axis for the fluctuations in the top panel are indexed by i and are each eight seconds apart, while the x-axis for the periodograms are signal frequencies in Hertz. Note the level of fluctuations in the spectra as well as the dominant periods in the periodograms: the latter exhibit decreasing power modulation with increasing frequency modulation, as expected for shortwave transmissions breaking through the Earth's ionosphere.

Techno-signature detection by ROLSES from the moon!

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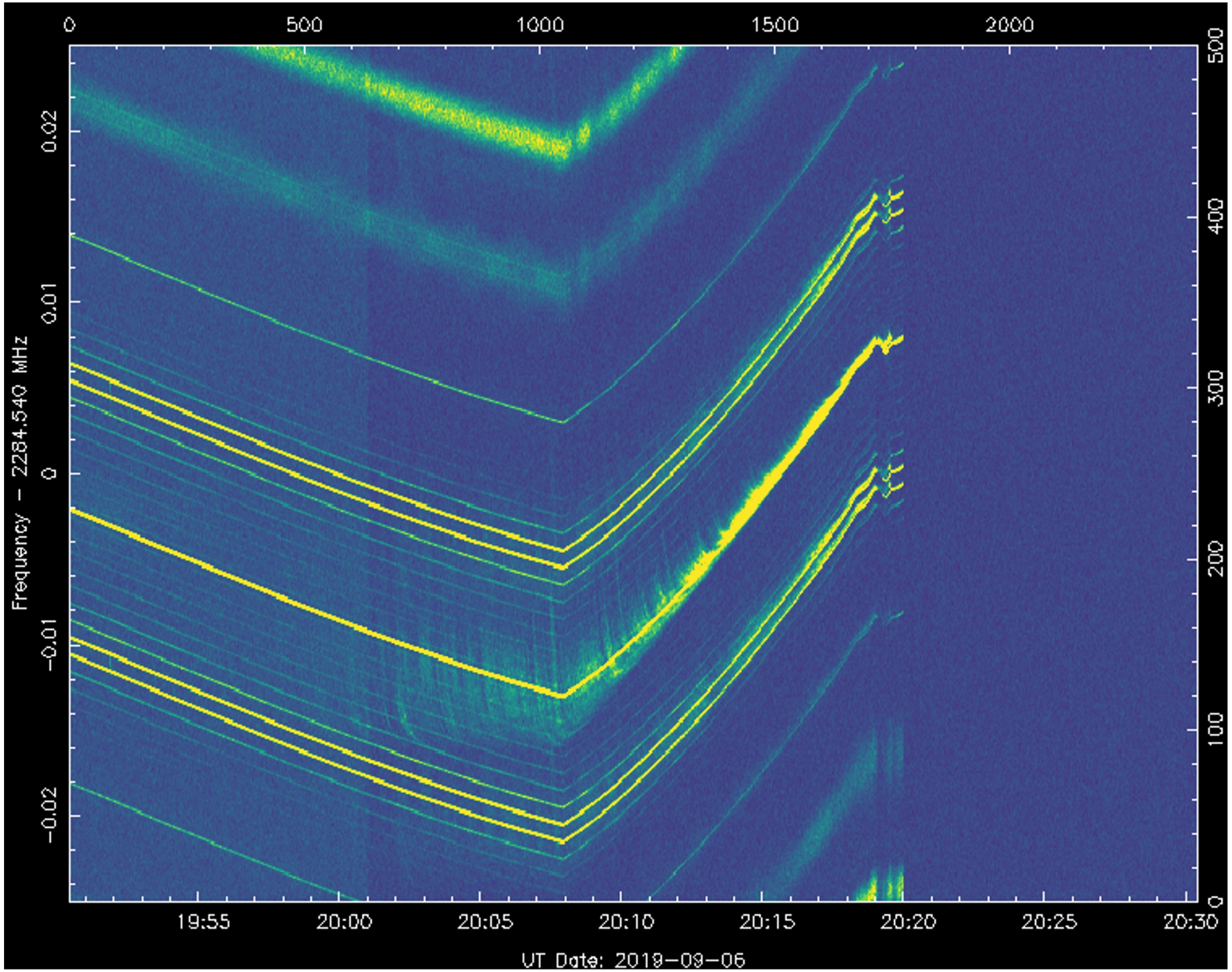
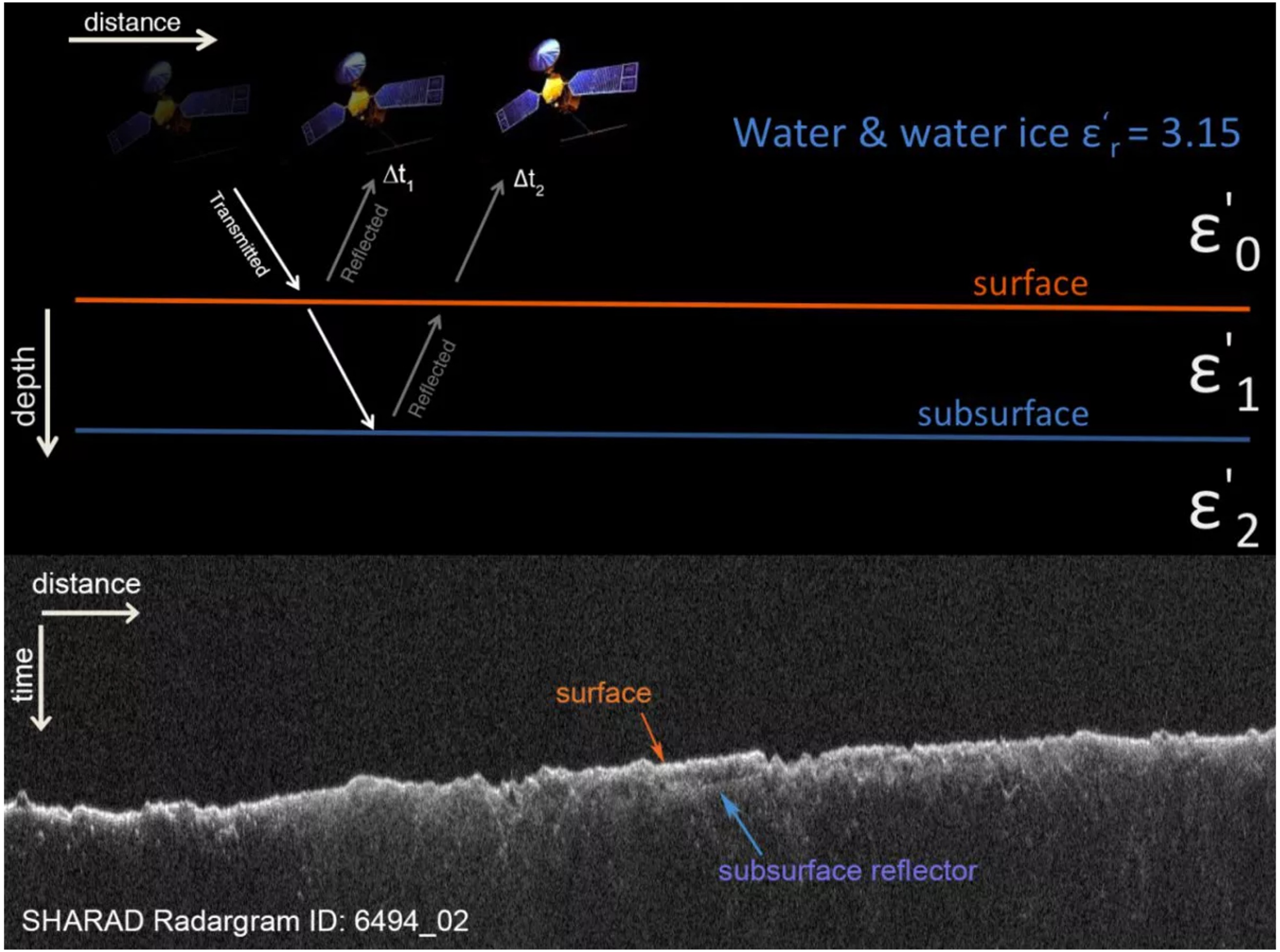


