On behalf of the ESA Astronomical Lunar Observatory Topical Team

MARC KLEIN WOLT, LEON KOOPMANS, CHRISTIAAN BRINKERINK, ALBERT-JAN BOONSTRA, MARK RUITER, LEONID GURVITS, DAVID PRINSLOO, HARISH VEDANTHAM, MICHEL ARTS, BORJA GUTIERREZ, JESSICA GRENOUILLEAU, JAN TAUBER

ASTRONOMICAL LUNAR OBSERVATORY

Radboud University

- MEASUREMENT OF GLOBAL 21-CM EMISSION: CONSTRAINING COSMOLOGICAL THEORIES
- DIRECTLY PROBING THE FORMATION HISTORY OF THE PRISTINE UNIVERSE
- FAR SIDE RADIO INTERFEROMETER: OPENING UP THE LAST VIRTUALLY UNEXPLORED FREQUENCY REGIME
- SYNERGY WITH HUMAN LUNAR EXPLORATION
- INTERNATIONAL LUNAR OBSERVATORY
- BUILDING ON- AND EXTENDING ON EUROPEAN HERITAGE

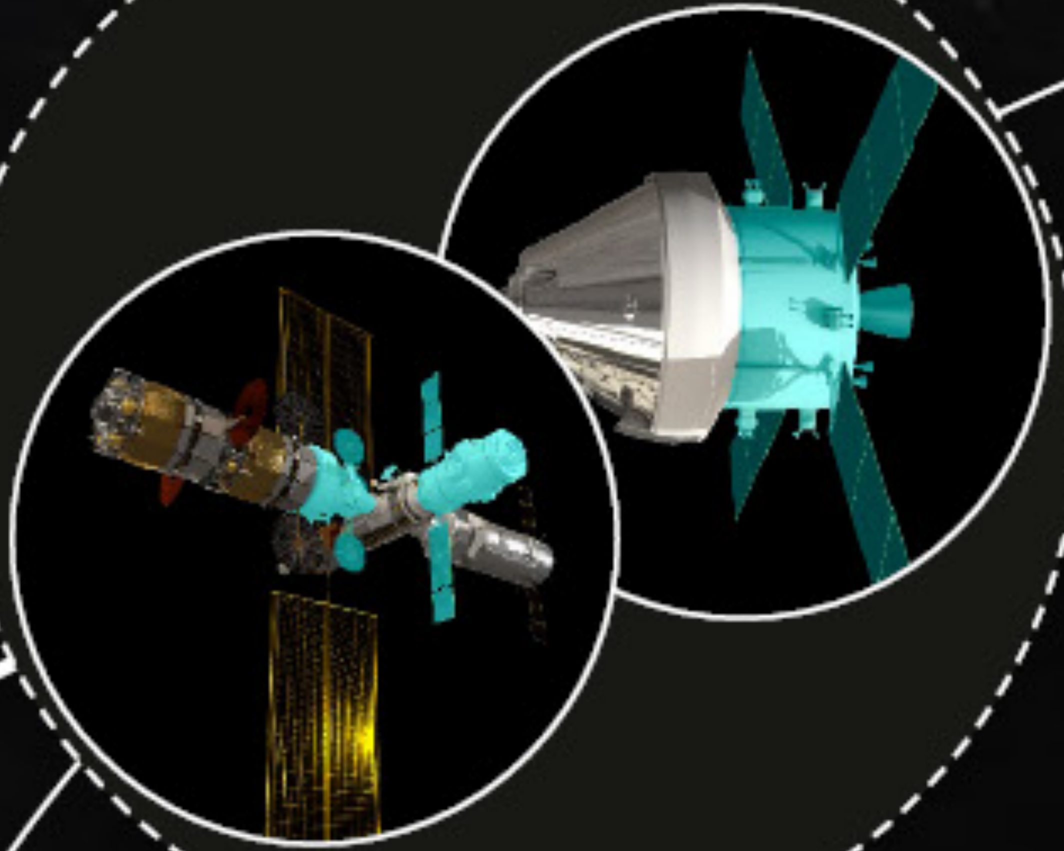
DISCOVERY MISSION FOR THE DARK AGES AND COSMIC DAWN

TERRAE NOVAE 2030+

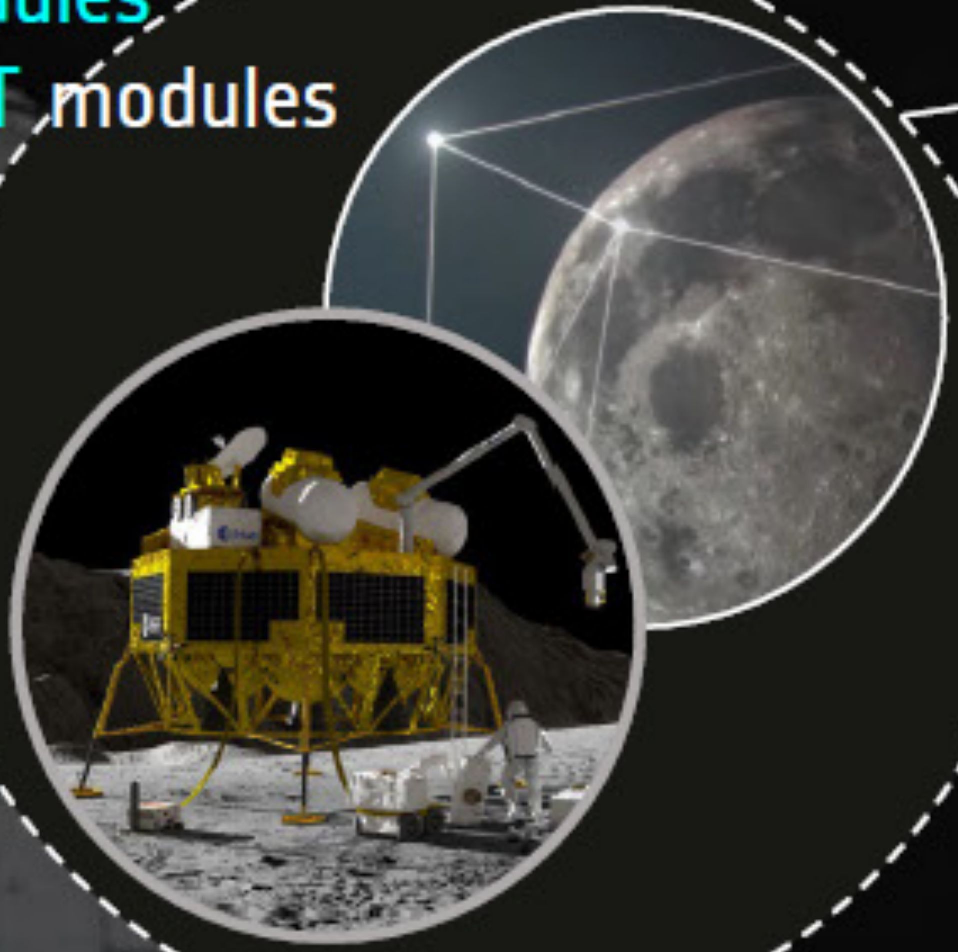
Long-term strategy @Moon

Cis-lunar access

ISS partnership extension
Orion's European Service Modules
Gateway's I-HAB and ESPRIT modules
Gateway astronaut flights
Gateway science



Surface access
Comms/nav services



Logistics and cargo
Comms/nav services
Collaborative science
Science on the Moon
Technical capabilities
Secure comms

In-space transportation

Redundancy
Mars transit demo
Sustainable access

Surface infrastructure

Power and resource provision
Extend missions duration (night survival)
Enable sustainability

Surface mobility

Support for base camp
Dissimilar redundancy
Extend "range" of science
Leverage expertise

- Contributions to partners
- European ambition

Moon Missions/Elements Study Candidates

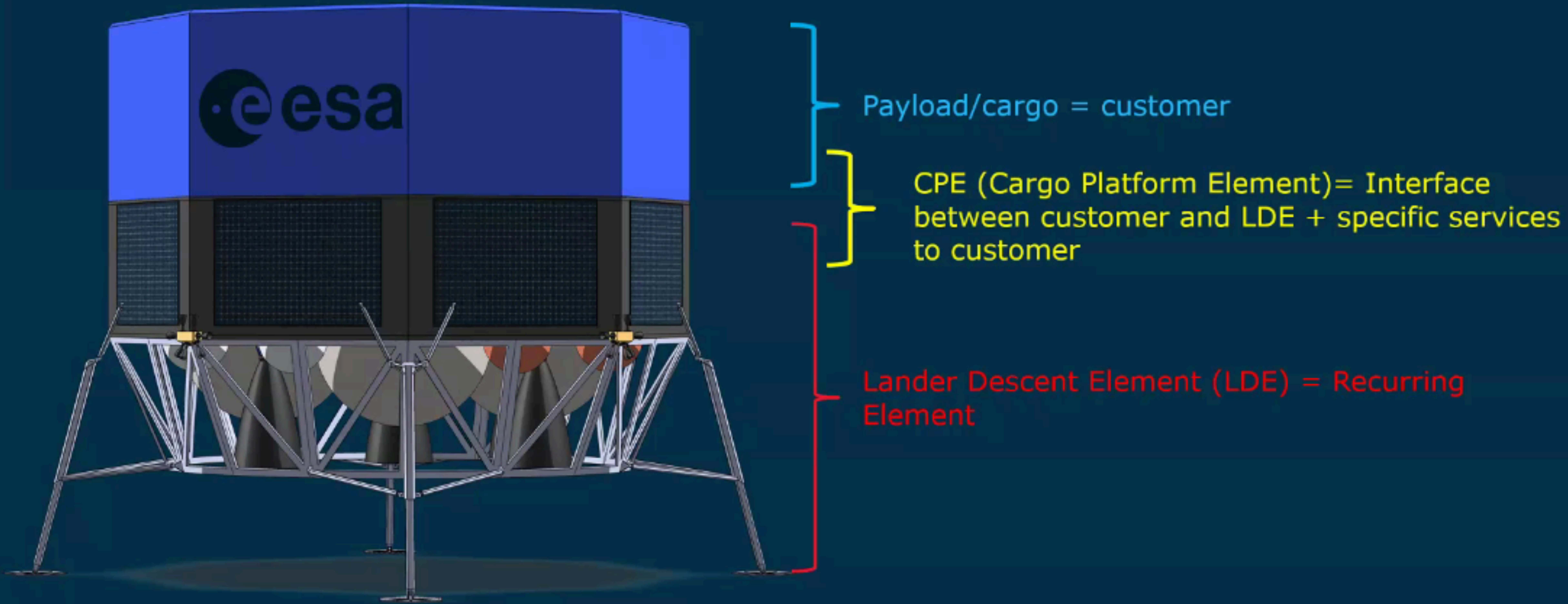
- *Cargo Logistic Mission (CDF study completed on Cargo CPE, pre-Phase A with Primes)*
- *POLESTAR (CDF study completed)*

- **Polar Explorer Mission (CDF study completed, pre-Phase A with Primes)**
- **Astrophysical Lunar Observatory (ALO) Mission (CDF study completed)**
- **Bioscience on the Moon Mission (CDF study completed)**
- Geology Mission (CDF study planned 2022)

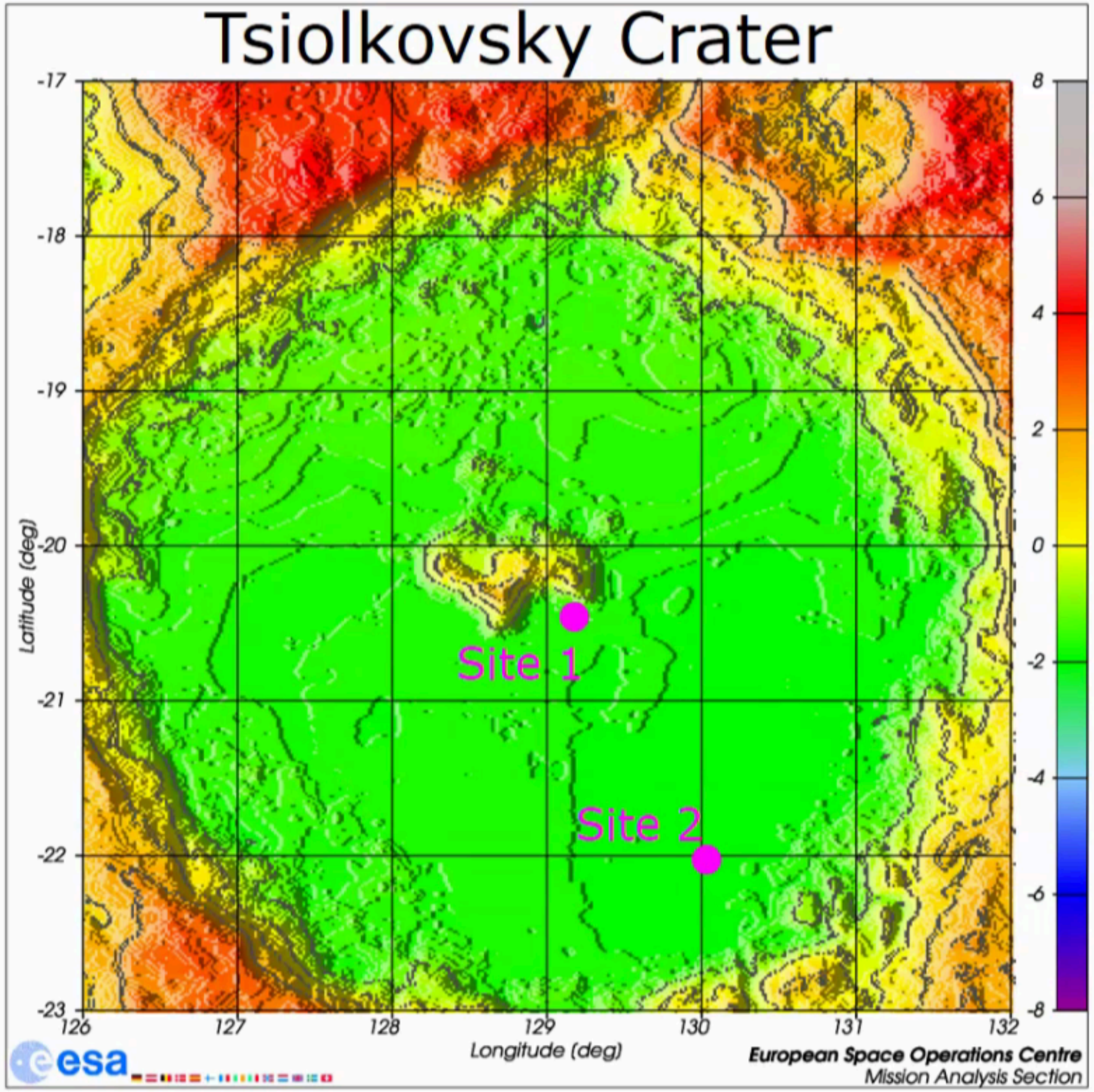
- **European Charging Station for the Moon (CDF study completed, pre-Phase A in preparation)**
- **European Moon Rover System (EMRS) (Pre-Phase A ongoing)**
- Versatile Mobility Platform & Habitation
- ISRU Pilot Plant Mission (CDF study complete in 2018, new CDF study planned in 2022)

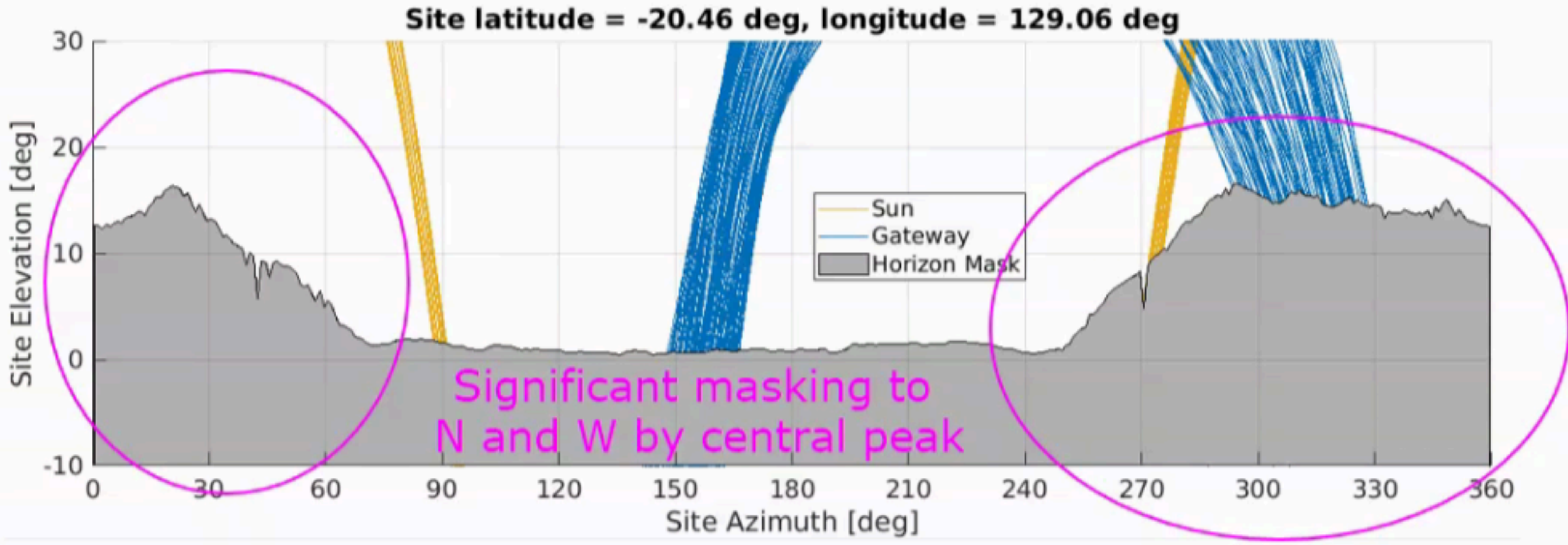
Preparing enabling infrastructure and capabilities

