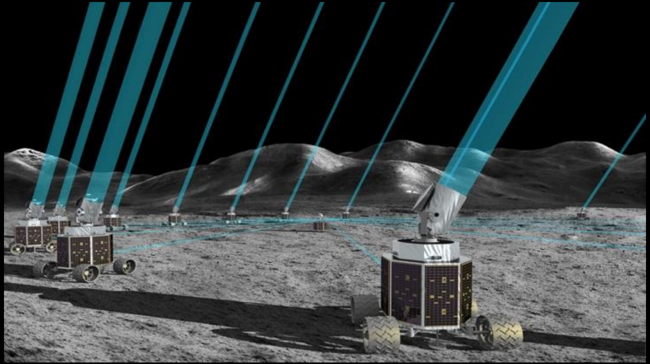
The Artemis-enabled Stellar Imager (AeSI):
Ultra-High-Resolution UV/Optical Astronomy from the Lunar Surface

Shore Leave - 2025 July 12



(Britt Griswold/GSFC)

Dr. Kenneth Carpenter

NIAC Fellow
HST Operations Project Scientist; RST Ground System Scientist
NASA Goddard Space Flight Center

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

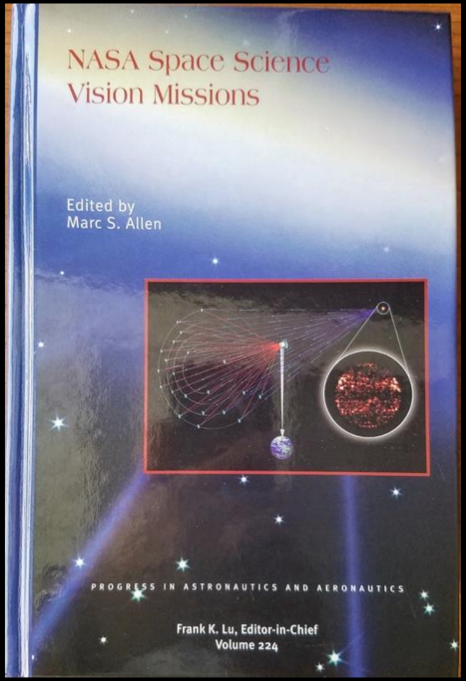
- Such facilities already exist on the Earth's surface and concepts have been developed for space-based interferometers, both free-flying and lunar
  - *Plans to establish a substantial lunar infrastructure via the Artemis Campaign now make lunar-based interferometers competitive with free-flyers*

- Our team was awarded a NASA Innovative Advanced Concepts Study in 2024 to assess whether we can build and operate, in collaboration with the human Artemis Program, *a long-baseline UV/Optical interferometer* on the lunar surface and
  - Determine whether it is competitive with the free-flying *Stellar Imager (SI)*
  - Enable the study of our Universe at Ultra High Definition in the UV/Optical (~200x HST Res.)

Why put Interferometers in Space or on the Moon?

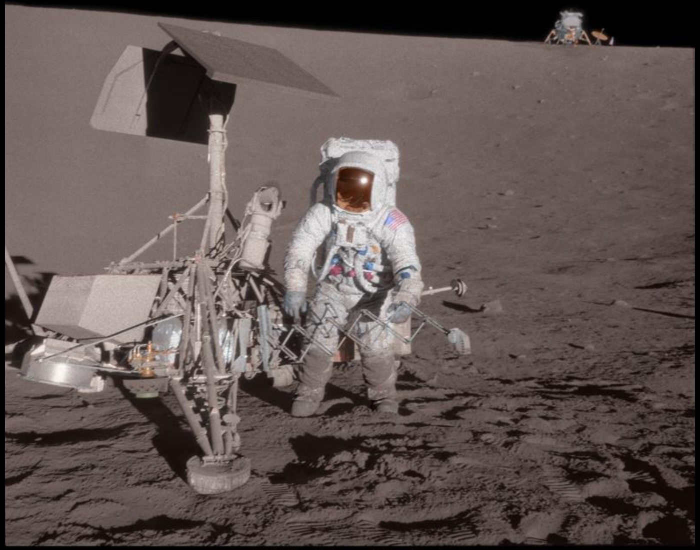
Required for studying the Universe in high-definition over a broad range of colors and timescales

- Broader wavelength coverage
- 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
  - No need for precision formation flying
  - Modest Seismic activity can be mitigated
- No atmosphere
  - More stable environment
  - Turbulence-free
  - Beams coherent over longer timescales
- 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)