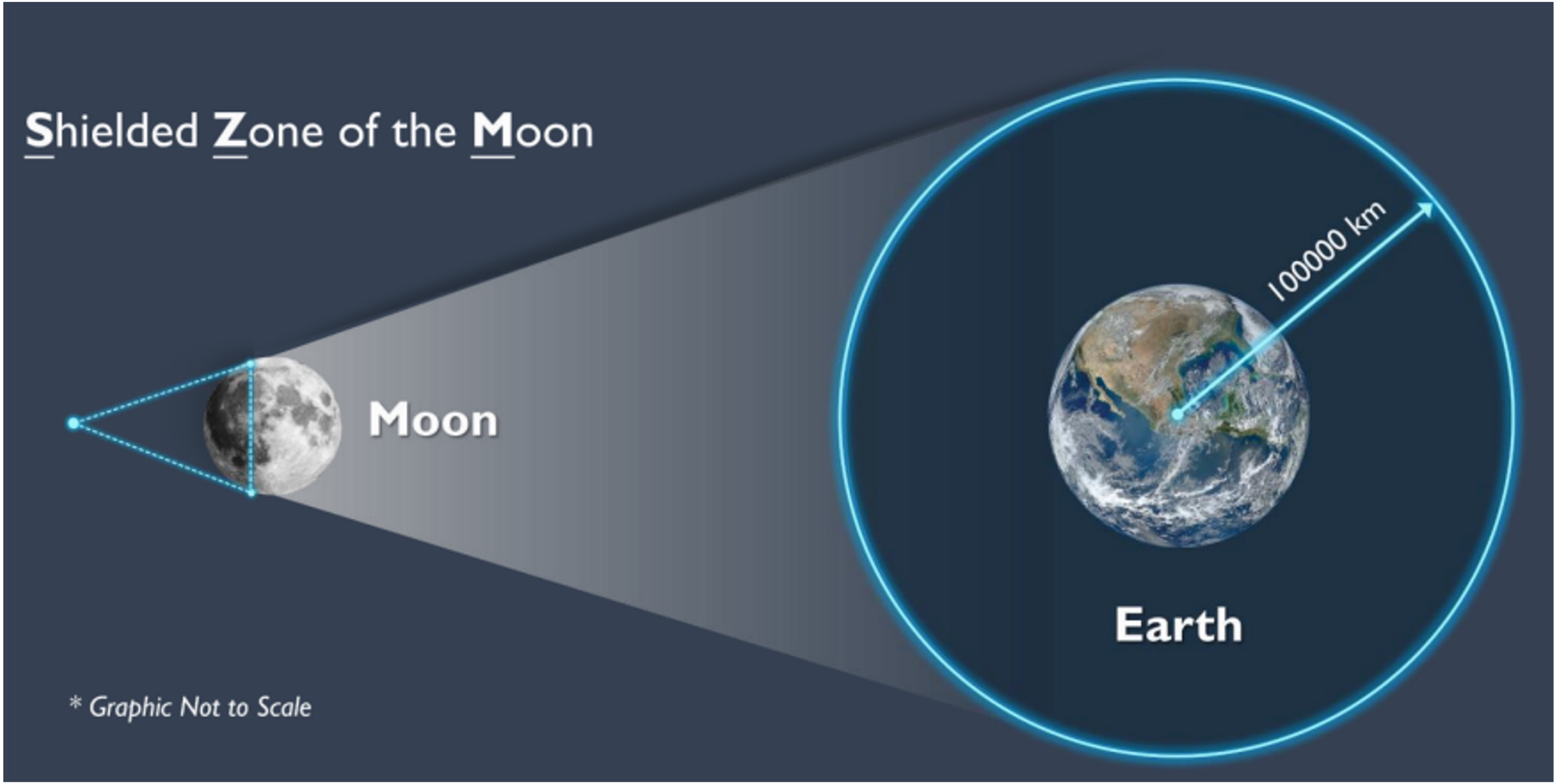
Observations of the Chandrayaan-2 lander's telemetry link - with the Dwingeloo radio telescope in the Netherlands

