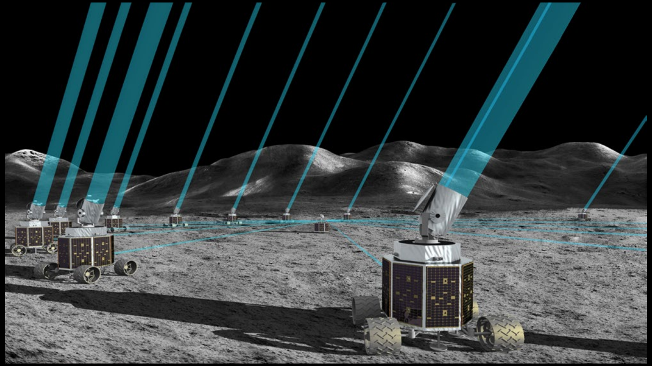
A Lunar-Based UV/Optical Interferometer

Presentation to the Committee on Key Non-Polar Destinations Across the Moon to Address Decadal-Level Science Objectives with Human Explorers: Panel on Heliophysics, Physics and Physical Science
Keck Center of the National Academies in Washington, DC – September 24-25, 2025

NASA Innovative Advanced Concepts



(Britt Griswold/GSFC)

Artemis-Enabled Stellar Imager
AeSI
A NASA Innovative Advanced Concept Study

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NIAC Fellow, HST Ops. Project Scientist

NASA's GSFC

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.*

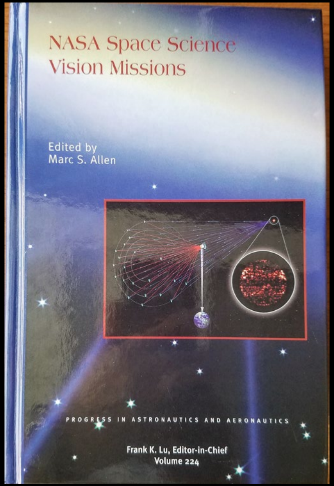
- Our first talk, given by Dr. Gioia Rau at your first Committee meeting, used the Artemis-enabled Stellar Imager (AeSI) as an illustrative case. I will continue to do so here and although I will include some of that material for completeness sake, *I will concentrate this 2nd presentation on providing additional details re: some important aspects of design & implementation of an UV/Optical Interferometer on the Moon.*

New Material – Providing a Closer Look at:

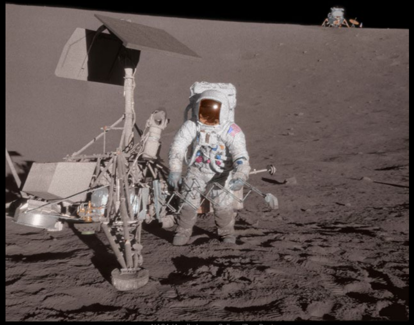
- The Driving Science Case
- Technology Readiness
- Rails as an alternative to free-roving mirror stations

- The staged development and deployment option and the possibility of open-ended growth and improvements
- Value of onsite humans to mission success and requirements to enable

Why put Interferometers in Space or on the Moon?



- Lack of an atmosphere (opacity, turbulence) enables:
  - Broader wavelength coverage
  - Higher angular resolution
  - Longer coherence times and thus greater sensitivity
- Being off the Earth enables:
  - Continuous observations over longer time periods
  - More stable environment
- Advantages of being on the Moon
  - Stable surface
    - Things stay put (seismic activity not a problem)
    - No need for precision formation flying
  - Planned Lunar Infrastructure can provide deployment & servicing support not readily available in deep space (~L2)
  - Dust can be mitigated: Chang'e-3 LUT telescope observed for years



NASA / Don Davis

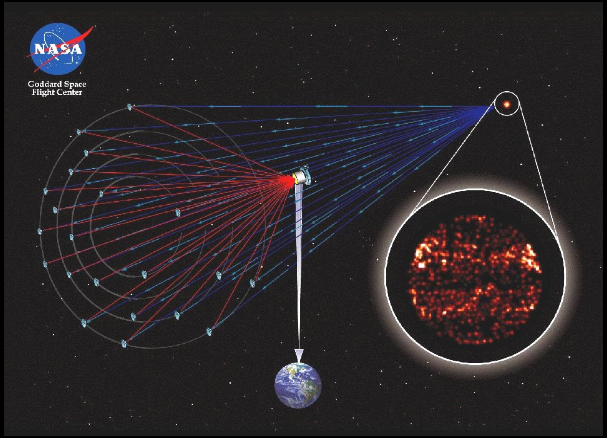
Two Options for Space-Based, UV/Optical Long-Baseline Arrays