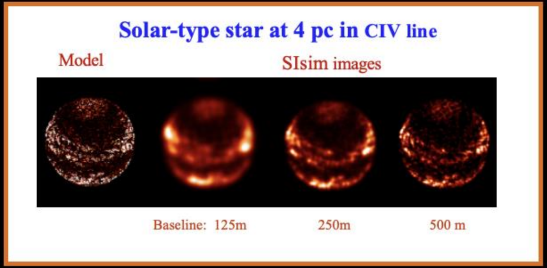


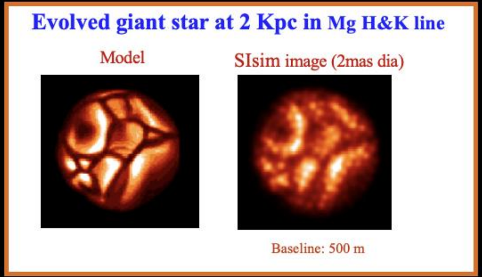
NASA / Don Davis

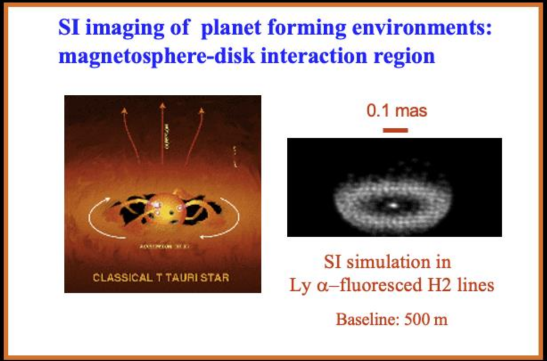
Driving Science Cases for a Long-Baseline UV/Opt. Space-Based Interferometer

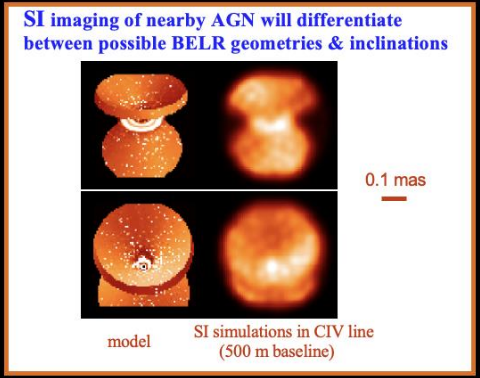
Solar/stellar magnetic activity and derivation of a truly predictive model of the underlying dynamo

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









Artemis-enabled Stellar Imager (AeSI)

is a UV-Optical, space-based interferometer for 0.1 milli-arcsecond spectral imaging of stellar surfaces and interiors and of the Universe in general.

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

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 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

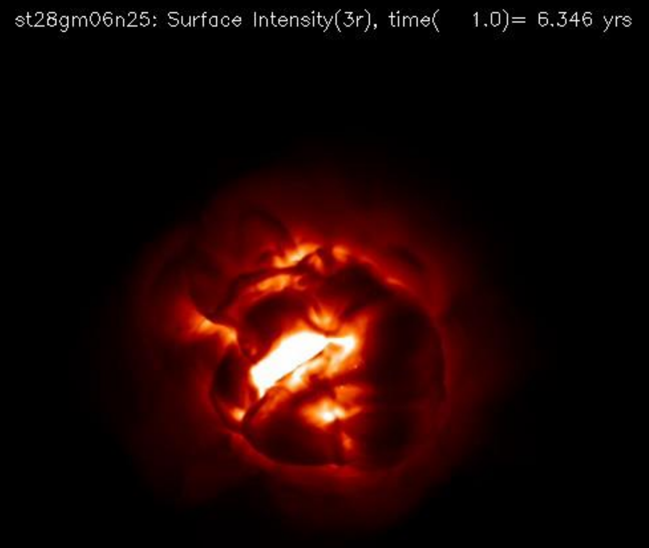
Interacting Binary Systems
resolve mass-exchange, dynamical evolution/accretion, study dynamos

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

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)

Free-flying (SI) vs. Lunar (AeSI) Option

Pierre Bely et al.[1] (1996): **unless there is a pre-existing infra-structure on the lunar surface,** it is easier and better to build a large space interferometer as a free-flyer.

[1] "Kilometric baseline space interferometry," Proc. SPIE 2807, Space Telescopes and Instruments IV, (12 October 1996)

→

2005:

"Vision Mission" (VM) Concept for a <u>free-flying</u>, long-baseline, UV/optical space interferometer called *Stellar Imager (SI)*

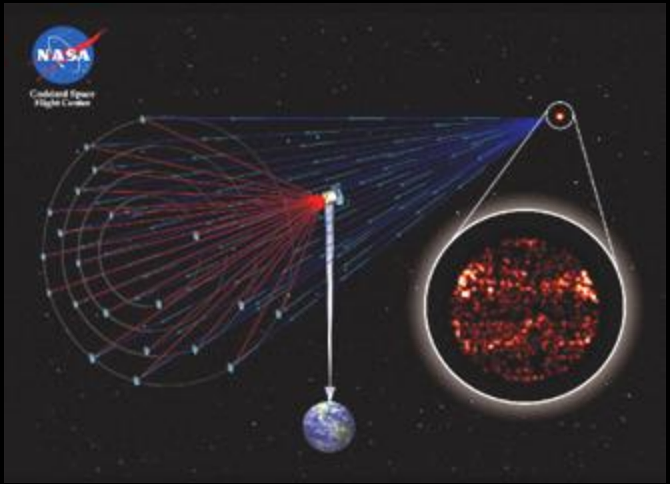
Now the Artemis Project plans to put humans and their infrastructure on the Moon within the next decade. It is time to consider in detail the lunar option!

