Artemis-enabled Stellar Imager (AeSI): Observing the Universe in High Definition

Dr. Kenneth G. Carpenter (NIAC Fellow; NASA/GSFC) and the AeSI Team*

kenneth.g.carpenter@nasa.gov | <https://hires.gsfc.nasa.gov/si/aesi.html>

Context/Background for AeSI

2005:
"Vision Mission" (VM) Concept for a free-flying, large baseline, UV-optical space interferometer called *Stellar Imager (SI)*

2024:
A new concept, derived from *SI* but intended for construction on the lunar surface and operated in conjunction with the human Artemis Program called *Artemis-enabled Stellar Imager* (AeSI)

What has changed in the last ~20 years? Why consider the lunar option now?

- The large "Vision Missions" (esp. interferometers) were mostly put on hold pending completion of JWST
- Per the Pierre Bely et al. study[1], it was perceived that **unless there was pre-existing infrastructure on the lunar surface,** it was easier and better to build a large space interferometer as a free-flyer. Therefore, the VM studies all considered free-flyers

[1] "Kilometric baseline space interferometry," Proc. SPIE 2807, Space Telescopes and Instruments IV, (12 October 1996); doi: 10.1117/12.255123

- With the Artemis project planning to put humans and their infrastructure on the Moon within the next decade, **now is the time to fully consider the lunar option!**

A New Hope for Space Interferometry

- The environment is changing with the Artemis Program and the aggressive push to establish a permanent human presence on the Moon. Building of the base is on track to begin within the next decade near the lunar south pole
- There is high interest in small science experiments that could take advantage of the infrastructure, and the scale of those opportunities will grow
- **Our NIAC study is investigating the possibility of constructing a large-baseline, UV/optical interferometer near this human base to leverage the Artemis infrastructure**

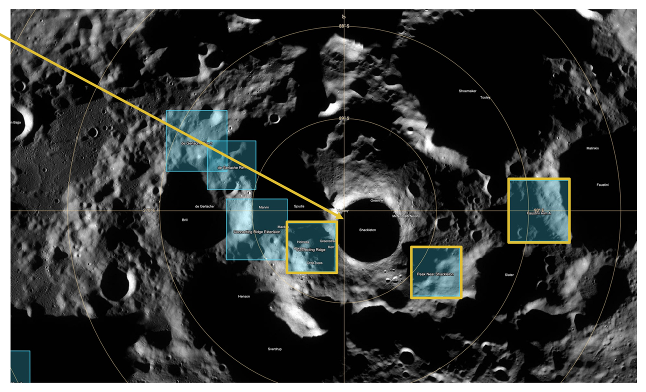

Fig. 1: *AeSI would be located adjacent to one of these potential locations for the permanent Artemis base (shaded in blue). For this study we considered: Connecting Ridge, Peak Near Shackleton, and Faustini Rim A (outlined in yellow).*

Heritage for AeSI: Stellar Imager (SI)

- UV-optical interferometer to provide 0.1 mas spectral imaging of numerous astronomical phenomena, esp. magnetic field structures that govern: formation of stars & planetary systems, habitability of planets, space weather, transport processes on many scales in Universe
- A "Flagship" (Vision) mission in the NASA 2005 SSSC Roadmap and a candidate "Pathways to Life Observatory" in the NASA 2005 EUD Roadmap
- Mission Concept
  - 20-30 "mirrorsats" formation-flying w/ beam combining hub
  - Launch to Sun-earth L_2
  - Mission duration ~10 yrs
  - Baselines ~ 100-1000 m

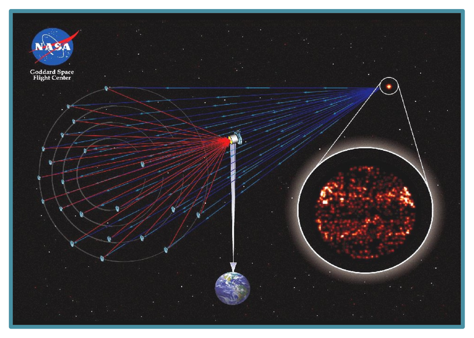

Fig. 2: http://hires.gsfc.nasa.gov/si/

Potential and Benefits

- **200x higher resolution than Hubble,** resolving stellar surfaces and inner regions of black hole environments
- **Perfect timing** to leverage planned Artemis human lunar infrastructure
- **Prospects superb:** ground-based optical interferometry works; forthcoming infrastructure makes lunar surface architecture both practical and compelling
- **Boldly expands realm of the possible:** many studies of free-flying space interferometers exist, but only limited studies of lunar designs (far-side radio)
- **The capabilities of *AeSI* are truly game-changing** *(Fig. 3)*, including resolving stellar surfaces and magnetic activity on nearby sun-like stars (~30 stars within 4 pc), convective cells on red supergiants out to 2 kpc, planet-forming regions, and the central regions of AGN