Uniqueness of the lunar RF environment

- Knife-edge and smooth sphere diffraction
- No atmosphere! Reduced attenuation
  - But not *nothing:* Tenuous ionosphere + surface boundary exosphere
- Challenging to model
  - Lack of information about the structure and composition of the lunar regolith - especially RF properties like di-electric constant
  - Finer cartographic models required for higher propagation model fidelity
    - Performance metrics of current models (Irregular Lunar Model - ILM, derived from the ITM)



Various ground penetrating RADARs have been operated, with proposals for future orbital platforms that can guide resource (sub-surface ice, lava tube) mapping


Shielded Zone of the Moon
Moon
100000 km
Earth
* Graphic Not to Scale

Current framework

UNITED STATES FREQUENCY ALLOCATIONS

THE RADIO SPECTRUM

RADIO SERVICES COLOR LEGEND

AERONAUTICAL MOBILE	INTER-SATELLITE	RADIO ASTRONOMY
AERONAUTICAL MOBILE SATELLITE	LAND MOBILE	RADIODETERMINATION SATELLITE
AERONAUTICAL RADIONAVIGATION	LAND MOBILE SATELLITE	RADIOLOCATION
AMATEUR	MARITIME MOBILE	RADIOLOCATION SATELLITE
AMATEUR SATELLITE	MARITIME MOBILE SATELLITE	RADIONAVIGATION
BROADCASTING	MARITIME RADIONAVIGATION	RADIONAVIGATION SATELLITE
BROADCASTING SATELLITE	METEOROLOGICAL	SPACE OPERATION
EARTH EXPLORATION SATELLITE	METEOROLOGICAL SATELLITE	SPACE RESEARCH
FIXED	MOBILE	STANDARD FREQUENCY AND TIME SIGNAL
FIXED SATELLITE	MOBILE SATELLITE	STANDARD FREQUENCY AND TIME SIGNAL SATELLITE

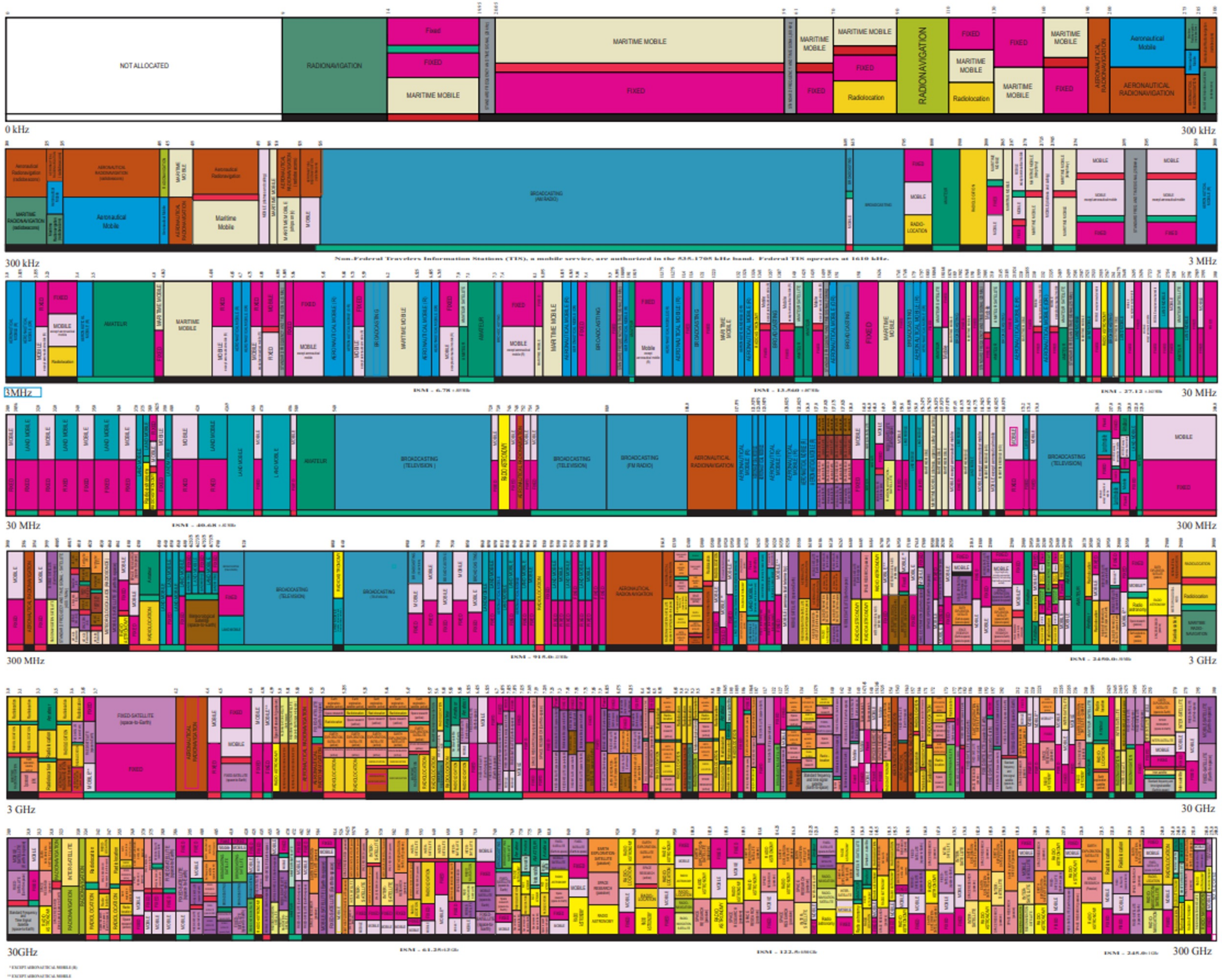
ACTIVITY CODE

FEDERAL EXCLUSIVE — FEDERAL/NON-FEDERAL SHARED — NON-FEDERAL EXCLUSIVE

ALLOCATION USAGE DESIGNATION

SERVICE	EXAMPLE	DESCRIPTION
Primary	FIXED	Capital Letters
Secondary	Mobile	1st Capital with lower case letters

U.S. DEPARTMENT OF COMMERCE
National Telecommunications and Information Administration
Office of Spectrum Management
JANUARY 2016