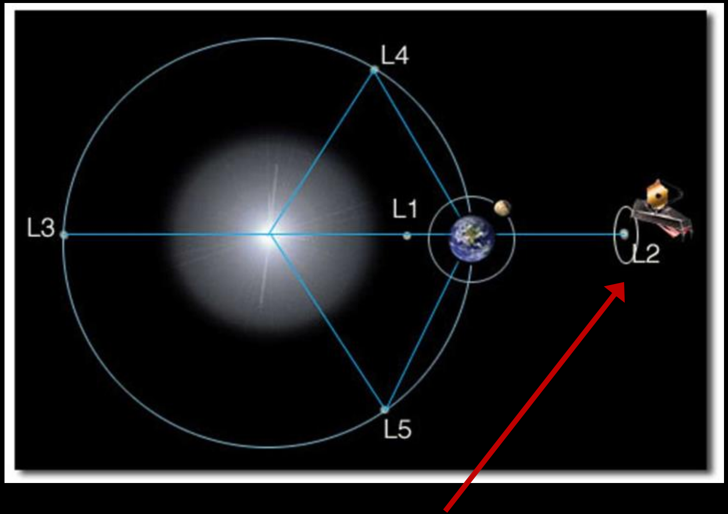
→

2024:

A new concept, derived from *SI* but intended for construction <u>on the lunar surface</u> and operated in conjunction with the human Artemis Program called *Artemis-enabled Stellar Imager* (AeSI)

Original SI Concept: 2005 Vision Mission (VM) Study





- A 0.5 km diameter UV-optical Interferometer near Sun-earth L2
- 30 primary mirrors, controlled by 1 hub; ***200x the angular resolution of HST***
- Significant Technology Challenges:
  - •Precision formation-flying of ~ 30 spacecraft & Precision metrology over multi-km baselines
  - •Autonomous Control of entire system & How do we test on ground before launch?

Learn more about Stellar Imager here: https://hires.gsfc.nasa.gov/si/

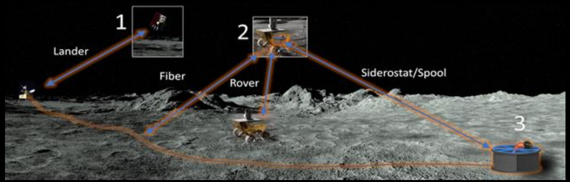
With the Artemis Project on track to put humans and their infrastructure on the Moon, **it is time to fully consider the lunar option!**

