Optical Interferometry on the Moon

Key Non-Polar Destinations Across the Moon
to Address Decadal-level Science Objectives with Human Explorers

Panel on Heliophysics, Physics, and Physical Science

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Introduction

- Need for higher angular resolution and sensitivity ➔ larger mirrors
  - Monolithic or segmented mirror face limits in size
  - Truly large (>1 km) “mirrors” require “sparse aperture”, interferometric designs

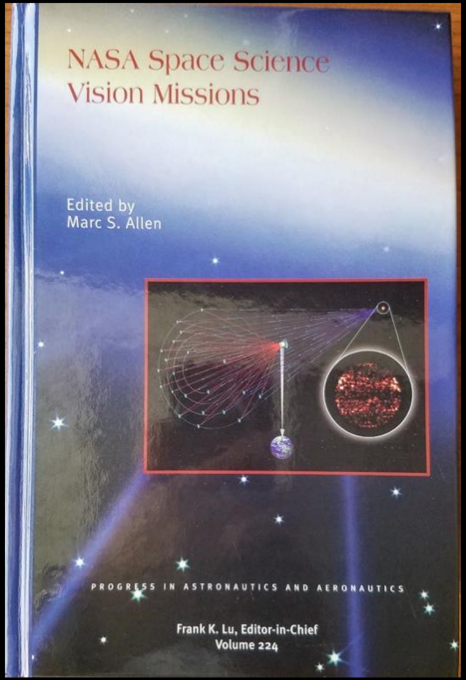
- Such facilities already exist on the Earth’s surface and concepts have been developed for space-based interferometers, both free-flying and lunar
  - Plans to establish a substantial lunar infrastructure via the Artemis Campaign now make lunar-based interferometers competitive with free-flyers

- Today I will discuss the prospects for Optical Interferometry from the Moon and highlight two concepts that illustrate one path toward truly ultra-high-definition observations of the sky at Ultraviolet and Optical Wavelengths

Why put Interferometers in Space or on the Moon?

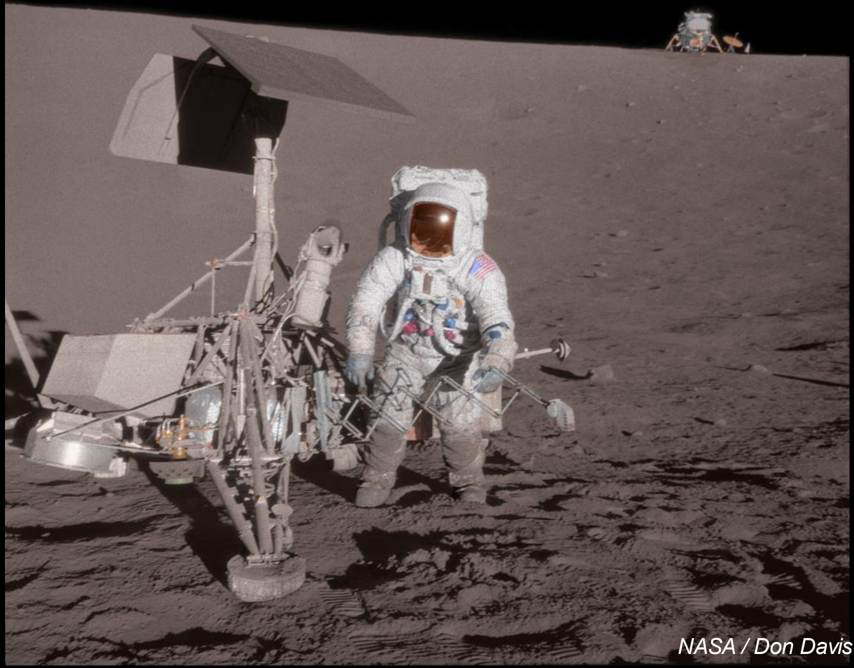
Required for studying the Universe in high-definition over a broad range of colors and times

- Broader wavelength coverage
  - due to Earth's atmosphere blocking much of the spectrum outside of the optical
- Higher angular resolution
- Observe continuously over long time periods
- More stable environment
- No atmosphere & no turbulence provide longer coherence times and enable much greater sensitivity



Why the moon?

- Stable surface
  - Seismology not a problem
  - Things stay put
  - No need for precision formation flying
- No atmosphere
  - More stable environment
  - Turbulence-free
  - Beams coherent over larger scales
- Dust can be mitigated
  - Chang’e-3 LUT telescope operated for years
- Small systems can outperform terrestrial, orbital systems
- Planned Lunar Infrastructure (Artemis, etc.) can provide deployment & servicing support not readily available in deep space (e.g., L2)