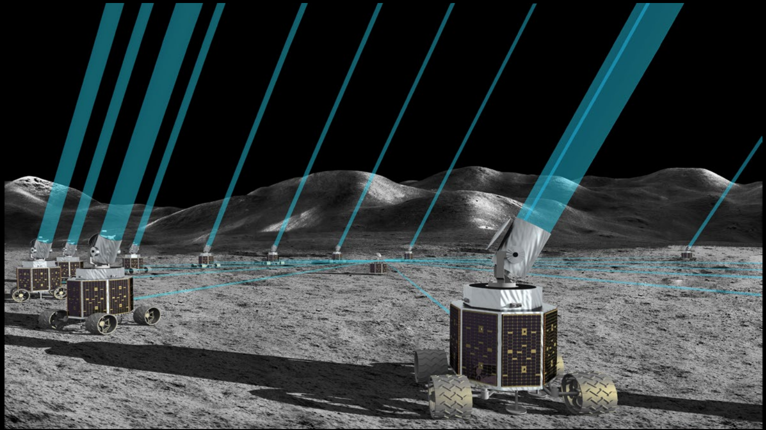
Stellar Imager (SI) Vision Mission Study (2005) explored a >500m diameter free-flying design to be located at L2.

Artemis-enabled Stellar Imager (AeSI) lunar-based concept developed with the support of a **NASA Innovative Advanced Concepts (NIAC) Phase 1 Study in 2024**.

End Goal in both cases: Enable the study of our Universe at Ultra High Definition in the UV/Optical (~200x HST ang. resolution).

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)
Tabetha Boyajian	Ground Interferometry Expert (LSU)	Gerard van Belle	Interferometry Expert, Mission Design Lead (Lowell Obs.)
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)

Artemis-enabled Stellar Imager (AeSI):

a UV-Optical, long-baseline (~1km) space-based interferometer for 0.1 milli-arcsec spectral imaging of stellar surfaces and interiors and of the Universe in general.

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

Science Goals

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 foot-points, magnetic field structure & star/disk interaction

Hot Stars

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

Supernovae & Planetary Nebulae

close-in spatial structure

Cool, Evolved Giant & Supergiant Stars

spatiotemporal structure of extended atmospheres, pulsation, winds, shocks

Interacting Binary Systems

resolve mass-exchange, dynamical evolution/accretion, study dynamos

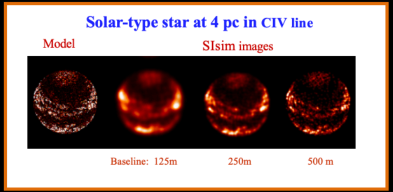
Active Galactic Nuclei

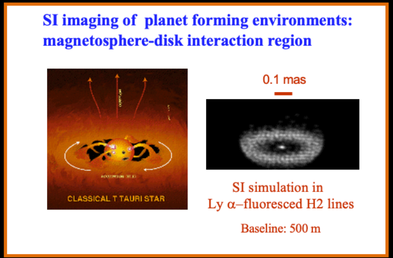
transition zone between Broad and Narrow Line Regions; origin & orientation of jets; distances

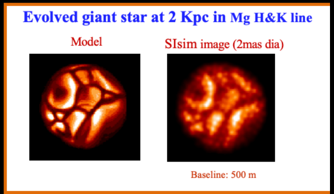
Exoplanet Host Stars

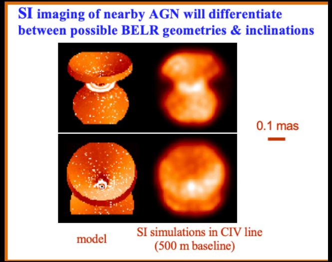
escaping atmospheres from gas giants; H II fluorescence in hot Jupiter atmospheres; transit light source effect

Stretch goal, with larger array diameters (>2 km): Black Hole Event Horizons



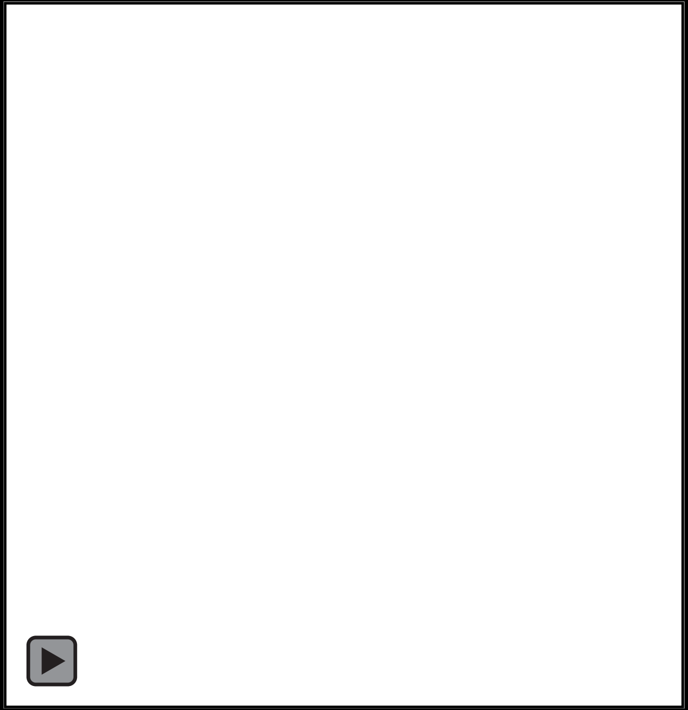






Not just spatial resolution - Observe the Dynamic Universe in near Real-Time - motions of and within objects visible on astonishing timescales!