First Step: NASA Innovative Advanced Concepts (NIAC) Phase 1 Study

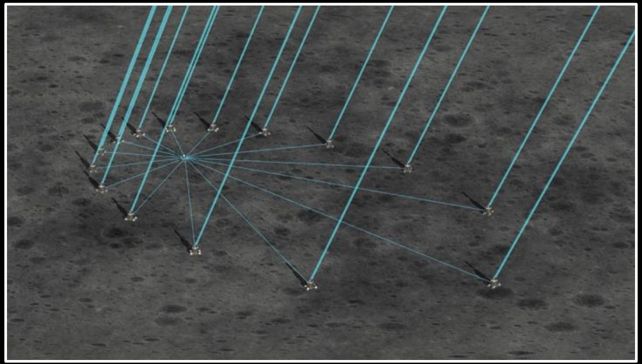
NASA Innovative Advanced Concepts

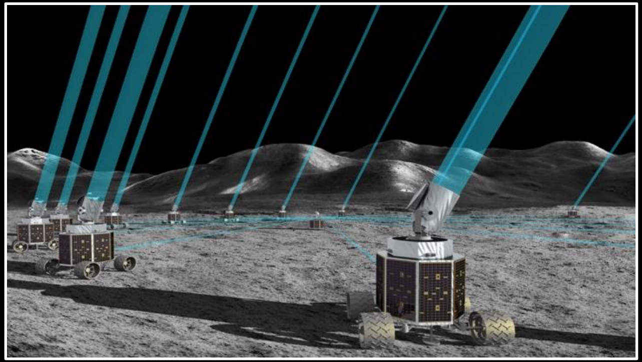
Our Proposed Approach

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

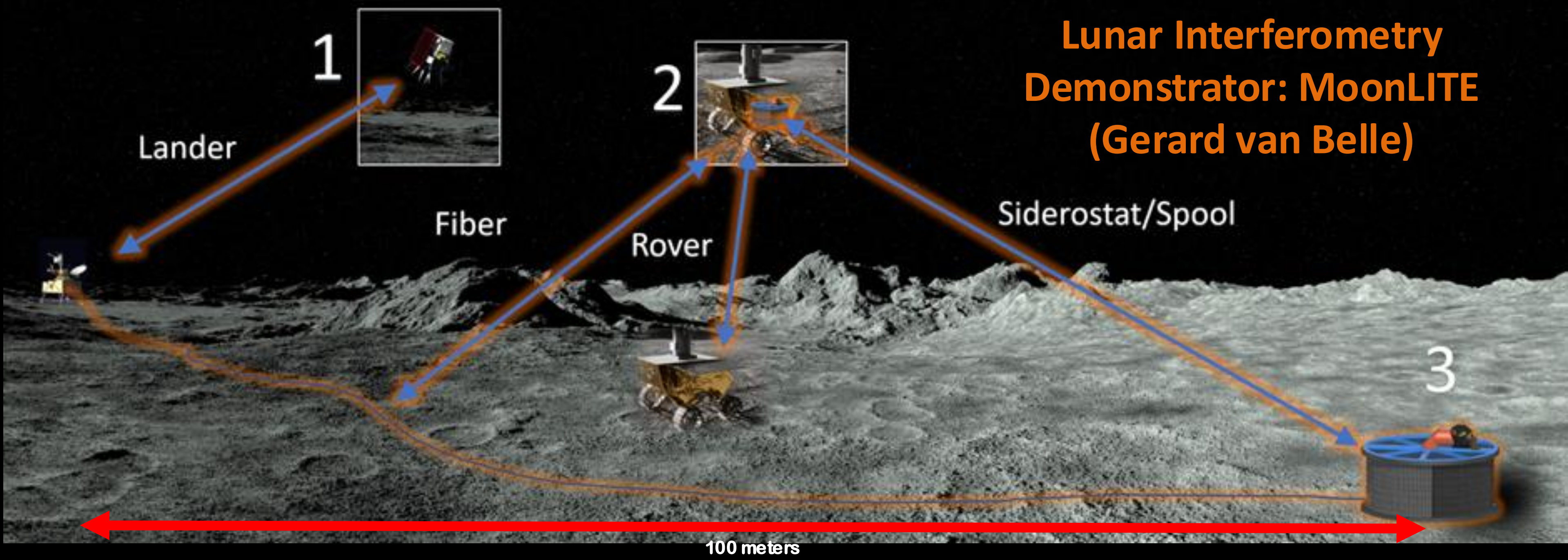


- In parallel, continue the development of a long baseline interferometer concept that will enable a quantum leap in our capabilities to observe the Universe in Ultra High Definition: Artemis-enabled Stellar Imager (AeSI).
    - Could be developed and deployed in multiple stages, building up gradually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





Lunar Interferometry Demonstrator: MoonLITE (Gerard van Belle)



- One deployment step for 2 × 50mm telescopes on a 100m baseline
- Simple system for sub-milliarcsecond size measurements of faint objects: beats world’s largest terrestrial interferometers by ~5 magnitudes

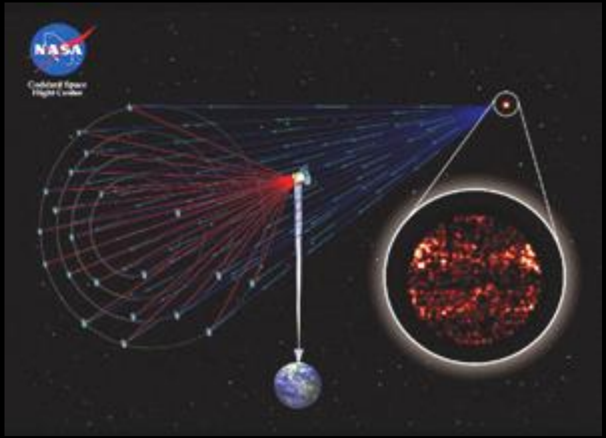
Pursuing the Grand Vision of Long-Baseline Arrays

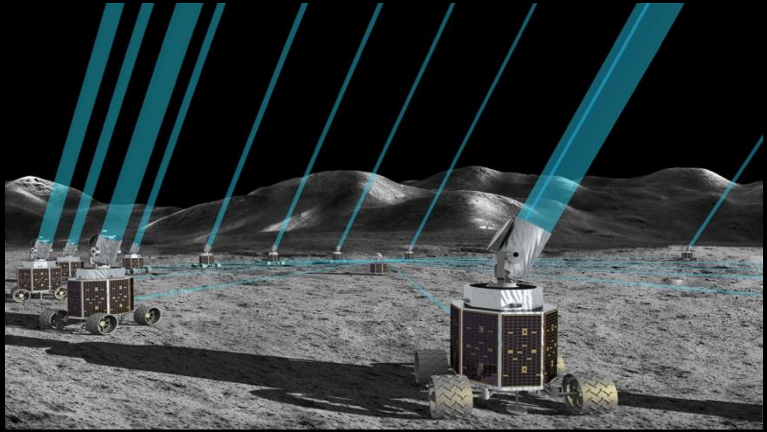
End Goal: Enable the study of our Universe at Ultra High Definition in the UV/Optical (~200x HST ang. res.).

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 Team

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

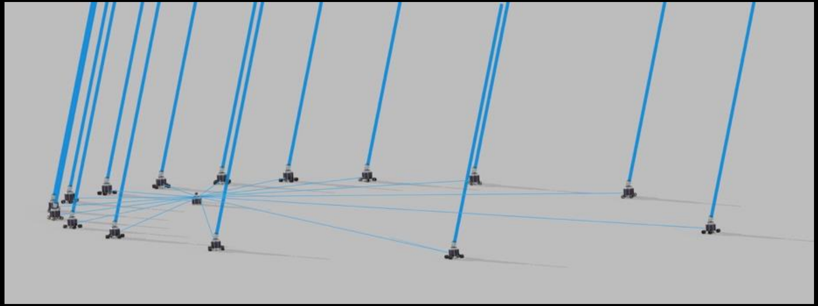
Ken Carpenter	NIAC Fellow, Mission Implementation Lead, IDC Coordinator
Tabetha Boyajian	Ground Interferometry Expert
Michelle Creech-Eakman	Ground Interferometry Expert
Margarita Karovska	Science Definition Co-Lead
David Leisawitz	Space Interferometry Expert
Jon Morse	Senior Advisor, Lunar Science & Infrastructure
Dave Mozurkewich	Lead System Engineer, Time Evolution of Observatory
Sarah Peacock	Science Definition, Study Co-Mgr, Outreach Co-Lead
Noah Petro	Artemis Expert
Gioia Rau	Science Definition Co-Lead, Study Co-Mgr., Outreach Co-Lead
Paul Scowen	Science Definition

