A Technology Whitepaper submitted to the 2010 Decadal Survey

Technology Development for Future Sparse Aperture Telescopes and Interferometers in Space

24 March 2009

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Abstract

We describe the major technology development efforts that need to occur throughout the 2010 decade in order to enable a wide variety of sparse aperture and interferometric missions in the following decade. These missions are critical to achieving the next major revolution in astronomical observations by dramatically increasing the achievable angular resolution by more than 2 orders of magnitude, over wavelengths stretching from the x-ray and ultraviolet into the infrared and sub-mm. These observations can only be provided by long-baseline interferometers or sparse aperture telescopes in space, since the aperture diameters required are in excess of 500m - a regime in which monolithic or segmented designs are not and will not be feasible - and since they require observations at wavelengths not accessible from the ground. The technology developments needed for these missions are challenging, but eminently feasible with a reasonable investment over the next decade to enable flight in the 2025+ timeframe. That investment would enable tremendous gains in our understanding of the structure of the Universe and of its individual components in ways both anticipated and unimaginable today.

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Introduction

The next major observational advances in astronomy will require quantum leaps in sensitivity (total collecting area) or in angular resolution (collector size/baselines). The former are being pursued with concepts such as the James Webb Space Telescope (JWST) and ATLAST, which use large segmented or filled apertures. The latter will be pursued with interferometric designs such as the EASI/Solar Viewing Interferometer (SVI), Space Interferometry Mission (SIM), Terrestrial Planet Finder-I (TPF-I), Stellar Imager (SI), Luciola (ESA concept), Life Finder (LF), Black Hole Imager (BHI), and Planet Imager (PI). SIM and TPF-I, if they fly, will primarily perform astrometry and low resolution imaging with modest baselines (~20 meters), while the true, high-resolution imagers SI, LF, BHI, and PI will require large baselines, from 0.5 to many kilometers. These future long-baseline observatories (i.e., space-based interferometers and sparse aperture telescopes) will achieve resolutions of 0.1 milli-arcsec (mas) or more, a gain in spatial resolution comparable to the leap from Galileo to HST. **As a result, spectral imaging observations from such facilities will enable major breakthroughs (see Table 1) in our understanding of the Universe – but *only* if investments in technology development are made in the current decade to enable the launch of such missions in the following decade(s).** In this whitepaper, we discuss, using the Stellar Imager (SI) as a prototypical example, the key technologies needed for these missions and outline a roadmap for developing the necessary technologies to enable this next generation of Great Observatories (see Fig. 1).

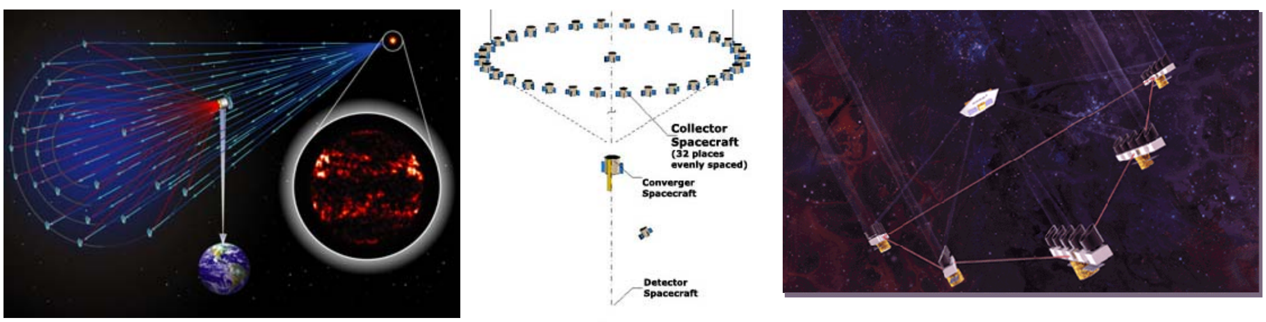


Figure 1: Examples of long-baseline, sparse aperture telescope/imaging interferometer concepts to perform ultra-high angular resolution imaging of the Universe. Left: the UV/Optical Stellar Imager (SI) which will image stellar surfaces & the central regions of AGN. Center: a Black Hole Imager (BHI) design to enable x-ray imaging of black hole event horizons. Right: the optical/IR Planet Imager (PI), whose goal is to image terrestrial-sized planets around other stars.

