The Fizeau Interferometer Testbed (FIT): Developing and Testing the Technologies Needed for Space-Based Interferometric Imaging Systems

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ABSTRACT

The Fizeau Interferometer Testbed (FIT) is a ground-based laboratory experiment at Goddard Space Flight Center (GSFC) designed to develop and test technologies that will be needed for future interferometric spacecraft missions. Specifically, the research from this experiment is a proof-of-concept for optical accuracy and stability, closed-loop control algorithms, optimal sampling methodology of the Fourier UV-plane, computational models for system performance, and image synthesis techniques for a sparse array of 7 to 30 mirrors. It will assess and refine the technical requirements on hardware, control, and imaging algorithms for the Stellar Imager (SI), its pathfinder mission, and other sparse aperture and interferometric imaging mission concepts. This ground-based optical system is a collaborative effort between NASA's GSFC, Sigma Space Corporation, the Naval Research Laboratory, and the University of Maryland. We present an overview of the FIT design goals and explain their associated validation methods. We further document the design requirements and provide a status on their completion. Next, we show the overall FIT design, including the optics and data acquisition process. We discuss the technologies needed to insure success of the testbed as well as for an entire class of future mission concepts. Finally, we compare the expected performance to the actual performance of the testbed using the initial array of seven spherical mirrors. Currently, we have aligned and phased all seven mirrors, demonstrated excellent system stability for extended periods of time, and begun open-loop operations using "pinhole" light sources. Extended scenes and calibration masks are being fabricated and will shortly be installed in the source module. Installation of all the different phase retrieval/diversity algorithms and control software is well on the way to completion, in preparation for future tests of closed-loop operations.

Keywords: Interferometry, Fizeau, optical, detectors

1. INTRODUCTION

The next major observational advances in astronomy will require significant leaps in sensitivity (i.e., total collecting area) and in angular resolution (i.e., collector size/baselines). Mission concepts for achieving ultra-high angular resolution images of celestial objects require long optical baselines (e.g., 0.5 km to many kilometers) and necessarily involve sparse apertures or interferometric designs. Earlier missions of this type, which include Space Interferometry Mission (SIM) and Terrestrial Planet Finder (TPF), will primarily perform astrometry and low resolution imaging with modest baselines (~20 meters), while their successors will include high-resolution imagers such as Stellar Imager (SI) (Carpenter, et al., 2004), Micro-Arcsecond Imaging Mission (MAXIM), and Planet Imager (PI). An efficient approach to obtaining such high-resolution images is via Fizeau interferometry using a large number of primary mirror elements (mounted on formation-flying microsats) to collect light over a broad and diverse set of baselines to create what is essentially a sparse aperture telescope.

In order to support the development of such missions, we have established the Fizeau Interferometer Testbed (FIT) at GSFC. The construction of the ground-based UV-optical FIT has been a collaborative effort since its inception in 2001. The effort is primarily intended to develop the optical control technology necessary to meet the requirements of SI and other space-based interferometry and sparse-aperture missions. It will be used to assess and refine technical requirements on the hardware and control algorithms needed for such missions. Its eventual goal is to demonstrate closed-loop control of a sparse, 30-element mirror array (i.e., by maintaining optical path lengths to an accuracy of ~ 5 nm and maintaining simultaneous, autonomous phasing of all mirrors) and to assess a variety of image reconstruction and control algorithms using real hardware.

2. DESIGN GOALS & THEIR VALIDATION

In its final form, this interferometer will include up to 30 distinct articulated mirrors and will be automatically controlled by a closed-loop feedback system, based on analysis of the science data stream. The primary goals are to:

a. Develop techniques for and demonstrate coarse phasing (initial alignment) to bring the individual mirror array elements from > 1 mm to ~ 2 microns alignment in piston and from > 10 arcminutes to < 10 arcseconds (~□/D of each sub-aperture) in tip and tilt from the ideal reference surface. Develop techniques for, and optimize, automating this; determine the time required and complexity of the process. Assess trades between software and hardware methods.