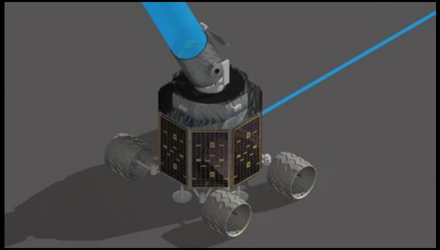
Breann Sitarski	Optical Engineer
Gerard van Belle	Interferometry Expert, Mission Design Lead
Jon Brashear	Grad. Student, Science/AI
Derek Buzasi	Astereoseismology
Jim Clark	Mechanical Engineer
Erik Wilkinson	System Engineer
Julianne Foster	System Engineer
Buddy Taylor	Mechanical Engineer
Walter Smith	Mechanical Engineer
Qian Gong	Optical Engineer
Bruce Dean	Optical Engineer/WS&C, AI/ML
Len Seals	Scattered Light/Optical Engineer
David Kim	Power Systems Engineer

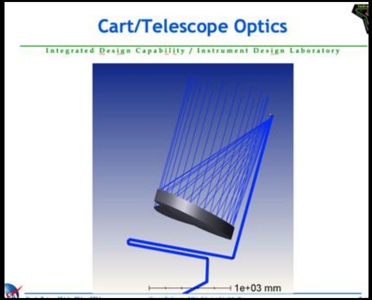
Baseline Design: GSFC Integrated Design Center (IDC)

Stage 1: 15 rovers, elliptical array to avoid long delay-lines. 1 km major-axis

Stage 2: 30 rovers, enhanced hub







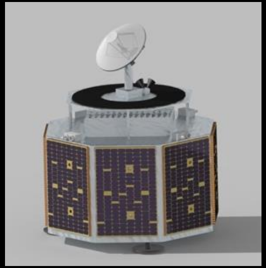
Mirror Station: artist's concept (B. Griswold) and internal optics (IDC/D. Mozurkewich)

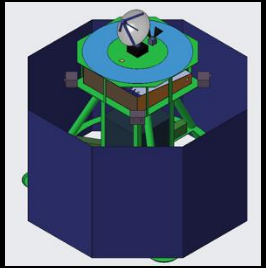
IDC: Engineering Study

- Systems
- Mechanical Design
- Optical Design
- Communications
- Thermal
- Power

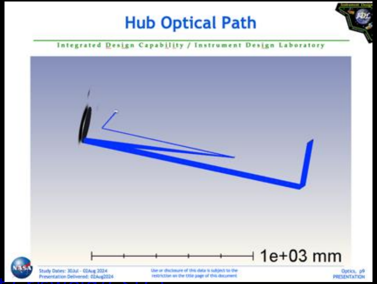
Conclusion: Feasible!!!