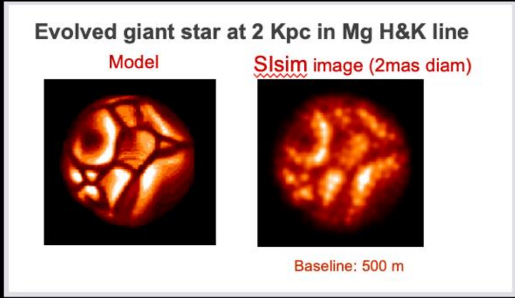

NASA / Don Davis

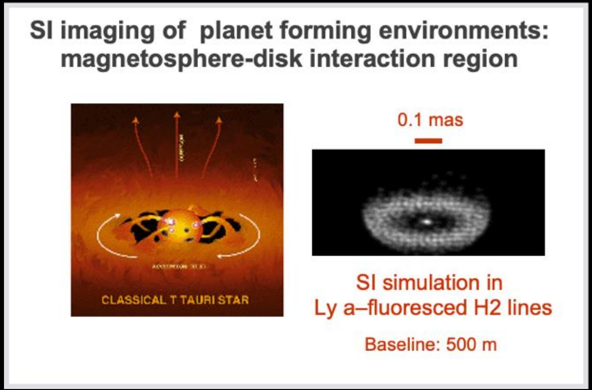
NASA/Apollo Image Gallery/Don Davis

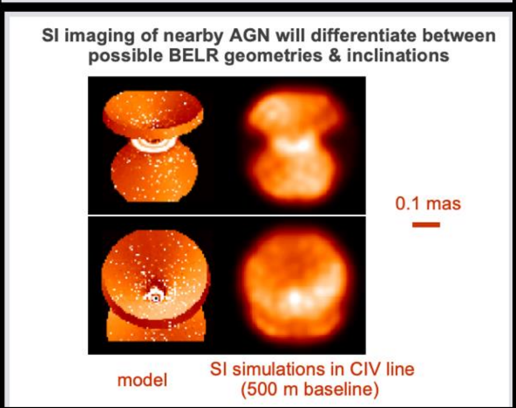
Driving Science Cases for a Long-Baseline UV/Opt. Lunar Interferometer

Solar/stellar magnetic activity and derivation of a truly predictive model of the underlying dynamo

Evolved giant/supergiant convection;
Planet-forming environments;
AGN BLR geometries & inclinations







A long-baseline, UV/Opt. space interferometer will see motions of and within objects on astonishing timescales

- Nearby stars will move across the sky during a typical length (~several hours) observation
- Physical processes will be directly visible
  - Mass transfer in binaries
  - Jets in young solar systems
  - Pulsation-driven surface brightness variation and convective cell structure in giants & supergiants

Freytag et al. (2017)

Artemis-enabled *Stellar Imager* (AeSI)

UV-Optical, space-based interferometer for 0.1 mas spectral imaging of stellar surfaces and interiors and of the Universe in general

It will resolve for the first time the surfaces and interiors of sun-like stars and the details of many other astrophysical objects & processes, e.g.:

Magnetic Processes in Stars
- activity and its impact on planetary climates, and on the origin and maintenance of life;
- stellar structure and evolution

Stellar interiors
- in solar and non-solar type stars
- Infant Stars/Disk systems
- accretion
- magnetic field structure & star/disk interaction

Hot Stars
- hot polar winds
- non-radial pulsations
- envelopes and shells of Be-stars

Cool, Evolved Giant & Supergiant Stars
- spatio-temporal structure of extended atmospheres
- pulsation, winds, shocks

Supernovae & Planetary Nebulae
- close-in spatial structure

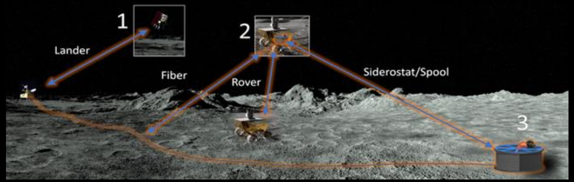
Interacting Binary Systems
- resolve mass-exchange, dynamical evolution/accretion, study dynamos

Active Galactic Nuclei
- transition zone between Broad and narrow Line Regions
- origin & orientation of jets
- Cosmological distance scale

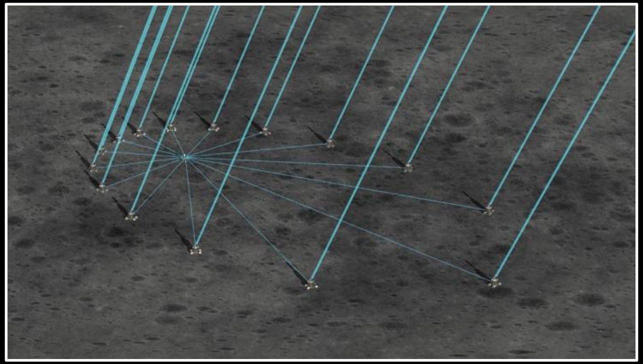
Exoplanets
- escaping atmospheres from gas giants; H II fluorescence in hot Jupiter atmospheres; transit light source effect