b. Develop and demonstrate wavefront sensing and active optical control, in closed loop, of the individual mirrors (tip, tilt, piston), on both point sources and extended scenes, and of the overall system to keep beams in phase and to optimize imaging. Determine the breakpoints between active (i.e., actuators are held in position during the science observation) and adaptive (i.e., actuators are continuously moved throughout the observation) optical control; assess whether adaptive control is necessary. Determine the affects of higher order modes (uncorrectable modes) due residual design aberrations, stress induced deformations and thermal/structural drift of the individual optics.

c. Determine control loop requirements for the control system to include: closed-loop wavefront accuracy, precision, bandwidth, computational complexity, stability, and open loop coarse ranging and if open- and or closed-loop internal metrology is required. Determine breakpoints between fine and coarse ranging, coarse phasing and internal metrology (i.e., sensing the errors within a given spacecraft). Develop requirements for vibration, radiometry, stray light and detectors. Flow this set of requirements into station-keeping, formation-wide metrology (i.e., sensing the errors in the rigid-body misalignments of each spacecraft), beam combination and low-, mid- and high-spatial frequency optical surface requirements for the individual array elements and beam-combination. Assess the science impact derived from these requirements and assess the current state-of-art (TRLs) in these technologies. Determine those technologies that require significant technology development and any limitations imposed on the science derived from the technology requirements.

d. Investigate the optimal sampling methodology of the Fourier UV-plane and the optimal implementation of that sampling via time-efficient and propellant-efficient re-configurations of the mirror array. Iterate with the GSFC Formation Flying group to identify methodologies that are simultaneously realistic from a formation-flying and sampling viewpoint.

e. Confirm achievable sensitivities for different Fourier UV-plane sampling methodologies and determine the optimal number of collectors, dish size, and formation size. Determine optimal focal lengths and beam combining strategies.

f. Validate existing, and develop and validate new analytic and computational models of system and component level performance to ensure they will enable realistic assessments of future detailed flight designs.

g. Assess proposed image synthesis algorithms and image reconstruction techniques that seem promising on theoretical grounds or on the basis of numerical simulations for utility and accuracy.

h. Identify and develop optimal control strategies across the optical and formation flying aspects of the testbed and for the mission design, e.g. how much control is relagated to the optical actuators as opposed to thrusters and the attitude control system. Compose these strategies into sets of viable control laws.

To achieve these goals, we will utilize both mechanical methods and numerical analysis comparisons to confirm the system's capabilities. The high-level approach to each system goal is shown below:

a. The optical alignment of Phase I of the FIT was carried out over a period of 5 months during the fall of 2003 (Petrone et al. 2004). The coarse alignment was accomplished using a Coordinate Measuring Machine (CMM), which enabled the placement of the vertex of each of the primary mirror segments on a predefined spherical surface of radius 4m with a precision of ~ 10µm. A dispersed-fringe-sensor (DFS) was used to further phase up the spherical elements on the primary to within ~ 1µm. Lastly, fine adjustments were made using the actuators, which have a resolution of a few tens of nanometers.

b. To demonstrate mirror open-loop control, a preliminary object, in the form of a known scene, will be imaged multiple times, with differing diversities (focus, wavelength, field), through to the CCD camera and the set of images subsequently processed using phase diversity to produce a joint estimate of the wavefront and the object. Comparisons between the initial object and estimated object will confirm the success level of the object reconstruction and will provide an estimator of the fidelity of the wavefront sensing (phase diversity). The known scene is in the form of a digital file that has been transferred to 35mm slide film. The transferrance process has it self been calibrated by scanning multiple calibration sources with a micro-densitometer to assess the modulation transfer function (MTF) of the process. The output, after processing, will be a digital rendition of the object, sampled on the same grid and registered to the original digital file. Thus a direct comparison can be obtained with repect to image quality in terms of rms difference, contrast versus spatial frequency a.k.a. as MTF. In this manner we can deduce the MTF of each stage of the process ultimately resulting in a realistic error budgeting formalism for Stellar Imager.

c. Optical sensing and control accuracy will be tested by intentionally misaligning the system to introduce pre-defined levels of wavefront error. Phase retrieval and phase diversity will be used to measure the wavefront error, and the resultant wavefront decomposed into the eigenmodes of the control system. These eigenmodes will be fed back to drive the wavefront error to a minimal rms deviation. These motions should correspond to the initial induced errors. The overall system response and correction of the optical misalignment will characterize performance; similar tests with respect to low frequency vibration will also be performed in closed-loop.