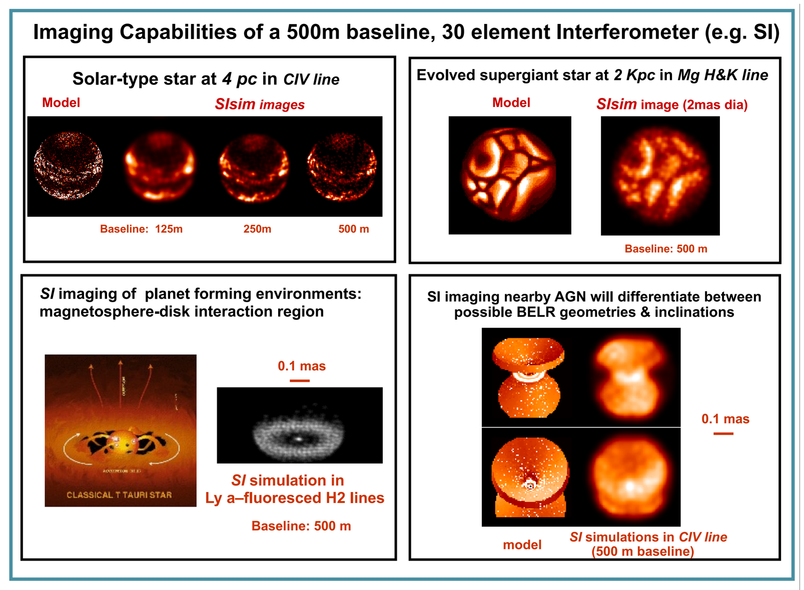

Fig. 3: *Simulations of what AeSI would image.*

Wide Range of Enabled Science:

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

Exoplanet Host Stars
transit light source effect, escaping atmospheres from gas giants, H II fluorescence in hot Jupiter atmospheres

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

Cool, Evolved Giant & Supergiant Stars
spatiotemporal 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; distances

Required Capabilities for UV/Optical Interferometer

- Wavelength coverage: 1200 – 6600 Å
- Access to UV emission lines from Lyα (1216 Å) to Mg II (2800 Å) for stellar surface imaging
  - important diagnostics of most abundant elements
  - much higher contrast between magnetic structures and background
  - smaller baselines (UV save 2-4x vs. optical, active regions 5x larger)
  - ~10-Å UV pass bands, e.g. C IV (100,000 K); Mg II h&k (10,000 K)
- Broadband, near-UV or optical (3,000-10,000 K) for high temporal resolution spatially-resolved asteroseismology to resolve internal structure
- Angular resolution of 50 μarcsec at 1200 Å (120 μas @2800 Å)
- ~1000 pixels of resolution over the surface of nearby dwarf stars
- Enable energy resolution/spectroscopy of detected structures
- Long-term (~ 10 year) mission to study stellar activity cycles:
  - individual telescopes/hubs can be refurbished or replaced

Innovations

- **Build:** 1 km baseline UV-Optical interferometer on the Moon
- **Novel technologies:** rovers to move primary mirror stations on lunar surface, hub to combine beams from stations in variable configurations, dust and scattered light control, technologies needed for long-baseline interferometers in space
- **Eliminates:** the need for precision formation flying
- **Science:** supports broad spectrum of science investigations
- **Timing:** can build as soon as infrastructure available on the Moon

Baseline Design

(Developed in collaboration with the GSFC Integrated Design Center)