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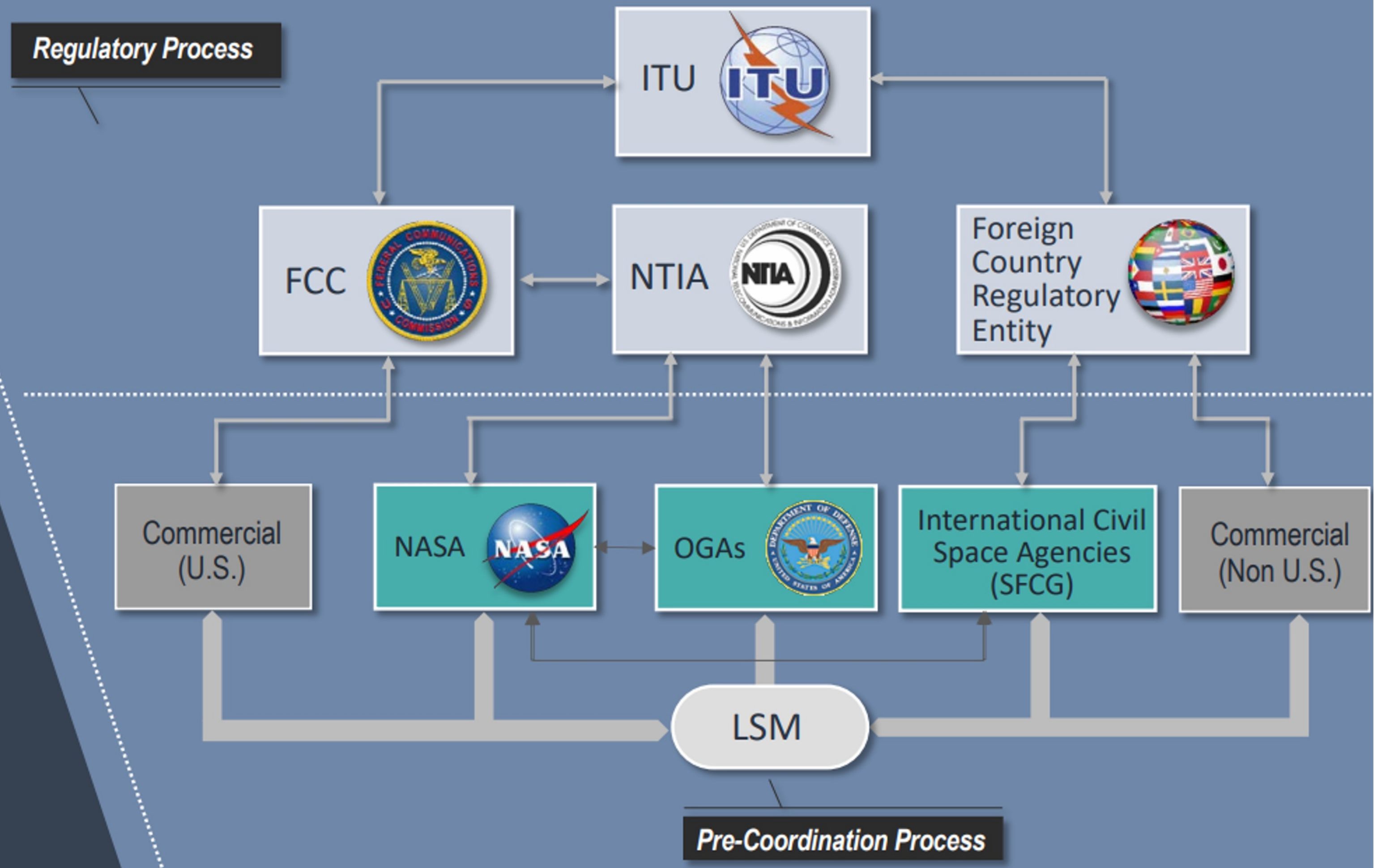
Pre-Coordination Process with LSM

- **Promote maximum compatibility and mission success** by facilitating technical analysis and pre-coordination between lunar-region missions, on a voluntary basis.
- **Identify/minimize/avoid problems** that might otherwise only be found during the formal regulatory process (by which time changes are costly to implement), or worse, during mission operations when interference has occurred.
- This model has worked well with the International Space Station; the need for pre-coordination is even greater in the lunar region.