Our Proposed Approach

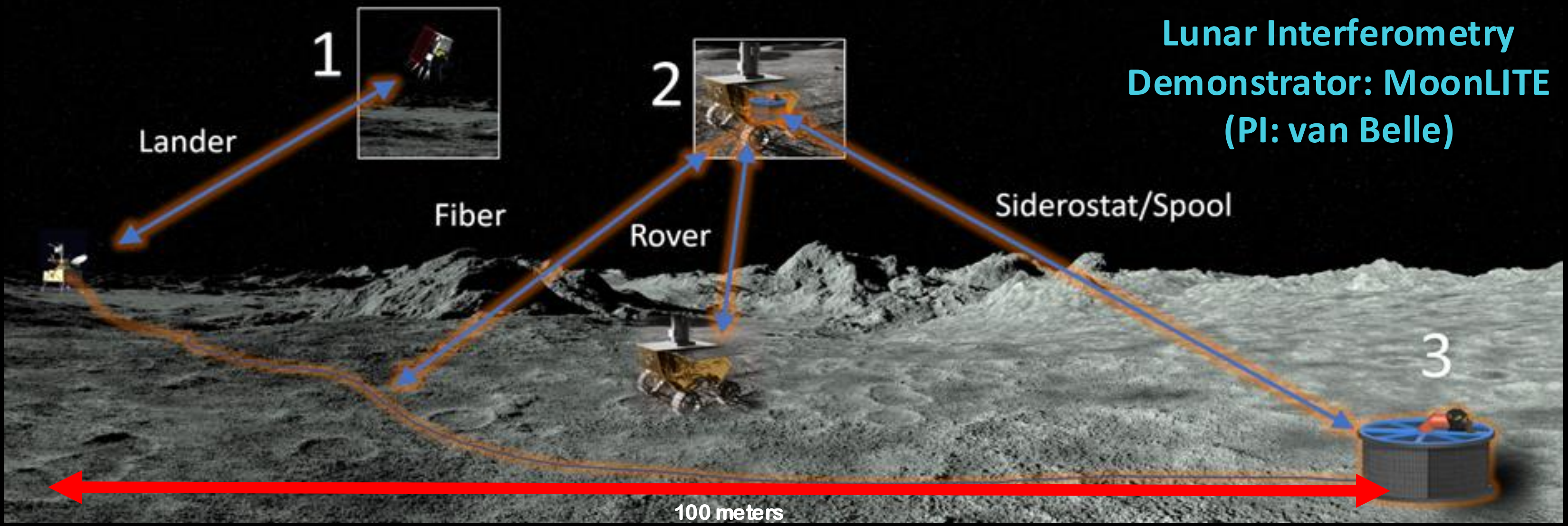
- Start with a small demonstration mission to show feasibility of interferometry from the Moon and to generate some early science results (MoonLITE)



- In parallel, continue the development of a long baseline interferometer concept that will enable a quantum leap in our capabilities to observe the Universe in Ultra High Definition: Artemis-enabled Stellar Imager (AeSI).
  - Could be developed and deployed in multiple stages, building up gradually from a small initial array to the full-size, 30-element design



Lunar Interferometry Demonstrator: MoonLITE (PI: van Belle)

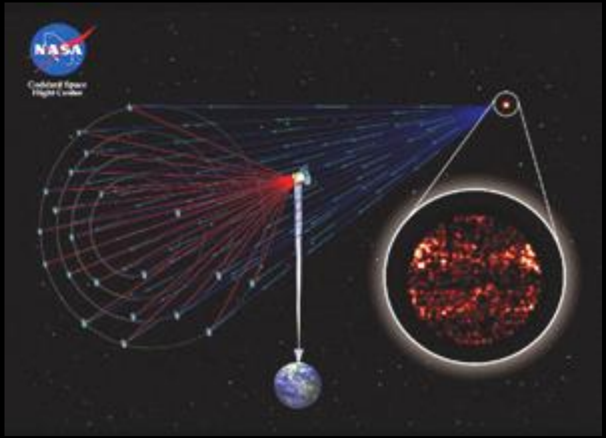


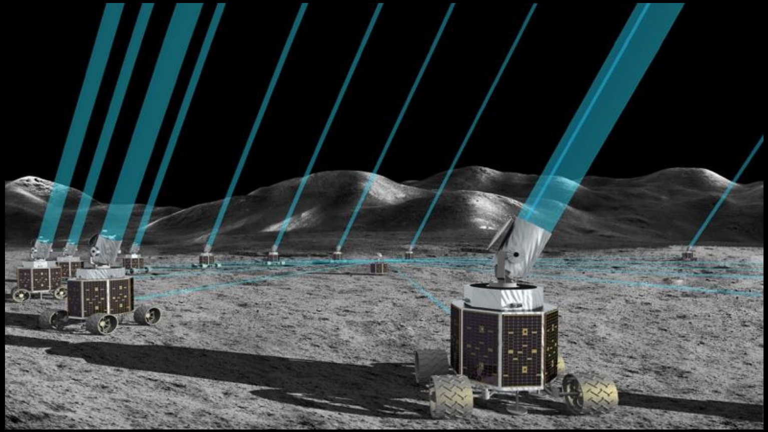
- (1) A CLPS-provided lander arrives at the lunar surface. (2) The CLPS-provided rover travels 100 meters away from the lander, unrolling a fiber umbilical (for power, communications, and optical fiber data transfer) (3) The outboard siderostat station is deployed. After calibration of the individual stations and the overall combined beams, science operations commence.
- One deployment step for 2 × 50 mm telescopes on a 100m baseline
- Simple system for sub-milliarcsecond resolution observations of faint objects
- Unprecedented sensitivity: beats world’s largest terrestrial interferometers by ~5 magnitudes

Pursuing the Grand Vision of Long-Baseline Arrays

- End Goal: Enable the study of our Universe at Ultra High Definition in the UV/Optical (~200x HST ang. res.)
- *Stellar Imager (SI)* Vision Mission Study (2005) explored a >500m diameter free-flying design to be located at L2.
- *Artemis-enabled Stellar Imager (AeSI)* lunar-based concept developed with the support of a **NASA Innovative Advanced Concepts (NIAC) Phase 1 Study in 2024**