The basic mathematics and principles of operation of interferometers are well understood and their feasibility has been demonstrated by the wide variety of optical and IR interferometers successfully operating on the ground (e.g., CHARA, COAST, NPOI, and VLTI). *Space-based interferometers have additional advantages:* the light collectors can more readily be positioned to maximize sensitivity to a particular range of spatial structure (enabling observers to take advantage of prior knowledge of the spatial structure of the source), they do not suffer from atmospheric wavefront distortion, they can point toward the source, minimizing geometric optical delay, thus mitigating the need for long delay lines, and, finally, they can operate in wavelength regions not accessible from the ground. A good general review of long-baseline optical (and IR) interferometry is given by Shao and Colavita (1992), while Bely (1996) compares free-flyer and moon-based kilometric baseline space interferometers. The latter study concluded that a free-flyer system is the better option of the two for a space-based system in the near-to-intermediate future and that a moon-based system is not credible until a manned lunar infrastructure is available. Current news on optical long-baseline interferometry can be found at URL: http://olbin.jpl.nasa.gov/.

Table 1: Primary Science Enabled by Space-Based, Sparse Aperture Telescopes and Interferometers

Mission	Prime Science Goals
Terrestrial Planet Finder – Interf. (TPF-I) http://planetquest.jpl.nasa.gov/TPF-I/tpf-I_index.cfm	detect/characterize Earth-like planets
Stellar Imager (SI) http://hires.gsfc.nasa.gov/si/	Understand dynamos & stellar magnetic activity and impact on life; structure & evol. of AGN; structure & evol. of stellar systems
Sub-mm Probe of Evol. Cosmic Struc. (SPECS) http://arxiv.org/ftp/astro-ph/papers/0202/0202085.pdf	IR and sub-mm "deep fields" of distant Univ.
Life Finder (LF) http://planetquest.jpl.nasa.gov/science/finding_life.html	Search for & characterize signs of life on exo-planets
Black Hole Imager (BHI) http://blackholeimager.gsfc.nasa.gov	Image Black Hole Event Horizons
Planet Imager (PI)	Image Earth-like planets around other stars

In the following sections we discuss the major technology challenges to building a large, space-based imaging interferometer like *SI* , the current state of the art of that technology, and the work that needs to be done in the coming decade to enable flights of such mission in the decade of the 2020's and beyond.

Key Technology Needs

The technologies to be discussed are needed to enable numerous missions being considered by NASA for flight, including the Great Observatory (GO) class missions named above, as well as smaller precursor missions using one or more of the technologies, such as the Fourier Kelvin Stellar Interferometer (FKSI), a space interferometry Pathfinder mission, selected Exo-Planet Probes, and ESA's Pegase. The major technology challenges (and approximate Technology Readiness Levels) to building SI and similar missions are:

- **formation-flying of numerous (>10) spacecraft (3-4)**
  - deployment and initial positioning of elements in large formations
  - real-time correction and control of formation elements
    - staged-control system (km → cm → nm)
  - aspect sensing and control to 10's of micro-arcsec
  - positioning mirror surfaces to 5 nm
  - variable, non-condensing, continuous micro-Newton thrusters
- **precision metrology over multi-km baselines (3)**
  - 2-nm level if used alone for path-length control (no wavefront sensing)
  - 0.5 microns if hand-off to wavefront sensing & control for nm-level positioning
  - multiple modes to cover wide dynamic range
- **wavefront sensing and real-time, autonomous analysis and optical control (4)**
- **methodologies for ground-based validation of large baseline, many-element distributed systems (2)**

- **additional challenges (perceived as "easier" than the above)**
  - light-weight (UV-quality for SI) mirrors with km-long radii of curvature, perhaps using active deformation of flats (3)
  - mass-production of "mirrorsat" spacecraft: cost-effective, high-volume fabrication, integration, & test (4)
  - long mission lifetime requirement

Precision formation flying techniques must accommodate the deployment and initial positioning of elements in large formations and the real-time correction and control of those elements at the cm-to-mm level, coordinated with the positioning of mirror surfaces on those spacecraft (for UV observations) to the 5nm level, which requires an overall staged-control system that works all the way from km → cm → nm scales. This will be done via autonomous staged-control systems which combine precision formation flying of spacecraft (the "mirrorsats" and the beam-combiner spacecraft) with precision active optical control of the mirror surfaces (i.e., their tip, tilt, piston, and translation). Metrology good to the 2-nm level must be enabled, if it is used alone for path-length control, but that requirement can be relaxed to 0.5 microns if the system hands-off to a wavefront sensing & control system for the nm-level positioning. To sense the aspect (pointing direction of the array) without wavefront sensing, we can use linear measurements from the hub spacecraft of 6 pm accuracy. Individual spacecraft pointing is at the arcsec level, with mirror surfaces controlled separately, to 1.5 mas. Finally, a problem that all large, distributed spacecraft systems must face, is how to perform final integration and test of a system whose components in actual operation may be kilometers apart.