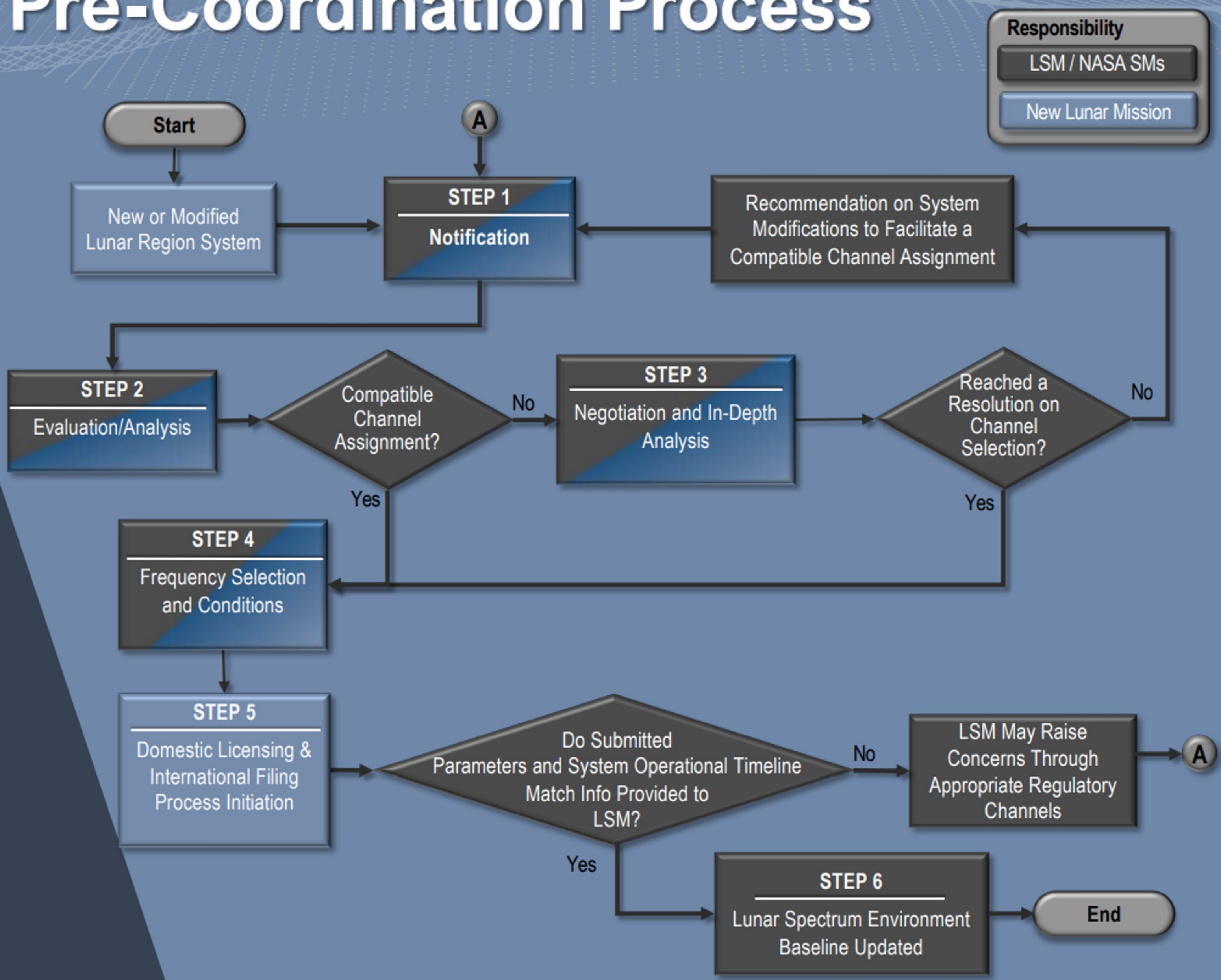


Lunar Pre-Coordination Process

- The Pre-Coordination Process aims to **minimize delays** or the need for rework during formal equipment certification and spectrum licensing efforts

- Process **supported by the Lunar Spectrum Management Portal*** (LSMP, see next slide for details)

*Note: LSMP does not support tasks involved in or which flow from licensing and filing activities.



LSM Portal

Background

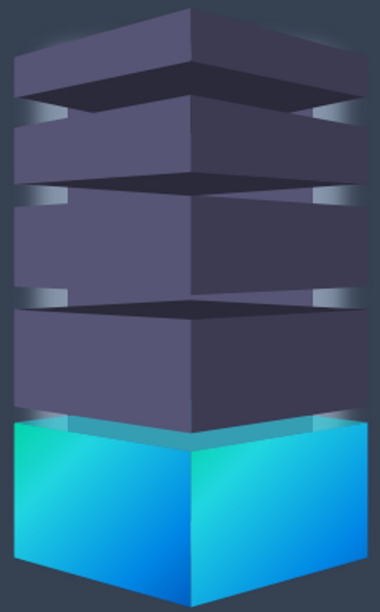
The LSM Portal serves as a centralized platform to help support the LSM in managing the Pre-Coordination Process and disseminating information about spectrum in the lunar region to stakeholders.

Key Functions

- LSM Portal enables lunar mission stakeholders to share information about new missions in the lunar region with the LSM and **supports pre-coordination activities**
- LSM Portal serves as centralized resource for **information about spectrum planning** in the lunar region

Key Resources

- Overview of relevant regulations and policies, and other government documents
- Summary information about known lunar region missions
- Overview of LSM role and Pre-Coordination Process
- Downloadable Lunar Frequency Selection Input Form to initiate Lunar Pre-Coordination Process



- **To gain access to the LSMP, contact SCaNVAS Support: support@scanvas.nasa.gov**
- **Request access to the "Lunar Spectrum Management Portal" and provide the name of the mission(s) you support**

Key takeaways:

- Spectrum is a long-lead item: atleast on par with other aerospace long-lead items.

- World Radio Conference (WRC) - the workhorse international co-ordination mechanism - is a <u>quadrennial</u> event:
  - First there has to be a consensus on setting an agenda item added for discussion at the next WRC
  - "Cislunar communications will feature at WRC-23 under Agenda Item 10, which calls for the drafting of future agenda items"
  - Takes several years to conduct studies (exacerbated by the lack of in-situ experiments/measurements - a chicken/egg problem)

Spectrum Drivers (1 of 2)

- **DWE Services between Earth and Lunar Vicinity**
  - Missions to the lunar surface and in the lunar vicinity share the same spectrum as other near-Earth systems including Earth orbiting satellites and terrestrial users
  - 2025 – 2110 MHz (Earth-to-space) and 2200 – 2290 MHz (space-to-Earth) frequency bands ("S-band") allocated to SRS are particularly congested and DWE links for lunar systems will exacerbate potential for interference among lunar vicinity and Earth-orbiting spacecraft
  - LunaNet spectrum architecture limits DWE links to 7190 – 7235 MHz (Earth-to-space) / 8450 – 8500 MHz (space-to-Earth) ("X-band") and 22.55 – 23.15 GHz (Earth-to-space) / 25.5 – 27.0 GHz (space-to-Earth) ("Ka-band") frequency ranges already allocated to SRS & widely implemented
- **Lunar In Situ Relay Services**
  - LunaNet spectrum architecture includes S-band and Ka-band frequency ranges for use by in-situ lunar relay services to lunar orbiting and lunar surface users
  - Partitioning use of frequency bands towards S-band for lunar proximity links and X-band / Ka-band for DWE links:
    - Enables efficient reuse of S-band within the near-Earth domain
    - Reduces interference experienced by in-situ lunar relay links, and
    - Reduces the size, weight, and power (SWaP) burden for lunar systems due to the shorter link paths

Spectrum Drivers (2 of 2)

- **Protection of the SZM**
  - SZM is an ideal physical location from which to conduct radio astronomy observations of celestial objects and phenomena not detectable by Earth-based radio astronomy systems
  - ITU Radio Regulations prohibit harmful interference to radio astronomy observations in the SZM
- **Future Extension and Scaling of LunaNet**
  - SFCG Recommendation 32-2R5 identifies the 37-38 GHz and 40-40.5 GHz frequency ranges for space-to-Earth and Earth-to-space communications support to lunar orbiting systems, respectively
  - While there is currently no satellite communications infrastructure on Earth that operates in these frequency ranges, an expansion of the LunaNet architecture is possible in this portion of the RF spectrum
  - Use of higher frequency bands (including optical wavelengths) will be driven by increasing congestion in the near-Earth environment in lower frequency bands

Investigations underway : The future..

