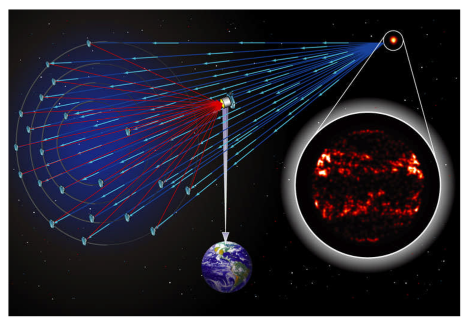
Steps Toward a UV/Optical Interferometer in Space: FIT, SIFFT, FFTB

Developing technologies needed to enable future large baseline, space-based interferometric and sparse aperture telescope missions.

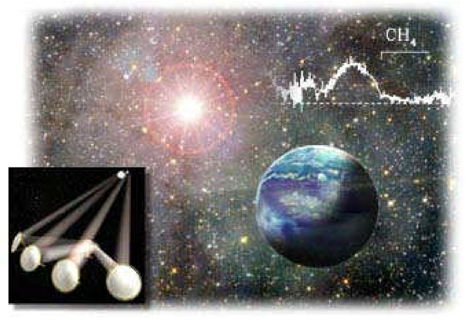
K. G. Carpenter, R.G. Lyon, A. Liu (NASA's GSFC),
E. Stoneking (NASA's GSFC),
P. Dogoda, P. Petrone (Sigma Sp.),
D. Mozurkewich (Seabrook Eng.),
D. Miller, S. Mohan (MIT), P. Stahl (NASA's MSFC)

Motivations/Drivers for the Development of these Technologies

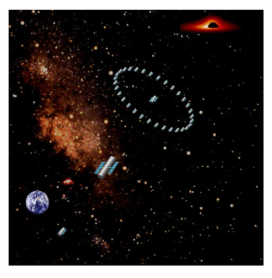
- Support the development of many future interferometric/sparse aperture missions being designed for ultra-high angular resolution observations of the Universe, including specifically the UV/Optical Interferometer Stellar Imager *(SI)*, but also the optical, x-ray, and IR missions such as: Life-Finder *(LF)*, Black Hole Imager *(BHI)*, and Planet Imager *(PI)*.



Stellar Imager (SI)
Stellar dynamos/magnetic activity
UV/Optical Interferometer



Life Finder (LF)
Searching for Signs of Life



Black Hole Imager (BHI/MAXIM)
X-ray Interferometer

Planet Imager
Terrestrial-Planet Imaging

Summary

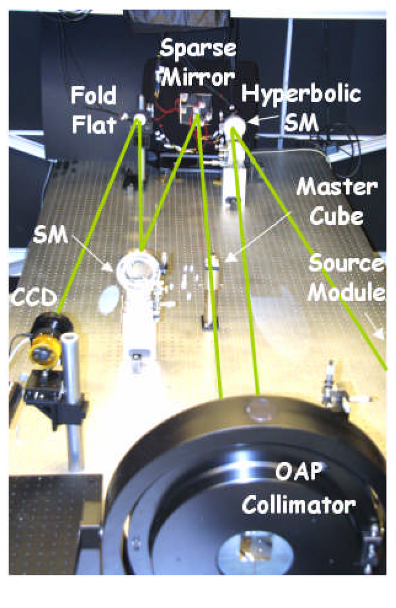
We summarize the goals and result-to-date of ROSES/APRA and GSFC-IRAD sponsored programs to develop two of the major technologies needed to enable the design and construction of future large baseline, space-based Interferometric and Sparse Aperture Telescope missions (e.g., Stellar Imager, Life Finder, Black Hole Imager, and Planet Imager). The Fizeau Interferometer Testbed (FIT) is being used to develop and demonstrate nm-level, closed-loop optical control of mirrors (i.e., control of tip, tilt, piston, translation of array elements) and the overall system to keep multiple beams in phase and optimize imaging of a Fizeau interferometric system and to assess various image reconstruction algorithms (phase diversity, clean, maximum entropy method, etc.) for utility and accuracy. The Synthetic Imaging Formation Flying Testbed (SIFFT) and the Formation Flying Testbed (FFTB) are, in parallel, being used to develop and demonstrate algorithms for autonomous cm/mm-level precision formation flying, which can be combined in the future with the higher precision optical control systems (e.g., those developed on the FIT) to fully enable synthetic aperture imaging systems. The ultimate goal of this research is the demonstration of closed-loop performance of a unified system which combines formation flying and nm-level optical control systems (based on analysis of the science data stream) to maintain phasing of a large array of space-borne mirrors, as needed for missions like those listed above, as well as smaller baseline Precursor missions that may pave the path to the larger strategic missions.

Goals

- Develop and demonstrate on the FIT nm-level optical control of a many-element sparse array
- Develop and demonstrate cm-level formation flying algorithms on actual hardware via SIFFT
- Develop and demonstrate (in a software simulator, the FFTB) the deployment of array spacecraft and the multi-stage acquisition of the target light from the individual mirrors by the beam combiner
- The Ultimate Goal: Develop and demonstrate Staged-Control Methodologies covering over 12 orders of magnitude (from nm to km scales)

The Fizeau Interferometer Testbed (FIT):
Development and demonstration of nm-level, closed-loop optical control of a many-element, sparse array