Technology Development Roadmap

A logical flow for the development of these and other needed technologies is shown in Figure 2.

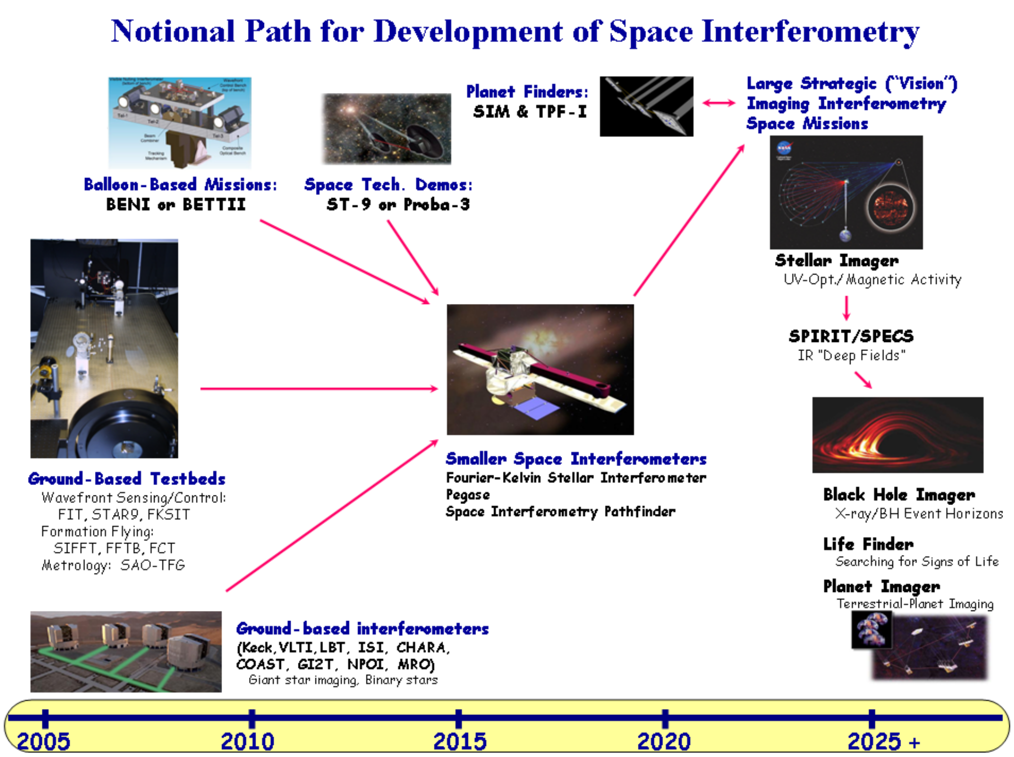


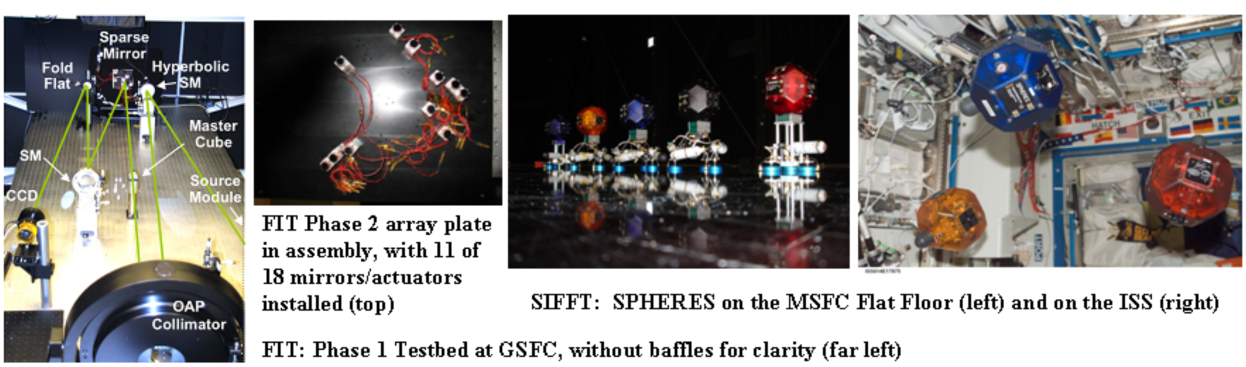
Figure 2: A logical development flow for Space Interferometry

As an example, the successful design and construction of SI will rely on the development and validation of a number of critical technologies highlighted in the preceding section. These include, e.g., precision formation flying (see Allen (2007) for a discussion of the station-keeping requirements), coarse ranging and array alignment, high-precision metrology, on-board autonomous computing and control systems, and closed-loop optical control to maintain array alignment based on the science data, along with a host of additional, somewhat easier challenges. A high-level technology roadmap for these is given in Table 2.