SI





AeSI

AeSI NIAC Phase 1 Concept Development Team

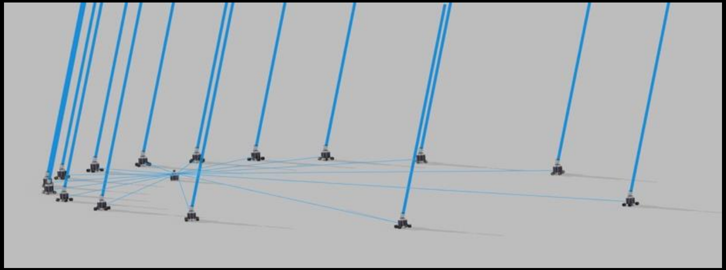
Mission concept under development by NASA/GSFC in collaboration with experts from Industry, Universities, and Astronomical Institutes

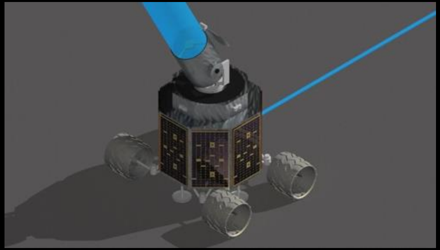
Ken Carpenter	*NIAC Fellow, PI of Phase 1 Study* IDC Coordinator (NASA-GSFC)	Breann Sitarski	Optical Engineer (GSFC)
		Gerard van Belle	Interferometry Expert, Mission Design Lead (Lowell Obs.)
Tabetha Boyajian	Ground Interferometry Expert (LSU)		
Michelle Creech-Eakman	Ground Interferometry Expert (MRO)	Jon Brashear	Grad. Student, Science/AI (CUA)
Margarita Karovska	Science Definition Co-Lead (CfA)	Derek Buzasi	Astereoseismology (U. Chi)
David Leisawitz	Space Interferometry Expert (GSFC)	Jim Clark	Mechanical Engineer
Jon Morse	Senior Advisor, Lunar Science & Infrastructure (Caltech)	Erik Wilkinson	System Engineer (BAE)
		Julianne Foster	System Engineer (BAE)
Dave Mozurkewich	Lead System Engineer (Seabrook Eng)		
Sarah Peacock	Science Definition, Study Co-Mgr, Outreach Co-Lead (UMBC/GSFC)	Buddy Taylor	Mechanical Engineer (GSFC)
		Walter Smith	Mechanical Engineer (GSFC)
Noah Petro	Artemis Expert (GSFC)	Qian Gong	Optical Engineer (GSFC)
Gioia Rau	Science Definition Co-Lead, Study Co-Mgr., Outreach Co-Lead (NSF, GSFC)	Bruce Dean	Optical Engineer/WS&C (GSFC)
		Len Seals	Scattered Light/Optical Eng/ (GSFC)
Paul Scowen	Science Definition (GSFC)	David Kim	Power Systems Engineer (GSFC)

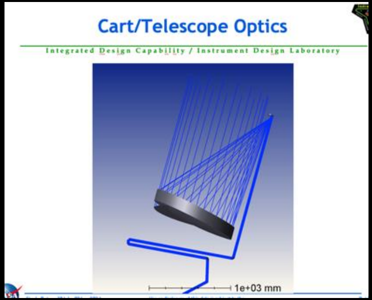
Baseline Design: GSFC Integrated Design Center (IDC)

- Stage 1: 15 rovers (mirrors) configured in 1-km major axis elliptical array to avoid long delay-lines

- Stage 2: upgrade to 30 rovers, enhanced hub
  - Could be deployed in smaller, more numerous stages if desired
  - Assumes near-polar site, but easily adapted to lower latitude site





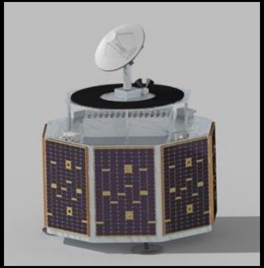


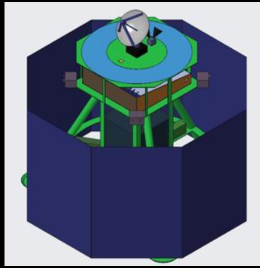
Mirror Station: artist's concept (B. Griswold) and internal optics (IDC/D. Mozurkewich)

IDC: Engineering Study
- Systems
- Mechanical Design
- Optical Design
- Communications
- Thermal
- Power

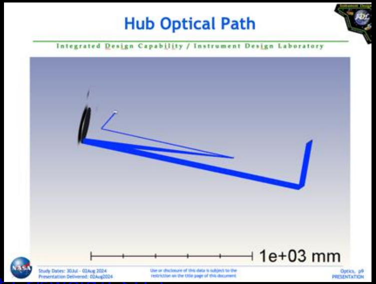
Conclusion: Feasible!

IDC provided many good recommendations for further studies and technology development.