d. Optimal sampling can be studied by manually simulating different rotational samplings through the FIT system and/or blocking different combinations of apertures. The quality of the output images will determine optimal system configurations versus number and placement of baselines and allow the team to provide input to any formation flying considerations.

e. System sensitivity will be characterized by varying the integration time of the detector to simulate different magnitude sources. Comparing the results to theoretical prediction models for wavefront control and image reconstruction will provide estimations of performance versus signal-to-noise ratio and contrast in the set of objects. These results will allow scalability to Stellar Imager.

f. Optical modeling is a very important issue as it is unlikely that a system such as Stellar Imager could be fully validated in any currently conceivable ground testing scenario. Thus the development and validation of high fidelity models via FIT is an important milestone. Models are under development for FIT, which can be readily expanded to Stellar Imager, and will be validated against actual laboratory data. This will produce a higher level of confidence in the modeling efforts. Actual system performance will also be compared to the performance predicted by current theoretical and computational models.

g. Existing image synthesis algorithms and image reconstruction techniques (maximum entropy, CLEAN etc.) will be applied to FIT data and the results compared to numerical simulations. Performance will be evaluated versus signal-to-noise ratio and spatial frequency content of both the object reconstructed image for various array configurations.

2.1 DESIGN REQUIREMENTS

The design requirements of the testbed, which flow down from the goals listed above, are the following:

a. The testbed should be a reduced-scale, traceable and scalable, model of a sparse aperture system (i.e. with multiple apertures directing light at a secondary mirror which reduce the light beam diameters), and combines (mixes) them and subsequently focuses them onto a single detector.

b. Multiple apertures must be modeled by assembling a true array of smaller mirrors, which can be individually articulated (tip, tilt, piston, and translation).

c. Incorporate actuator stages to control individual tip, tilt, and piston of each array element.

d. Include a filter wheel with narrow band filters representing various bandpasses as would be obtainable from energy resolving detectors.

e. Procure a set of calibration and science scenes to image through the system to assess the impact of the system on various spatial frequency content. Ensure that these scenes are traceable to digital scenes.

f. A computer sufficient for implementing sampling algorithms and collecting data to be used in deconvolution exercises, as well as for performing closed-loop control of mirrors (control tip, tilt, piston, translation of array elements) and overall system to keep beams in phase and to optimize imaging.

g. Provide for inclusion of metrology equipment (e.g., laser gauges) on the testbed.

h. Enable analysis of time-variable scenes for examination of effects of UV-plane coverage vs. time.

To date, the FIT team has satisfied all of the requirements mentioned above for the seven-element version (Phase I of FIT). The testbed is indeed a realistic interferometric system in the visible wavelengths, with currently an array of seven apertures that can be individually controlled in 3-dimensions (piston/tip/tilt). The light from the array is combined and focused through the system to the detector. There exists a computer controlled, six-position filter wheel for wavelength/bandwidth selection. The filter wheel is currently populated with narrow band filters ranging from 11 nm to 55 nm, though provisions have been made to augment this selection by repopulating or replacing the existing wheel. There is also a computer controlled linear stage for scene insertion. Each scene plate holds six scenes that may be commanded into precise alignment at the focal plane of the collimating optics. All scenes incorporate fiducials that are used to assist in the angular alignment of the image with respect to pixels in the CCD focal plane. A metrology system is also scheduled to be incorporated in the testbed in early summer.

3. FIT DESIGN

The team chose a Fizeau interferometer, which offers several advantages over the more typical Michelson configuration (Zhang 2003). Since the Michelson approach requires that the beams from all of the elements be combined and interfered pair-wise with each of the other beams, the total number of elements is limited to 10 or less in order to avoid overly complicated beam-combiner designs. The Michelson option thus requires numerous reconfigurations of the array to obtain full baseline coverage. The Fizeau approach, on the other hand, could possibly utilize a much larger number (~30) of simpler and less expensive spherical mirrors distributed on a spherical surface. The light beams from all the elements would be combined simultaneously on one detector; alternatively they could be picked up and combined in subsets if desired. This option requires far fewer reconfigurations to obtain a synthesized image, and utilizes fewer reflections.