Table 2: Technology Roadmap for Space Interferometers

Technology Needed by SI	Current TRL	Development Plan and/or Candidate Technologies	Readiness Date
Most Significant Challenges			
Precision Formation Flying of large arrays	3-4	SIFFT/SPHERES & GSFC Distributed Space Systems Roadmap, Pathfinder (2015)	2014 Pathfinders 2018 Full GO's
Wavefront Sensing & Control and Closed-Loop optical path control of many-element sparse arrays	4	Fizeau Interferometry Testbed (FIT), Pathfinder (2015)	2013
Methodologies/control processes for ground-based I&T of distributed systems	2	GSFC Distributed Space Systems Roadmap (Figure 3.20 in full SI Report), Pathfinder	2016
Easier Challenges			
Aspect Control to 10's of μarcsecs	3	Trade external metrology vs. wavefront sen.	2018
Precision Metrology over long baselines	3	JPL & SAO metrology labs	2014
Mass-production of spacecraft (e.g., SI "mirrorsats")	4	TBD (but see BATC approach in section 3.18 of full SI Vision Mission Report)	2015
Lightweight, UV-quality mirrors with km-long radii of curvature	3	Chen et al. (2003)	2015
Methodologies for combining 20-30 simultaneous beams	4	Ground-based interferometers, FIT	2012
Variable, non-condensing μN thrusters	4	FEEPs, etc.	2013

The major challenges on this technology development list are being attacked via a number of ground-based testbeds (Carpenter 2006a; also see Fig. 3) to develop and assess precision (to the cm level) formation flying algorithms and closed-loop optical control of tip, tilt, and piston of the individual mirrors in a sparse array, based on feedback from wavefront analysis of the science data stream. The GSFC Fizeau Interferometer Testbed (FIT) is developing closed-loop optical control of a many-element sparse array (7 elements in Phase 1, 18 elements in Phase 2), as well as assessing and refining technical requirements on hardware, control, and imaging algorithms.



FIT Phase 2 array plate in assembly, with 11 of 18 mirrors/actuators installed (top)

SIFFT: SPHERES on the MSFC Flat Floor (left) and on the ISS (right)

FIT: Phase 1 Testbed at GSFC, without baffles for clarity (far left)

Figure 3: The FIT and SIFFT hardware at GSFC, MSFC, and on the ISS.

GSFC, MIT, and MSFC are collaborating on an experiment, the Synthetic Imaging Formation Flying Testbed (SIFFT), utilizing the MIT SPHERES hardware on the MSFC Flat Floor facility and inside ISS to test cm-level formation flying algorithms. The GSFC Formation Flying Testbed (FFTB) is a software simulation facility that has been used to develop deployment of array spacecraft and the multi-stage acquisition of target light from the individual mirrors by the beam-combiner. The Wavefront Control Testbed (WCT) is being used to study image-based optical control methods for JWST, while the Wide-Field Imaging Interferometry Testbed (WIIT) is studying extending the field of view of Michelson imaging interferometers. Metrology Testbeds are in operation at SAO (Phillips & Reasenberg, 2005), JPL (Lay, 2003), and GSFC (Camp, 2005) and the SIM project has made tremendous progress in this arena as well. Figure 2 shows a graphical representation of flow of technology development and mission capabilities for space-based interferometric facilities, from ground-based testbeds and operational interferometers to space missions that will logically precede and follow SI. Although this set of experiments is making steady progress on the technology development, almost all are operating on very small budgets which are uncertain from year to year and overall progress is slow. **It is critical that the Decadal Survey recognize that the support for these efforts must be both more substantial and longer term if the technologies are to be available and ready for flight in the decade of the 2020's.**

One of the more interesting technology options that is being pursued is an investigation of how much of the measurement and control job (of the various spacecraft and mirror surfaces in the distributed system) can be done purely by "external" (to the science data stream) metrology using, for example, lasers and at what point, and if, it will be necessary to handoff the measurement and control job to a system based on feedback from analysis of the science data stream. The "baseline" SI mission concept in fact assumes that the external metrology system has measurement and command authority down to the millimeter or, if possible, the micron level and that a "closed-loop" optical control system, based on phase diversity analysis of the science data stream, takes over at smaller scales to obtain control down to the nanometer level. The exact point at which that handoff occurs in the multi-stage control system is one of the interesting points still to be resolved. The SI technology development plan is based on pushing both technologies to their limits, i.e., driving the external metrology to the smallest attainable scales (effectively testing in the process if we can do the "entire job" this way) and driving the development of the wavefront sensing & control to the largest possible scales, until we can show that the two systems will in the end have a significant region of overlap in their control authority.