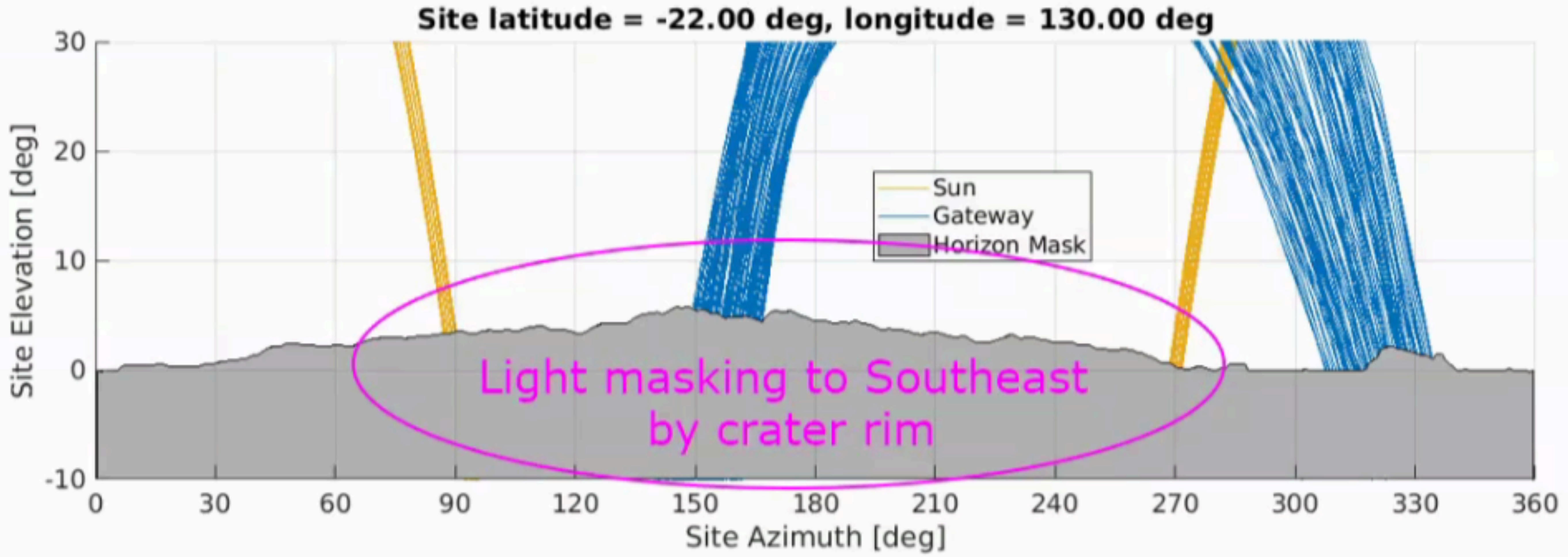
European Large Logistics Lander

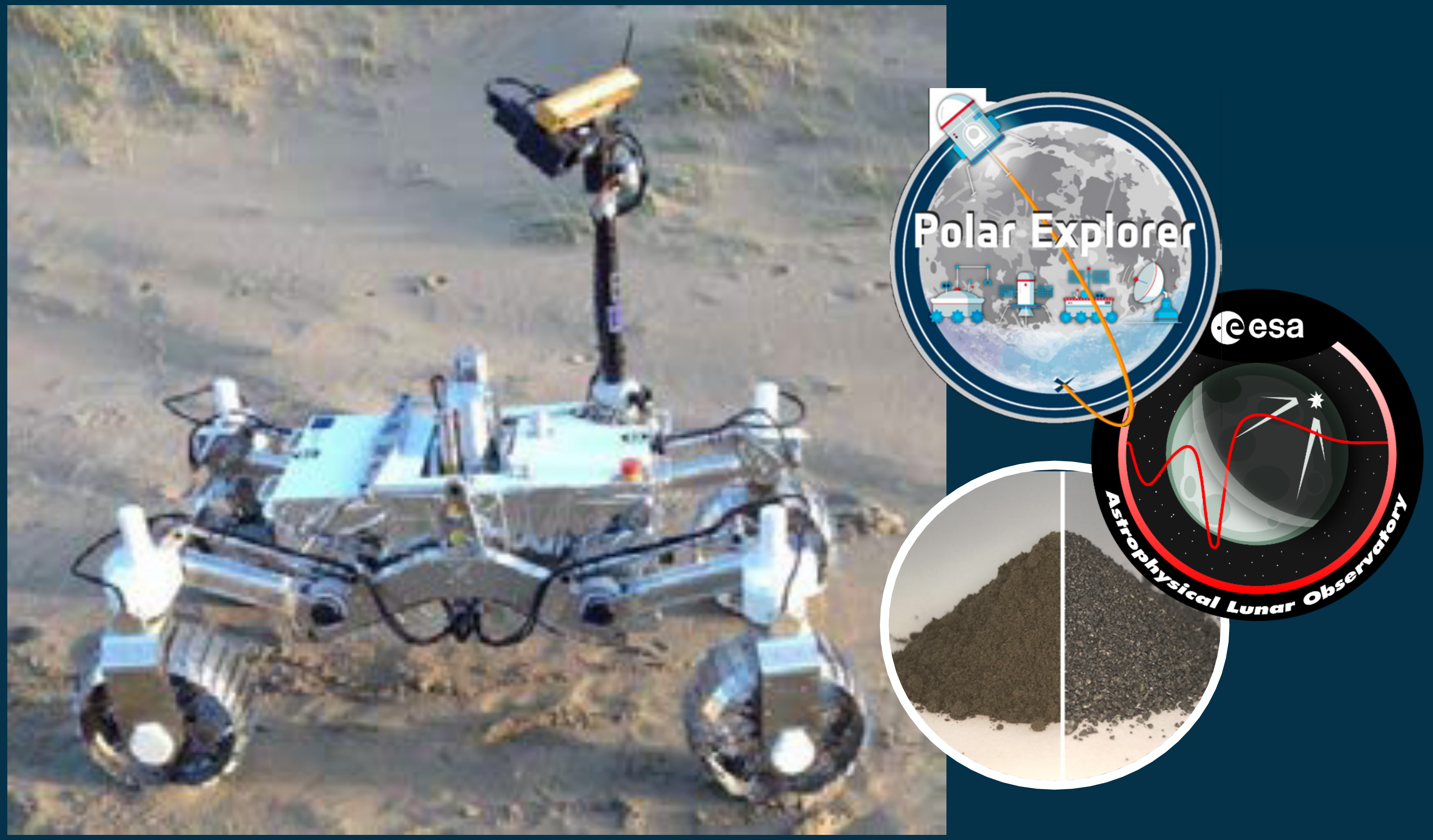


Horizon Masks: Optimise the Landing Location









Description

- Multi-purpose modular mobility solution for future EL3 mission concepts requiring rover element:
  - Polar Explorer (science rover)
  - ALO (antenna deployment)
  - ISRU Pilot Plant (excavator rover)
- Mobility class of few hundreds of kg
- Precursors ground demonstrations using challenge-based innovation to attract non-space industry SMEs, start-ups, incl. in smaller participating states

European Moon Rover System (EMRS)

Technology

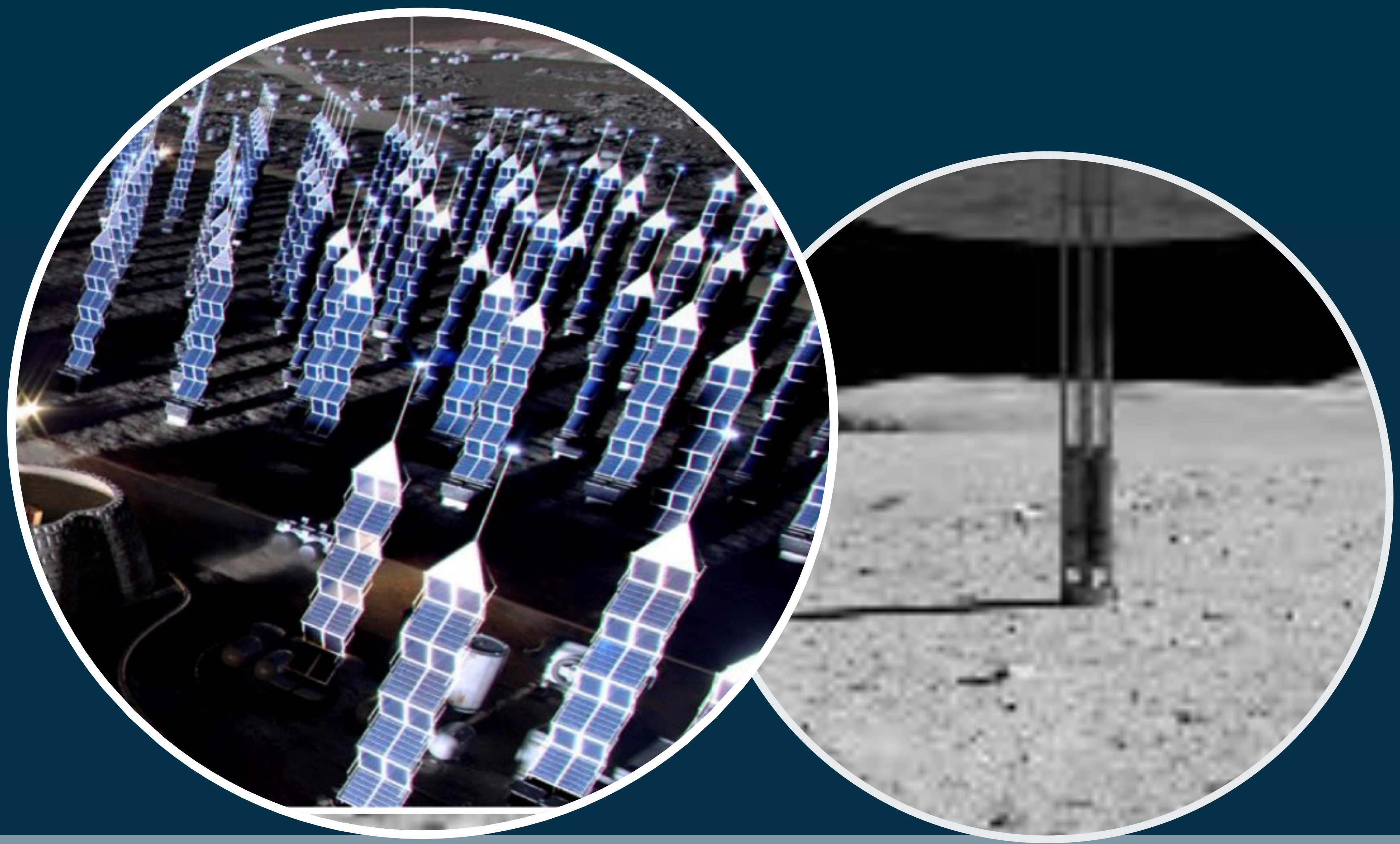
- Surface mobility considered key for planetary exploration
- Built on ExoMars/SFR rover heritage
- Technology maturation themes (e.g.):
  - Locomotion
  - Power, thermal & night survival
  - Communications & Navigation
  - Robotics
  - Dust resilience, etc.

Science

- Science instrumentation based on mission concept
- Closure of knowledge gaps around surface mobility and exploration in lunar environment

Schedule

- Pre-Phase A
  CDF (PE, ALO) completed in 2020/21
  Ongoing pre-phase A in 2022
- Potential Phase A/B1
  Advanced rover study in parallel to EL3 and payload developments in P3
  (possibility to be provided / co-developed by national agencies)



Description

- EL3 based surface power station based on photovoltaics and RFCS system, possibly mini-nuclear reactor
  - ❖ Local power element for robotic and human surface activities
  - ❖ Potential contribution to Artemis surface architecture (or for other partners)
  - ❖ Communication (to Earth, Relay Orbiter, Surface network) as additional service

European Charging Station for the Moon

Technology

- Technology maturation for power generation and storage subsystems
  - RFCS technology
- Leverage heritage and industrial capacity for solar power satellites
- Investigate technologies for use power charging
- Wireless power transfer demonstration

Science

- SciSpacE strategy is in development.
- Applied sciences investigations
- Other opportunistic science

Schedule

- PrePhase A
  CDF completed in 2021
  Pre-phase A planned In 2022
- Potential Phase A/B1
  Study to mature infrastructure concept and interfaces starting in 2023
- Potential Phase B2-C/D
  Implementation decision at CM25+

Description

- Scale and demonstrate lunar oxygen production from regolith, building on ISRU demo and ground based work
- Potential contribution to Artemis base camp (or other partners), potentially including excavation rover
- Secure roles for European industries in space resources market

ISRU Pilot Plant

Technology

- Technology maturation for ISRU processing (e.g. sounding, drilling, excavation, characterisation, processing), incl. ground prototypes
- Advancement of mobile excavation rover

Science

- SciSpacE strategy is in development.
- Science investigations could look at:
  - resource characterisation and interaction with the environment
  - Applied sciences related to sustainability
  - Investigation of biosystem integration in mining and processing

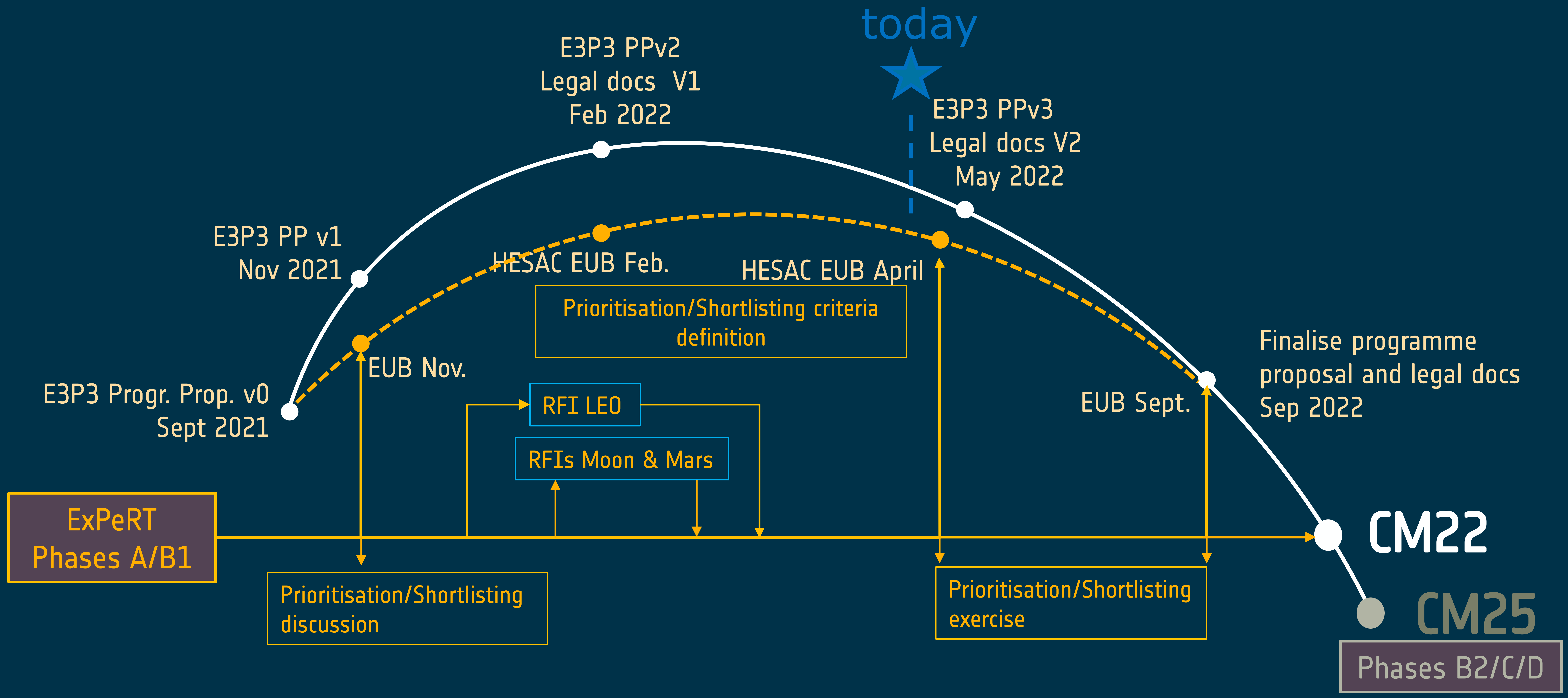
Schedule

- PrePhase A
  CDF completed in 2018 (old concept)
  CDF update planned in 2022
- Potential Phase A/B1
  Study to mature infrastructure concept and interfaces starting in 2023
- Potential Phase B2-C/D
  Implementation decision at CM25+

Phase A/B1 Studies in Period 3

Note: A notional process flow is shown.

Roadmap CM22 – European Exploration Envelope Programme (E3P3)



EUB = European Utilisation Board (Delegation level)

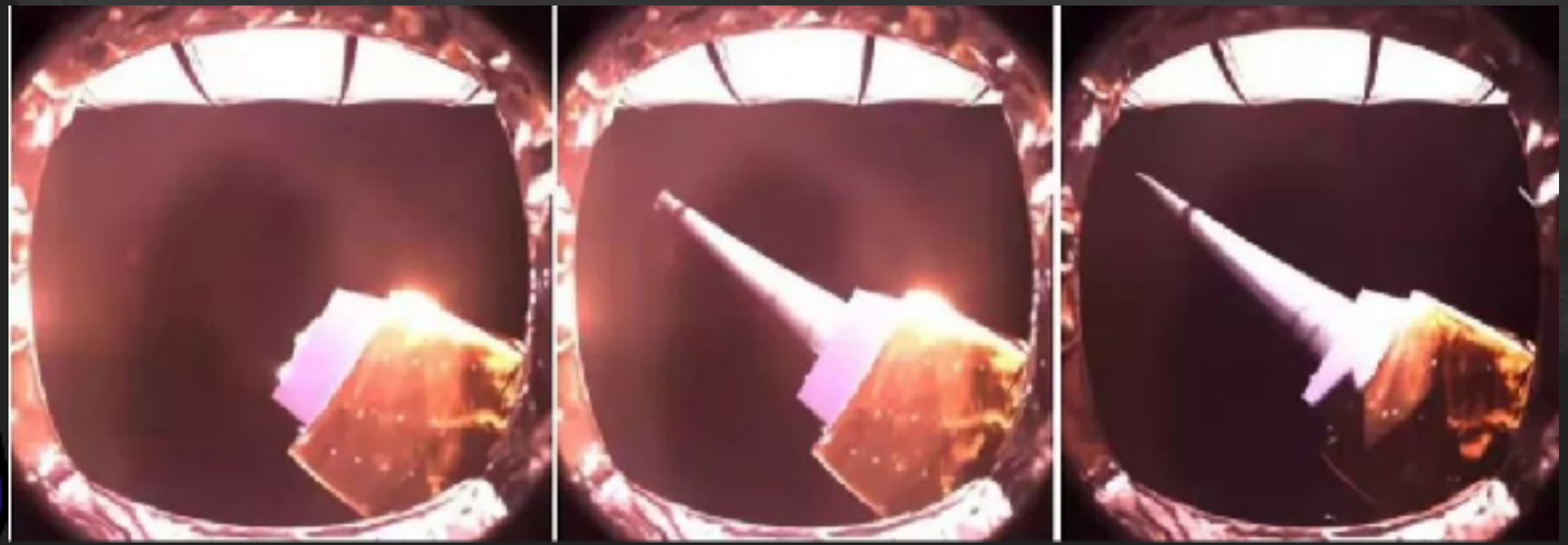
OBJECTIVES OF THE ALO TOPICAL TEAM

- Define the science objectives
- Define the scientific requirements
- Coordinate the technology developments

RADBOUD RADIO LAB

PREDEX
PRECURSOR DARK AGES EXPLORER

Astrophysical Lunar Observatory

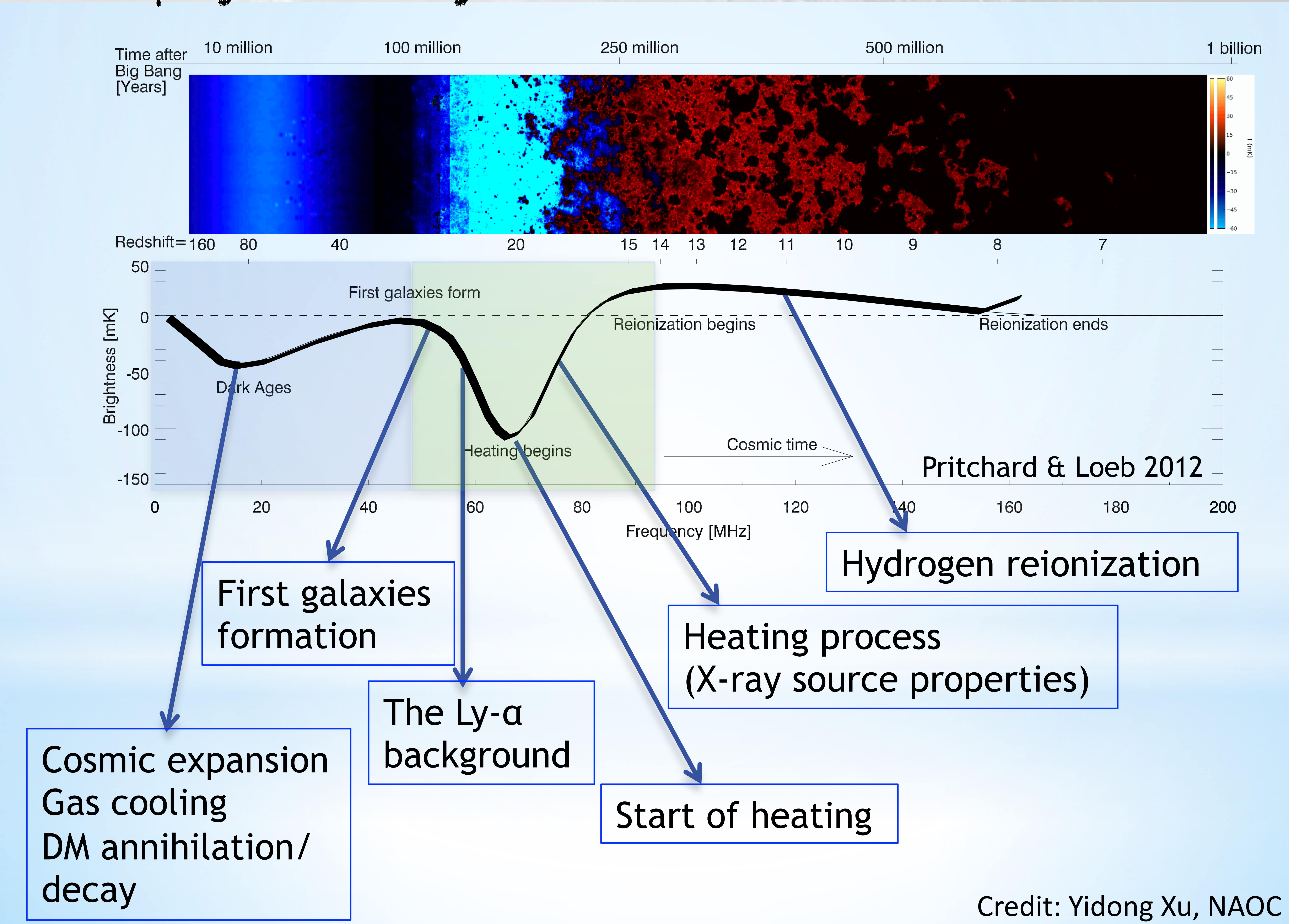


EXPECTED 21 CM GLOBAL SIGNAL FROM STANDARD MODELS

Interplay between Hydrogen and "the rest of the Universe"