3.1 OPTICS

Phase I of the FIT functions at optical wavelengths and uses a minimum-redundancy array (Golay pattern) for the primary mirror segments. Both a HeNe laser and a broadband light source are used to illuminate a user selectable set of pinholes, calibration masks and extended scenes. The set of pinholes vary from 10 to 50μm in diameter and extend from below the resolution limit to slightly larger than the resolution limit. The scenes are located in the focal plane of the collimator mirror assembly, which consists of a hyperboloidal secondary and an off-axis paraboloidal primary. The collimated light is then intercepted by the elements of the spherical primary mirror array, which relay it to the oblate ellipsoid secondary mirror, which finally focuses it onto the image focal plane. Table 1 presents the optical components and their associated specifications.

Element	Specification
Collimator secondary	radius of curvature 2.863m, conic -6.65, diameter 84mm, decenter 53.5mm, distance to the next element 2.2m.
Collimator primary	radius of curvature 6m, conic -1, (usable) diameter 254mm, decenter 200mm, distance to the next element 2.5m.
Imager primary	radius of curvature 4m, (usable) diameter 254mm, decenter 280, distance to the next element 1.414m.
Imager secondary	radius of curvature 1.463m, conic 4.5, diameter 110mm, decenter 81mm, distance to the next element 2.948m.

Table 1: Optical Specifications

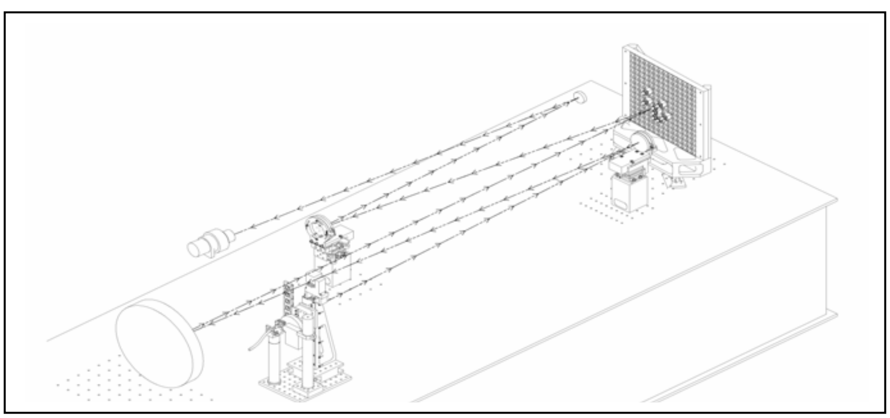

Figure 1: Sketch of FIT optical path

Figure 1 shows a schematic drawing of the FIT optical path design. An off-axis hyperboloidal secondary mirror is used to relay the beam of light, originating from the source, to the sparse array of spherical mirrors mounted on an aperture plate. Each of the spherical mirrors is mounted on three degree-of-freedom (piston/tip/tilt) piezo actuators mounted on an aperture plate; in addition, the mirrors can be moved (manually) on the aperture in one inch increments on a rectilinear grid. We currently use two identical Fingerlakes CCD cameras fed by a Pelicle beamsplitter. Future consideration of an optical trombone arrangement near the focal plane will allow an in-focus as well as an out-of-focus image to be simultaneously recorded on two CCD arrays for phase-diversity wavefront sensing analysis.

Figure 2 shows a close-up view of the array plate. The beam after the spherical mirrors is collimated and impinges on the off-axis parabolic collimator mirror. Following this mirror is an off-axis elliptical mirror, which images the scenes onto the detector arrays. For more detailed information, see Zhang (2003).