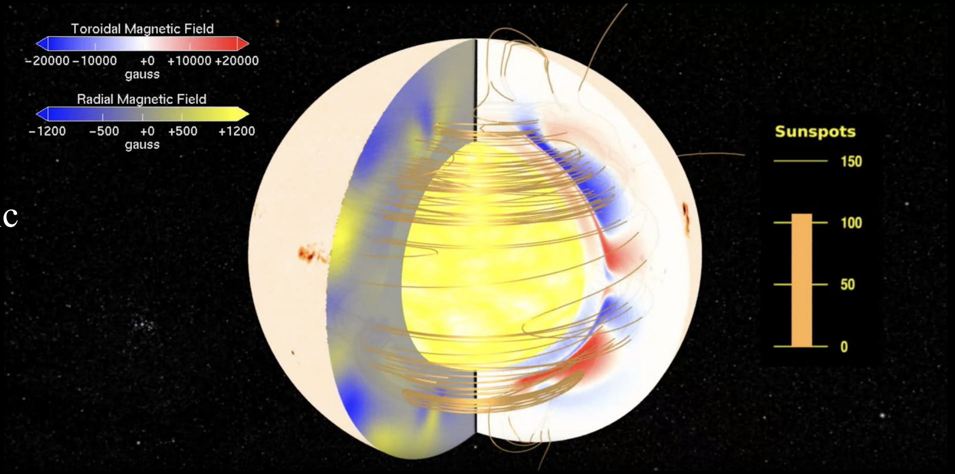
- nearby stars will move across the sky as we observe (real-time proper motions!)
- physical processes will be directly visible
  - mass transfer in binaries
  - pulsation-driven surface brightness variations and convective cell structures in giants & supergiants
  - jets in young solar systems



A closer look at *The* Driving Science Case - 1

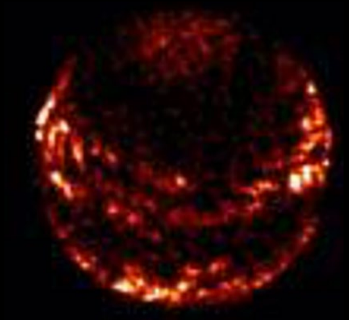
- **Study of Solar/stellar magnetic activity and the derivation of a truly predictive model of the underlying dynamo**
  - Current models do not predict start/maximum/end times or intensity of next solar max, despite decades of high-resolution solar data
  - Needed to understand the central stars of our own and of exoplanet systems and their impact on the habitability of surrounding planets

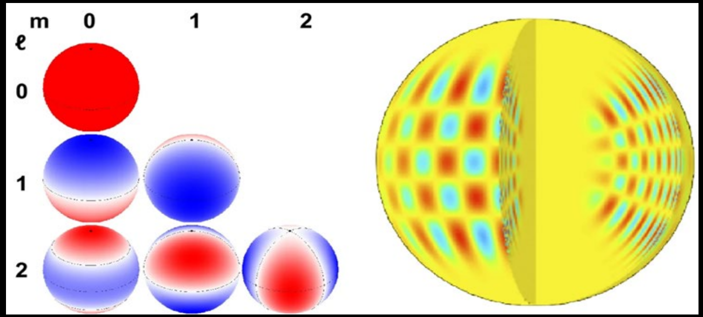
Right: Simplified Solar dynamo model simulates how the Sun's magnetic field grows and sustains itself by channeling convective energy. Reproduces key solar magnetic behaviors, including cyclic oscillations, magnetic migration toward the equator ("Butterfly Diagram"), and polarity reversals. But even best models do not reliably predict start, max, end times or intensity of next solar max. (image: NASA/SVS/Tom Bridgman 2008)

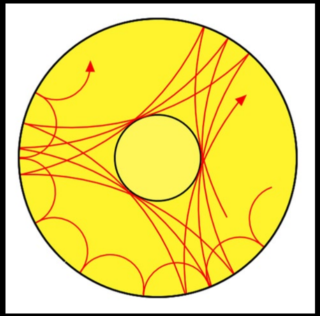


A closer look at *The* Driving Science Case - 2

- Required: an ensemble study of other Sun-like stars with a variety of parameters (chemical composition, mass, surface gravity, luminosity, etc.) with both high-resolution surface imaging and spatially-resolved asteroseismology to determine interior structure.
  - determine the characteristics of their stellar magnetic activity and cycles and compare with each other and the Sun.
  - *This may be the Rosetta Stone that unlocks the mysteries of a truly predictive dynamo model for the Sun and other stars.*