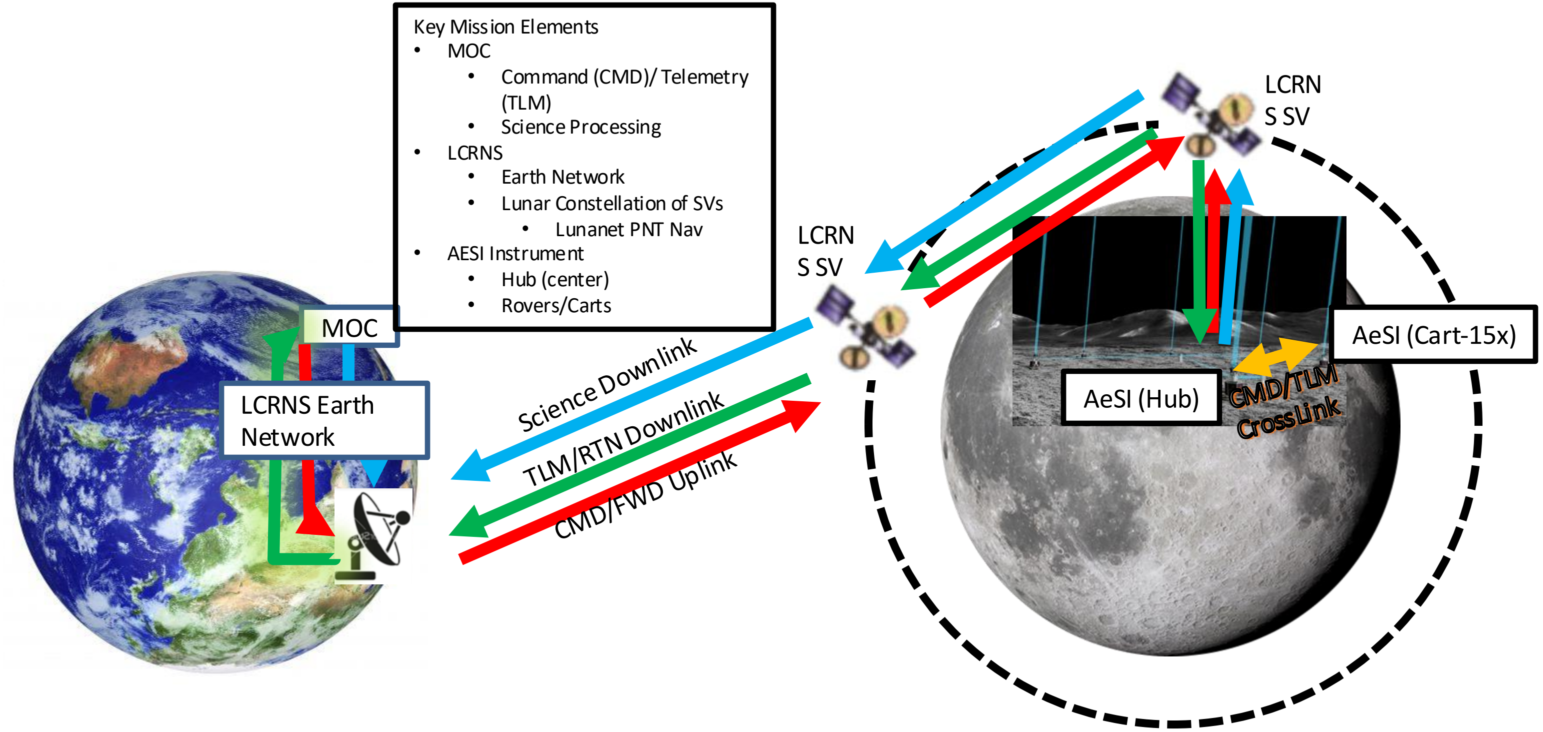


Hub: artist's concept (B. Griswold) and internal details/ optics (IDC & D. Mozurkewich)



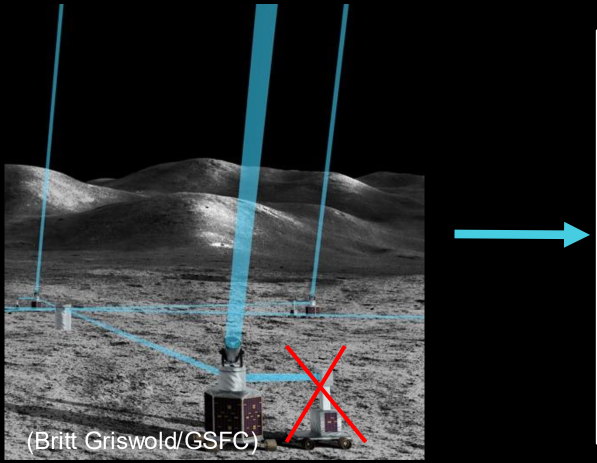
(Britt Griswold/GSFC)

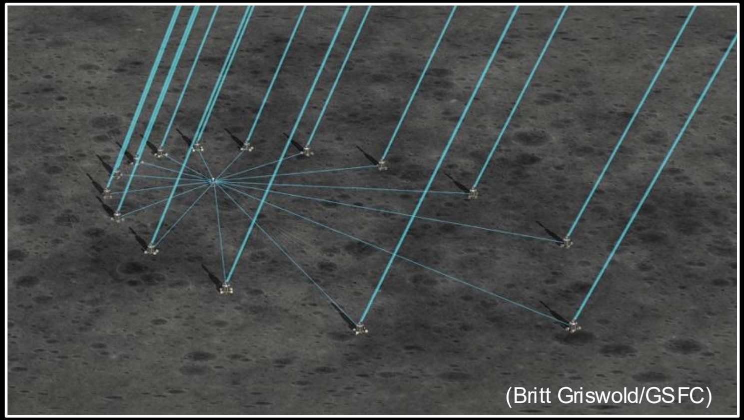
Notional AeSI Mission Architecture (GSFC IDC)