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



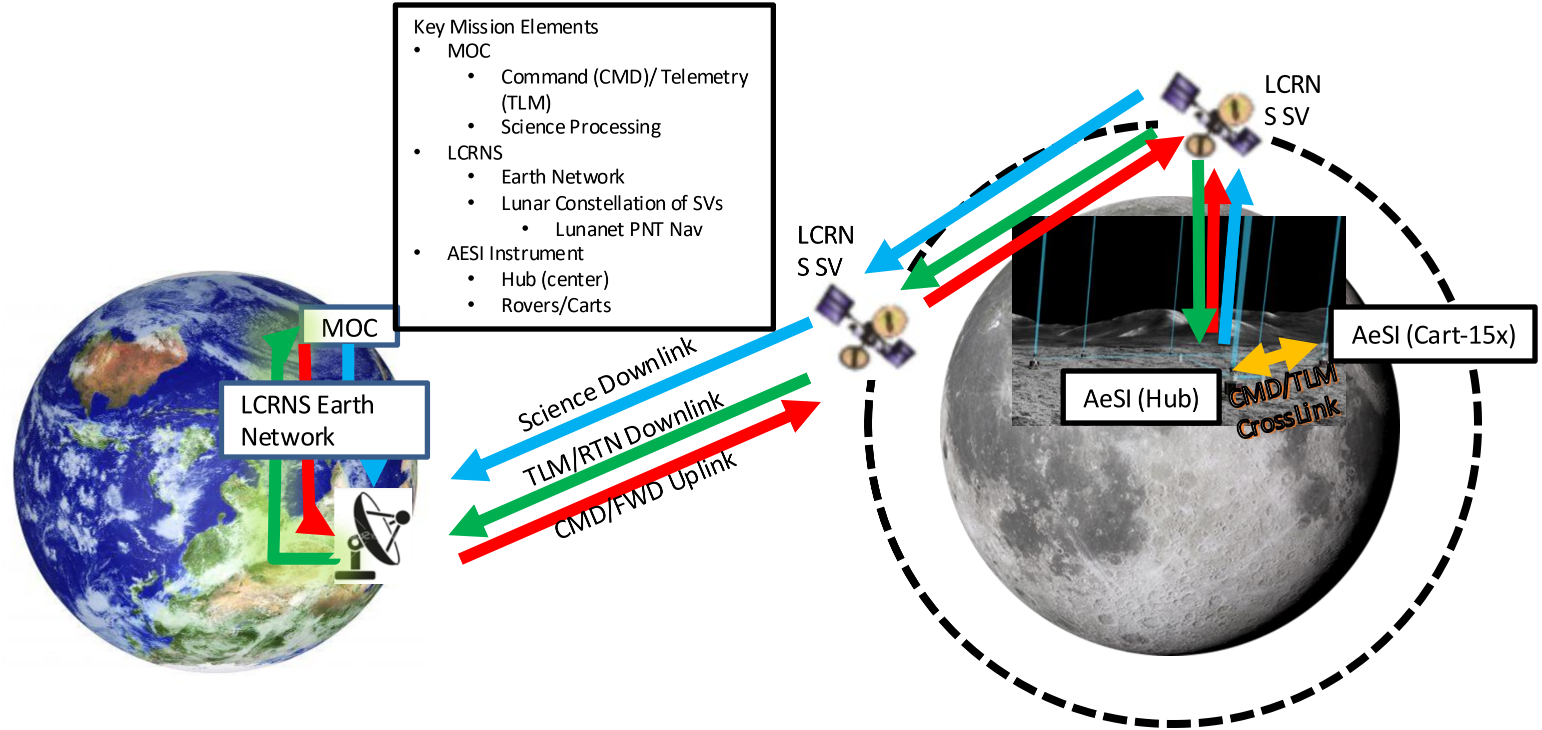


Hub: artist's concept (B. Griswold) and internal details/ optics (IDC & D. Mozurkewich)



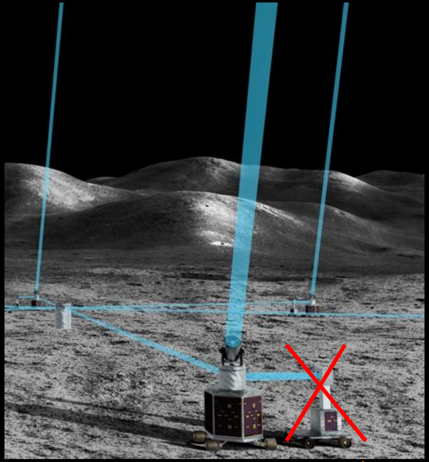
(Britt Griswold/GSFC)

Notional AeSI Mission Architecture (GSFC IDC)

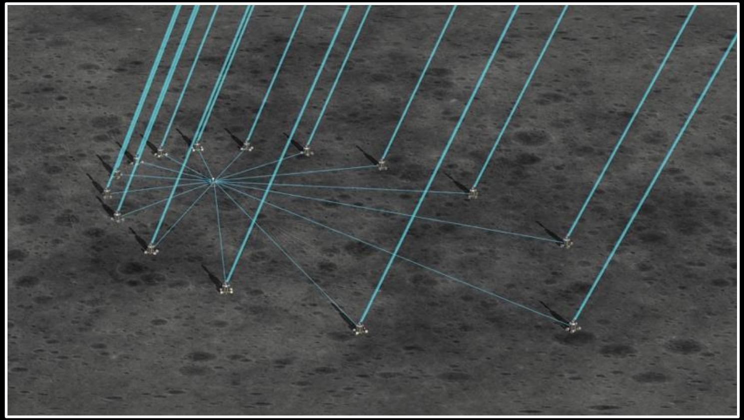


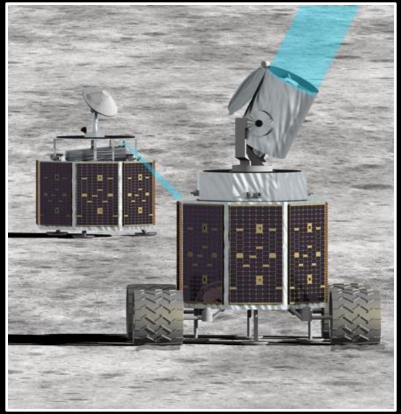
Biggest Improvements from Phase 1 Study

- 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



(Britt Griswold/GSFC)