Dark Ages

Cosmic Dawn



Credit: Yidong Xu, NAOC

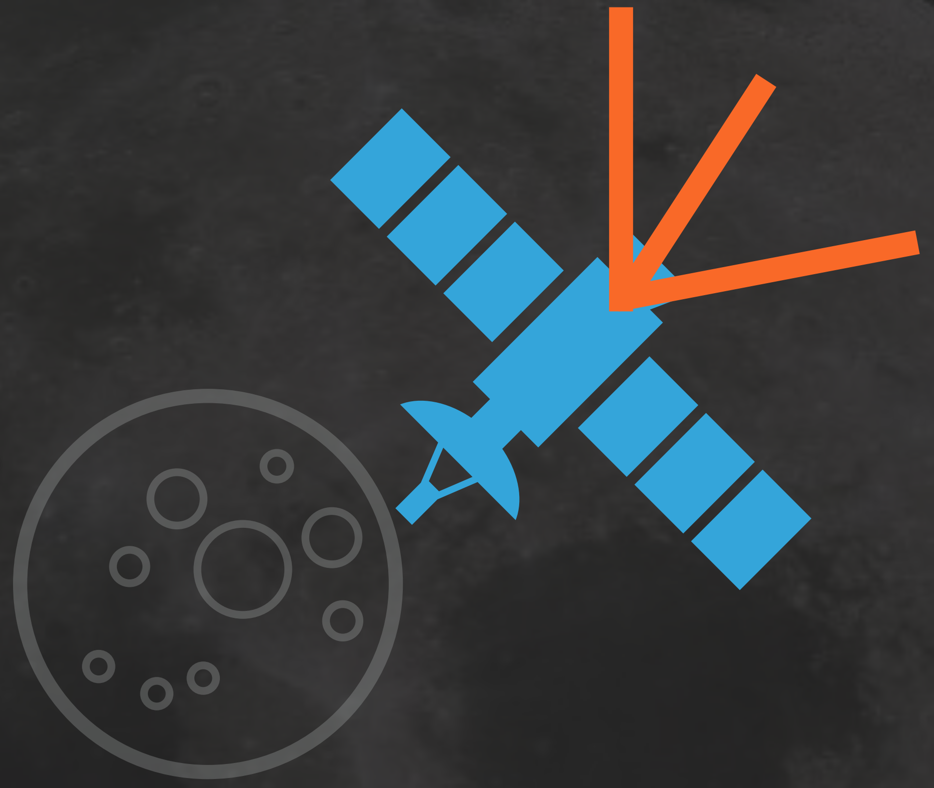
SCIENCE & SCALABILITY

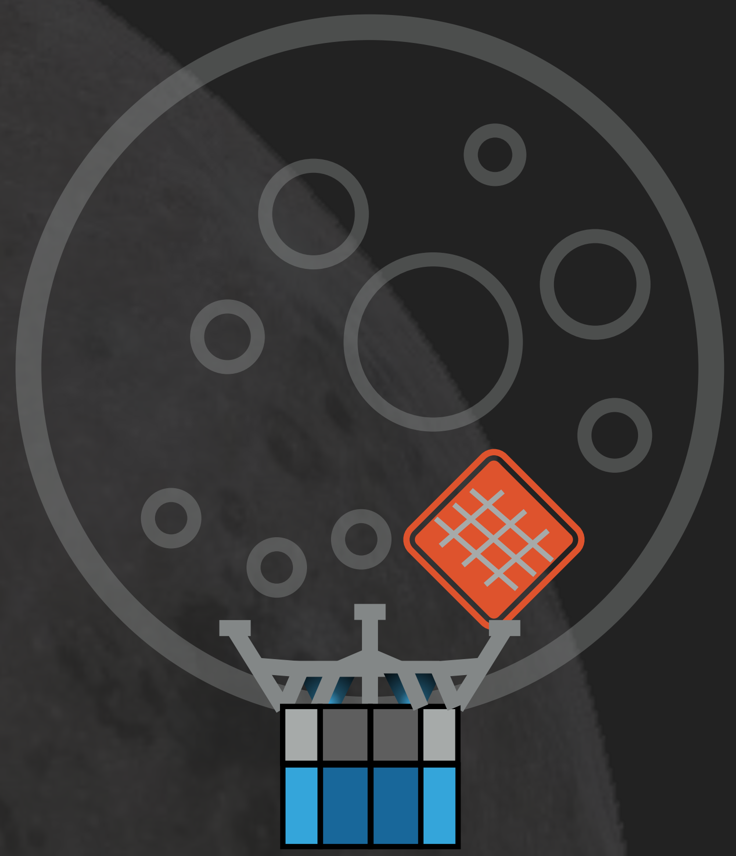
Number of antennas - Array concept	Global Dark Ages signal (DA)	Global Cosmic Dawn signal (CD)	Dark Ages Power Spectra	Dark Ages Tomography	Cosmic Dawn Power spectra	Cosmic Dawn Tomography
1	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 2000 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 17 hours.	N/A	N/A	N/A	N/A
2	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 1400 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 12 hours.	N/A	N/A	N/A	N/A
3 (all outriggers)	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 1150 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 10 hours.	N/A	N/A	N/A	N/A
4 (all outriggers)	For z = 80 (17.5 MHz), bandwidth 10 MHz, deltaT = 10 mK: t_int = 1000 hours.	For z = 20 (70 MHz), bandwidth 1 MHz, deltaT = 10 mK: t_int = 8.5 hours.	N/A	N/A	N/A	N/A
4 x 4	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 20, k from 0.003 to 0.1 (see plot 1 in the 'sensitivity plots' tab)	TBD
8 x 8	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 22, k from 0.003 to 0.1 (see plot 2 in the 'sensitivity plots' tab)	TBD
16 x 16	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 22, k from 0.003 to 0.2 (see plot 3 in the 'sensitivity plots' tab)	TBD
32 x 32	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 25, k from 0.003 to 0.1 (see plot 4 in the 'sensitivity plots' tab)	TBD
64 x 64	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 27, k from 0.003 to 0.1 (see plot 5 in the 'sensitivity plots' tab)	TBD
128 x 128	N/A	N/A	S/N << 1	TBD	S/N > 1 for z = 28, k from 0.003 to 0.1 (see plot 6 in the 'sensitivity plots' tab)	TBD

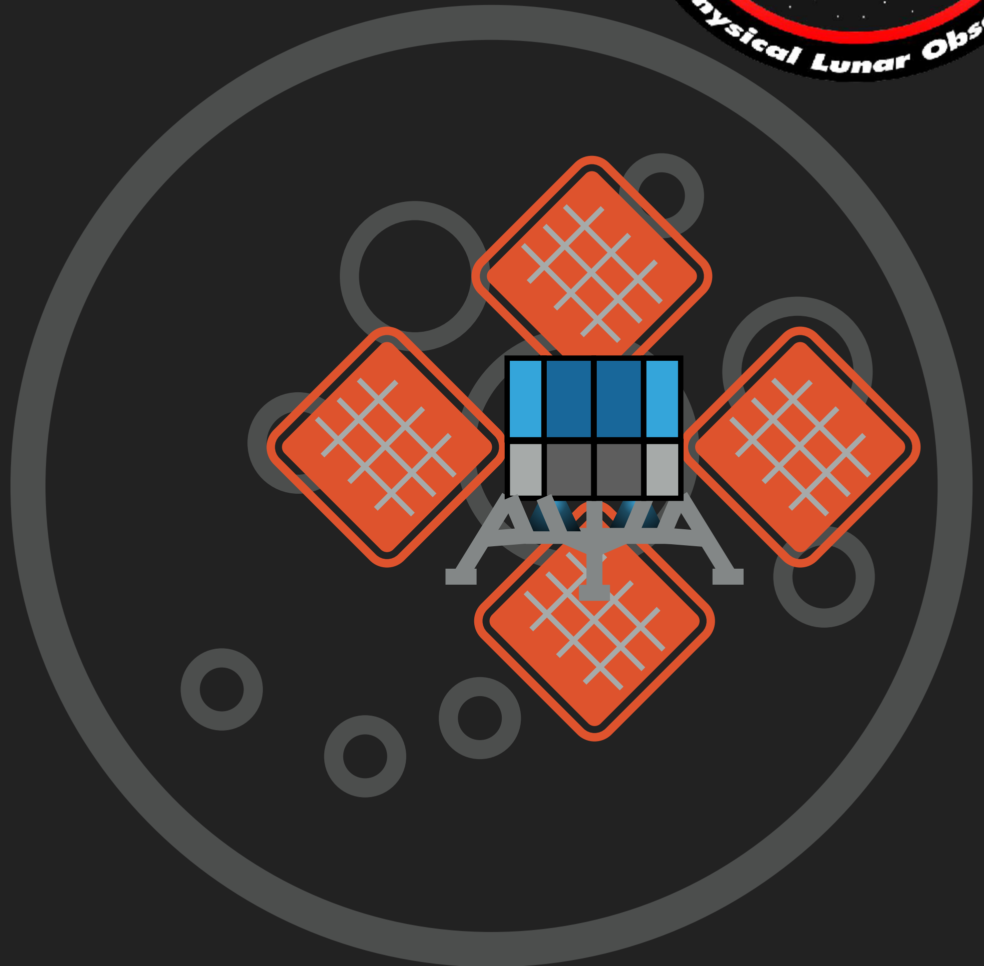
ASTRONOMICAL LUNAR OBSERVATORY

TECHNOLOGY ROADMAP

Towards an array on the moon







2022	June 10 2022	July 2022	Nov 2022	2025	2029	2035?
ALO TT & CDF PreDEX Pre-Phase A	ALO Roadmaps Draft	ALO Roadmaps	ESA Ministerial	MoonLight Demonstrator (ESA): Technology demonstrator	South Pole mission: ALO pre-cursor	Far side mission: ALO array
		Pre-Phase A studies		Miniaturised electronics RFI, EMC mitigation techniques Data processing	Printed antennes Deployment Interaction with Lunar Regolith Interferometry in space Distributed data processing	

Some scaled budgets for illustration

ONLY TO ILLUSTRATE ORDERS OF MAGNITUDE

Array Size	Antennas Mass* [t]	Hubs Mass** [t]	Harness Mass [t]	Station Mass [t]	Total Mass*** [t]	Data rate **** [kbps]
4x4=16	**0.03**	**0.05**	**0.01**	**0.50**	**0.98**	**0.6**
8x8=64	*0.12*	*0.20*	*0.03*	*0.69*	*1.43*	*5*
16x16=256	*0.5*	*0.8*	*0.1*	*1.4*	*3.2*	*40*
32x32=1024	**1.9**	**3.2**	**0.5**	**4.5**	**10.5**	**300**
64x64=4096	*7.6*	*12.9*	*2.2*	*16.6*	*39.7*	*2,400*
128x128=16384	**30.3**	**51.6**	**10.2**	**65.4**	**157.8**	**19,500**

Number of Hubs = Number of Antennas / 16
* Single antenna dipole mass: ~2kg
** Single hub mass w/o antennas or harness: ~50kg
*** Includes rover ~400kg
**** Only for imaging experiment array (global detection experiment is 1,000 kbps/antenna)
NOTE: Expected downlink capability < 25-50 Mbps

Baseline is 4*4 - exploring technology developments to go to 32*32 or 128*128

TECHNOLOGY DEVELOPMENTS

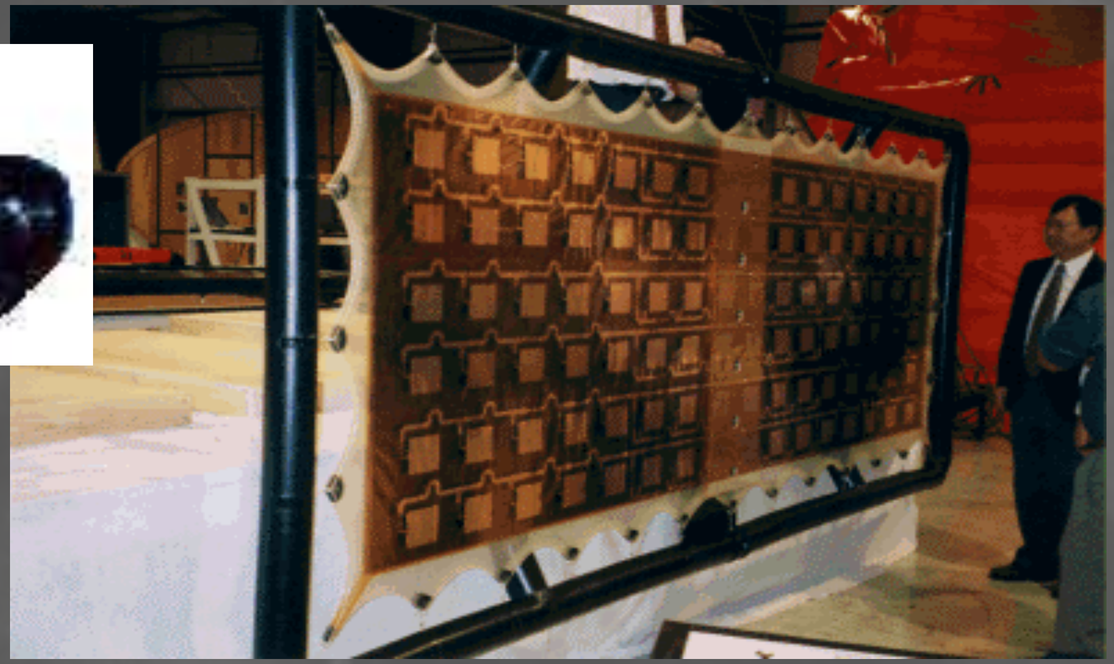
What can be done in the scope of the ALO TT?

- Within the ALO scope there are certain developments we can push for, and others that we should follow.
- Technology developments on wireless/optical communication, solar panel technologies & other power solutions (also for night survival), robotics are also happening outside the scope of ALO, these should be identified and followed.
  - In ALO we should push for optimisation of mass - power - data via the developments on the:
    - Antenna;
    - LNA (analogue electronics);
    - Receiver (digital electronics);
    - Data processing architecture (distributed data processing).
- Focus on inflatables and integration off the antenna systems and electronics, and possibly power generation.

TECHNOLOGY DEVELOPMENTS

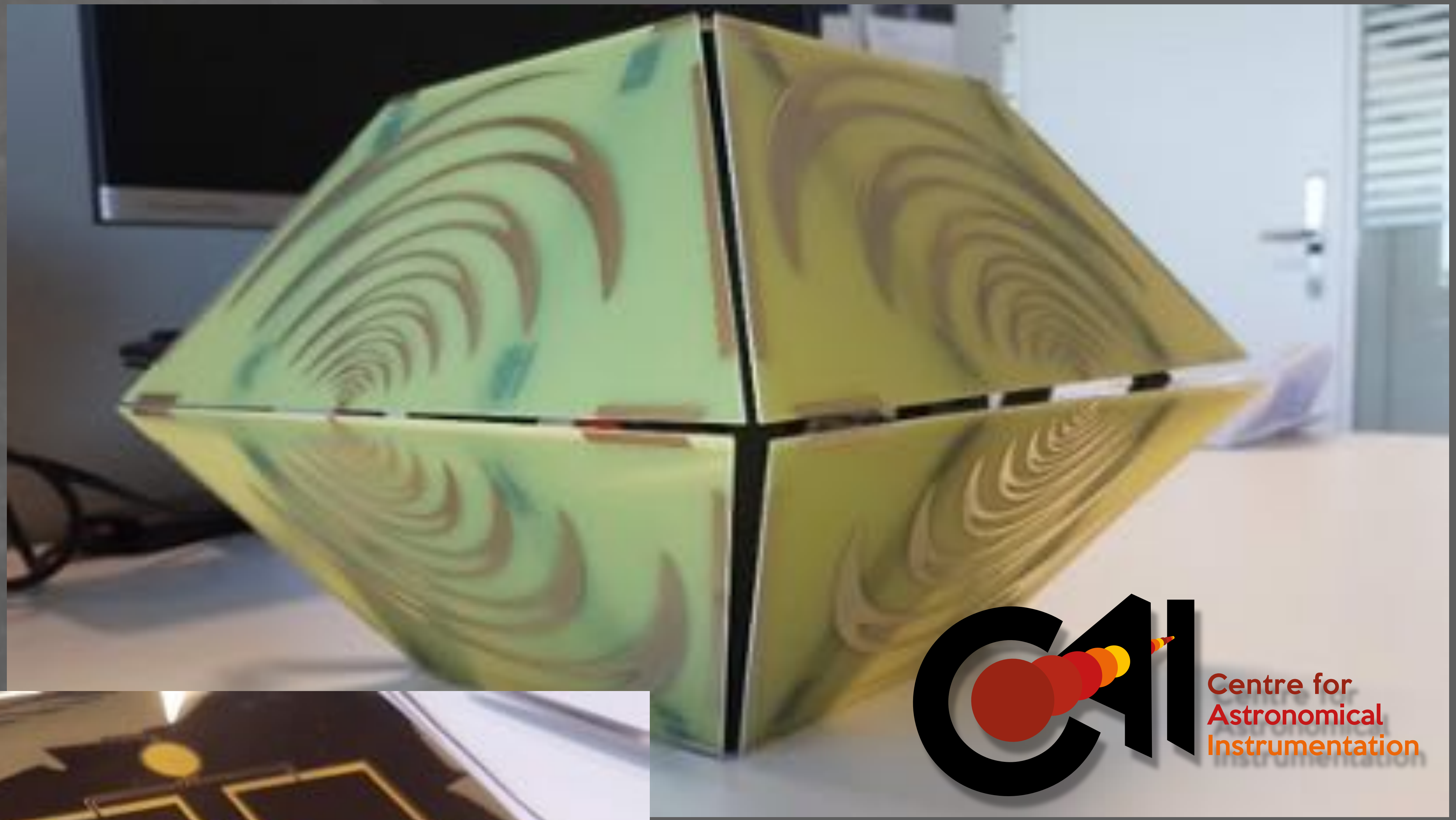
Optimisation of Mass - Power - Data: printed antennas & Inflatable structures

Roll-up Antenna (stowed)