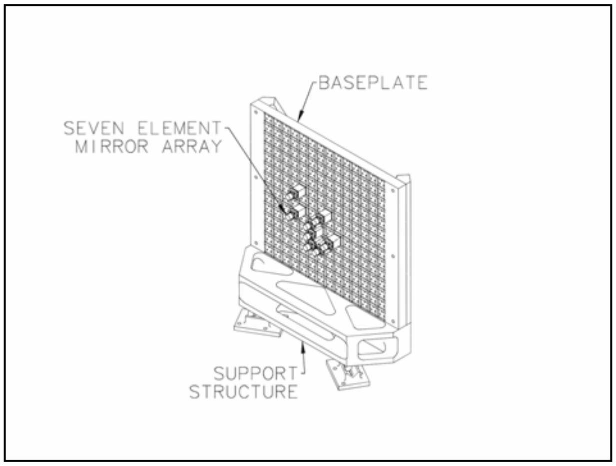

Figure 2: Sketch of array plate and current mirror/actuator configuration

3.2 DATA ACQUISITION SYSTEM

An MS Windows box controls an external National Instruments (NI) chassis containing two analog output cards. The Thorlabs controllers are actuated by issuing commands to the analog output cards with the NI box. The peizo actuators control the articulated primary mirror elements. The acquired data is relayed to a back-end parallel computer for analysis, and the result is fed back to the Windows box to be translated into the actuator control signals. In the current configuration, there are seven driving power supplies, one per mirror; each controls three degrees-of-freedom for each mirror.

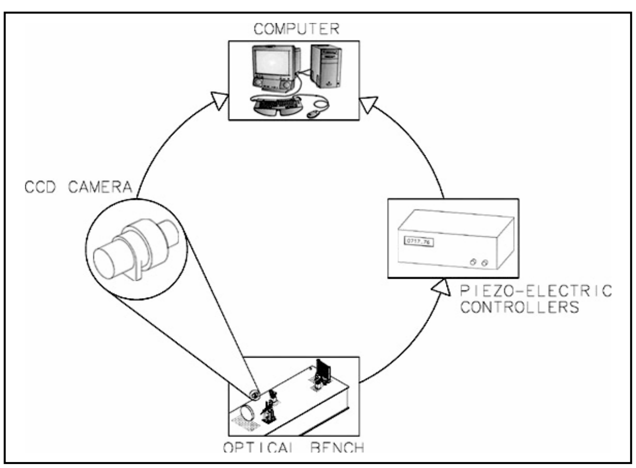

Figure 3: External System Components of the FIT

Figure 3 graphically presents the components driving the system as the source light progresses through the system. Two primary graphical user interfaces (GUI) have been developed to control the actuators and step through the control loop. The first GUI allows the user to manually control the piezo mirror actuators to allow for ease of actuator movement and image collection. The second GUI is designed to allow for manual stepping through the control loop by the use of a set of buttons and slides. Individual functions include triggering the cameras, calibrating the images, performing wavefront sensing using various phase retrieval and phase diversity algorithms, generating actuator commands, and then applying the commands. A third GUI will be developed for closed-loop control. Further details on the data acquisition process and wavefront sensing can be found in Lyon et.al (2004a,b).

4. TECHNOLOGY APPLICATIONS

The technology being developed in this investigation is needed for an entire class of future mission concepts. While the primary application of the FIT is to explore the principles of and requirements for the Stellar Imager (SI) mission concept, the results are of critical importance to all Fizeau imaging interferometers and large, sparse aperture telescopes. The results are needed for both formation-flying and truss-mounted architectures, since the optical-path control problems are the same for both. The specific areas that are being addressed, along with their respective experiment plans, are the following:

wavefront sensing: Baseline validation and residual wavefront errors will be analyzed, at first, using phase retrieval to determine the residual sub-aperture and full-aperture aberrations of an unresolved point source. A narrowband in-focus and out-of-focus point source image will be propagated through the system to acknowledge wavefront recovery using all of the apertures at the actuator midpoints. Ultimately, phase diversity will be used to characterize resolved extended sources. Multiple images of the same resolved, but unknown, source will be simulatenously processed to jointly recover the wavefront and the deconvolved object. Reconstruction of the phase errors in the incoming wavefront will also allow simultaneous assessment of the software.

actuators & optical control: Piston, tip, and tilt sensitivities need to be established relative to focus diversity. The experiment will determine phase retrieval sensitivity and actuator influence functions. The actuator piston/tip/tilt will be mapped to wavefront piston/tip/tilt, respectively, and at first, individually. Then mixed sensitivities (in piston, tip, and tilt simultaneously) will be analyzed to determine the correlations between the influence functions in mapping from the actuator to the wavefront.