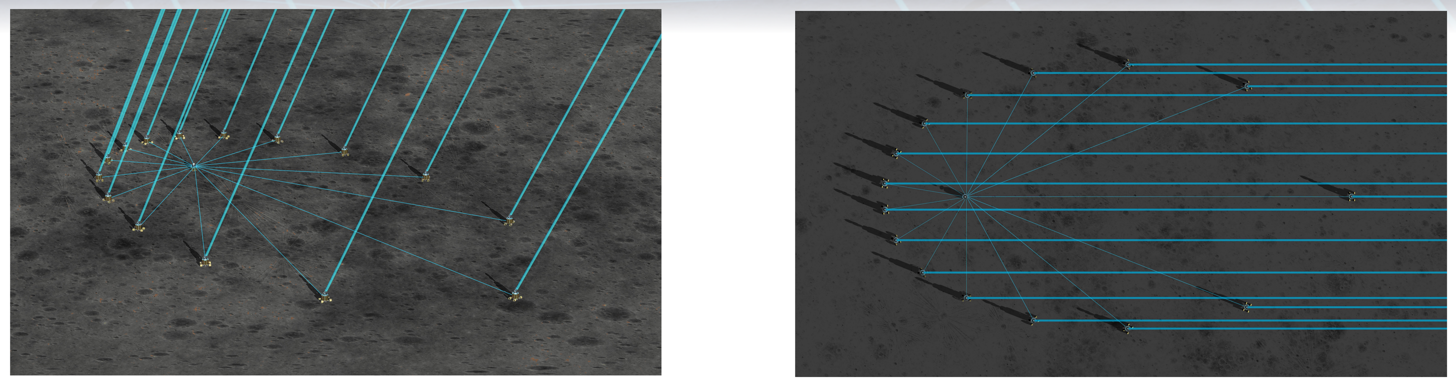

Fig. 4: *Hub and cart arrangement with the initial 15 rovers. When viewing a target off-zenith, the array elements will be distributed along an ellipse elongated in the direction of the target (max diameter = 1 km) (**left**: angled view, **right**: top-down view).*

- 1 km major-axis lunar-surface-based UV-optical Michelson interferometer, built and operated in conjunction with the human Artemis Program
- **Stage 1:** 15 primary, 1 meter mirror elements focusing on a beam-combining hub *(Fig. 4)*
  Stage 2: increase to 30 mirror elements and make enhancements to the hub
- Uses rovers in an elliptical array to provide path-length equalization without long delay-lines
- A long-term mission (>10 years) is required to study stellar activity cycles:
  - individual telescopes/hub can be refurbished or replaced by human or robotic servicing

Conclusion from IDC study: AeSI has been deemed feasible! Gained several recommendations that require further study and technology development

Rover/Primary Mirror Station Design

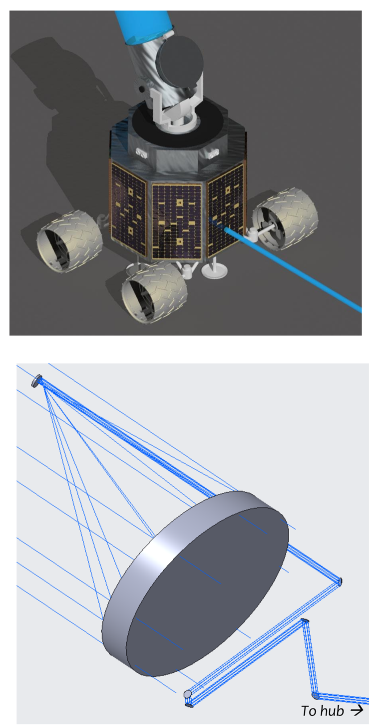

Fig. 5: **Top**: *Artist rendering of the 1-m primary mirror on a rover with standing legs deployed during observations.* **Bottom**: *Optical design for the rovers. The light beam extends out of the image to the central hub, following the paths shown in the bottom of Fig. 6.*