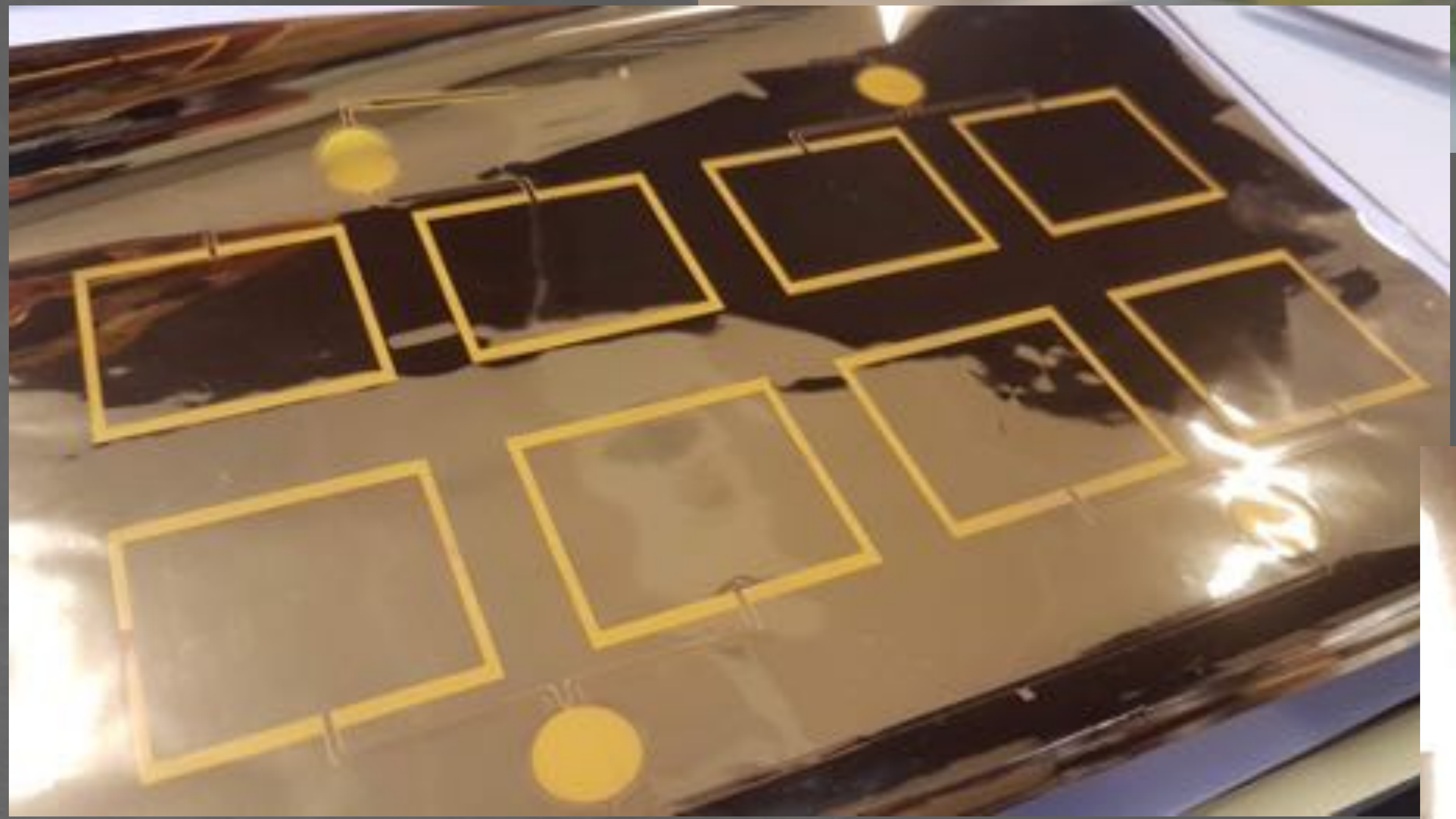


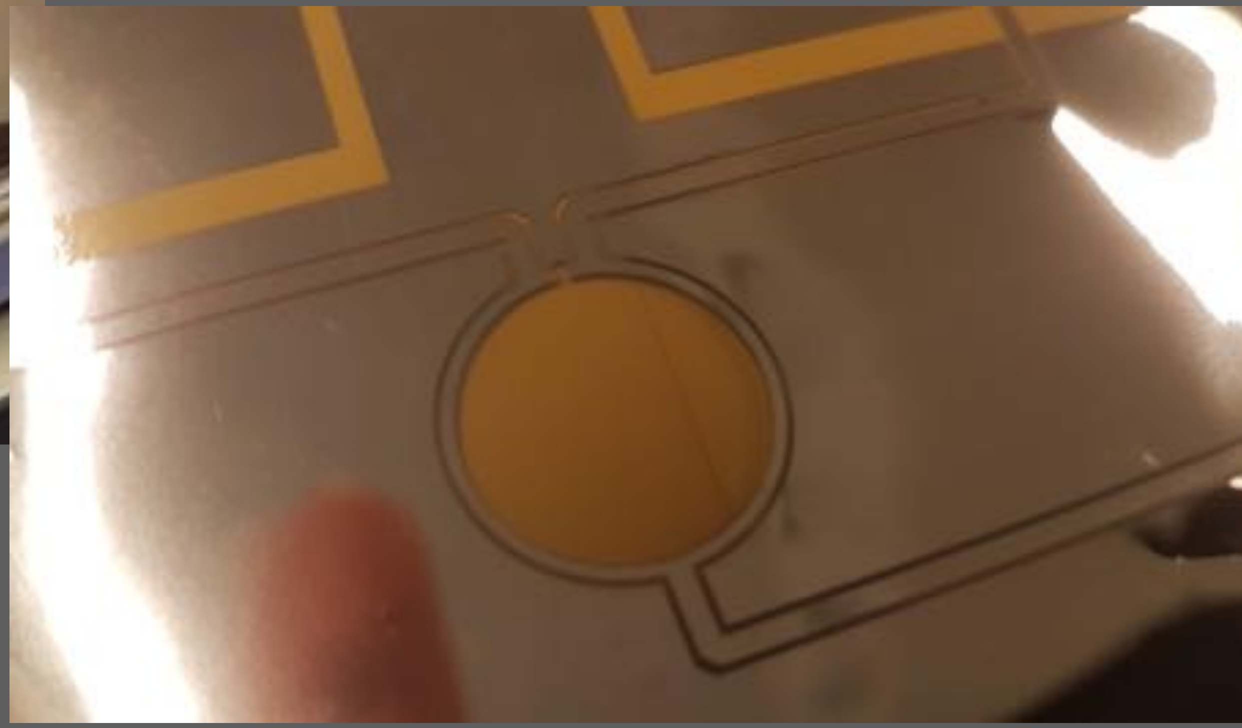
Fully Deployed Antenna

JPL Design



ASTRON Design



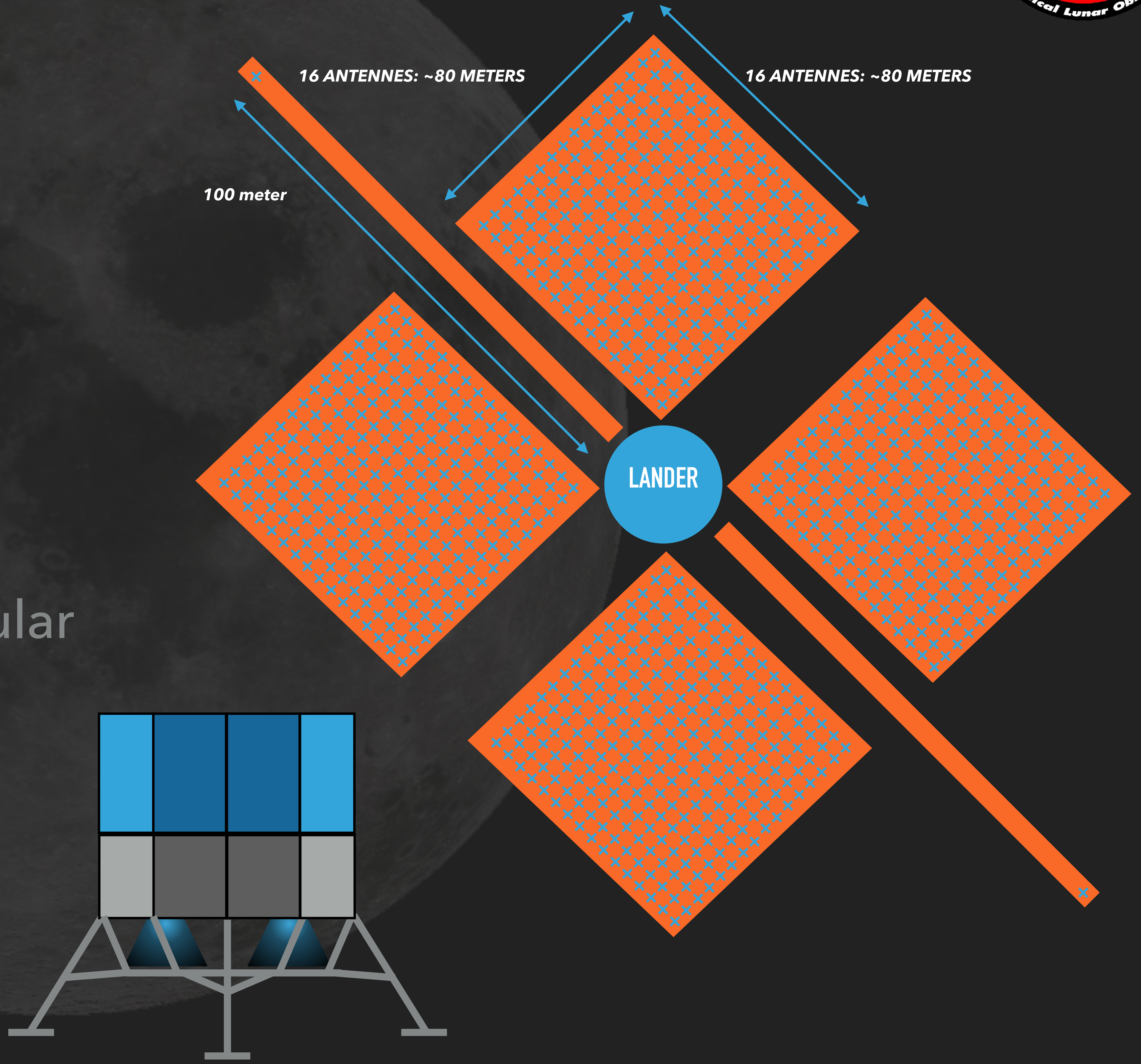


TUe - CAI Design: inflatable antenna
test at a balloon this year

FUTURE CONCEPT?

Provisional concept

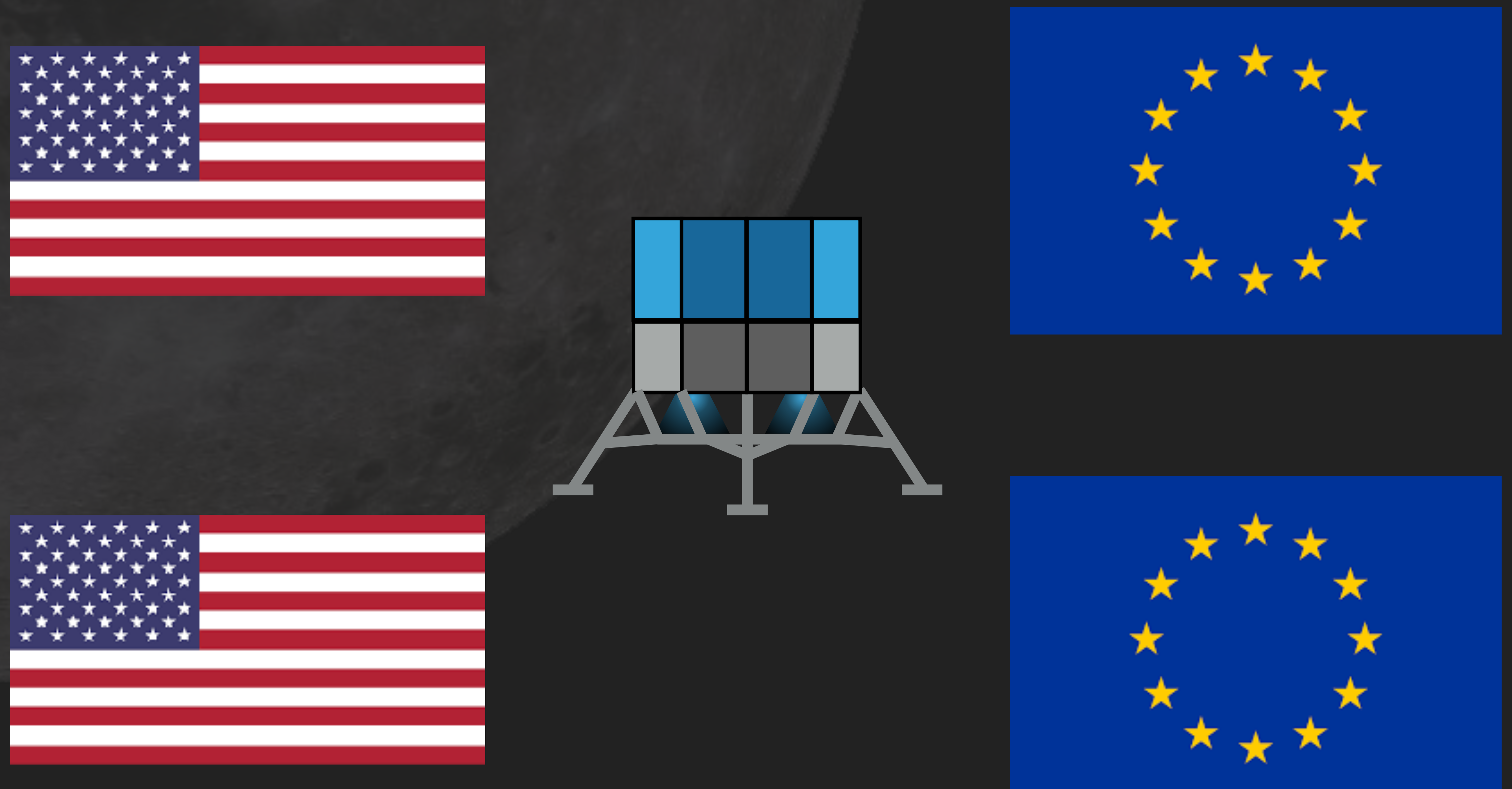
- 5 meter long crossed dipoles printed on Kapton
- **To allow more science: 32 * 32=1024 (minimal) or 128*128=16384 (ideal) antennas**
- Inflatable kapton “air-mattress”
- No rover, scalable, deployment and regular distribution **combined** in one solution
- One antenna concept for all science
- Further integration:
  - Analogue & Digital Electronics?
  - Solar panels printed on Kapton?



INTERNATIONAL LUNAR OBSERVATORY

INTERNATIONAL COLLABORATION ON SCIENCE EXPLORATION ON THE MOON

- OBJECTIVE:
  - LONG-TERM: WORK TOWARDS ONE COMMON DESIGN, BUILD THE ARRAY FROM MULTIPLE LAUNCHES BY INDIVIDUAL PARTNERS
  - SHORT-TERM: IDENTIFY AND COLLABORATE ON TECHNOLOGY DEVELOPMENTS
  - LIKE ALMA AND SKA



DOE-NASA Cross-Agency Activities

Anže Slosar, Brookhaven National Laboratory

Unique Science from the Moon in the Artemis Era workshop

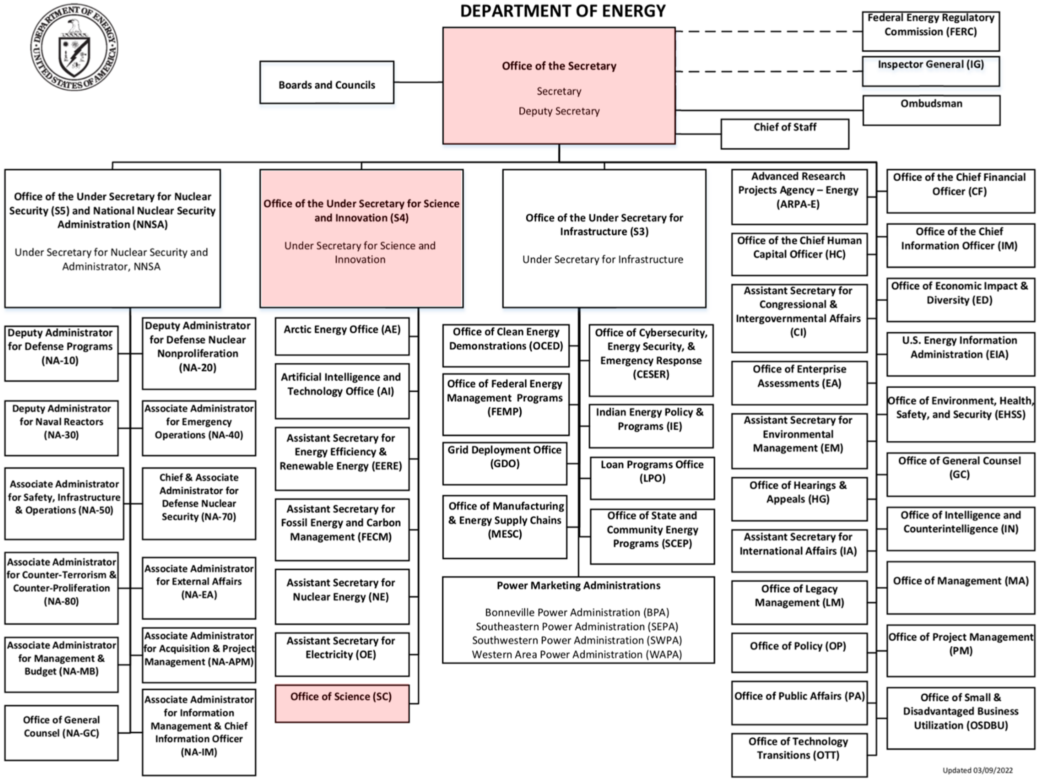
June 6, 2022

@BrookhavenLab

Introduction

- I will focus on *scientific collaboration* between NASA and DOE
- LuSEE-Night is an example of a recent (and funded) successful collaboration (see Bale's talk)
- I will try to explain how DOE works so that we will have many successful missions in the future
- NASA and DOE collaborated in other ways in the past:
  - DOE provided nuclear fuel for Voyages and Mars rovers

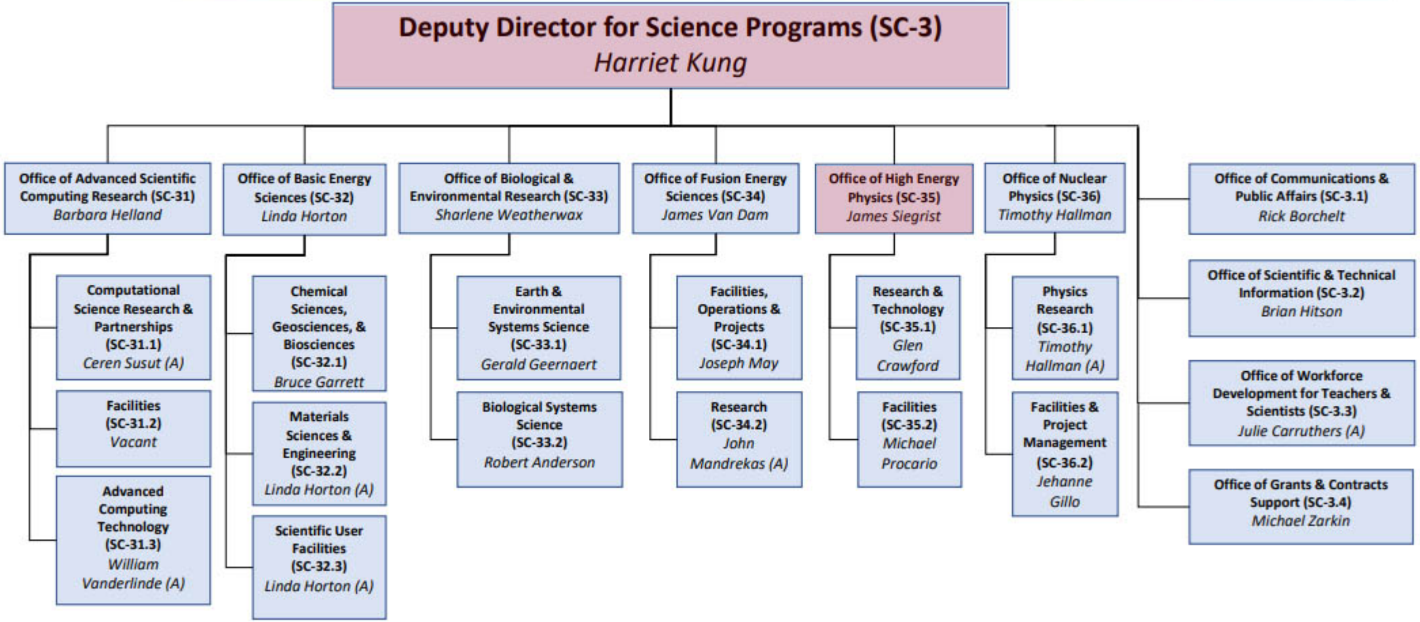
Science within Department of Energy



Brookhaven National Laboratory

Office of Science

Office of Deputy Director for Science Programs (SC-3)



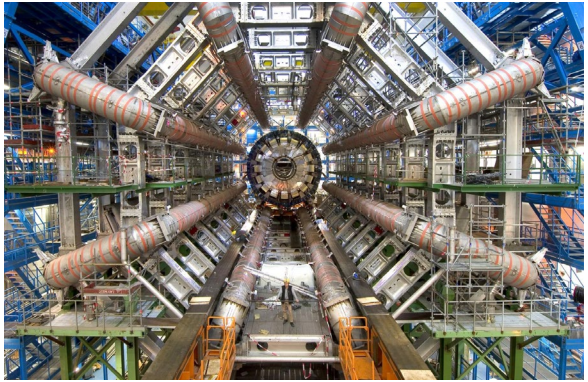
High Energy Physics

- Divided into
  - Energy Frontier
  - Intensity Frontier
  - **Cosmic Frontier**
  - Theoretical, Computational, and Interdisciplinary Physics
  - Advanced Technology R&D
  - Accelerator Stewardship

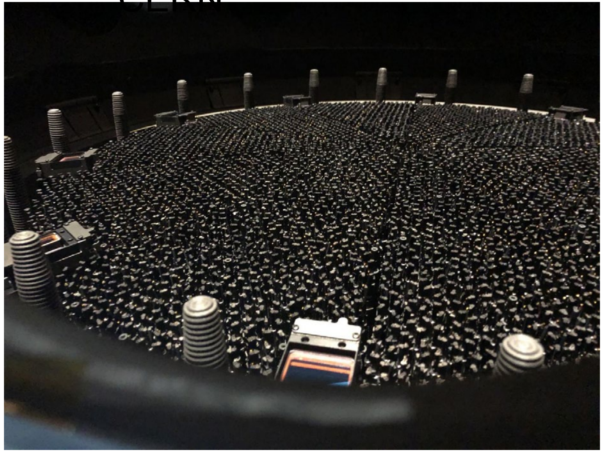
- Total budget of HEP is ~1 billion dollars
  - majority goes into traditional HEP

DOE HEP is particle physics

- There is no “astro” in our name
- Cosmic Frontier within HEP is about answering questions about our Universe that are of interest to *Particle Physicists:*
    - What is the nature of Dark Matter
    - What is the nature of Dark Energy
    - What can we learn about cosmic inflation
    - …
- DOE very sensitive about scope creep



ATLAS detector at CERN

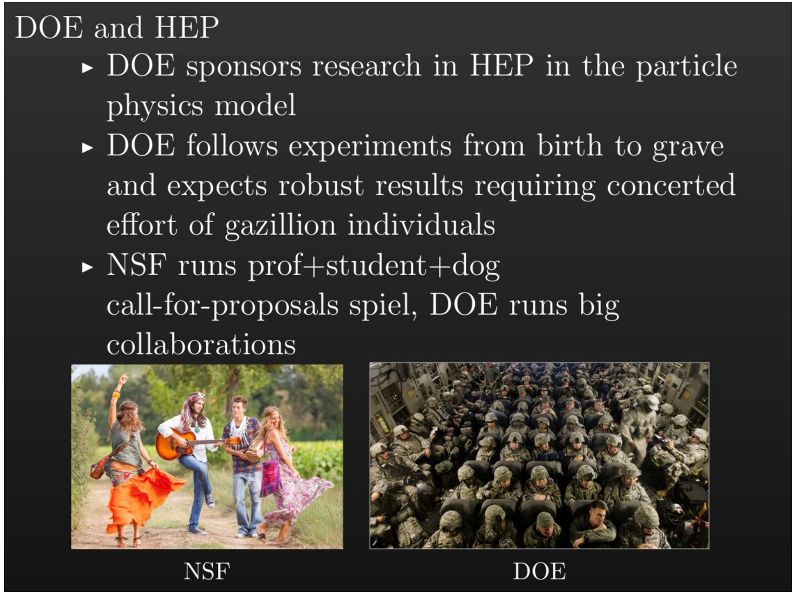


DESI focal plane

Brookhaven National Laboratory

DOE HEP is a mission driven agency

- DOE is a mission driven agency
- What constitutes a mission is decided through:
  - Snowmass Process -> P5
  - (Decadal Survey of Astronomy and Astrophysics)
- DOE does experiments, not facilities:
  - in addition to hardware, always funds collaboration to do analysis and write DOE science papers
  - Collaborations are borg affairs:
    - no PIs, no first authors
- Note that LuSEE-Night is an exception, almost unheard of

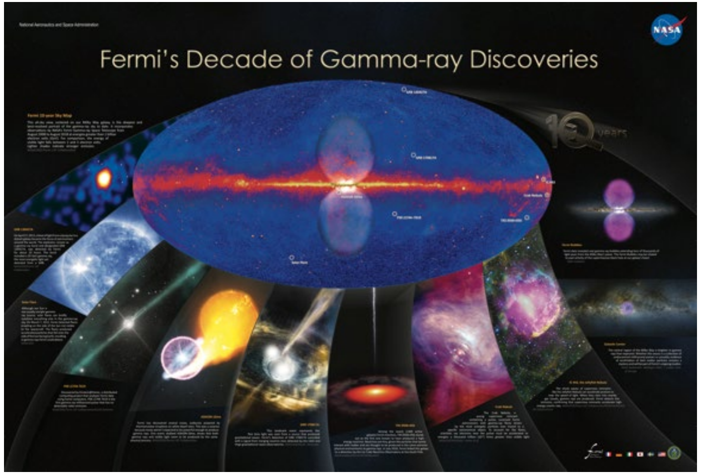


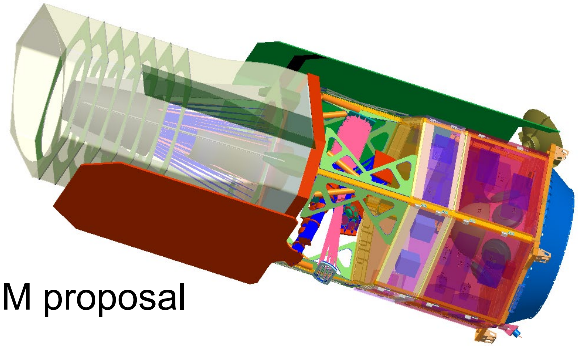
Old slide explaining NSF vs DOE model.