The results from these testbeds and various mission studies will be combined with experience from ground-based interferometers (see Table 3) to enable one or more small, space-based Interferometry Pathfinder mission(s), which will use a small number of elements (3-5) with smaller baselines (20-50m) and frequent array reconfigurations (to fill in the Fourier uv-plane and enable high quality imaging) to both accomplish important new science and demonstrate in space the technologies needed for the full-up Strategic Missions. Such a Pathfinder mission could perhaps be flown as part of an Origins Probe program and launched in the coming decade. One or more such Pathfinder missions are possible, including UV/Optical, IR, and/or X-ray Pathfinder(s) These Probes would lay the ground-work for the long-baseline, Strategic Missions that will do true high angular resolution interferometric imaging, including SI, BHI, SPECS, LF, and PI.

Table 3: Technologies of Ground-based Observatories paving the way for space interferometers

Mission	Description	Enabled Technologies
COAST	Optical Michelson interferometry; baselines up to 100m to give images with a resolution down to 1 milliarcsecond	high resolution imaging, multiple-beam combination
NPOI	Optical interfermeter with imaging subarray baseline lengths from 2.0 to 437 m; laser metrology system from 19 m to 38 m; best angular resolution of the imaging subarray is 200 microarcsec	fast delay lines; close phase demonstration; visible light beam combination; synthesis imaging
CHARA	Optical/IR interferometer; 200 micro-arcsecond resolution; maximum baseline of 330 meters	visible light synthesis imaging; optical path length equalization
KI	Optical/IR interferometer, expanding from 2 to 6 elements; narrow-angle differential astrometry with a precision of 30 microarcseconds	metrology systems, control systems; path length equalization
MROI	Optical/IR 10-element interferometer; first science operations in 2011	aperture synthesis imaging with many elements; closest to SI in concept of any ground facility
VLTI	IR 7-element interferometer; maximum baseline of large unit telescopes is 130m, and 200m for auxiliary telescopes; best resolution for large telescopes is 1.5 milliarcsec and 1 milliarcsec for aux telescopes	high resolution imaging
LBT	IR 2-element interferometer; 2 8-m primaries, each F/1.142; 22.8 m baseline	full coverage of Fourier UV-plane

The Technology "Tall Poles" – Recommendations for Investment in the coming decade

We have identified four items as representing the "tall poles" in the technology development plan for space-based sparse aperture telescopes and interferometers: Precision Formation Flying (PFF), Closed-Loop nm-Level Optical Path-length Control (many-element sparse array phasing) via Wavefront Sensing, Precision Metrology over km-long baselines, and the Integration & Testing of long-baseline, distributed spacecraft observatories. These are the areas within which we believe significant investments must be made in the coming deacade to enable the missions discussed above in the following decade(s). We discuss each of these in a bit more detail below.

Precision Formation Flying (PFF)

PFF system technology is critical for a broad range of future NASA Space Science missions, including the Terrestrial Planet Finder-Interferometer (TPF-I), the Black Hole Imager (BHI), the Submillimeter Probe of the Evolution of the Cosmic Structure (SPECS), Life Finder (LF), and Planet Imager (PI), to name a few. Furthermore, the technology development occurring for other formation flying and distributed spacecraft missions, including Magnetospheric Multi-Scale and the Laser Interferometer Space Antenna, feeds into the interferometry technology roadmap as well. A high-level view of how the some of the technologies from these missions and science areas feed into the SI development process, as well as a collection of requirements, are shown in Figures 4-5.

Under the context of the New Millennium Program ST-9, the formation flying community was brought together to identify the critical capability requirements for *precision formation flying* for the Science Mission Directorate. Figure 4 shows the roadmap developed by a cross-cutting team consisting of GSFC, JPL, AFRL, NRL, industry, and academia, to represent the progression of capabilities needed vs. rolled up formation flying capability (expressed in terms of formation control precision requirements). "Relative navigation" requirements in this table include the "end-to-end" requirements all the way down to the measurement of the mirror surfaces, i.e., not just of the gross spacecraft

	2012	2019	2022	2024	2028
Science	Magnetospheric	Planet detection and identification	Black Hole Imaging	Asteroseismology	Imaging Planets
Formation Characteristics with Representative Mission Concepts	Loose formations (MMS)	Sub-micron relative position estimation; cm s/c position control, 5 s/c (TPI)	Micron Relative Navigation; micron s/c position control; 25 s/c (MAXIM)	Nanometer relative navigation; Nanometer control; 30 s/c (Stellar Imager)	< Nanometer relative navigation; Nanometer control; 30+ s/c (PI, LF)