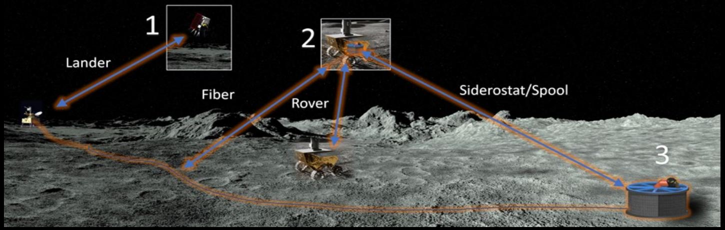




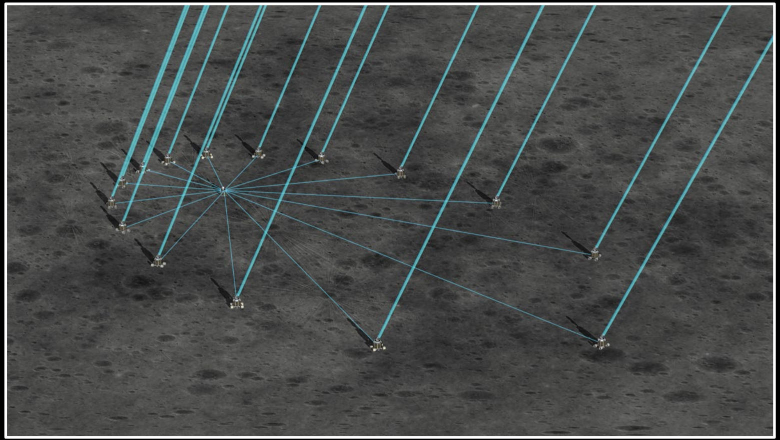
Left: Surface Magnetic Activity (CIV 1550 A); Right: Astereoseismolgy - low vs. high degree modes probe different depths; high-degree modes (l>3) require spatial resolution of light variations

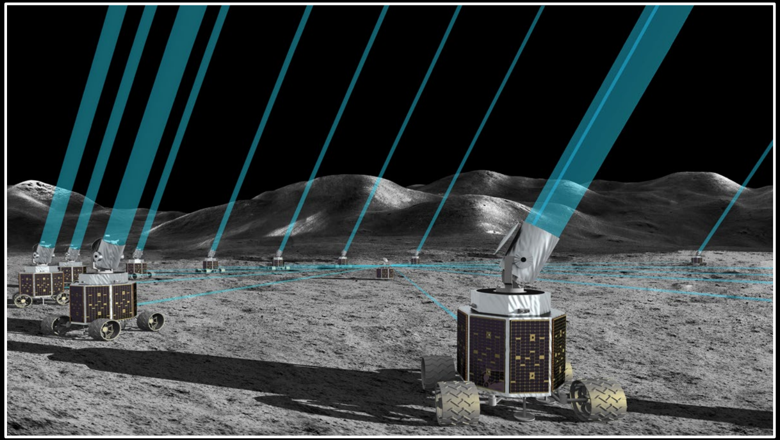
Our Proposed Approach

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



- 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).





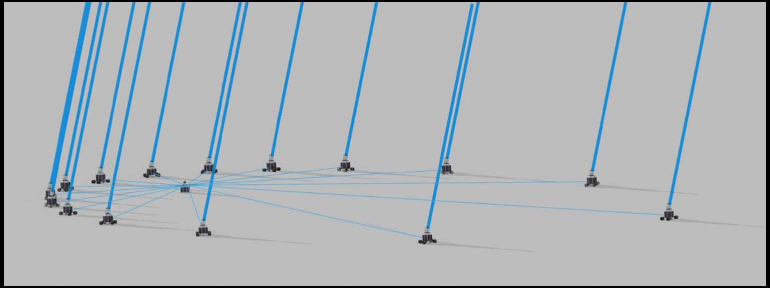
NIAC Phase 1 Design: GSFC Integrated Design Center (IDC)

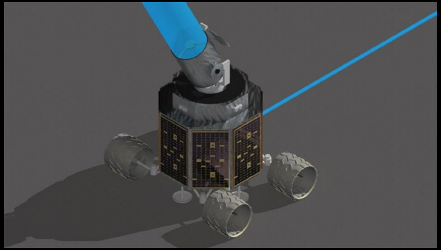
Stage 1: 15 rovers (mirrors) configured in 1-km major axis elliptical array to avoid long delay-lines

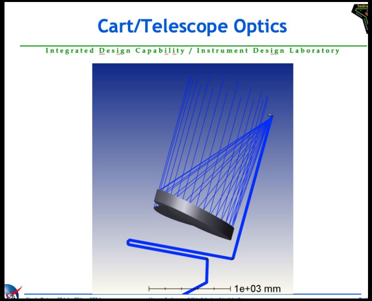
Stage 2: upgrade to 30 rovers, enhanced hub

Could be deployed in smaller, more numerous stages if desired

Assumes near-polar site, but easily adapted to lower latitude site





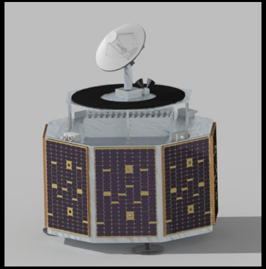


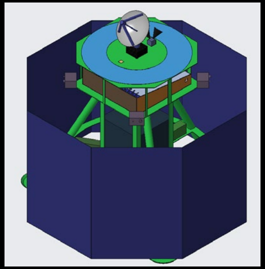
Mirror Station: artist's concept (B. Griswold) and internal optics (IDC/D. Mozurkewich)

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

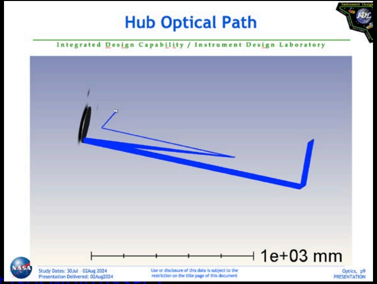
Conclusion: Feasible!!!