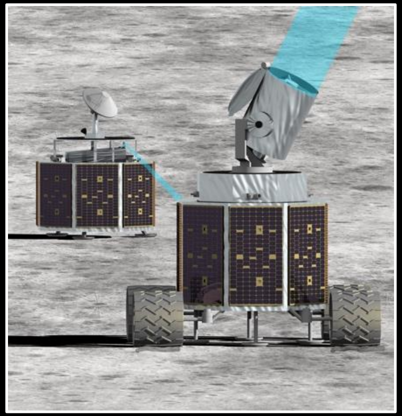


Biggest Improvements in Phase 1 Study

- Eliminated 2nd set of rovers for delay-line optics by using asymmetric primary array configurations to remove large path-length differences (target-to-primary-to-hub) for off-zenith targets; remaining delay line can be fit inside rovers



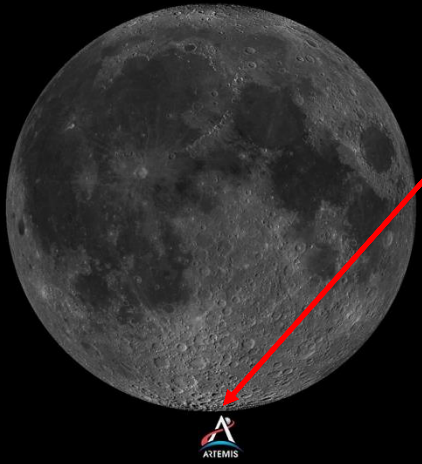




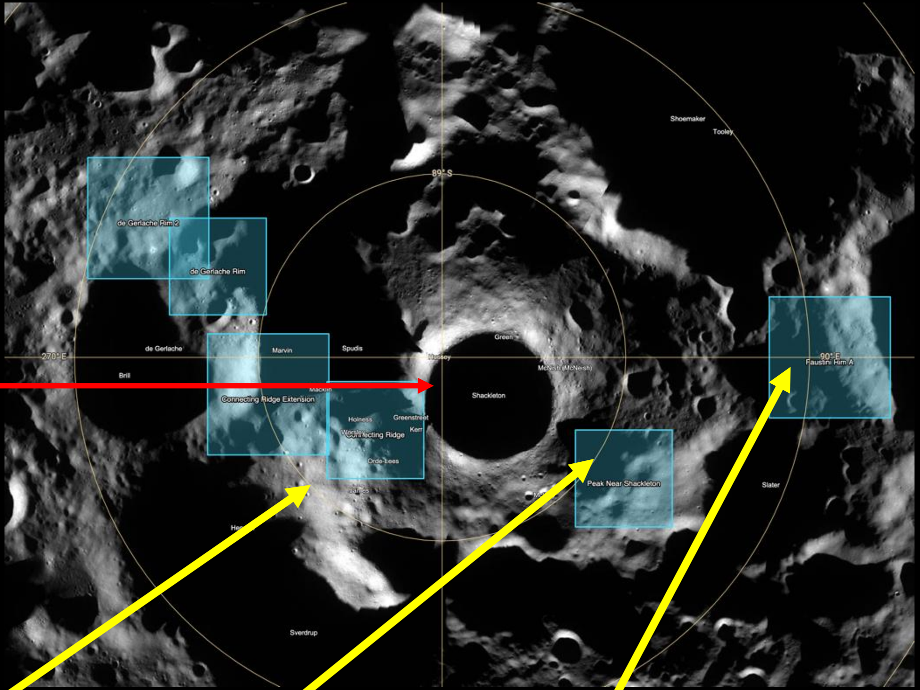
- Primary mirror sizes increased to improve sensitivity, array baseline increased to maintain resolution while going deeper into sky for more targets
- Viable sites have been identified for both original & “new 9” candidate Artemis bases

AeSI Candidate Sites

Illustrative viable ***AeSI*** sites near some of the original candidate Artemis base locations