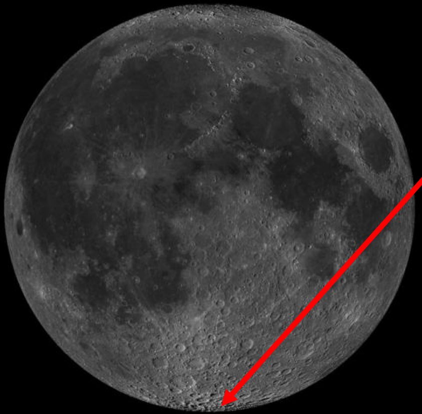




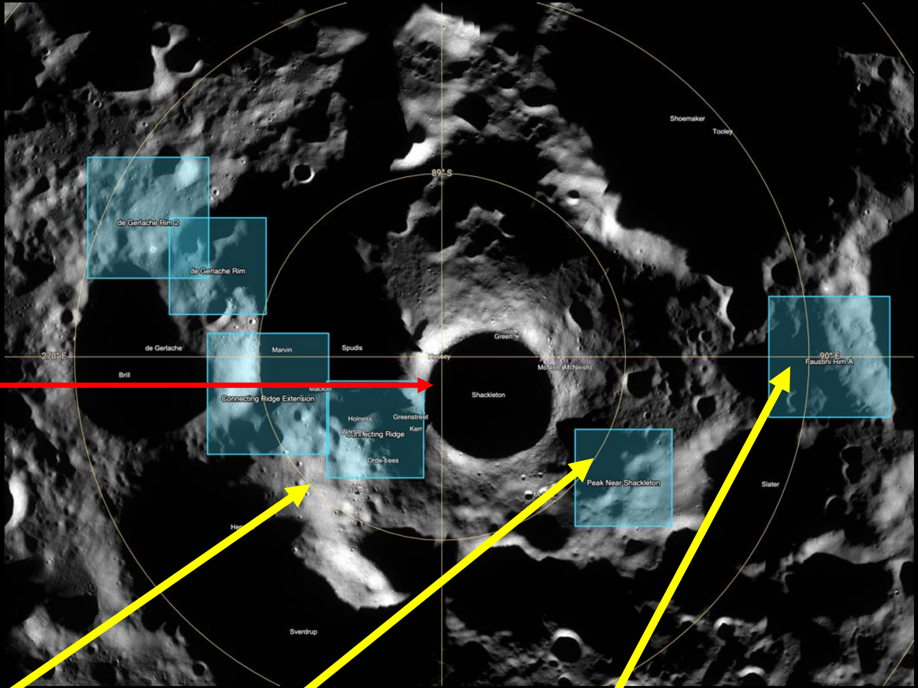
(Britt Griswold/GSFC)

- 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

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



Shackleton Crater
South Pole

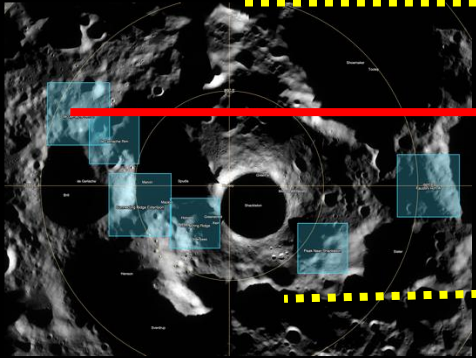


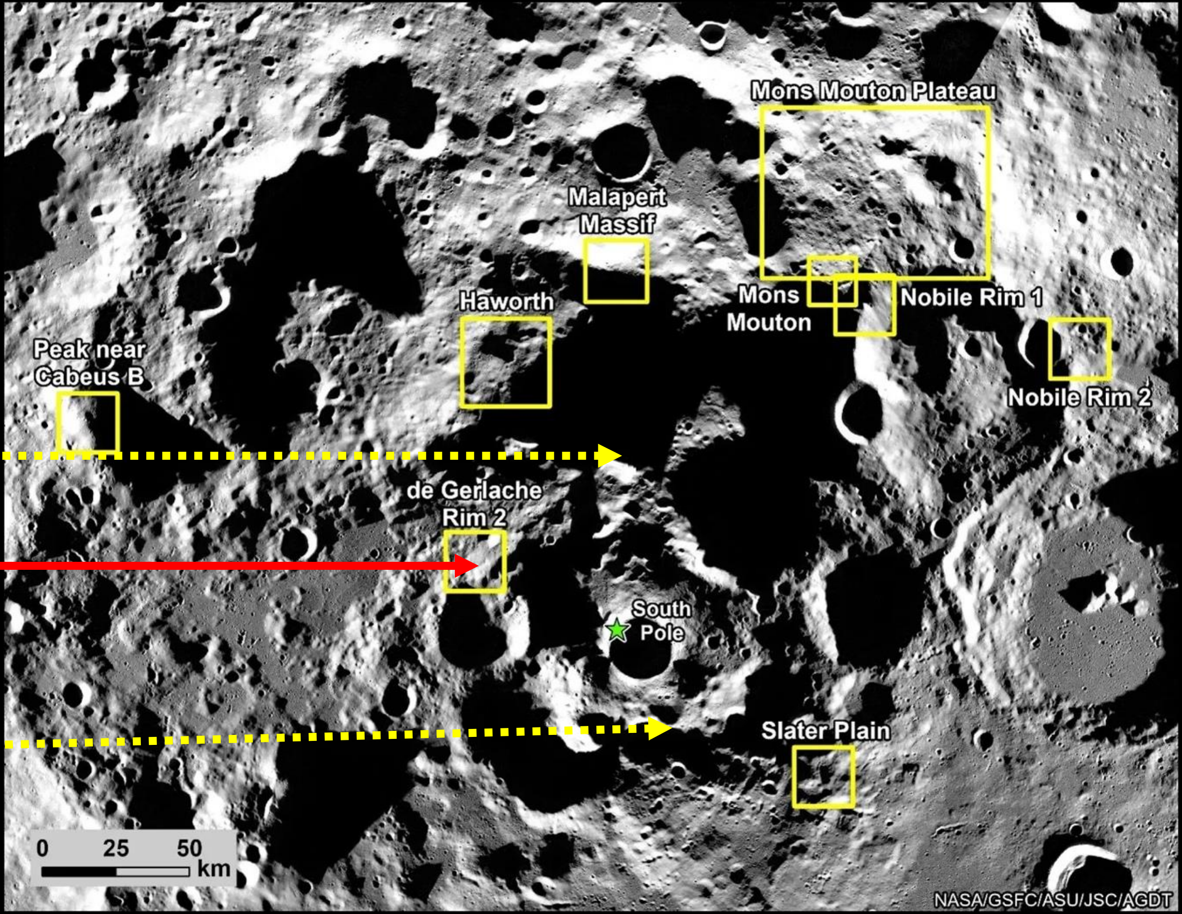
Candidate AeSI Sites near: Connecting Ridge, Peak Near Shackleton, and Faustini Rim A