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





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

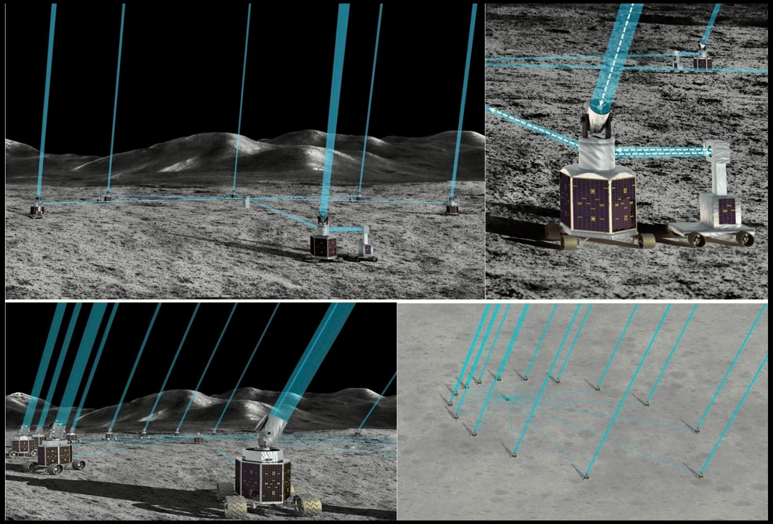


(Britt Griswold/GSFC)

Most important changes from 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

Figure: The pre-Phase I concept (*top line*) vs. the Phase I Baseline design (*bottom line*).



(Britt Griswold/GSFC)

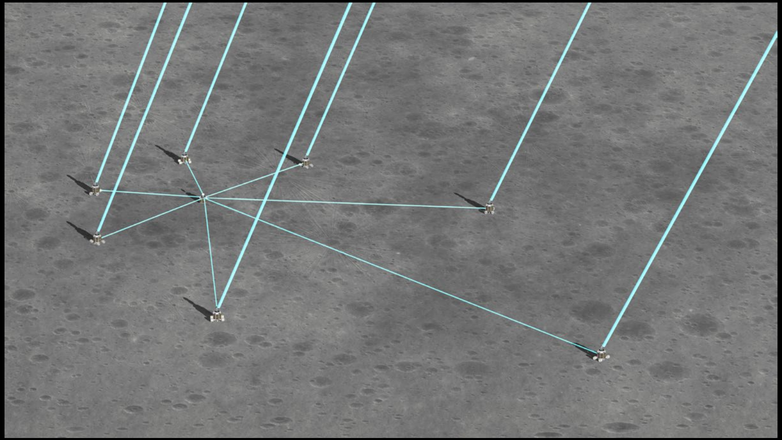
- Primary mirror sizes increased to improve sensitivity, array baseline increased to maintain resolution while going deeper into sky for more targets (*needed if near pole*)
- Viable sites identified for both original & “new 9” candidate Artemis bases

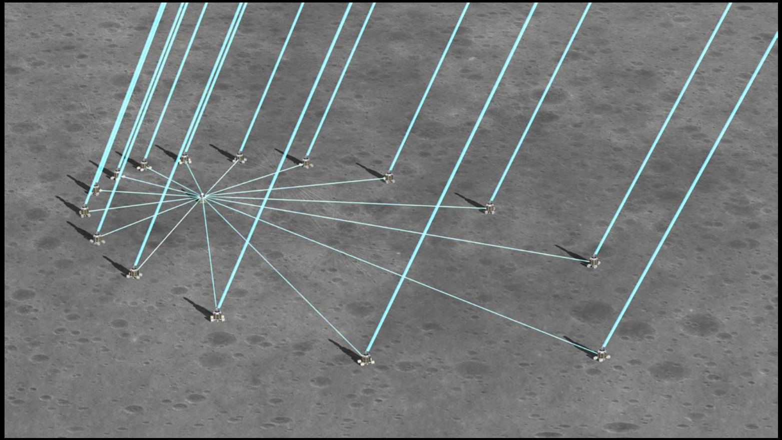
A Closer Look: Technology Readiness

- **The Moon is an ideal place for the first productive uv/optical/ir interferometers in space** because, compared to an orbiting (free-flying) instrument, the technology is more mature:
  - The moon allows us to use a design that is more similar to what we have done on the Earth, improving readiness while providing all the advantages of being in orbit (minus full sky coverage). And we get close to full-sky if we're located at the lunar equator.
  - For the instrument, there are only a couple of items that have to be developed, the most important of which is the alignment and control systems AND we have a plan to demonstrate those systems
    - Requiring roughly 2 to 3 years, 4 FTE, $150K hardware.
    - It is a fairly low-cost demonstration program, though does not yet include the space qualification of the design.
  - For the full mission, there are real issues involving infrastructure power, communications, data handling. Artemis solves these but with the cost of less efficient observing, *if* we are located near the polar regions.