Shackleton Crater
South Pole

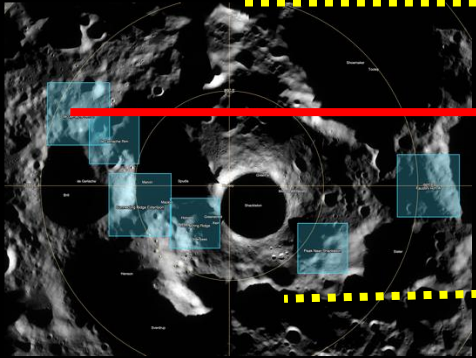


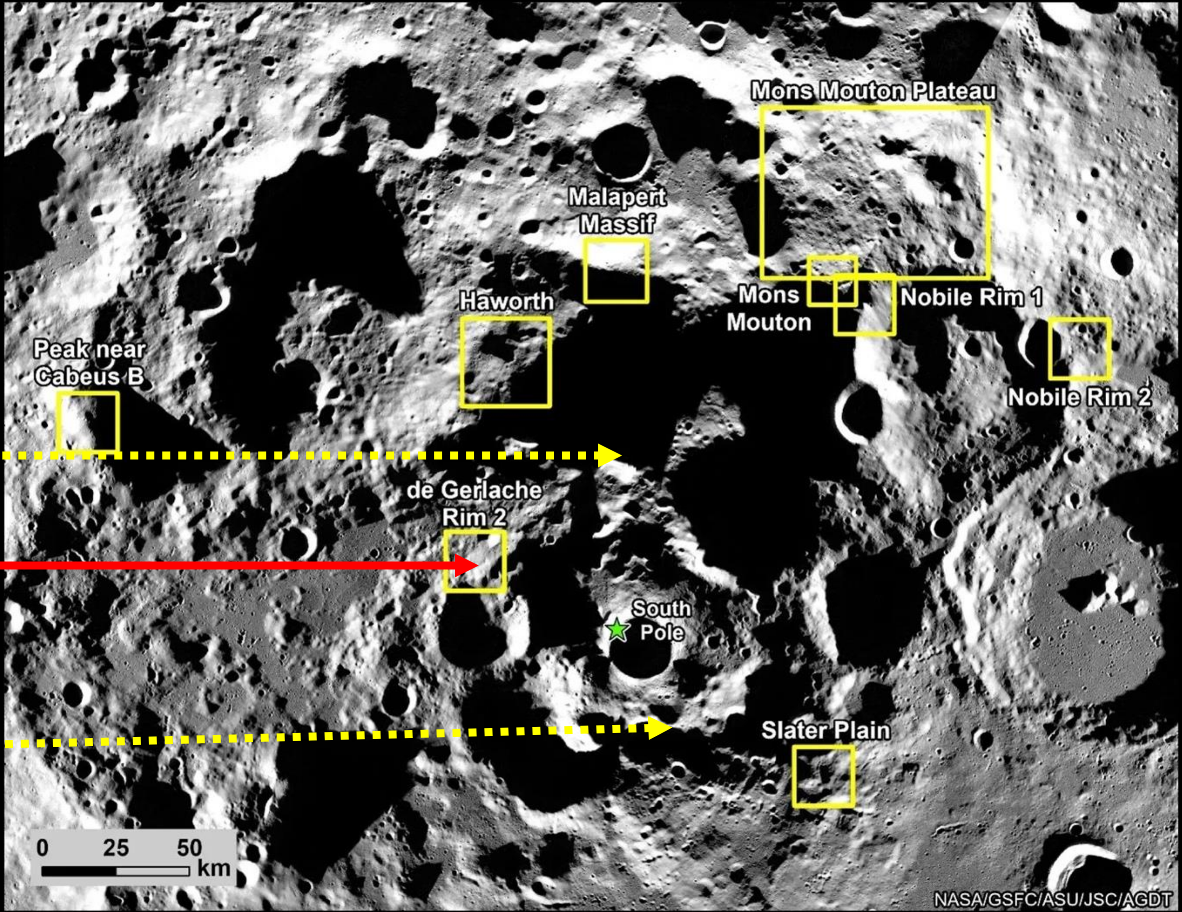
Candidate AeSI Sites near:
Connecting Ridge, Peak Near Shackleton, and Faustini Rim A

Note: Equally good sites can be found near the “new 9” candidate Artemis base locations

“New 9” Artemis Candidate Sites

- Range further from South Pole (better for AeSI)
- Have 1 site in common with original list: “de gerlache Rim 2” (red line)



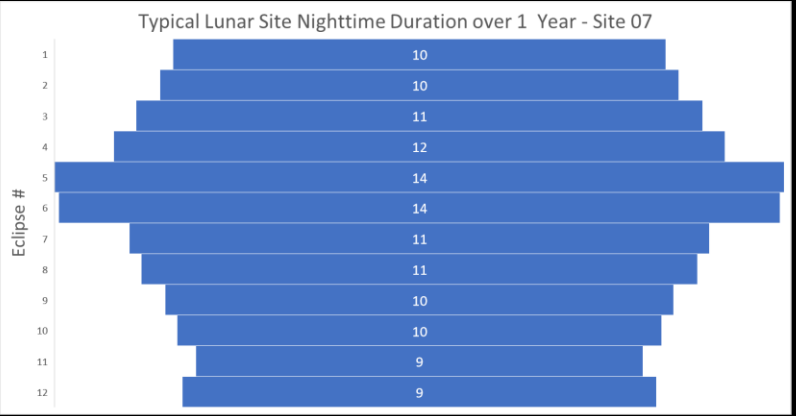


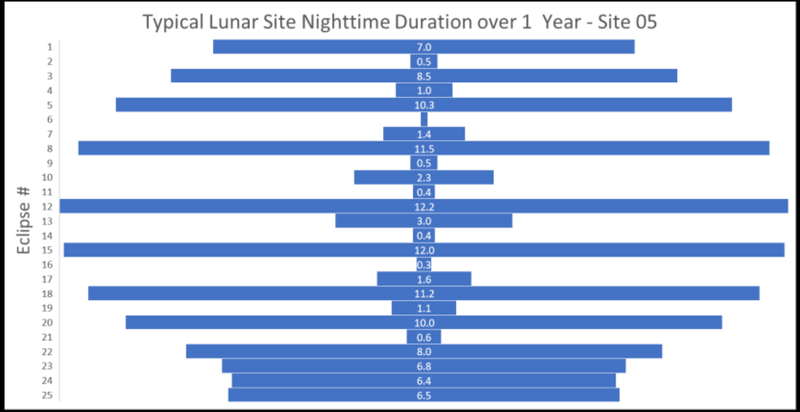
Challenges from South Pole Locations Planned for Artemis

- Solar illumination varies **a lot** near the Lunar South Pole (Heritage Analysis from Erwan Mazarico)

Site 07. No midnight sun. Seasonal variation in nighttime duration: 9-14 days

Site 05: Both midnight sun and blockage during the day. Seasonal variation (7-13 days) and shorter duration shadowing (0.1-3 days)





- The number of targets accessible over the course of the year is significantly limited by a South Polar location. This drives the size of the mirrors and overall array baselines to larger, more expensive values to obtain the required sample-sizes

A non-polar site is of great interest for AeSI!