image reconstruction algorithms: Algorithms have been created to determine point source and extended scene focus diversites. The actuators will be perturbed, and then diversity images collected, and phase retrieval performed to correct motions in open-loop. This process will determine if the recovered positions match the input positions. Results will also determine the error in the estimation of wavefront and in the setting of actuator positions.

closed-loop control: After the above experiments have been successfully demonstrated in the open-loop configuration, closed-loop control of the phase retrieval process will be assessed. Early results will determine mid-term stability of lab environment, any slow thermal drifts, and overall stability of components and actuators. Later, perturbations will be introduced into the system, such as thermal cycling, point source and extended scenes, and random noise. These perturbations will allow characterization of transient response and sensitivity, control methodology for formation flying, and degradation of errors with wavefront recovery, respectively.

5. PERFORMANCE & FUTURE PLANS

The first phase of the FIT (seven-primary elements) has completed initial alignment and is now in operation. We have begun to test various wavefront sensing and control algorithms and to probe the design and performance requirements needed to enable nanometer-level control of numerous simultaneous optical paths. The source module of the Phase I FIT currently only consists of a set of pinholes and spectral filters. The extended scene and calibration masks are currently being fabricated and will shortly be installed in the source module. The LabView interface and installation of all the different phase retrieval/diversity algorithms and control software is well on the way to completion.

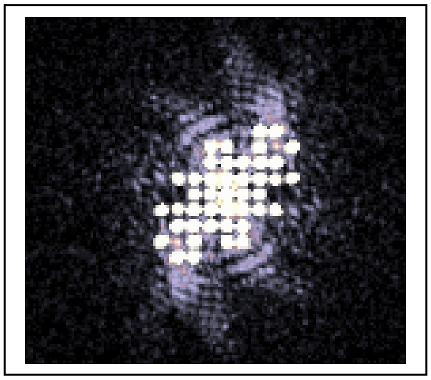

Figure 4: UV Plane image of the 7-Aperture Configuration

Figure 4 shows the first UV plane image of the seven-aperture system. It shows the region in the Fourier plane where we have spatial frequency information. The image is log-stretched. The background structure (the rings) are two orders of magnitude down from the ideal UV pattern, thus phase retrieval (and image deconvolution) will work very well. The white circles are from the actual data. This is the 2D spatial Fourier transform of a narrowband PSF, which yields the 2D autocorrelation of the pupil function with itself. Thus this shows the spatial frequency response of the system. Deconvolution is limited by the noise and artifacts in the gaps between the white circles. Our SNR(fx,fy) is ~ 100.

Figure 5 shows the first FIT fringes obtained through the system. Both images are log plots, with the left image the simulated one and the right image the actual one. The phased image is at $\lambda = 0.6$ µm, $\Delta\lambda = 70$ nm. These images have been stretched to show the Airy rings; the core structure is saturated.

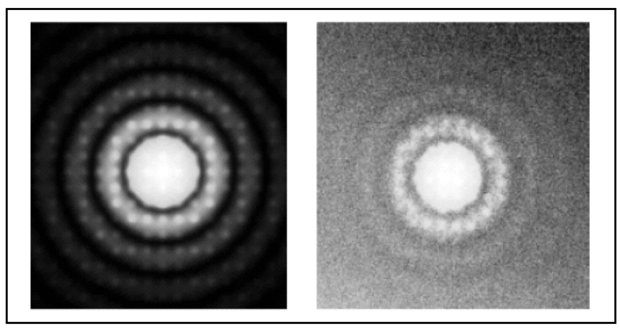

Figure 5: First-light Fringes of the 7-Aperture System

Calibration efforts are currently underway to characterize the pupil mapping and piston/tip/tilt sensitivities, as well as baselining the actuators and residual wavefront errors. Calibration data will then be integrated into the software to evaluate the efficiency of the data collection process and GUIs. Both open-loop and closed-loop control of the testbed with a point source and then with extended scenes will be demonstrated using the 7-mirror configuration. The final phase will incorporate up to30 mirrors in order to characterize more realistic samplings that may be needed for future space-based interferometer missions.

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