A Closer Look: A staged-deployment – 1 (evolved Phase 1 design)

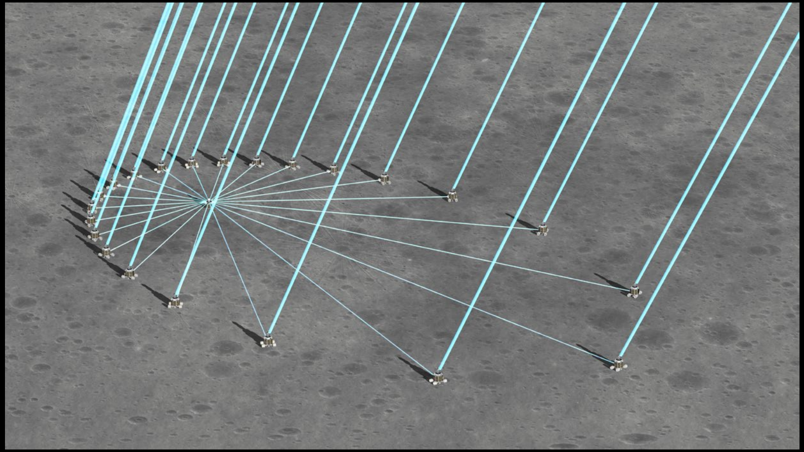
- Start with an array with a modest # mirror stations (elements), then build with time toward larger arrays. Helps with both technical and cost issues.
- Stage 1: Start with 7 elements.
    - Still can do science, as long as we can efficiently reconfigure the array and the source is not varying too quickly. But it will take longer to get each obs.
- Stage 2: add 8 elements to get 15 total (as in NIAC Phase 1 baseline design)

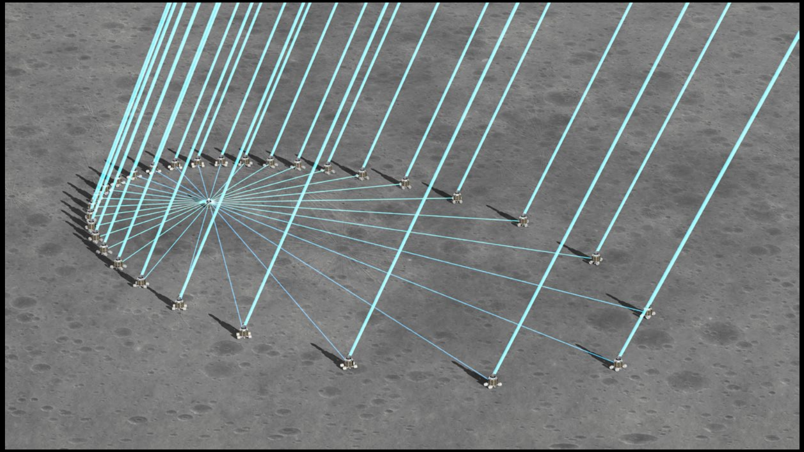




A Closer Look: A staged-deployment - 2

- Stage 3: add 7 elements, to a total of 22
- Stage 4: add another 8 elements to reach 30 elements, which allows imaging targets with few or no array reconfigurations, i.e., ~snapshot mode
- Each Stage improves the observing efficiency, types and the number of targets that can be observed, as well as the temporal resolution possible





A Closer Look: A staged-deployment - 3

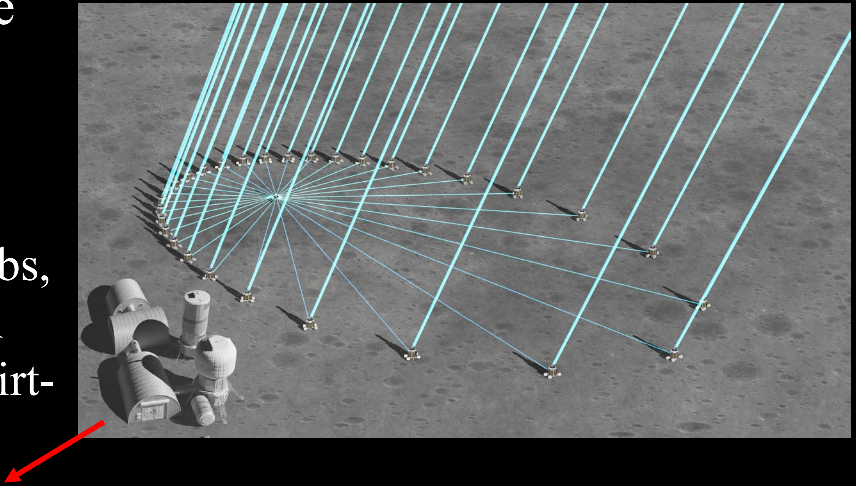
- In the spirit of Walt Disney:
  AeSI "will never be completed. It will continue to grow as long as there is imagination left in the world."
  - ~HST which was upgraded with new instruments during each servicing mission to keep it on the leading edge of space astronomy for decades
  - Provides the possibility of improved Hubs to utilize new detectors, mirror coatings, etc., as well as more mirror elements
  - Maximum Baselines can be expanded with time, as desired to obtain increasingly higher angular resolution on the sky