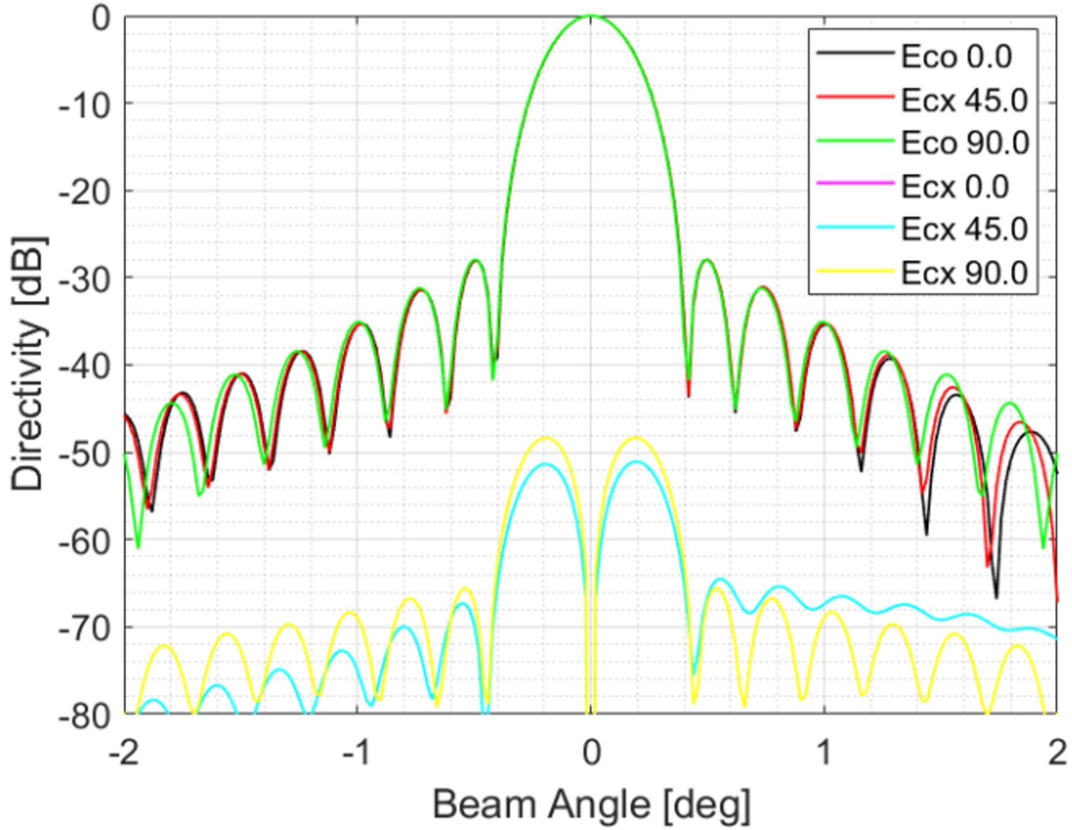
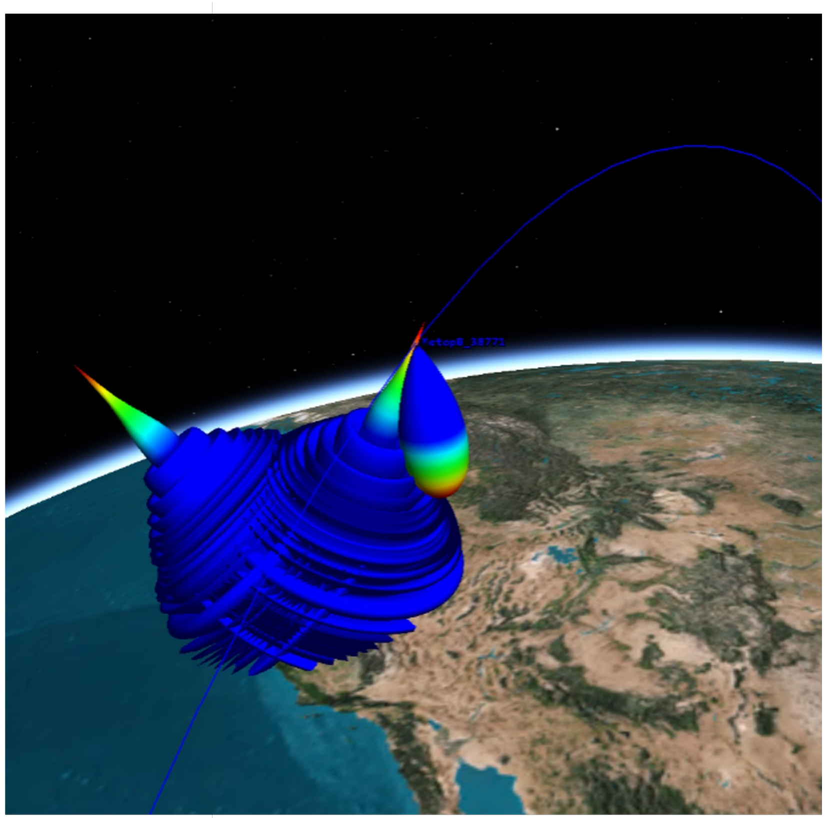
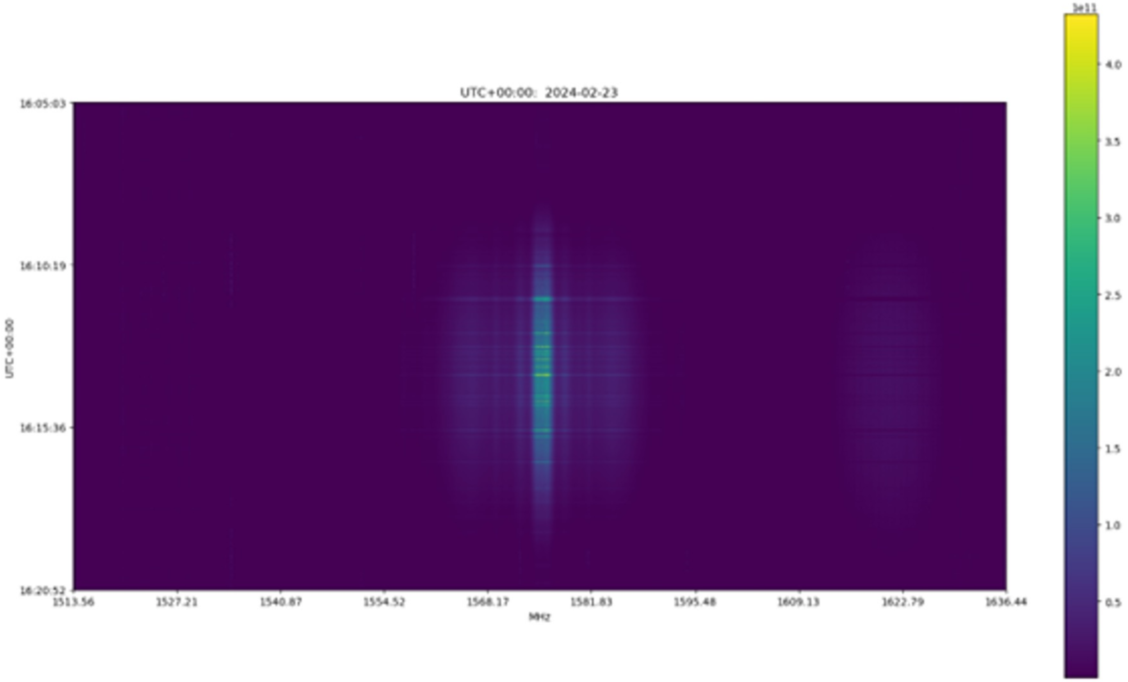