Figure 4: Science Capability/Formation Flying Capability Progression

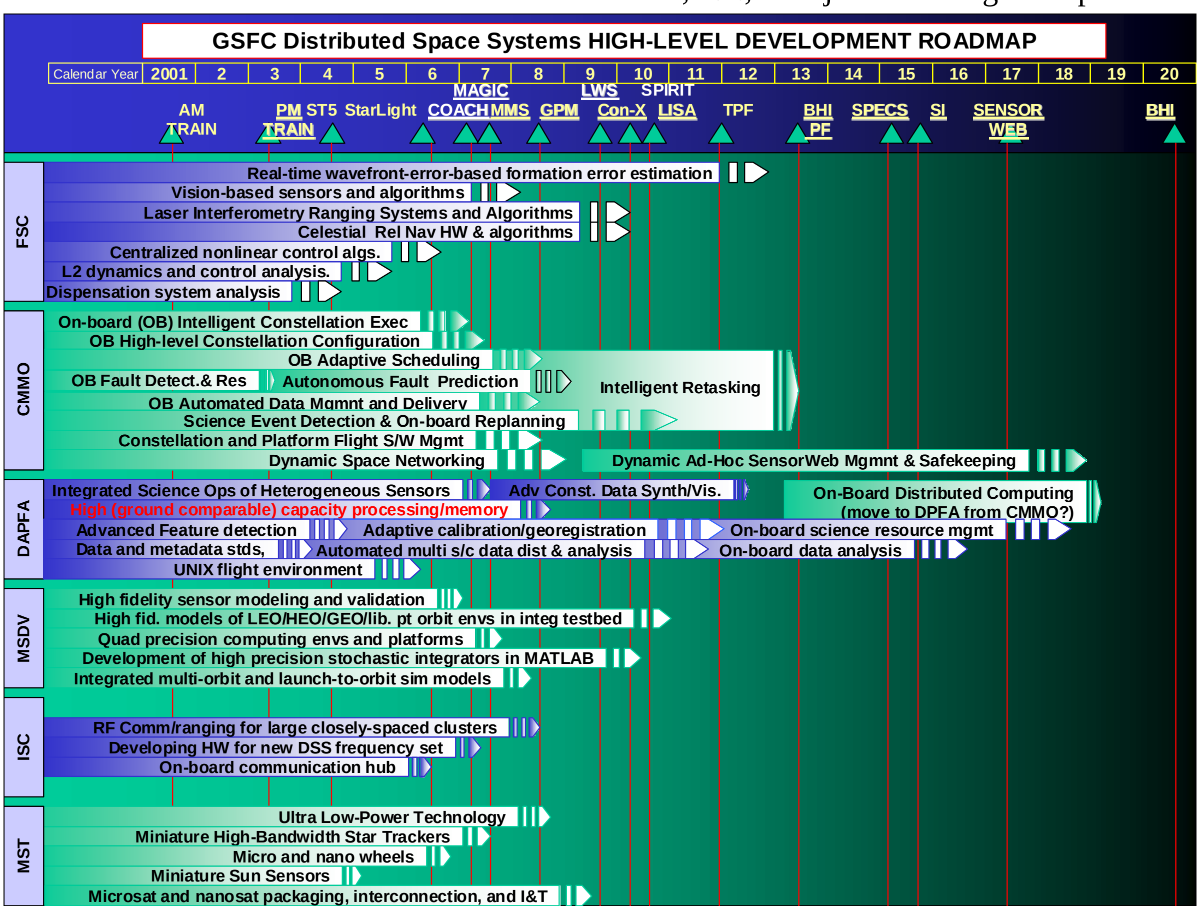


Figure 5: Formation Flying Technology Development Roadmap

positions. Some of the associated relative control requirements may therefore be accommodated through the motion of actuated mirrors and not solely by spacecraft maneuvers. An overall Formation Flying Technology Development Roadmap is shown in Figure 5.

Closed-Loop nm-Level Optical Path-length Control via Wavefront Sensing

In any many-element sparse-aperture telescope or Fizeau interferometer, the most critical concern is how to get the light beams from the various mirror elements into phase and how to maintain that alignment over time. At the highest level, this requires that the optical path lengths from the celestial target to each mirror and onward (perhaps, but not necessarily, via numerous intervening reflections) to the final detector be identical to within about 1/10 of a wavelength. In the case of SI, the most stringent requirement is from the shortest wavelength of the planned observational capability, i.e., the wavelength of the CIV doublet at 150 nm, which produces a requirement that the optical paths be held identical to within about 5 nm. It is unclear at this time whether external (to the science data path) metrology and control systems will be able, in the time frame under consideration, to attain this precision by themselves. It is therefore necessary and prudent to pursue alternatives for the finest level of control (down to the nm level). The best candidate for such an alternative requires the use of the actual science data itself (or light that is somehow sent through the same optical paths). Preliminary studies of SI concepts have envisioned a hand-off from the external (perhaps based on laser ranging) metrology systems to systems based on analysis of the actual science data stream to get from the cm/mm to the nm level of control.