Brookhaven National Laboratory

Past NASA-DOE collaborations

- Successes include Fermi-GLAST
  - Gamma ray telescope still in operation
  - Interesting sociology in collision of NASA requirements on public data and DOE Collaboration model
- Less successful include SNAP/JDEM:
  - Eventually superseded by WFIRST / Roman
  - SNAP would have been a game-changing instrument if launched in 2000s





JDEM proposal

Renewed Interest in Collaboration

- NASA - DOE MOU signed in 2020
- Followed by RFI:
  - HEP from the Moon
  - HEP from the Space Station
  - HEP from synergies between Rubin, Roman, Euclid
- The RFI was really a community sounding exercise
- This was a very top-down driven development

Department of Energy

Department of Energy and NASA Sign Memorandum of Understanding

OCTOBER 20, 2020

Energy.gov » Department of Energy and NASA Sign Memorandum of Understanding

WASHINGTON, D.C. – Today, U.S. Secretary of Energy Dan Brouillette and NASA Administrator Jim Bridenstine signed a new memorandum of understanding (MOU) furthering the longstanding partnership between the Department of Energy (DOE) and NASA that has enabled 50 years of notable space exploration.

The agreement – discussed during the October 2020 Secretary of Energy Advisory Board meeting – supports President Trump's Space Policy Directive-1 and other U.S. national space policies. Under the directive and NASA's Artemis program, America will land the first woman and the next man on the Moon by 2024 and establish sustainable lunar exploration by the end of the decade to prepare for the first human mission to Mars.

"From achieving a better understanding of the Moon, to providing the nuclear fuels to propel Voyager 1 and 2 into space, DOE and NASA have been strong collaborators in our Nation's space mission for decades," said Secretary Brouillette. "This new MOU will continue our esteemed work together as this Administration strives to reach the next generation of space innovations and exploration."

"Artemis depends on a coalition of partners across U.S. government, industry, and the world," said NASA Administrator Jim Bridenstine. "The DOE's energy, science, and technology expertise remains crucial to the success of NASA missions. Together, we will mature and ready systems for exploring more of the Moon and venturing humans farther into space, all for humanity's benefit on Earth."

Request for Information Related to High Energy Physics and Space-Based Astrophysics

JANUARY 22, 2021

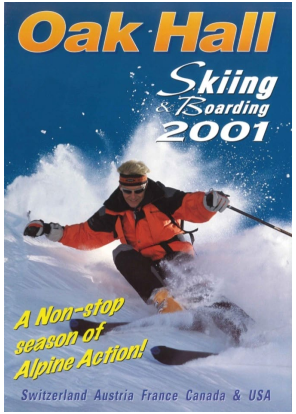
Office of Science » Request for Information Related to High Energy Physics and Space-Based Astrophysics

On behalf of the Department of Energy's (DOE) Office of Science and the National Aeronautics and Space Administration's (NASA) Science Mission Directorate, we invite interested parties to respond to this Request for Information (RFI) on collaborative activities that further scientific advances in high energy physics and space-based astrophysics, in support of our shared scientific goals.

Brookhaven National Laboratory

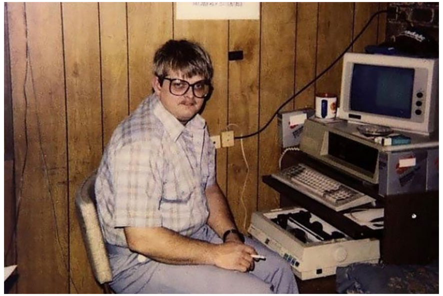
Snowmass process

- Name comes from a Colorado ski resort where early meetings took place
- It is a community driven process to develop new ideas for *High Energy Physics*
- The nominal ethos remains: let’s have fun, bang heads together and come up with the future



Snowmass 2001

Snowmass 2013 (Snowmass on the Mississippi, hosted by Minnesota U)



Snowmass 2022 (thank you covid!)

Snowmass and P5

- Major Initiative prioritization in the HEP community proceeds in 2 steps:
  - **Snowmass**: A series of workshops culminating in a written proceeding, collecting broad community input (2013 Proceeding)
    - Organized by the APS Division of Particles & Fields (DPF)
    - 2021 Snowmass web site: see esp. Cosmic Frontier WGs
    - Latest Snowmass to conclude October 2022
  - **P5** (Particle Physics Project Prioritization Panel)
    - Subpanel of High Energy Physics Advisory Panel (HEPAP)
      - HEPAP: Advisory panel to DOE Office of HEP and NSF Math. & Physical Science Directorate
    - P5 issues a report with priorities in different budget scenarios, along with a timeline of construction & operation (Building for Discovery: P5 2014 report, exec summary)
- The 2014 P5 report has been highly successful in that the advice has been followed (reasonably) closely, and the major new initiatives included are either imminent or under way.

Parting thoughts

- We are retrospectively inserting LuSEE-Night into Snowmass
- LuSEE-Night was enabled by:
  - DOE wish for more medium and small sized projects
  - CLPS is such added value that the offer was too good to miss
  - being top-down meant it was easier to get extra funding from Congress
- However:
  - LuSEE-Night “skipped the line” in the Snowmass / P5 process
  - Need to reappear in the next iteration with strong support if this science is to continue after LuSEE-Night pathfinder

National Aeronautics and Space Administration

NASA Lunar Spectrum Management: Enabling and Protecting Lunar Science & Exploration

Briefing to NESC "Unique Science" from the Moon in the Artemis Era

Cathy Sham

NASA Lunar Spectrum Manager (LSM)

NASA SOMD Space Communications and Navigation (SCaN) Program Office
Spectrum Policy and Planning Division

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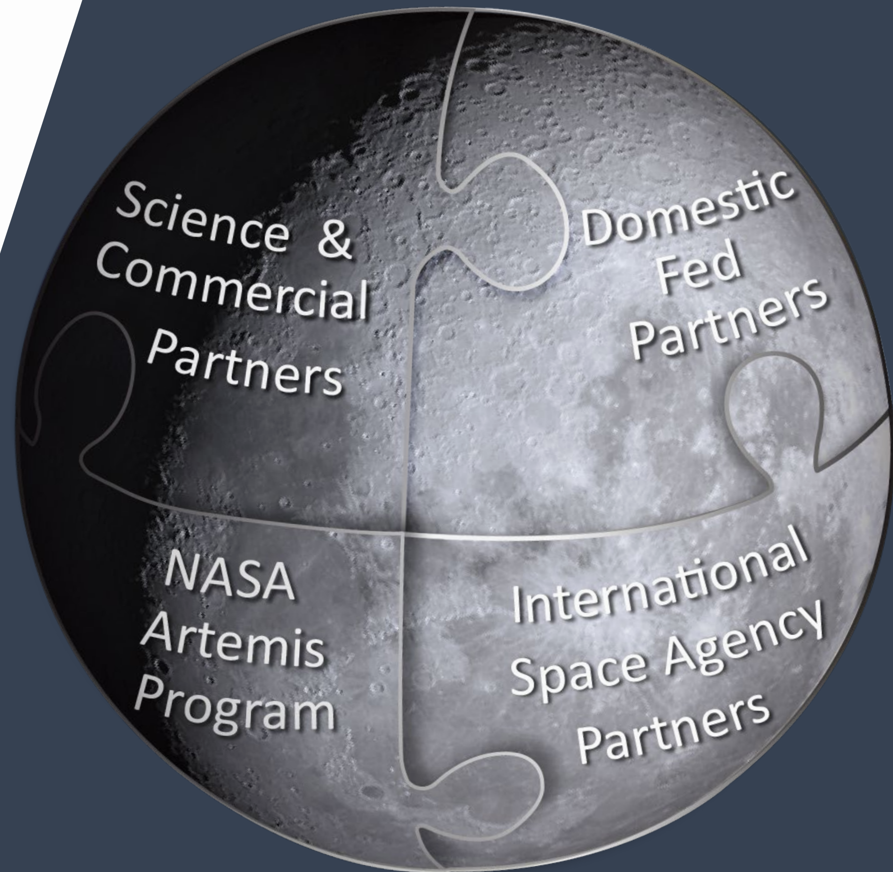
7-9 June 2022

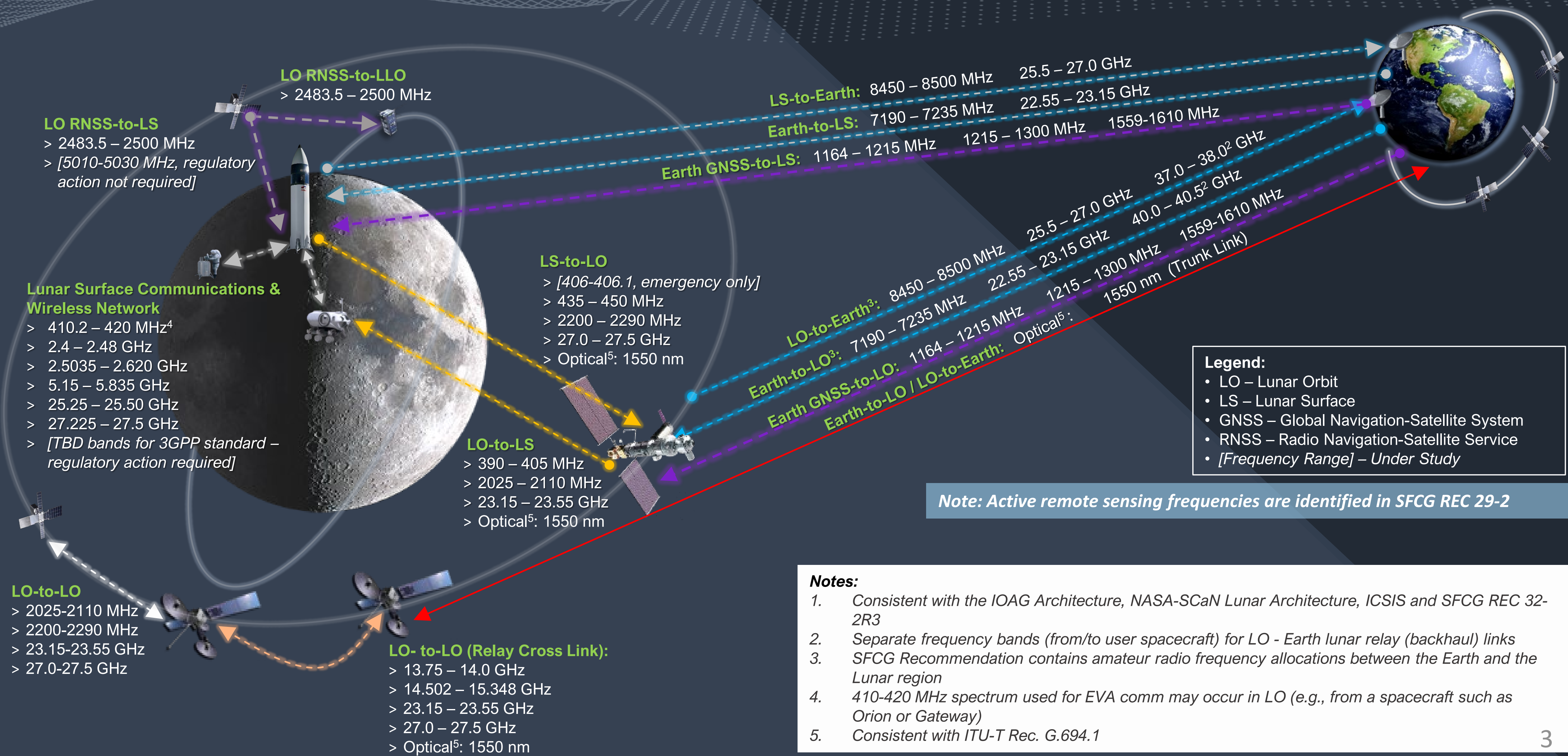
Overview

- NASA is charged to return humans to the Moon in cooperation with private industry and international partners
  - NASA is providing leadership and vision to develop an interoperable space communications & navigations architecture to support government and private space exploration, especially spectrum required to support science that depends on data from both passive and active sensing
  - NASA's Lunar Spectrum Manager (LSM) serves as a centralized focal point in the lunar region for advanced spectrum planning and facilitating mission system development and pre-coordination to mitigate potential interference for government, private sector, and international entities to operate joint and/or independent missions.



Electromagnetic Spectrum for Lunar Region

Radio Frequency[1] and Optical

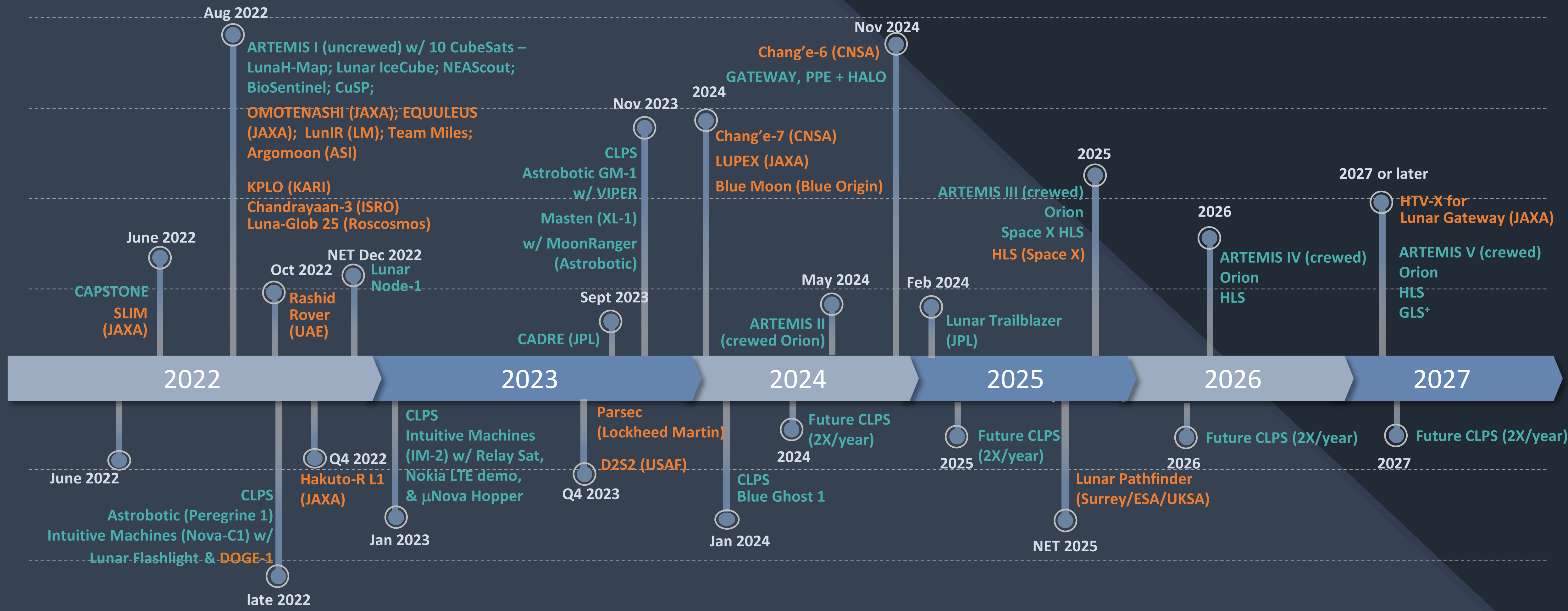


Legend:
- LO – Lunar Orbit
- LS – Lunar Surface
- GNSS – Global Navigation-Satellite System
- RNSS – Radio Navigation-Satellite Service
- *[Frequency Range] – Under Study*

Note: 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 32-2R3*
2. *Separate frequency bands (from/to user spacecraft) for LO - Earth lunar relay (backhaul) links*
3. *SFCG Recommendation contains amateur radio frequency allocations between the Earth and the Lunar region*
4. *410-420 MHz spectrum used for EVA comm may occur in LO (e.g., from a spacecraft such as Orion or Gateway)*
5. *Consistent with ITU-T Rec. G.694.1*

Lunar Mission Landscape*



TBD Launch Date

CUE3 (UC Boulder)
Cislunar Explorers (Cornell)

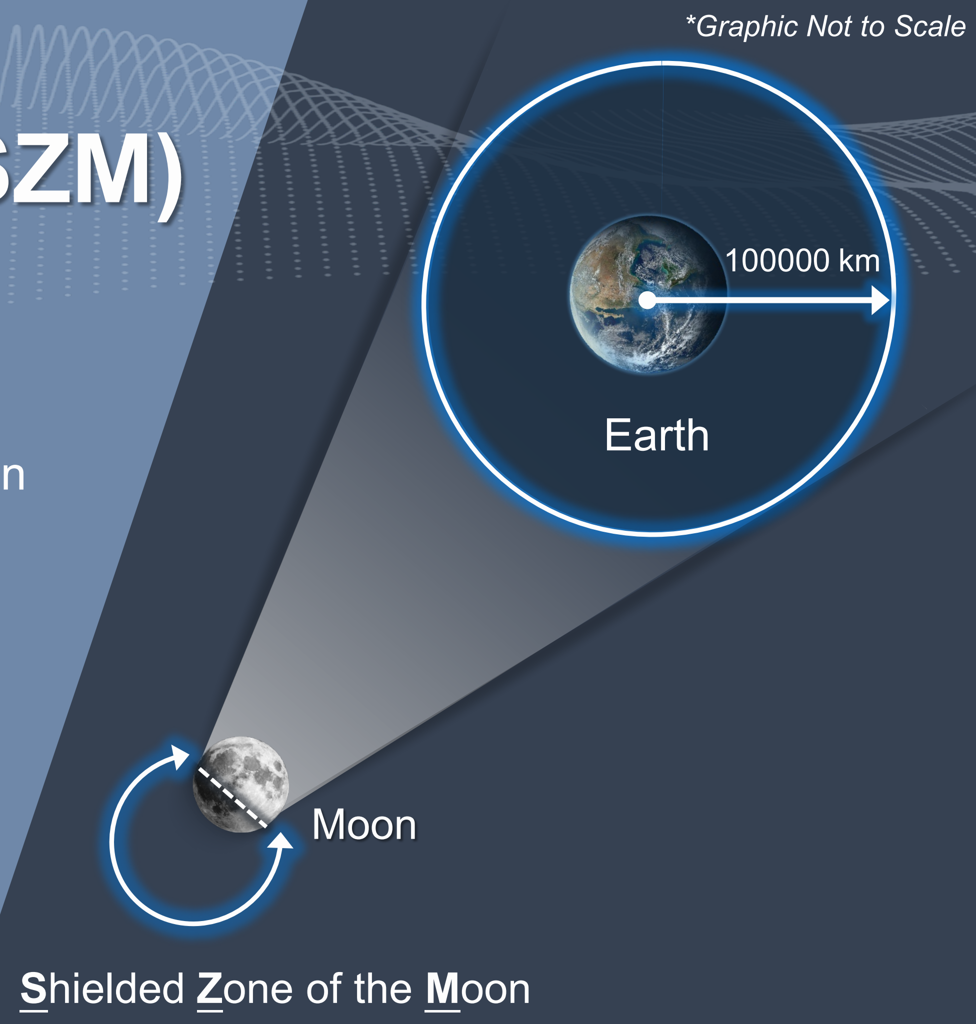
■ NASA and NASA-Partner Lunar Activities (including CLPS missions)

■ Other Lunar Activities (e.g. International Space Agencies, Commercial Ventures)

* Suite of lunar missions being actively supported and/or monitored by the LSM as of June 2022

Shielded Zone of the Moon (SZM)

- Maintaining the SZM as a zone **free from radio interference** for its value for passive observation, while recognizing the requirement for radiocommunication transmission in **support of science objectives** (essential transmissions)
- Regulations in place to protect the SZM:
  - ITU Radio Regulations
  - ITU-R REC RA.479-5 (2003), ITU-R REC RA.769-2 (2003)
  - SFCG Recommendations 32-2R3 & 29-2, SFCG Resolution 23-5
  - International Astronomical Union (IAU) Resolution B16



SFCG Resolution 23-5 ***Protection of Future Radio Astronomy Observations in the Shielded Zone of the Moon***

RESOLVES

- Member Agencies inform the SFCG of plans of radio astronomy observation in the SZM,
- Member Agencies work with IUCAF for missions to the Sun-Earth L2 and for deep space missions,
- Possibility of developing a new SFCG Recommendation after completing study on issues of compatibility between a radio astronomy observatory in the SZM vs. radiocommunications requirements of deep space and L2 missions.