A Closer Look: Current design uses independent rovers but there is an attractive alternate design: Rails!

- Rails could make reconfigurations faster and easier, fewer degrees of freedom to control, no worry about unsmooth terrain, etc.
- Similar to that used at the VLA radio array (right)
- Rails could be linear or curved out from hub
- Require less energy to move mirror carts, power could be supplied along rails rather than carried on-board the carts
- Con: would likely require rails be constructed on the lunar surface (see FarView concept)

The Value of Humans on-site for AeSI

- On-site Astronauts will be of great value to AeSI, especially in its deployment, commissioning, and servicing.
  - This requires a habitat and hanger-like facilities in which extra mirror carts, hubs, and components could be housed and in which the astronauts could work in a shirt-sleeve environment on complex tasks.

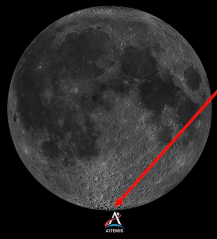


- An ongoing presence would allow for the continuing servicing of components, e.g., there might always be a spare mirror cart or two in the hanger being refurbished for use when there is a failure in the operating array. New hubs could be prepared in that same hanger.

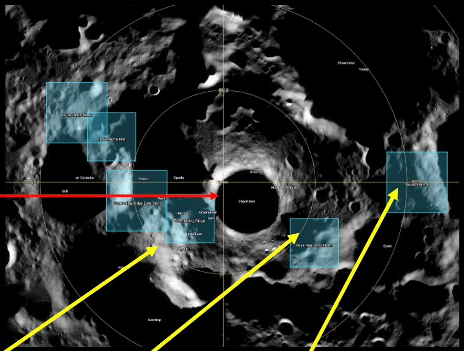
A non-polar site is of great interest for AeSI

- Current Plans dictate a south polar site in the vicinity of an Artemis Base
  - Primary advantage of such a location is the robust support that would be available from the Artemis base, in terms of infrastructure and astronaut & robotic support of the observatory.
  - But there are major disadvantages of polar sites, as shown on the next two slides.

Illustrative viable ***Artemis-enabled Stellar Imager (AeSI)*** sites near some of the original candidate Artemis base locations.



Shackleton Crater
South Pole



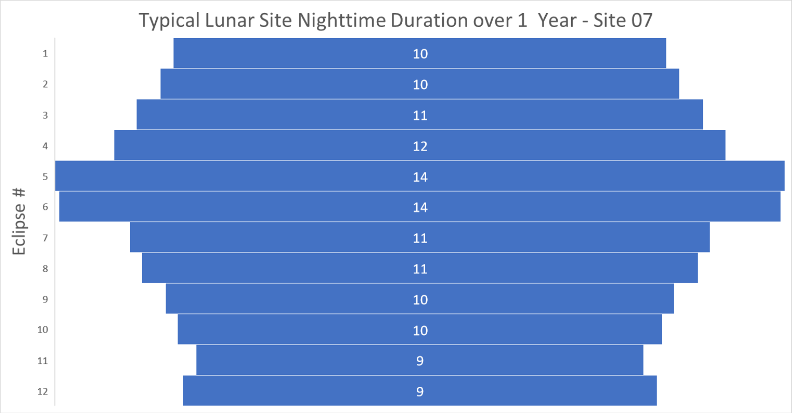
Candidate AeSI Sites near: Connecting Ridge, Peak Near Shackleton, and Faustini Rim A

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

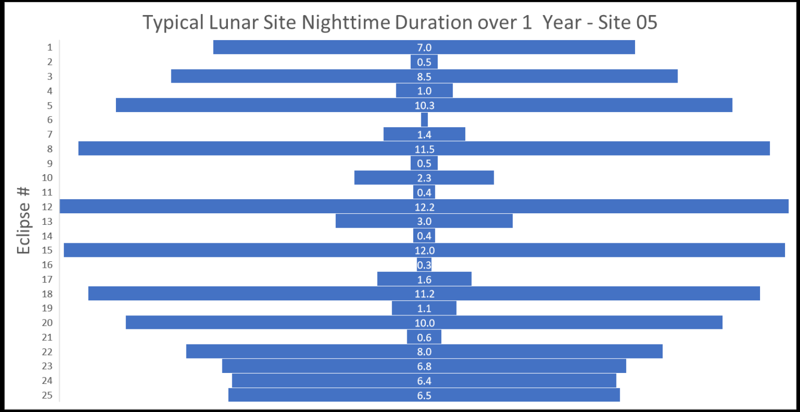
Challenges from South Pole Locations Planned for Artemis