Optical image-analysis methods, such as phase diversity (Lyon et al. 2004a, 2004b), exist that theoretically are capable of determining the errors in the locations and attitude of the mirror array elements from numerical analysis of the distorted image created by the combined beams. The output from such an analysis can then be used to correct the positions (tip, tilt, and piston) of the individual mirrors to improve and maintain the image quality. It is important to demonstrate that these theoretical capabilities will work in the real world since they are critical to the eventual success of sparse-aperture systems.

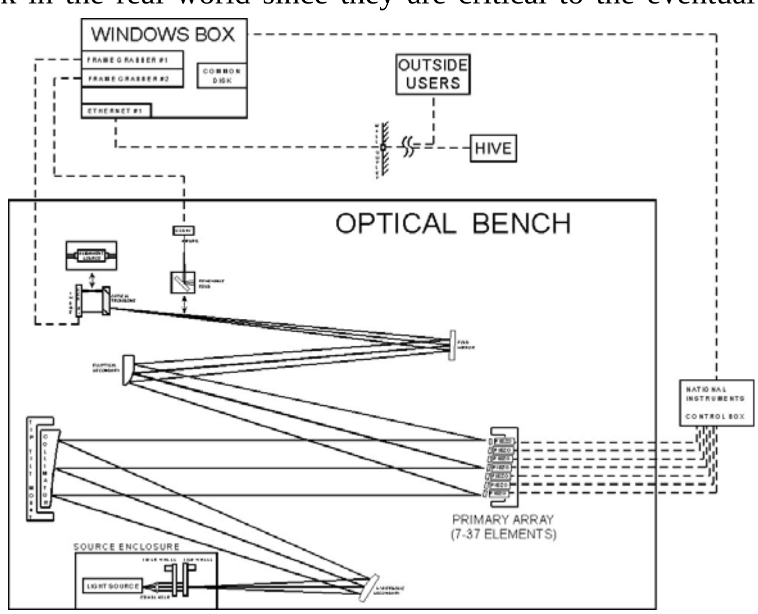


Figure 6: A block diagram of the FIT experiment to develop sparse array closed-loop phasing.

Goddard Space Flight Center (GSFC), Seabrook Engineering , and Sigma Space Corporation are operating the Fizeau Interferometer Testbed (FIT) at NASA/GSFC (Fig. 6). It is being used to explore the principles of and requirements for the *Stellar Imager* mission concept and other Fizeau Interferometers and Sparse Aperture Telescope missions (Lyon et al. 2007). FIT utilizes a large number of truly separate, articulated apertures (each with 5 degrees of freedom: tip, tilt, piston, and 2D translation of array elements) in a sparse distribution. It has the long-term goal of demonstrating closed-loop control of articulated mirrors and the overall system to keep beams in phase and optimize imaging. FIT also enables critical assessment of various image reconstruction algorithms (phase diversity, clean, MEM, etc.) for utility and accuracy by application to real data. FIT Phase I (7 primary mirror elements) is now in operation and Phase 2 (18 elements) is now under construction. The main components of the Phase 1 FIT are schematically illustrated in Figure 6. This, and similar work with the STAR9 experiment at LMATC, needs to be continued and expanded.

Long Baseline Precision Metrology

In order to enable the missions discussed above, interferometric range sensing with picometer accuracy will be required, between spacecraft separated by km distances. Missions employing dozens or hundreds of distance gauges are envisioned. Current capabilities must be enhanced in accuracy, range, speed of operation, and slew rate. The technology must be made ready for use in space, employing suitable components and demonstrating reliability. In addition, particularly for missions considering many distance gauges, a substantial reduction of the cost per gauge and improvements in modularity and simplification of setup will enable some missions, and for others in the conceptual design stage, will provide options. The SAO Metrology Testbed is based on the successful development of the Tracking Frequency Gauge (TFG) and could provide a platform for demonstrating metrology over long paths, 3-D metrology, a compact multi-beam launcher, and metrology of sub-nm precision at low cost.

Integration and Test of Long-Baseline, Distributed Aperture Systems

Finally, one of the most challenging technology needs for SI and all large, distributed spacecraft missions: how does one test and validate on the ground, prior to flight a system whose components are numerous (~30) and whose separations in flight are order of 100's of meters to many kilometers? This is also a critical need for, e.g., TPF-I/Darwin, BHI, LF, and PI. The likely solution is a combination of intense testing at the component level with extensive simulations of the system level performance, but the details need considerable work.