Protection of the Lunar Environment for Radio Astronomy & other unique science

NASA is actively involved in domestic and international coordination forums to ensure protection of spectrum for passive remote sensing and radio astronomy applications

ITU-R Working Party 7D (under Study Group 7) is studying:

- Technical and operational characteristics of radio astronomy observations to be performed in the SZM
- Effects of lunar environment on radio astronomy in SZM
- Options to minimize impact from radiocommunications services in lunar region on radio astronomy in SZM

Recognizing that ,

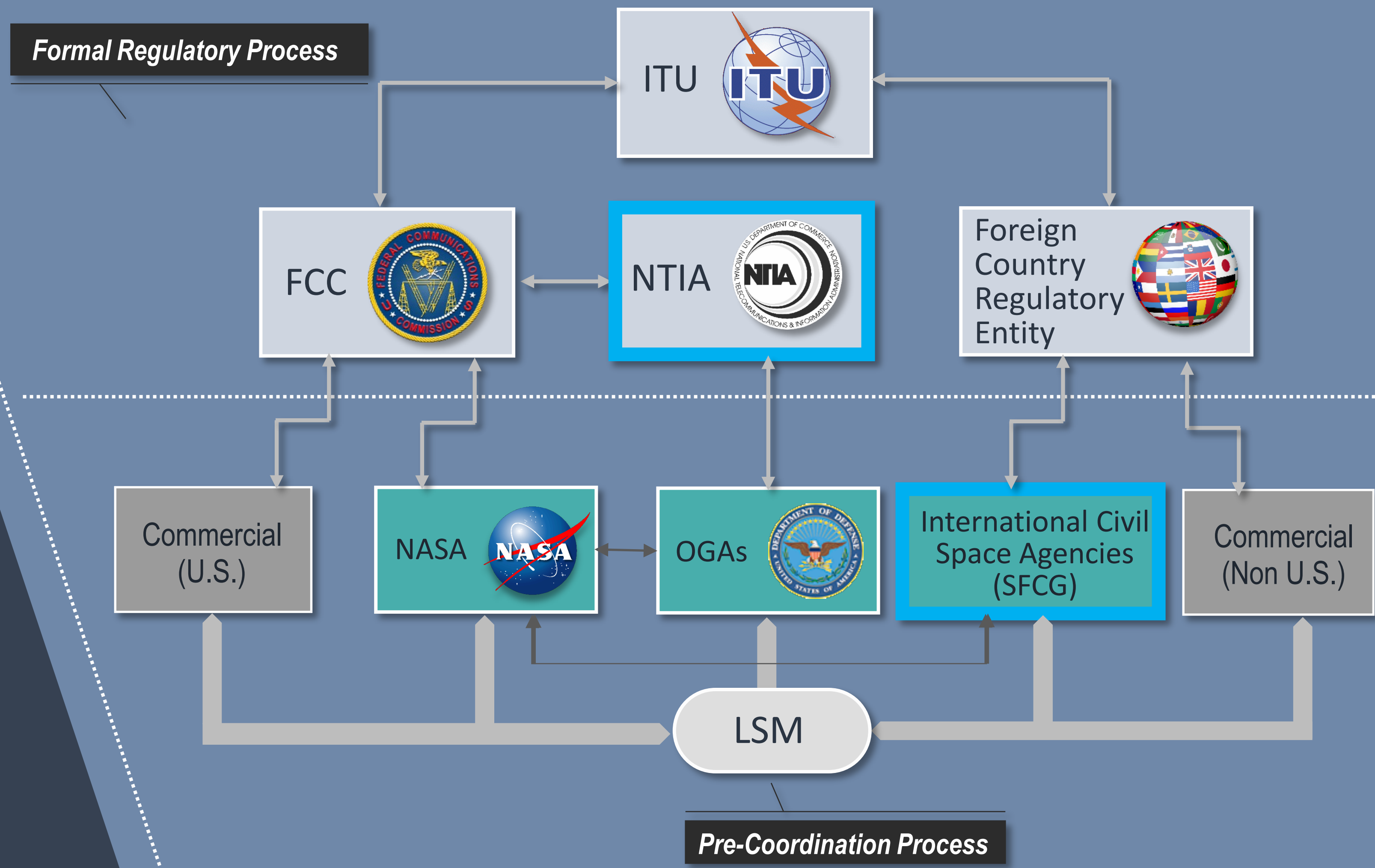
- Frequency bands allocated to Earth exploration-satellite service (EESS), space research service (SRS), and radio astronomy service (RAS) are driven by:
  - Knowledge that different atoms and molecules, particularly atmospheric gases, emit and absorb electromagnetic energy at discrete resonant frequency bands described by the laws of quantum mechanics; and/or
  - Feasibility of sharing frequencies with other allocated radio services
- Radio Frequency Interference (RFI) can corrupt desired science measurement and depends on what the sensor is intended to measure and sensor system design
  - When interference does occur to the sensor, it is difficult to correct or compensate and so data is often flagged simply as being lost
    - Passive sensors and radio astronomy systems are particularly sensitive to RFI, as they are designed to detect very weak energy levels

Pre-Coordination Process with LSM

Pre-Coordination promotes maximum compatibility and mission success by facilitating technical analysis and pre-coordination between lunar-region missions

- **Lunar Working Group,** chaired by NASA, to assist NTIA IRAC Subcommittees in assessing lunar region spectrum-dependent systems proposals during spectrum certification, ITU filing initiation, and frequency assignment processes.

- **SFCG Administrative Resolution A40-1,** encourages lunar mission planners at member agencies to seek assistance from NASA's LSM during the initial formulation phase or as early as possible during the planning phase, and to provide current technical, operational and mission information and timely updates to facilitate frequency selection studies and interference analysis.



Takeaways

Earlier Technical Collaboration

- Identify and understand spectrum requirements of science missions to support functions and mission objectives
  - Pre-coordination is recommended for both missions and any payloads planning to use RF equipment in the lunar region
- Identify possible technical and spectrum licensing concerns
- Identify pre-coordination paths

+

Benefits

- Assist with frequency selection and definition of spectral emission masks as required for communications and navigation services, while protecting science services
- Facilitate coordination, ahead of initiation of regulatory process, to minimize delays/rework during formal equipment certification and spectrum licensing efforts

+

Contact the LSM

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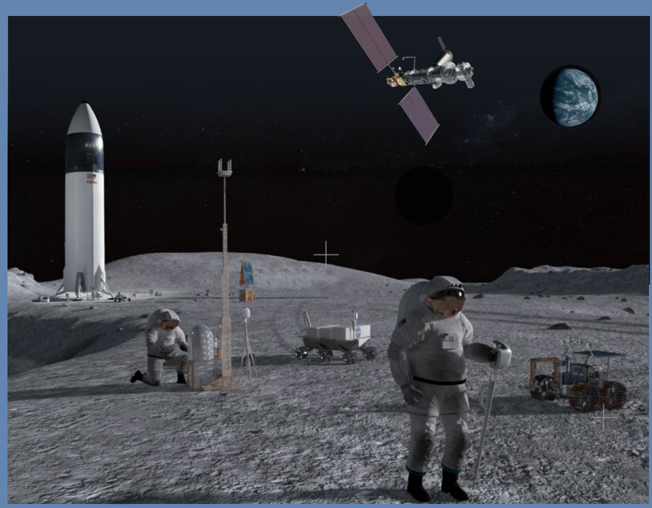
Catherine.c.sham@nasa.gov



Site Selection for Radio Telescopes on the Far Side of the Moon

Jack O. Burns[1], Neil Bassett[1], Stuart Bale[2], Anže Slosar[3], Maria Banks[4], Paul Niles[5]

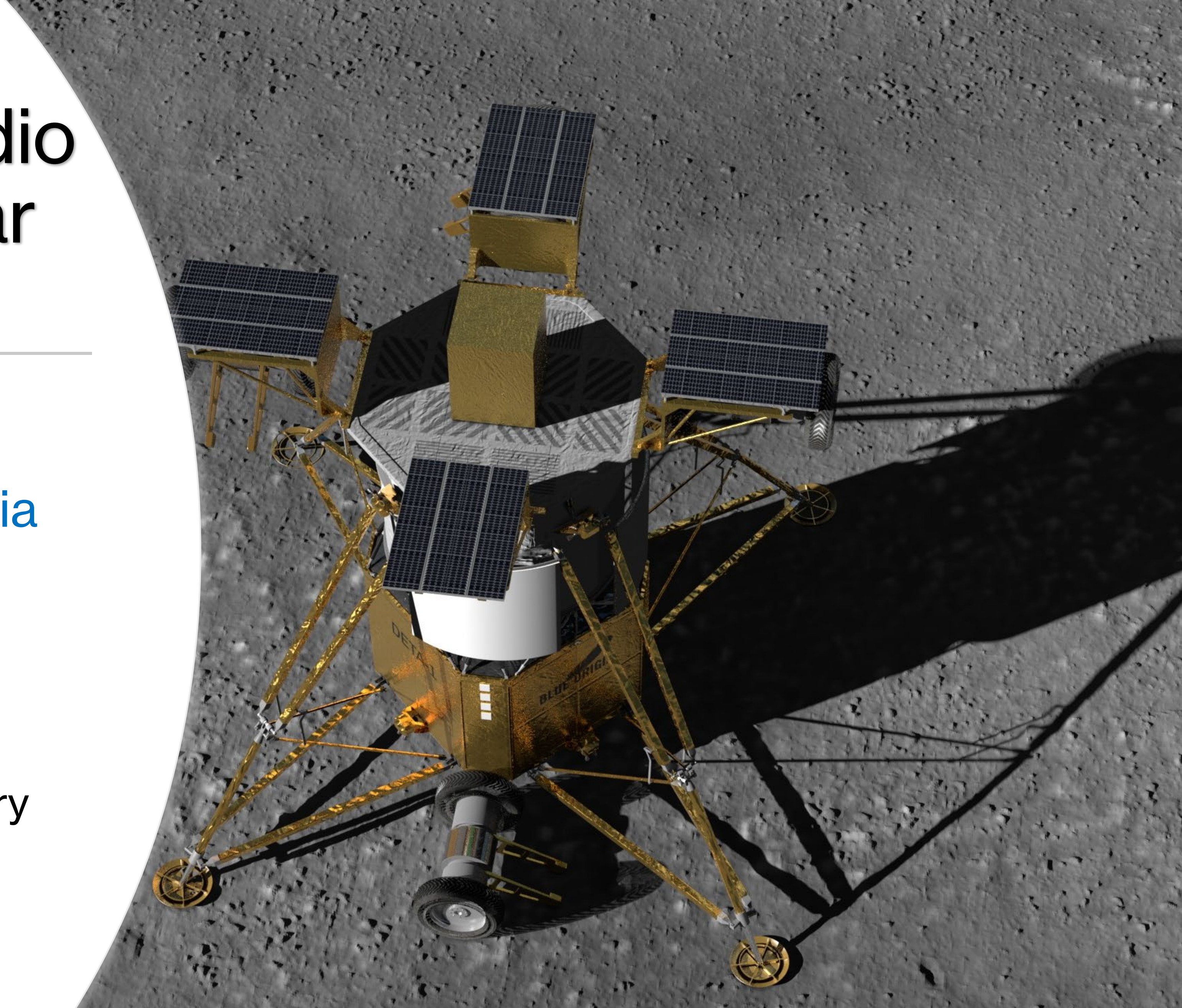
[1]University of Colorado at Boulder

[2]University of California at Berkeley

[3]DOE Brookhaven National Laboratory

[4]NASA Goddard Space Flight Center

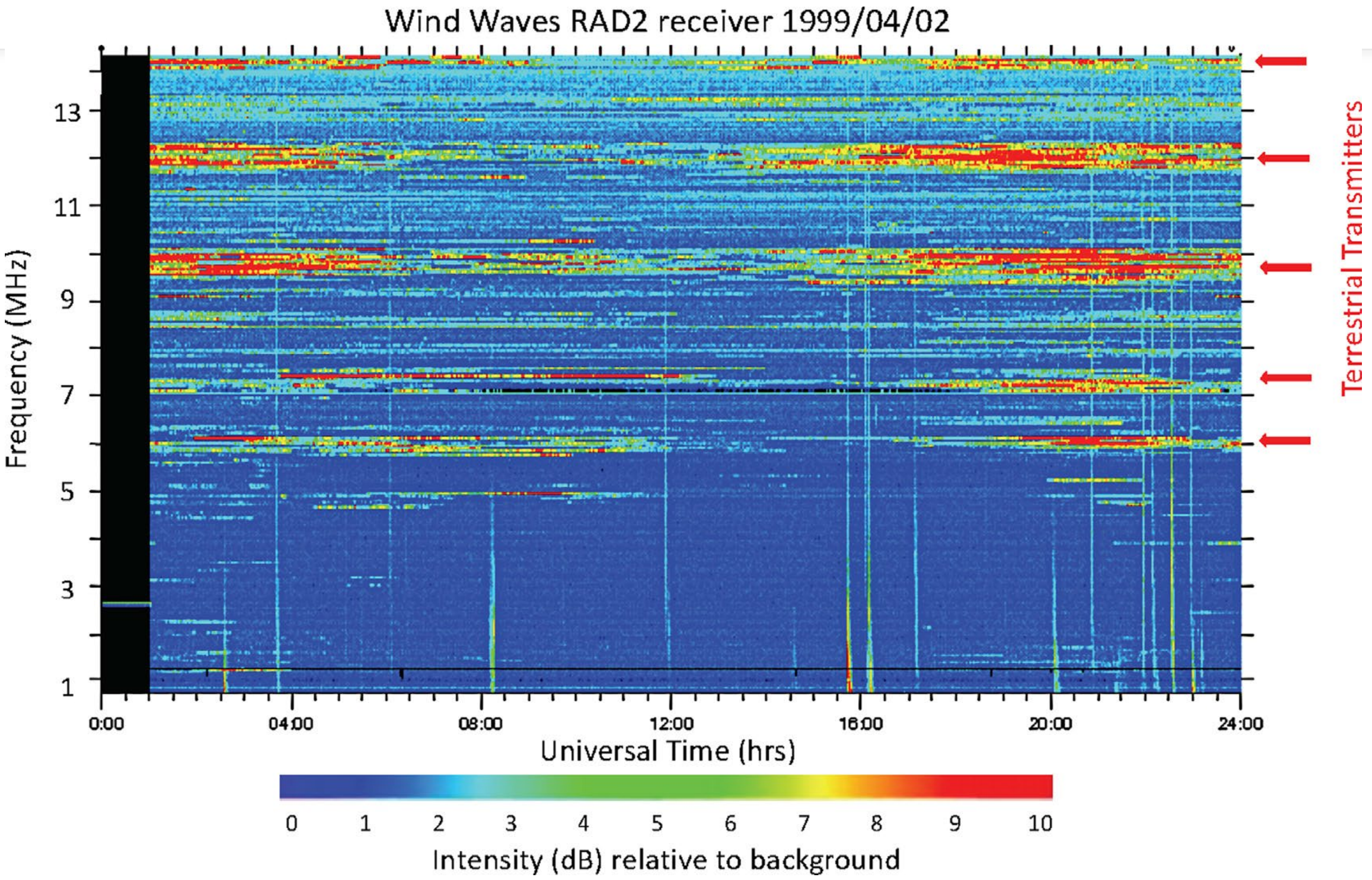
[5]NASA Johnson Space Center



Unique Science from the Moon in the Artemis Era Workshop
NASA KSC, 7 June 2022

The Earth is NOT Quiet below 15 MHz!

Data from the WAVES instruments on the Wind spacecraft taken from the vicinity of the Moon in 1999. The data show contamination from both terrestrial RFI (horizontal bands) and solar radio bursts (vertical lines). The intensity is measured relative to the galactic brightness. The intensity scale is limited to the maximum measured intensity, which is well below the saturation level of the instrument.



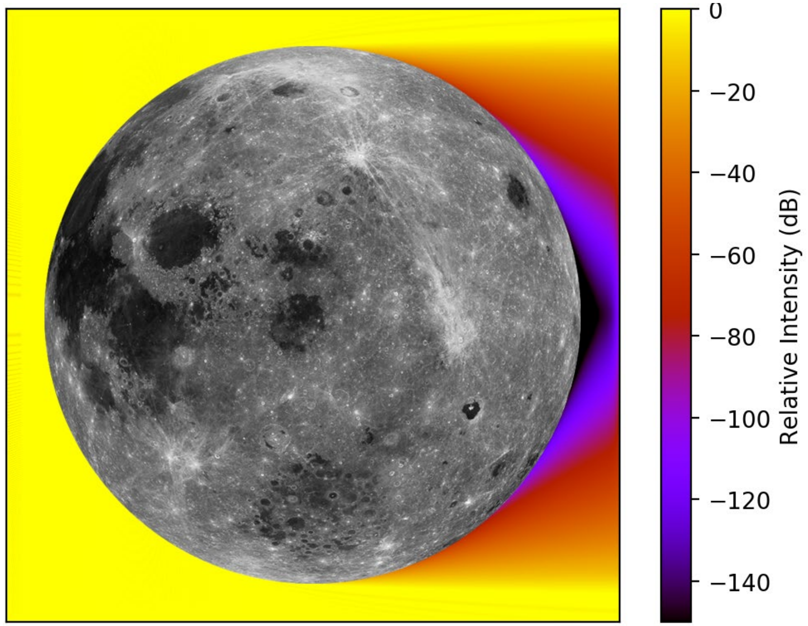
Radio-quiet on the Lunar Far Side: Stay clear of the edges!

Available online at www.sciencedirect.com
ScienceDirect
Advances in Space Research 66 (2020) 1265–1275
ELSEVIER
ADVANCES IN SPACE RESEARCH (a COSPAR publication)
www.elsevier.com/locate/asr

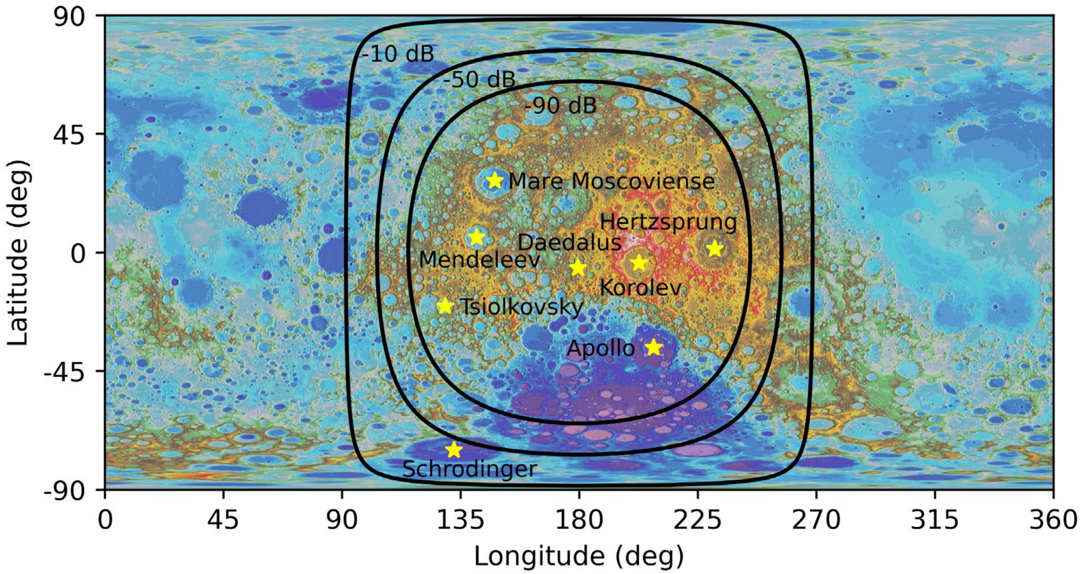
Characterizing the radio quiet region behind the lunar farside for low radio frequency experiments

Neil Bassett [a,*], David Rapetti [a,b,c], Jack O. Burns [a], Keith Tauscher [a,d], Robert MacDowall [e]