- 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



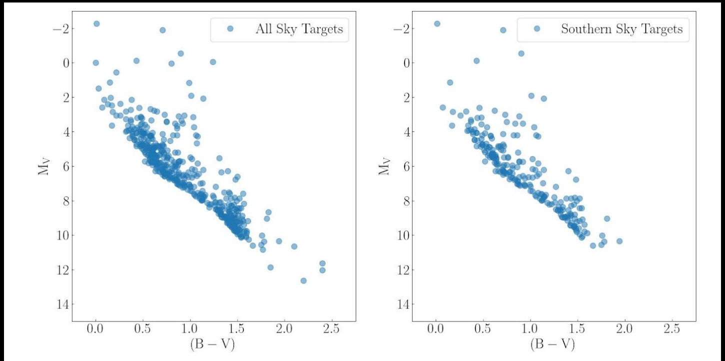
Site 05: Both midnight sun and blockage during the day. Seasonal variation (7-13 days) and shorter duration shadowing (0.1-3 days)



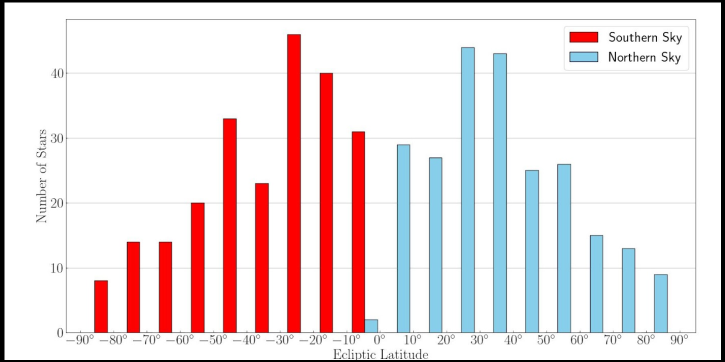
- *The number of targets accessible over the course of the year is significantly limited by a South Polar location. This drives the size of the mirrors and overall array baselines to larger, more expensive values to obtain the required sample-sizes.*

A non-polar site would be of great value to AeSI or 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
- Concern: unless Artemis decides to establish bases at lower latitudes, this will limit availability of human (astronaut) support.



462 solar-type stars available for surface imaging in 20-parsec sample. Left: all-sky sample for *AeSI* at equatorial latitudes. Right: the right panel shows the sample for a south polar location on the lunar surface.

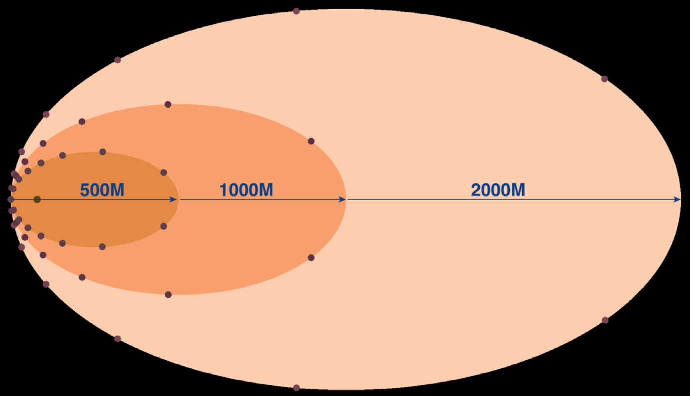


Distribution of Target Stars in sample on left with ecliptic latitude. Many targets are unavailable from the South Polar Regions of the Moon.

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)



Adjust baseline to obtain req'd resolution

- Astereoseismology operations
  - month-long, high-cadence observations to observe intensity variations over resolved stellar disks to probe interior structure

Deployment, Servicing with Artemis

- The launch & transportation to the lunar surface near an Artemis base camp is one of the primary contributions of Artemis to AeSI. Candidate launch vehicles include: Starship (used in Phase 1 design), New Glenn, SLS
- AeSI's location on the Moon means 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 increasingly important if we are able to site the observatory at lower lunar latitudes to improve science productivity

Servicing Details: Maintenance

- 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 a nearby 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 a nearby 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.

Servicing Details: Upgrades

- The primary upgrade foreseen for AeSI is an increase in the number 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 elements.
  - 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 that may be of interest would be to 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

- Low UV-Sensitivity due to # of reflections in delay-lines requires:
  - Better-reflectivity UV mirror coatings
  - More sensitive detectors, esp. for 1200-1600 A
- 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*
- Refine dust/scattered light control, human/robot servicing mix, & overall control sys.
- Pursue Remote Power Station Options to enable more continuous operations
  - Near Pole: Solar arrays on higher illumination, nearby peaks
  - Everywhere: Nuclear source (over nearby hill?), Supplied by Artemis infrastructure

AeSI Mission Concept Homepage

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