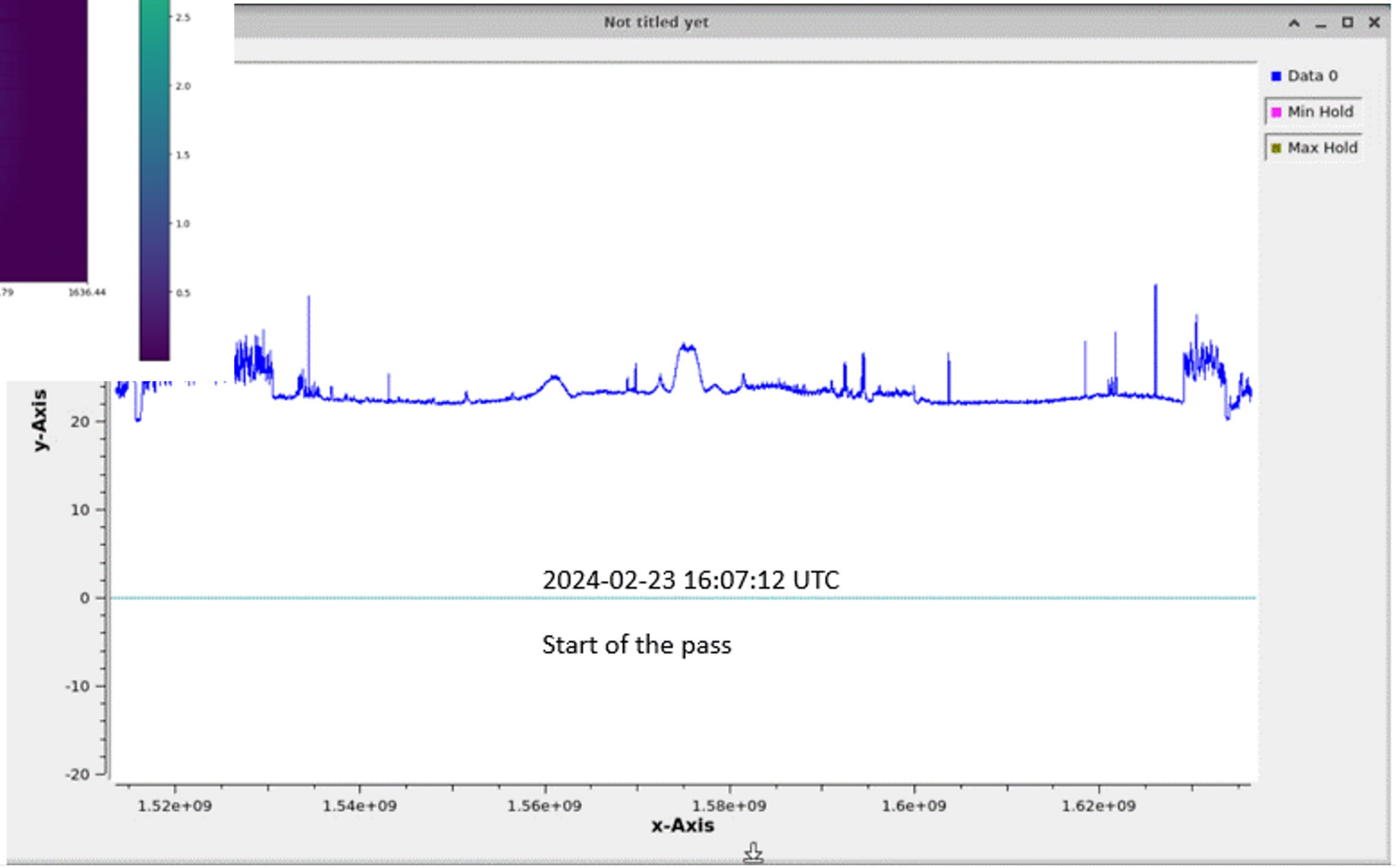
Figure 4: The main beam of the ATA optics with the 2.6λ hybrid mode conical horn. The full width half maximum of this beam is $\sim 0.8°$. The main beam cross-polarization is $\sim$ 48dB when generated with an ideal hybrid mode feed.