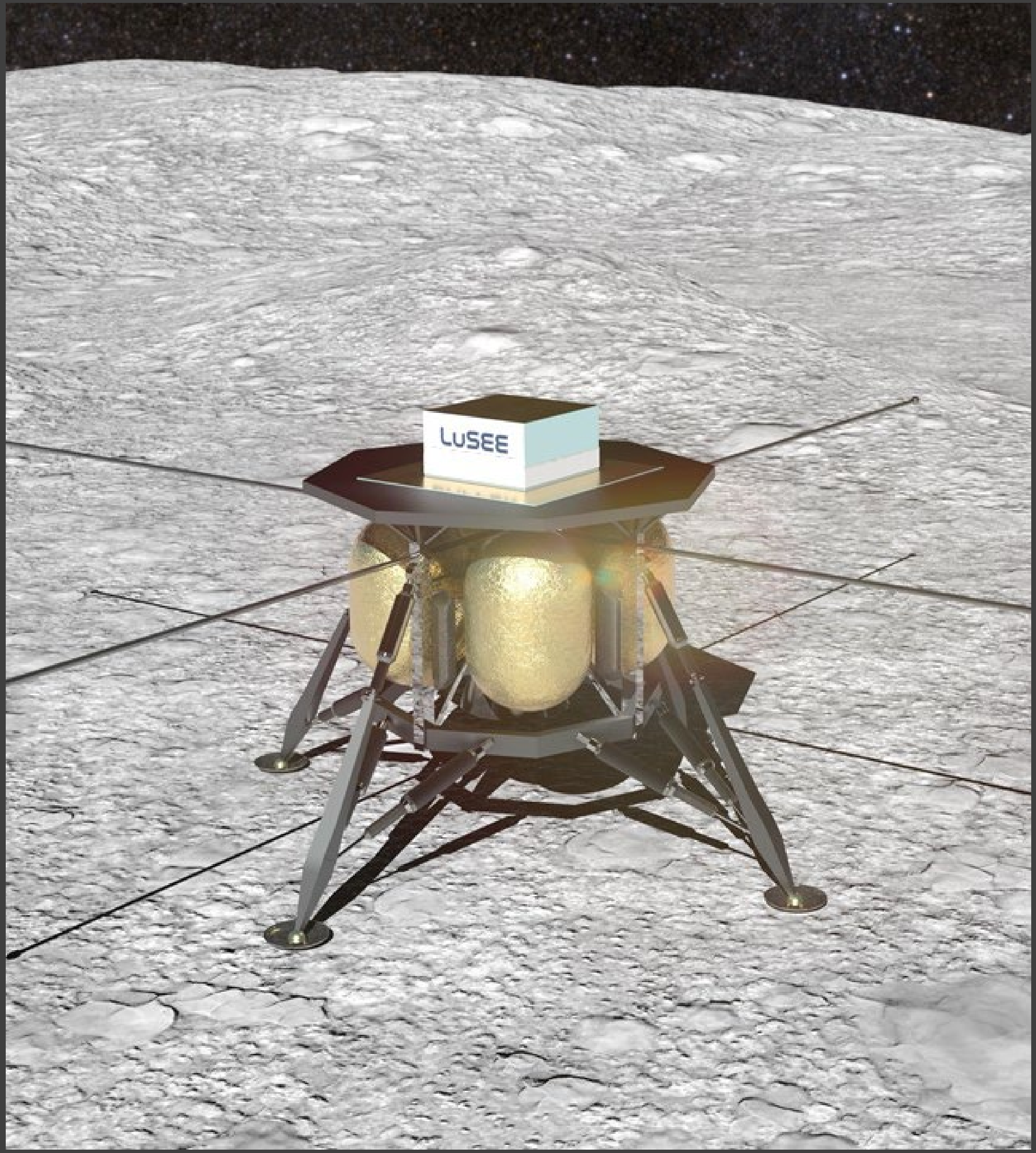
[a] Center for Astrophysics and Space Astronomy, Department of Astrophysical and Planetary Science, University of Colorado, Boulder, CO 80309, USA
[b] NASA Ames Research Center, Moffett Field, CA 94035, USA
[c] Research Institute for Advanced Computer Science, Universities Space Research Association, Mountain View, CA 94043, USA
[d] Department of Physics, University of Colorado, Boulder, CO 80309, USA
[e] NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA



Results of a 4000 x 4000 km finite difference time domain numerical simulation of the lunar radio environment at 30 kHz. RFI incident from the left is attenuated behind the Moon on the right. Higher frequencies exhibit even greater levels of attenuation due to the decreasing effect of refraction around the limb of the Moon.



Map of RFI suppression at 100 kHz based upon numerical simulations from Bassett et al. (2020). Contours indicate suppression of -10, -50, and -90 dB relative to the incident intensity. Map colors indicate elevation.



Landing Site Selection for The Lunar Surface Electromagnetics Experiment (LuSEE)

Stuart D. Bale (PI), Keith Goetz, Peter Harvey, John Bonnell, Jack Burns, Thierry Dudok de Wit, Bob MacDowall, David Malaspina, Marc Pulupa, Anze Slosar, Aritoki Suzuki + a big LuSEE science team

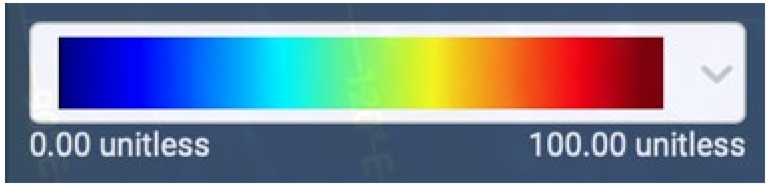
Initial criteria for CS-3 landing site for LuSEE-Nite

- Between: 30 to -30 latitude, 150 to 210 E longitude => radio-quiet at all frequencies.
- Thermal issues close to the equator.
- Are magnetic anomalies (within 10s of km) a problem? -> locally uniform magnetic field
  - Data: K/LP Mag.A. at the surface – Total, Kaguya and Lunar Prospector magnetic anomaly map at the surface of the total intensity created using surface vector mapping.
  - Lunar swirls map
- High crustal thickness; locally uniform crustal thickness: 25 km or greater
  - Data: GRAIL Crustal Thickness Model 3
- Low slopes (<10 degrees)?
  - Data: SLDEM2015 Slope
  - LROC NAC stereo where available (will be requested once candidate landing sites have been identified)
- Low rock abundance; locally uniform (low) thermal inertia
  - Data: Diviner
- Avoid proximity to geologic structures (lobate scarps, wrinkle ridges, etc.) – ~10 km radius
- Low likelihood of hazards (craters, boulders)
  - Will complete hazard mapping once candidate landing sites have been identified.
- Low surface roughness/ruggedness
  - LOLA Roughness at 25m scale – Average: map of the altimetric roughness, or root mean squared variation in height, of the five adjacent spots returned from a single laser pulse acquired by the LOLA instrument. This product represents the mean (average) of binned
- Preference for landing on a flat topographic high to maximize sky accessibility

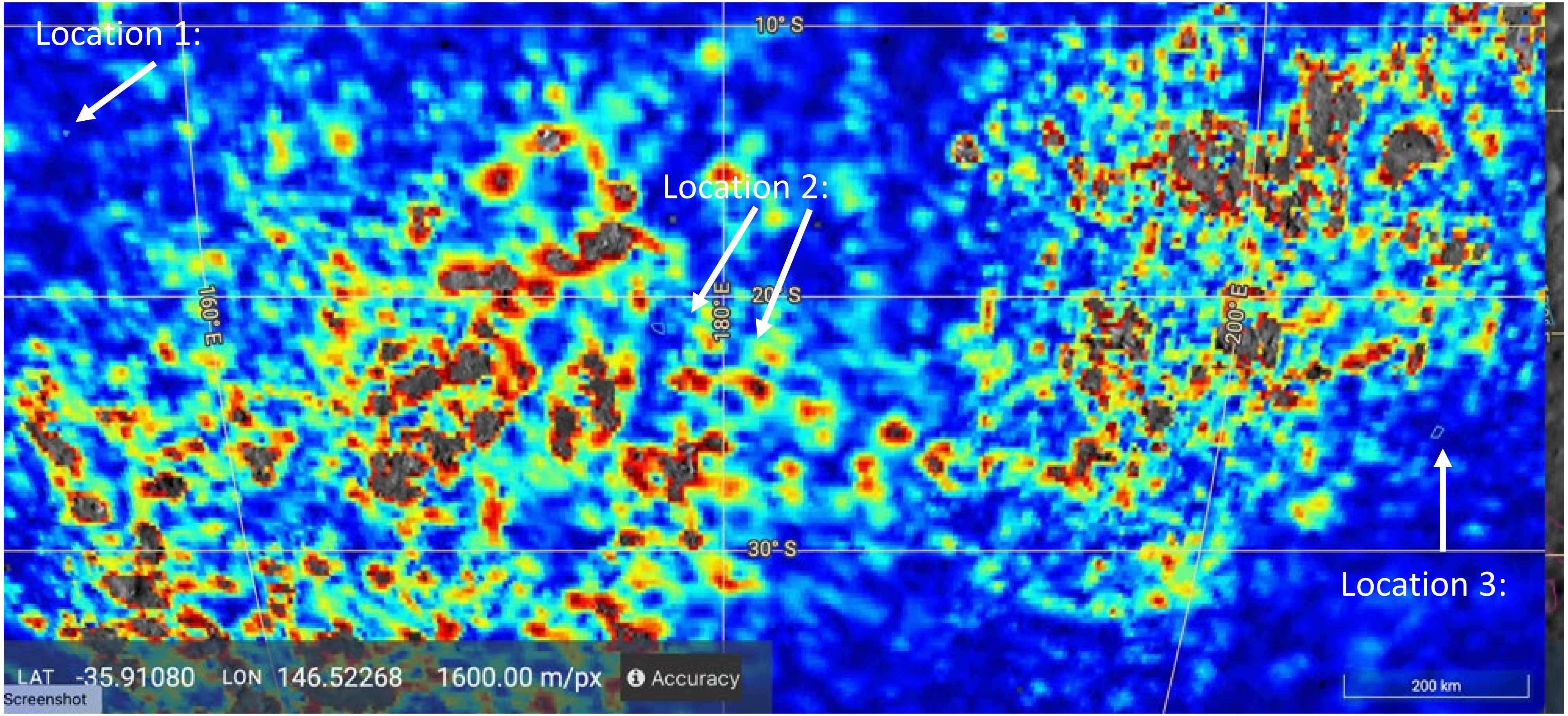
- Areas with existing LROC NAC stereo coverage, generally do not meet the other criteria

- Identify locations where we could potentially place a 100 meter ellipse.

Higher latitude southern hemisphere locations (between 20-30 degrees S latitude: until we know our temperature constraints)

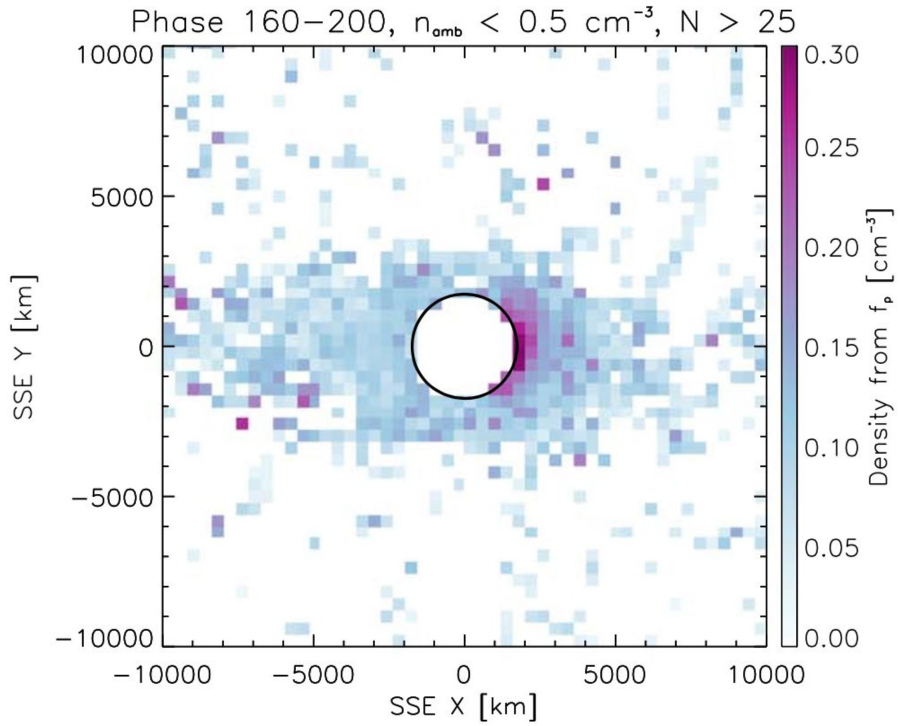


K/LP Mag.A. at the surface – Total, Kaguya and Lunar Prospector magnetic anomaly map at the surface of the total intensity created using surface vector mapping.



But, are Magnetic Anomalies a driver for site selection?

- Surface plasma sheath:
  - The dayside lunar photoelectron sheath has densities up to ~10^2 cc^{-1}
  - The nightside lunar sheath is much less dense, <0.1 cc^{-1}
  - No real evident concern for ionospheric cutoffs at 100 kHz or higher
- Crustal magnetic fields:
  - Dayside crustal field interactions are complex and have been correlated with copious wave emission <10 kHz
  - No immediate evidence comes to mind for an unusually complex plasma interaction within nightside crustal fields
    - In fact, most crustal field mapping observations are explicitly done on the nightside to avoid any distortions of crustal fields by plasma interactions



There is no discernable local ionosphere on nightside above background (~0.1 cc^{-1})

Analysis courtesy of Andrew Poppe, SSL/UC-Berkeley

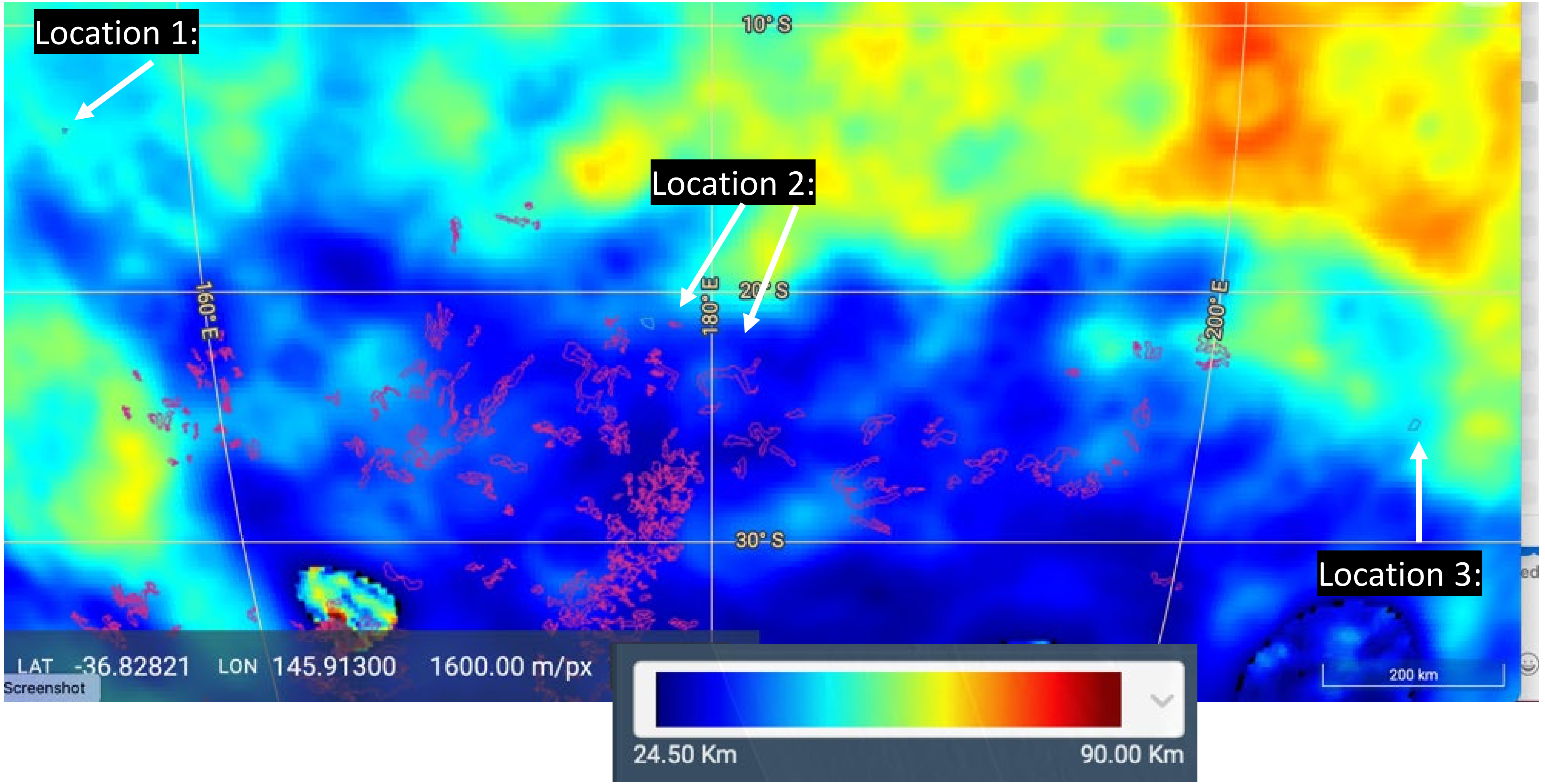
Higher latitude southern hemisphere locations (between 20-30 degrees S latitude: until we know our temperature constraints)

GRAIL Crustal Thickness Model 3

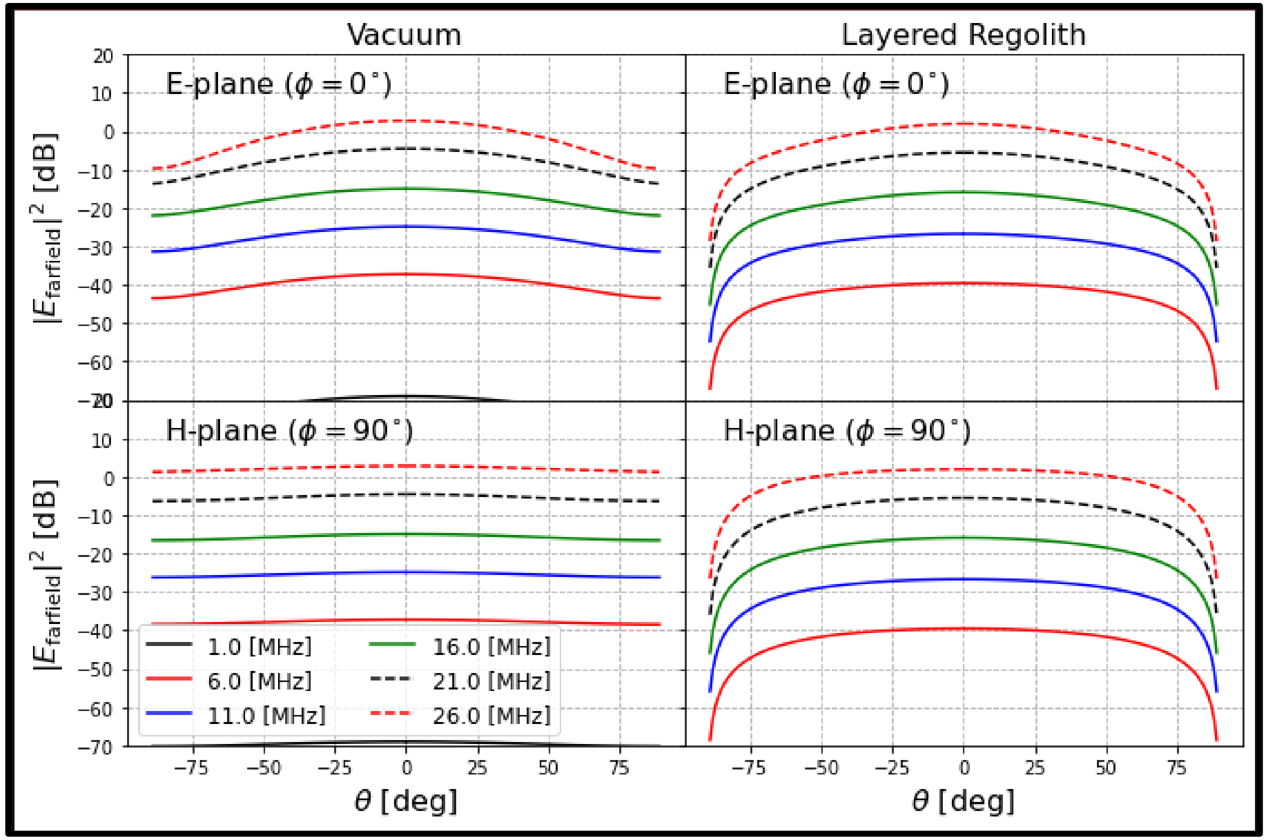
Pink = mapped swirls (both are more than 100 km away from swirls)

Concerns?:

- Regional crustal thickness variability



Example of how antenna beam is affected by layered dielectric regolith



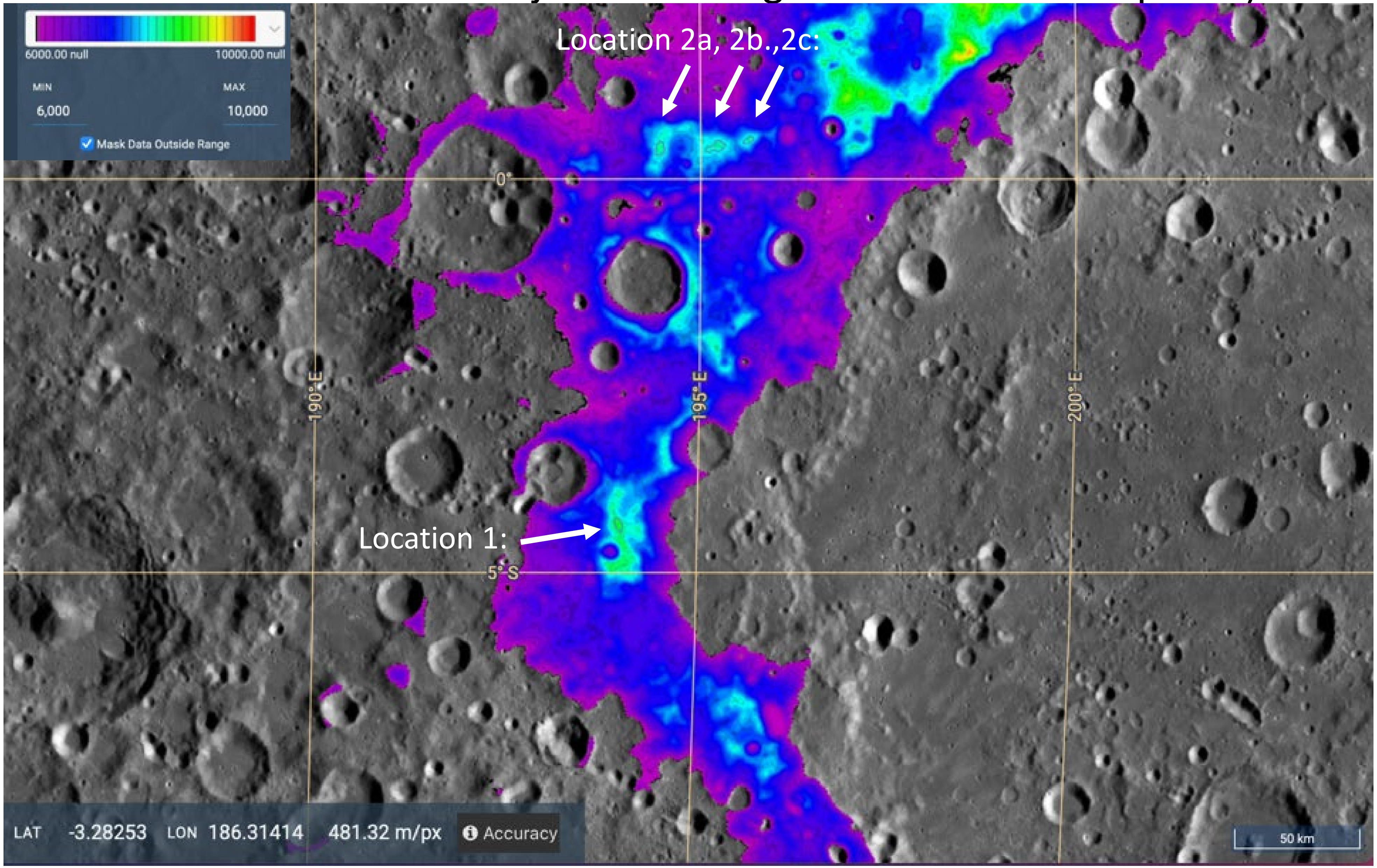
CST Microwave Studio EM simulations of the ROLSES dipole beam, including the IM-1 lander, in free-space and on the lunar surface.