Hub Design

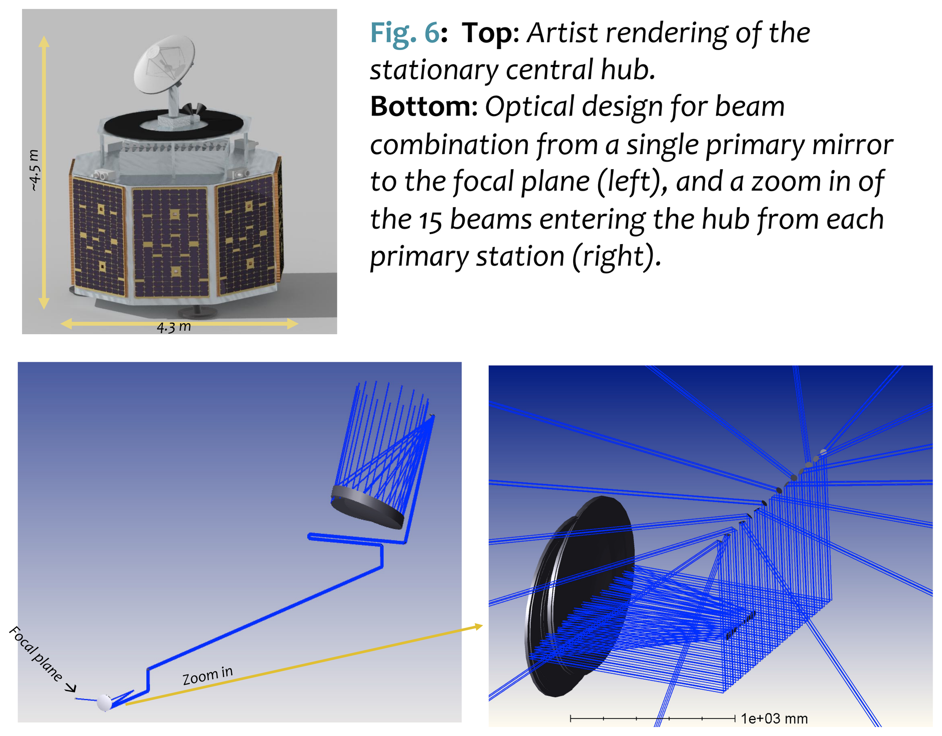

Fig. 6: **Top**: *Artist rendering of the stationary central hub.* **Bottom**: *Optical design for beam combination from a single primary mirror to the focal plane (left), and a zoom in of the 15 beams entering the hub from each primary station (right).*

Artist renderings by B. Griswold (NASA/GSFC), internal optics by the IDC & D. Mozurkewich

Preliminary Results

Major Improvements from the Initial Design

- Removed second 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 lines can be fit inside the primary mirror rover
- Increased size of primary mirrors to improve sensitivity (0.5 → 1 m)
- Increased baseline of initial array (0.5 → 1 km) to maintain resolution while going deeper into sky for more targets (driven by paucity of targets visible from lunar south pole)

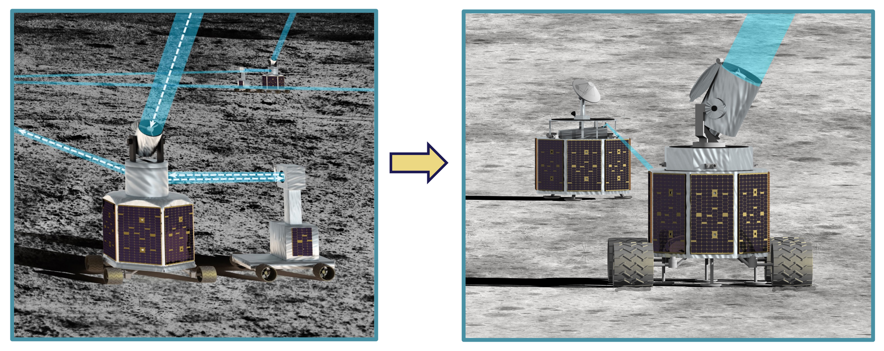

Fig. 7: **Left**: *Initial AeSI double-rover design.* **Right**: *New single-rover design with light path to hub shown.*

Challenges/Future Work

- Low UV sensitivity due to number of reflections in delay-line part of the system
- Surviving lunar night and enabling more continuous observations when the array is in shadow; future work includes investigating remote power station options such as: a solar array located on a nearby peak with more illumination, a nuclear power source located over a nearby hill, or having power supplied by Artemis infrastructure
- Refining support needed from Artemis infrastructure (humans and/or robots)
- Investigate possibility of putting primary mirror carts on rails

*AeSI Team

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

K. G. Carpenter (NASA/GSFC), Fellow
T. Boyajian (LSU)
J. Brashear (CUA)
D, Buzasi (FGCU)
J. Clark (NRL)
M. Creech-Eakman (NMT/MROI)
B. Dean (NASA/GSFC)
J. Foster (BAE Systems)
Q. Gong (NASA/GSFC)
M. Karovska (CfA)
D. Kim (NASA/GSFC)
D. Leisawitz (NASA/GSFC)
J. A. Morse (CalTech)
D. Mozurkewich (Seabrook Engineering)
S. Peacock (UMBC-NASA/GSFC)
N. Petro (NASA/GSFC)
G. Rau (CUA-NASA/GSFC)
P. Scowen (NASA/GSFC)
L. Seals (NASA/GSFC)
B. Sitarski (NASA/GSFC)
W. Smith (NASA/GSFC)
B. Taylor (NASA/GSFC)
G. Van Belle (Lowell Obs.)
E. Wilkinson (BAE Systems)

SCAN ME

NASA Innovative Advanced Concepts