Summary

We have summarized the major technology development activities that need to occur throughout the decade of the 2010's in order to enable a wide variety of sparse aperture and interferometric missions in the following decade. These missions are critical to achieving the next major revolution in astronomical observational capabilities by dramatically increasing the achievable angular resolution by more than 2 orders of magnitude, over wavelengths stretching from the X-ray and Ultraviolet into the infrared and sub-mm. These observations can only be provided by long-baseline interferometers or sparse aperture telescopes in space, since the aperture diameters required are in excess of 500 m – a regime in which monolithic or segmented designs are not and will not be feasible - and since they require observations at wavelengths (X-ray, UV, far-IR, sub-mm) not accessible from the ground. Mission concepts which could provide these invaluable observations in the UV/Optical are NASA's Stellar Imager (Carpenter et al. 2008) interferometer and ESA's Luciola (Labeyrie et al. 2009) sparse aperture hypertelescope. Other concepts would provide similar capabilities in the X-ray (BHI, Gendreau et al. 2004), optical/IR (TPF-I, TPFSWG Report 2007), and IR/sub-mm (SPECS/SPIRIT, Leisawitz 2004). The technology developments needed for these missions are challenging, but eminently feasible with a reasonable investment over the next decade to enable flight in the 2025+ timeframe. That investment would enable tremendous gains in our understanding of the structure of the Universe and of its individual components in ways that we cannot even imagine today.

References

Allen, R. 2007, “Station-Keeping Requirements for Constellations of Free-Flying Collectors Used for Astronomical Imaging in Space,” PASP, 119, 914

Bely, P. & the Space Interferometry Study Team, 1996 (June), ESA publication SCI(96)7

Camp, J., 2005, “Laser Metrology and Hexapod Control Testbed”, private communication.

Carpenter, K.G., Schrijver, C.J., Karovska, M., SI Study Team. 2008, “SI – The Stellar Imager”, in *NASA Space Science Vision Missions*, ed. M. Allen, (Progress in Astronautics and Aeronautics, vol. 224, pp. 191-227; AIAA)

Chen, P., Carpenter, K.G., Romeo, R.C., 2003. in “Future EUV/UV and Visible Space Astrophysics Missions and Instrumentation”. Edited by J. Chris Blades and Oswald H. W. Siegmund, Proceedings of the SPIE, Volume 4854, pp. 21-28

Gendreau, et al. 2004, in UV and Gamma-Ray Space Telescope Systems, Proceedings of the SPIE, Volume 5488, 394-402, "MAXIM: the black hole imager"

"Terrestrial Planet Finder Interferometer Science Working Group Report", edited by P. R. Lawson, O. P. Lay, K. J. Johnston, & C. A. Beichman, JPL Publication 07-1 (2007)

Labeyrie et al., (2009), Experimental Astronomy: Volume 23, Issue1, Page 463 and

Lay, O.P., Dubovitsky, S., Peters, R. D., Burger, J. P., Ahn, S.-W., Steier, W. H., Fetterman, H. R., Chang, Y. “MSTAR: a submicrometer absolute metrology system”, 2003, Opt. Lett. 28, 890

Leisawitz, D. 2004, Advances in Space Research, 34, 631-636, "NASA's far-IR/submillimeter roadmap missions: SAFIR and SPECS"

Lyon, R.G., Carpenter, K.G., Petrone, P., Dogoda, P., Liiva, P., Marzouk, J., Solyar, G., Mazzuca, L., 2004a, “Fizeau Interferometry Testbed Wavefront Control”, in Optical, Infrared, and Millimeter Space Telescopes, Proceedings of the SPIE, Volume 5487, 963--974

Lyon, R.G., Carpenter, K.G., Huet, H., Cottle, P., Petrone, P., Dogoda, P., Liiva, P., Marzouk, J., Solyar, G., Mazzuca, L., Zhang, X. 2004b, ``Building the Fizeau Interferometer Testbed", Proc. IEEE Aerospace Conference

Lyon, R.G., Carpenter, K.G., Liu, A., Petrone, P., Dogoda, P., Reed, D., & Mozurkewich, D. *Wavefront Sensing and Closed-Loop Control for the Fizeau Interferometry Testbed*, Proc of SPIE 6687, San Diego CA, August 2007

Phillips, J.D and Reasenberg, R.D.: 2005, "Tracking Frequency Laser Distance Gauge," *Review of Scientific Instruments*, **76**, 064501

Shao, M. and Colavita, M. M. 1992, in Ann. Rev. Astron. & Ap, Vol. 30, p. 457-498