Analysis courtesy of Bang Nhan, NRAO

Search A: flat topographic highs to maximize sky accessibility
(note that the northern three locations are just a few degrees north of the equator)

LROC WAC Global mosaic (+ LOLA) – Green is higher elevations

Concerns:
- Proximity to equator (temperature constraints)
- Proximity to large Korolev crater (constraints on subsurface homogeneity)
- Regional crustal thickness variability



Search A: flat topographic highs to maximize sky accessibility (note that the northern three locations are just a few degrees north of the equator)

GRAIL Crustal Thickness Model 3

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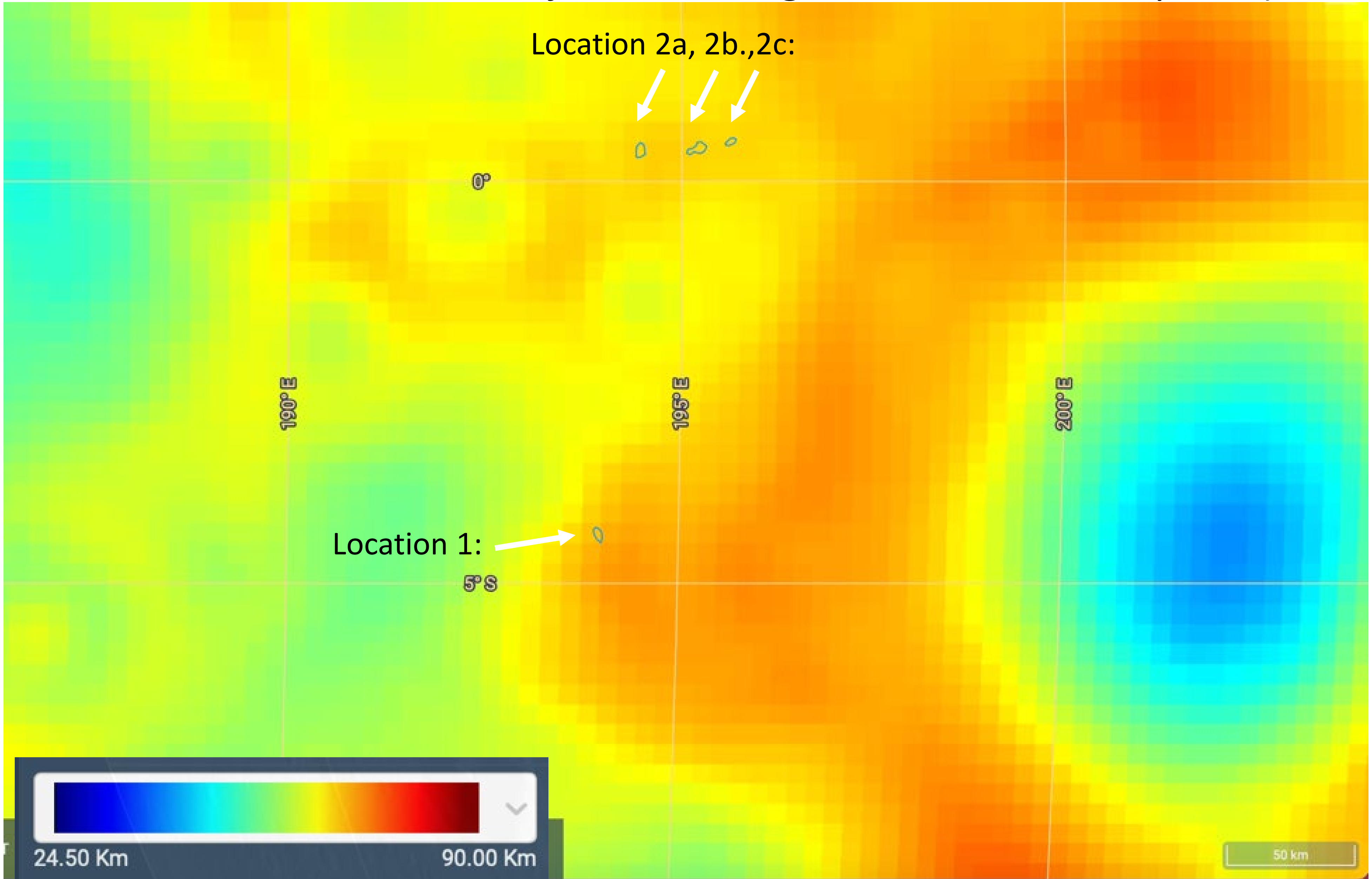

Lunar Horizon Features influence amount of visible sky, time variability of signals & diffraction

THE ASTROPHYSICAL JOURNAL, 923:33 (15pp), 2021 December 10 https://doi.org/10.3847/1538-4357/ac1cde

CrossMark

Lost Horizon: Quantifying the Effect of Local Topography on Global 21 cm Cosmology Data Analysis

Neil Bassett[1], David Rapetti[1,2,3], Keith Tauscher[1], Bang D. Nhan[4,5], David D. Bordenave[4,5], Joshua J. Hibbard[1], and Jack O. Burns[1]

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[3] Research Institute for Advanced Computer Science, Universities Space Research Association, Columbia, MD 21046, USA
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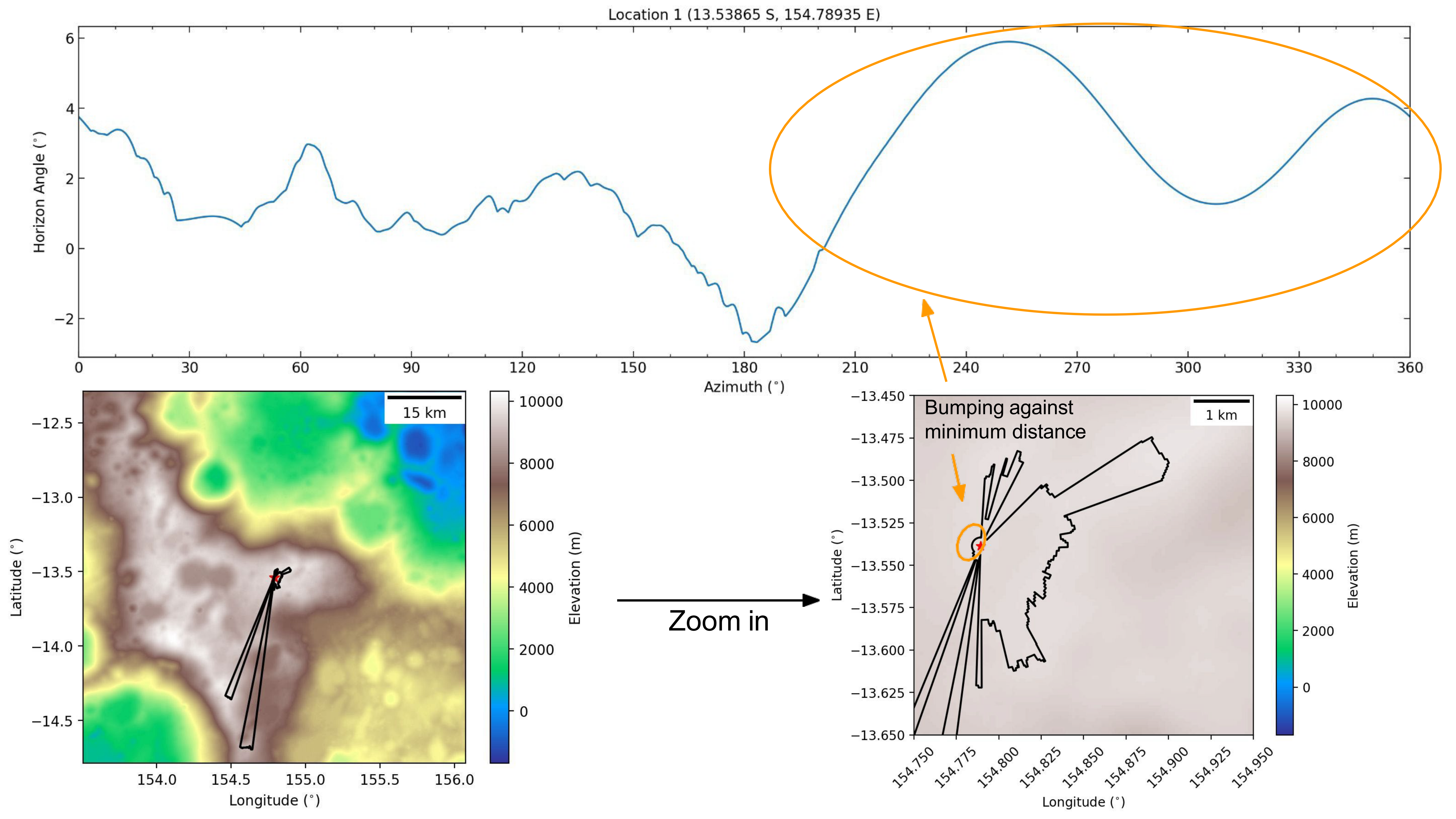
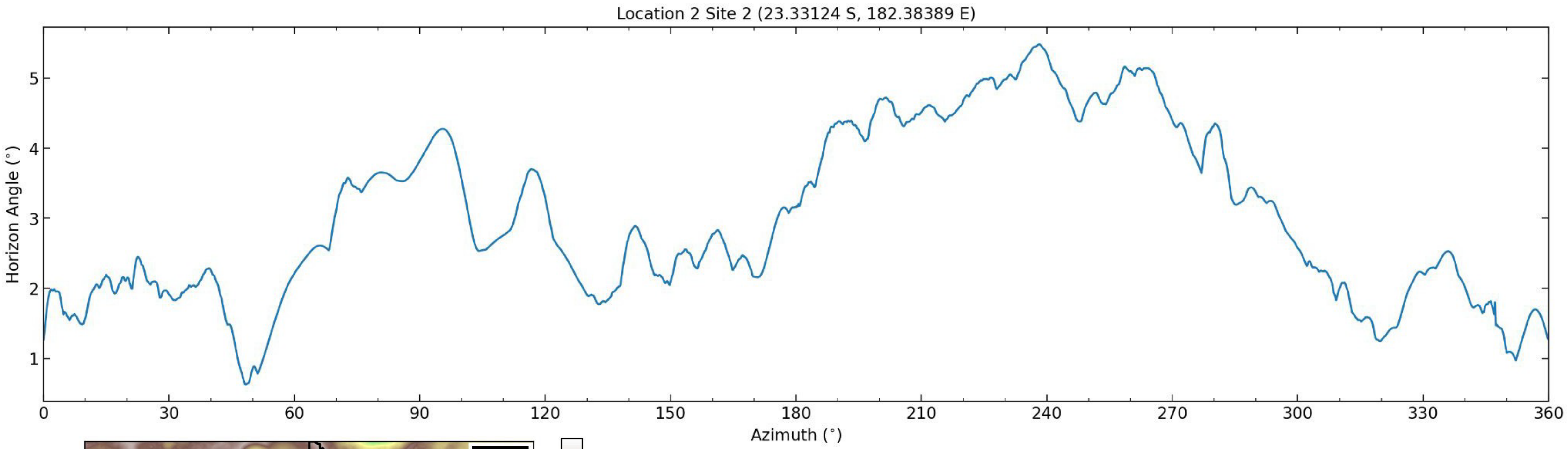
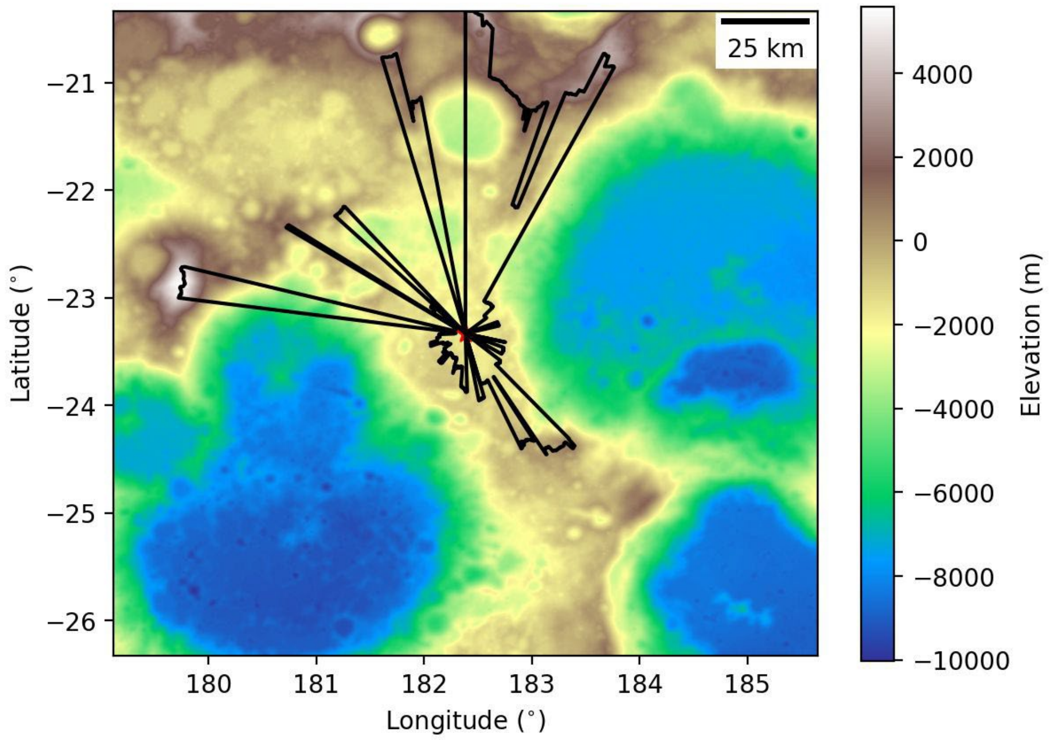
Received 2021 June 7; revised 2021 July 26; accepted 2021 August 10; published 2021 December 8

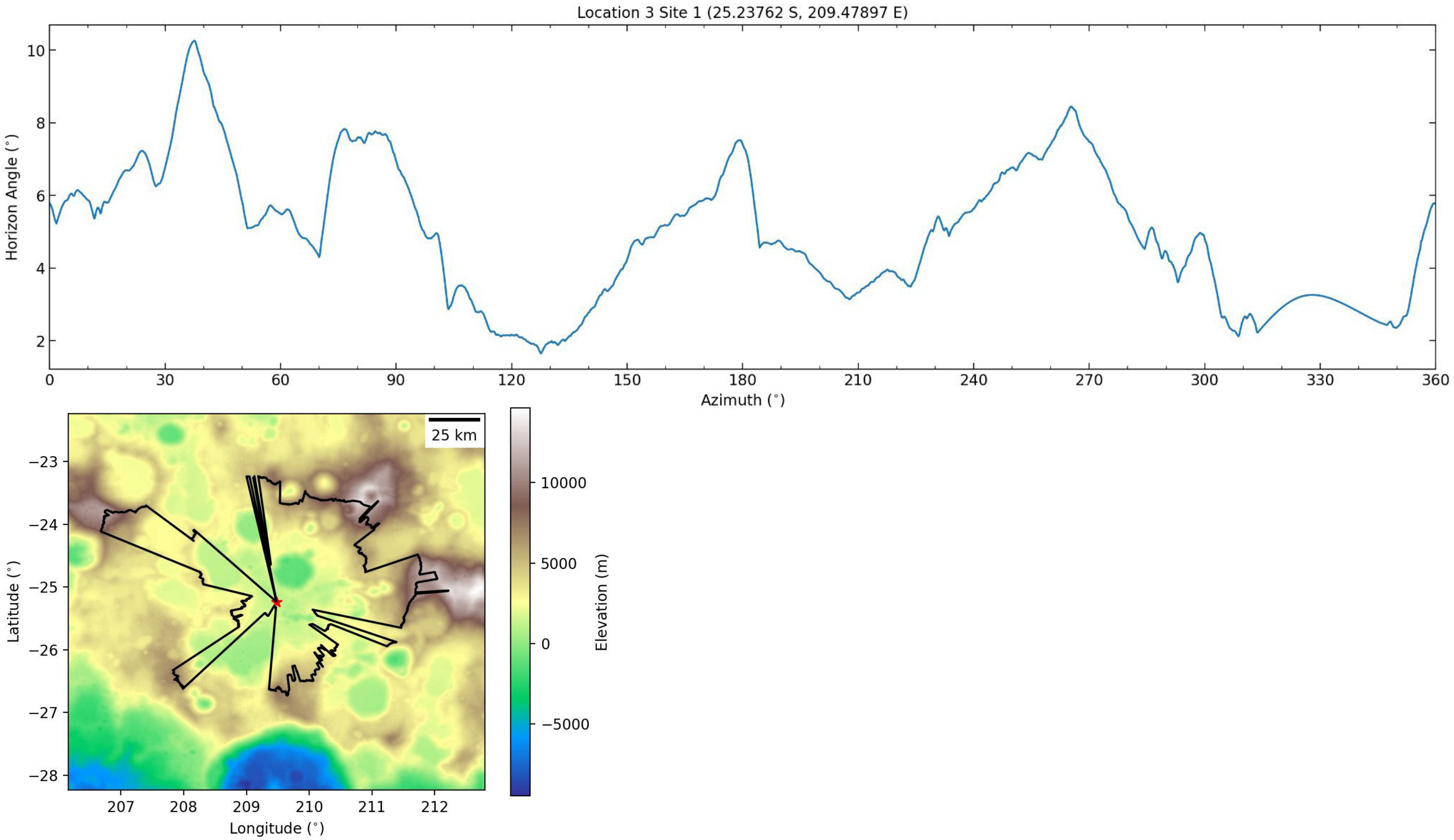


Location 1 (13.53865 S, 154.78935 E)
Horizon Angle (°)
Azimuth (°)
15 km
Latitude (°)
Longitude (°)
Elevation (m)
Zoom in
Bumping against minimum distance
1 km





Lunar horizon is rugged in the highlands on the far side!



Location 3 Site 1 (25.23762 S, 209.47897 E)
Horizon Angle (°)
Azimuth (°)
25 km
Latitude (°)
Longitude (°)
Elevation (m)

Summary of Lunar Radio Telescope Site Selection

- Go to the Moon's far side for radio-quiet but stay away from the limb to avoid RFI diffraction effects. Best location is $\pm$50° of Earth antipode on lunar far side.
- Thermal effects on spacecraft, antennas, and science instruments can be substantial near the Equator.
- High crustal thickness and well-mixed regolith is preferred to minimize interactions of the radio antenna beam with subsurface reflectors.
- Low slopes, low rock abundance, and avoidance of geological structures preferred.
- Preference for landing on a flat topographic high to maximize sky accessibility
- Smooth horizon preferred, but difficult to find on the far side. At minimum, need 360° panoramic reasonably high- resolution imaging of horizon from the telescope location so we know the horizon accurately.