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

“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)



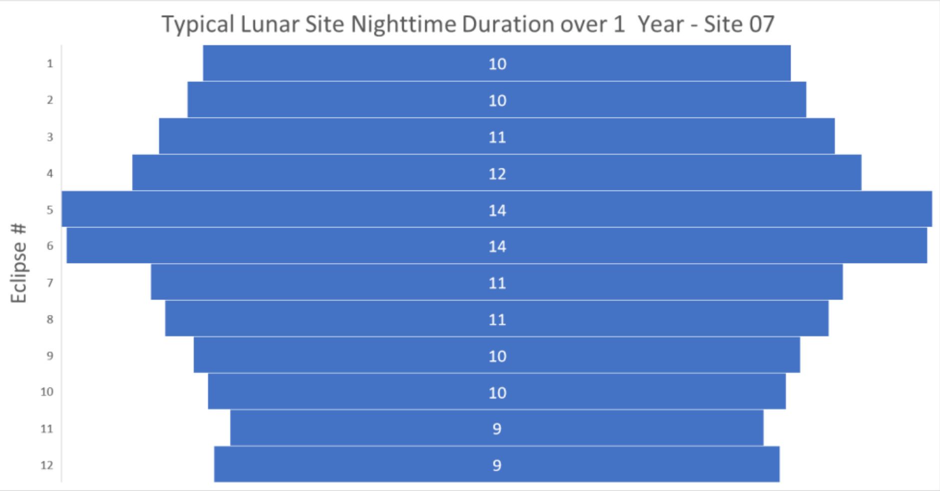


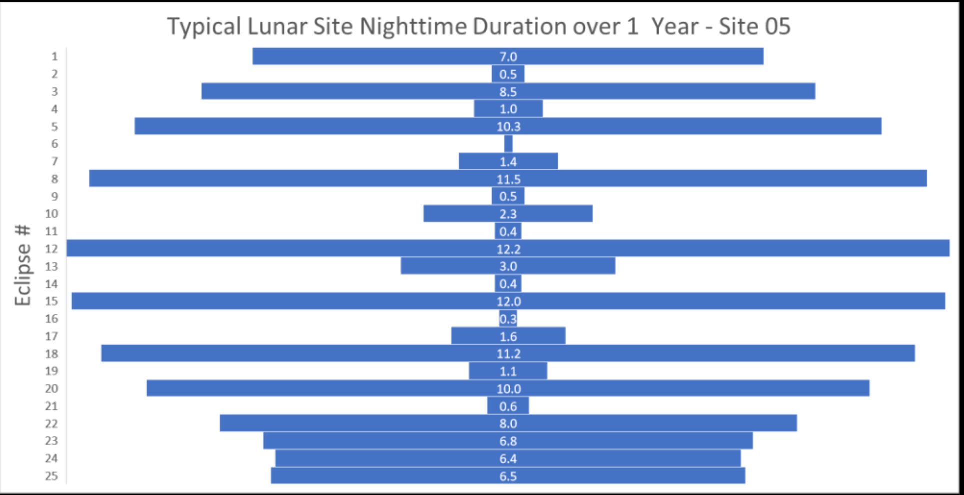
Solar Illumination Varies a *Lot* Near the Lunar South Pole!!!

- From 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)





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, astronaut support, and robotic support for deployment, servicing, and upgrade of the observatory.
  - Primary disadvantage is the much smaller # of targets visible at the high ecliptic latitudes visible from there

- A site at a lower lunar latitude would be of 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
  - Unless Artemis decides to establish bases at lower latitudes, this will limit availability of human (astronaut) support, but 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.

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 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 baseline 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 increasing 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 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.

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: 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

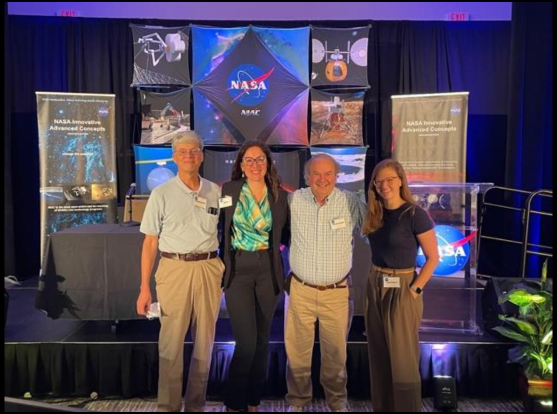
Challenges and Future Work

- Low UV-Sensitivity due to # of reflections in delay-lines 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, consider rails vs. rovers

- 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!

2024 NIAC Symposium: AeSI



2024 NIAC Symposium: Some Fun Moments

Surprise Panel! Rick Loverd (Dir, Sci & Info Exchange), Angela Harvey (Horror Writer), Jenny Lumet (SNW, ST Academy), Michelle Paradise (ST: Discovery)

A Tale of Two Brins –
An uplifting experience!

For Additional Information

- AeSI Homepage
  - https://hires.gsfc.nasa.gov/si/aesi.html

- Follow me on my personal Social Media accounts:
  - @kenastro (bsky.social)
  - @KenAstro1804 (IG)
  - @kencarpenter2504 (YouTube)
  - (though be warned you'll get a lot of Star Trek, Disney, and Renaissance Festival info & photos as well as NASA & Hubble!)