Current plan: South Pole

South polar site close to Artemis Base
Pro
Robust support that would be available from the Artemis base
Astronauts could provide: infrastructure, astronaut support, and robotic support for deployment, servicing, and upgrade of the observatory

Current plan: South Pole

South polar site close to Artemis Base	
Pro	**Contra**
Robust support that would be available from the Artemis base	much smaller # of targets visible at the high ecliptic latitudes
Astronauts could provide: infrastructure, astronaut support, and robotic support for deployment, servicing, and upgrade of the observatory	More costly: as a consequence of the above, the size of the mirrors and overall array baselines need to be larger and more expensive to obtain the required sample-sizes
	Variations in day/night time influence power system design, as prolonged darkness necessitates greater energy storage, while frequent transitions between light and shadow drive more extreme thermal fluctuations and increase instances of dust levitation, all of which must be carefully considered for sustained lunar operations

Non-polar Option

Site at Lower Lunar Latitude
Pro
Great value to AeSI or, in fact, any astronomical observatory!
The number of astronomical targets observable over the course of a year is ~2x larger at low latitudes (lunar and ecliptic!) vs. what can be seen from polar regions
Duration of daylight and dark, nighttime hours is much more regular and allows for a better, more efficient, and more highly productive design and operations concept

Non-polar Option

Site at Lower Lunar Latitude	
Pro	**Contra**
Great value to AeSI or, in fact, any astronomical observatory!	Unless human base is present at lower latitudes, this will limit availability of astronauts support. **<u>However</u>** an increase in robotic support may be able to make up much of the difference. The original deployment mission may have to be direct-to-site in this case
The number of astronomical targets observable over the course of a year is ~2x larger at low latitudes (lunar and ecliptic!) vs. what can be seen from polar regions	
Duration of daylight and dark, nighttime hours is much more regular and allows for a better, more efficient, and more highly productive design and operations concept	

Observation Scenarios

- Observing plan depends substantially on whether we can operate through night
  - If solar powered, would observe mostly during day with batteries providing survival heater power and perhaps some limited-time observing at night
  - If nuclear powered (fission surface reactor), could operate day and night
- Normal mode operations
  - Observe a series of targets (solar type stars, AGN, symbiotic stars), obtaining sub-milli-arcsec UV/optical still images
  - Observe selected targets to view spatio-temporal changes on short timescales (days)
- Astereoseismology operations
  - month-long, high-cadence observations to observe intensity variations over resolved stellar disks to probe interior structure

Deployment & Servicing

- The launch & transportation to the lunar surface near an Artemis base camp is currently one of the primary contributions of Artemis to AeSI. Candidate launch vehicles include: Starship (used in baseline design), New Glenn, SLS
- Lunar location of AeSI's → servicing will be much easier than at L2
  - Utilize the resources of Artemis to transport new hardware from Earth to the Lunar surface & then to observatory site
  - Use a mixture of human and/or robotic services to perform both maintenance and upgrades
  - Robots could become increasing important if we are able to site the observatory at lower lunar latitudes to improve science productivity

Maintenance of AeSI over time

- The interferometer is modular and most servicing would likely be done by replacing one of the carts (primary mirror stations/“array elements”) with a spare
  - The cart with the failed component could be brought back to an Artemis site and repaired, if possible, to serve as a spare to be used to accommodate future failures
  - The observatory is tolerant to the temporary loss of one or more array elements, so scheduling of such replacements can be done in a way that fits Artemis requirements
- The hub is a more complex and stationary element, but it could be designed to have modular components that would permit servicing in-situ by robots or astronauts
  - In the case of a failure that could not be handled in such a manner, we would need to transport it back to an Artemis site and either repair it there or deploy a new unit
  - Building a spare hub and one or more spare carts/mirror stations is highly desirable
- Dust Removal by robots or astronauts if needed

Upgrades

- Primary upgrade: increase in the # of array elements from the original # deployed, to the final desired (30)
  - Could start with 7 or 15 and build up in staged fashion to 30
  - Mostly just requires deploying additional mobile carts carrying the new array element
  - However, we either need to design the central hub to handle 30 incoming beams originally, make it easy (via modular design) to enhance it to accommodate more beams on-site, or plan to replace the hub when adding array elements
    - Current design is to deploy a hub that is capable of handling up to 30 elements from the start
- Other upgrades: install new, more efficient detectors and/or mirrors with higher reflectivity if dramatic improvements are made over the years in either or both
  - These would likely be done by replacement of carts & hub but on-site component replacement is an option

Challenges and Future Work

Challenges and Future Work

- Low UV-Sensitivity due to # of reflections in delay-lines require:
  - Better-reflectivity UV mirror coatings
  - More sensitive detectors, esp. for 1200-1600 A
- Refine dust/scattered light control, human/robot servicing mix, & overall control sys

- Pursue Remote Power Station Options to enable more continuous operations, even in array night
  - Solar arrays on higher illumination, nearby peaks
  - Nuclear source over nearby hill
  - Supplied by Artemis infrastructure

- South Polar location significantly limits #targets visible
  - the ability to site the array at lower, non-polar latitudes would tremendously increase the scientific productivity of the observatory and unlock AeSI's full potential!

AeSI Mission Concept Homepage

https://hires.gsfc.nasa.gov/si/aesi.html

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