- FIT is a ground based testbed designed to
  - – explore principles of and requirements for Stellar Imager & other Fizeau Interferometer/Sparse Aperture Telescopes (e.g. MAXIM, LF, PI), enable their development, reduce technical and cost risks
  - – utilize 7-18 separate articulated apertures, with tip, tilt, and piston automatically controlled on each
  - – validate new and existing analytic and computational models to ensure realistic performance assessment of future flight designs
  - – demonstrate closed-loop control of system based on analysis of science data stream
  - – evaluate and demonstrate performance of new and existing image synthesis algorithms and successful image reconstruction from actual laboratory sparse aperture/interferometric data



- Recent Results, FIT:
  - – Phase retrieval code, in "C", has been developed for the wavefront sensing from the 7 apertures. Code solves for wavefront (WF) piston, tip & tilt over set of apertures.
  - – Direct Solve Phase Retrieval (DSPR) code has been developed which solves for piston, tip, tilt from a single in-focus white light image (Patent applied for).
  - – Sensitivity Matrix to convert the WF piston, tip and tilt to actuator voltages which drive mirrors has been computed.
  - – The control loop has been "closed" (in an autonomous sense) for two elements, work continues on 3-7 elements
  - – "coarse" acquisition (moving beams to center of detector from any position on detector) and "coarse-coarse" acquisition (finding beams even when they don't fall onto the detector to start with) are in development

Formation Flying Testbed (FFTB):
Development and demonstration of micrometer-level formation-flying algorithms in a software simulation environment:

All stages of formation acquisition have been successfully simulated, modeling the dynamics of the full Stellar Imager (SI) architecture (5-km focal length, 30 mirrorsats, one collector at Sun-Earth L2):

- **First stage: Radio Frequency Formation Acquisition.** Formation acquisition from an unknown initial state has been successfully demonstrated using only omni-directional radio frequency ranging sensors and an innovative algorithm for relative position determination.
- **Second stage: Laser Metrology Acquisition.** This control stage closes a control loop around laser ranging measurements to control relative hub-mirror range to the micrometer level, as well as transverse position control to the 10-cm level. This acquisition stage has been successfully demonstrated in simulation, including the effects of sensor noise and non-ideal thrusters.
- **Third Stage: Coarse Spot Acquisition**. Using sensors on entrance baffle plate of the hub spacecraft, the mirror spacecraft are controlled to steer target starlight into the baffle openings and onto the detector.
- **Fourth Stage: Fine Spot Acquisition**. Feeding back the spot location on the detector, both the hub and mirror spacecraft are controlled to steer target starlight spots to the center of the detector, completing the formation acquisition sequence.

Acknowledgements

We gratefully acknowledge support of these investigations from NASA via the ROSES/APRA and Small Business Investment Research (SBIR) programs and from the NASA/GSFC Internal Research & Development Program.

For more information on SI and the FIT:

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

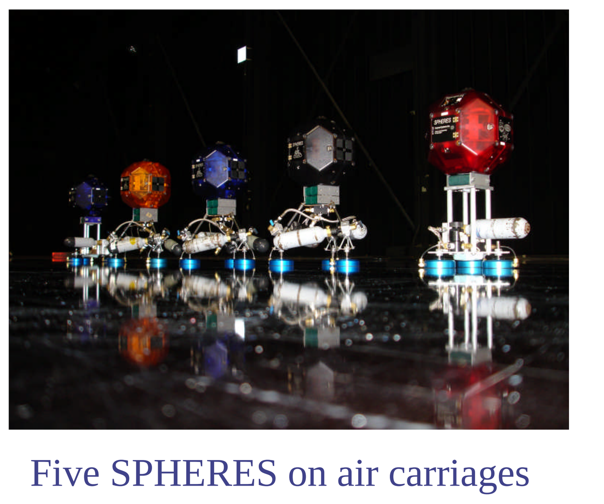
and for more information on SPHERES/SIFFT:

http://ssl.mit.edu/spheres/index.html

The Synthetic Imaging Formation Flying Testbed (SIFFT):
Development & demonstration of cm-level precision formation flying of multi-element arrays

- SIFFT is a ground based testbed designed to
  - – Enable, along with FIT, synergistic development of technologies needed to support space-borne synthetic aperture ultra-high resolution imaging
  - – Develop and demonstrate algorithms for autonomous precision formation flying which can, in the future, be combined with higher precision optical control systems
  - – Set requirements for future staged-control systems
  - – Be created at relatively low cost by utilizing equipment from existing MIT-developed SPHERES (**S**ynchronized **P**osition **H**old **E**ngage and **R**eorient **E**xperimental **S**atellites) experiment on the MSFC Flat Floor Facility
- Areas of investigation include:
  - – Formation Capture (deployment)
  - – Formation Maintenance
  - – Formation Reconfiguration
  - – Synthetic Imaging maneuvers (retargeting and reconfig.)

One SPHERES unit



Five SPHERES on air carriages on MSFC Flat Floor

- Recent Results, SIFFT:
  - – Goal: demonstration of formation control of 3 floating SPHERES satellites in an equilateral triangle and reconfiguration of the formation by rotating and expanding the formation. Achieved in multiple stages:
    - Formation control on 2 SPHERES one fixed
    - Formation control and reconfiguration with: a) 2 satellites,1 fixed, 1 floating, b) 3 satellites, 1 fixed, 2 floating, c) 3 satellites, 1 attitude hold only, 2 floating (position and attitude hold), d) 3 satellites, 1 attitude hold and angle rotation, 2 floating (position and attitude hold)
  - – These tests demonstrated centimeter level control of a formation, as well as attitude and position reconfiguration capability. The next major step will be to include a search algorithm such that the satellites are able to acquire each other from any orientation and relative position.