Dynamic Sharing

SOPP Verification





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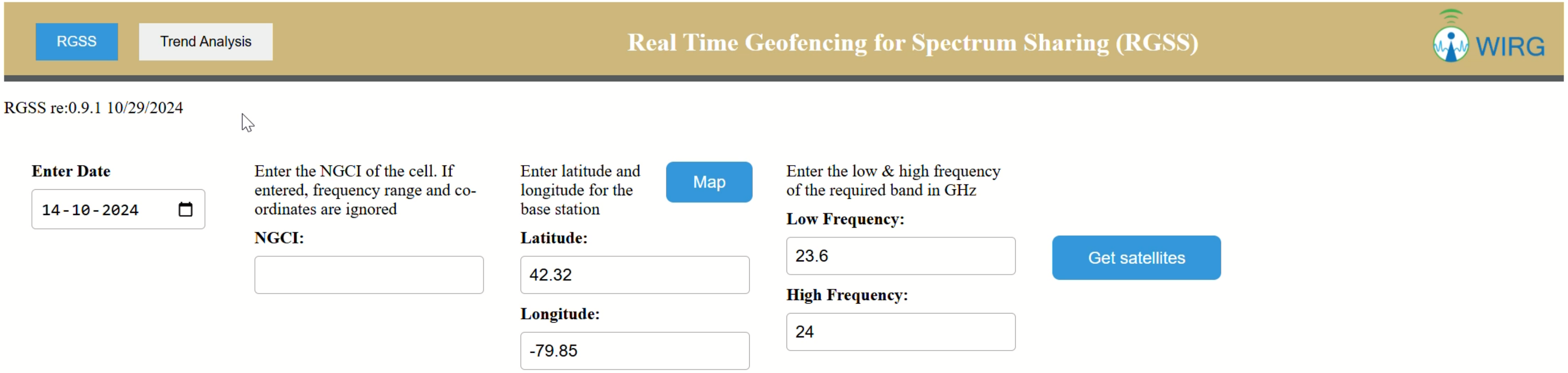
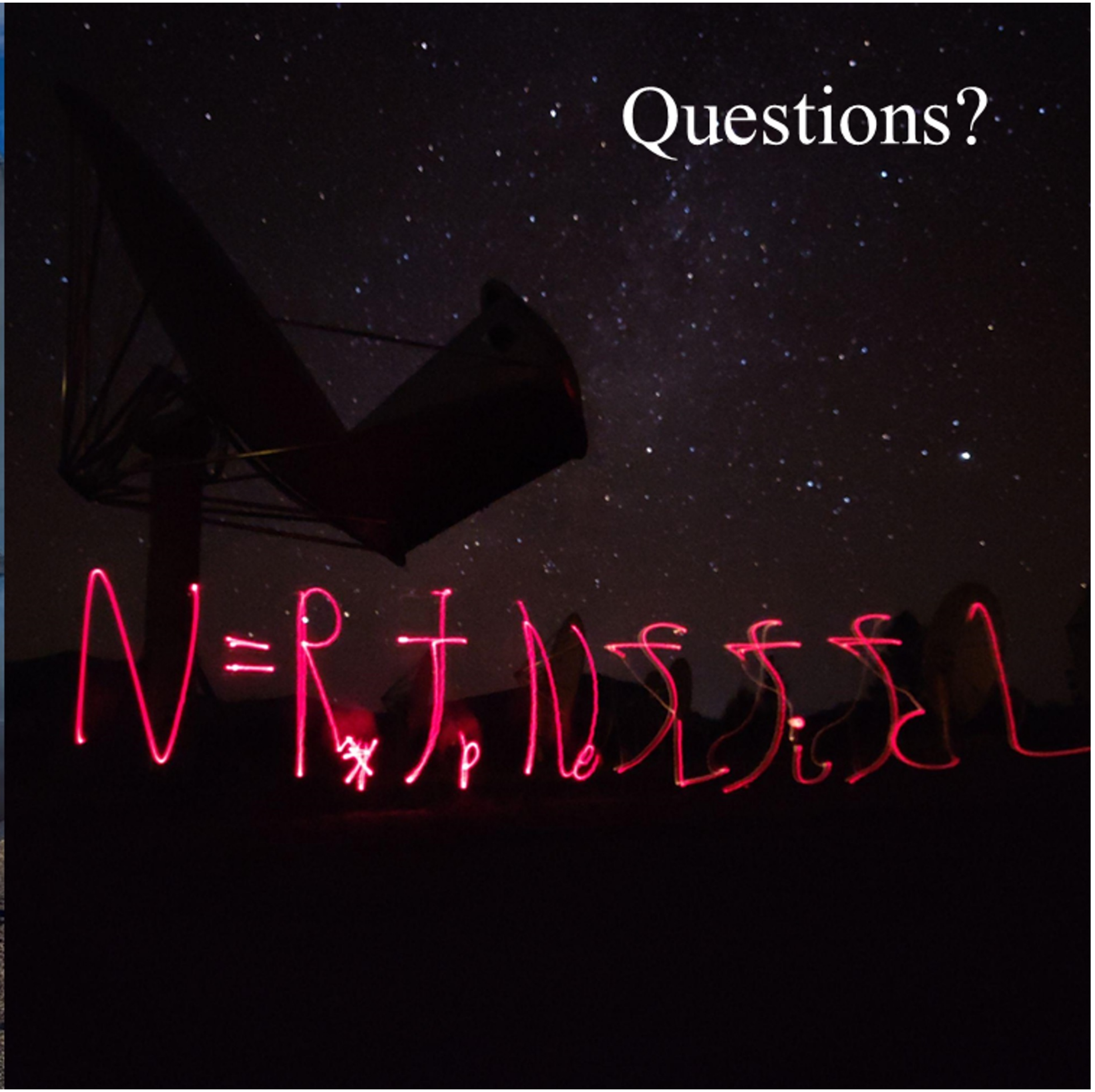
Start of the pass



A proof of concept demonstration of Real-time Geospatial Spectrum Sharing



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