NGST OTA Optical Metrology Instrumentation and Conceptual Approaches

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Abstract

An Integrated Product Team (IPT) was formed to develop a detailed concept for optical test methodology for testing of the NGST individual primary, secondary and tertiary mirrors and the full telescope system on the ground. Optical testing is a significant cost driver therefore the testing has to understood in detailed fashion early. A brief summary of the preliminary metrology test plan at the mirror component and telescope system level is presented.

1. Introduction

NGST will be one of the most challenging programs ever undertaken because of the size of the optics (8 m primary mirror), very light weight of the mirrors, and the very low operating temperature (35K). The objective of the NGST optical test program is to verify that the optical system meets its performance requirements on orbit. Since NGST is a cost capped mission, all the testing that one would wish to do may not be possible and a balance will have to be found between level of testing and acceptable risk.

Because the validation of the optics is such an essential part of the NGST program, NGST Optical Testing IPT was formed to develop a strawman test program for testing the mirror components and the telescope system in order to identify the main issues and demonstrate feasibility. The products of the IPT are a metrology test plan at the mirror component and telescope system level, and the early development of specialized metrology instrumentation to facilitate testing at both component and system level at ambient and cryogenic temperatures. The metrology test plan will include test and instrumentation concepts that could be used, facilities and facility modifications that are required and cost estimates for the test program. The team responsible for the study includes the authors of this paper. The prime contractor representatives on the team are P. Atcheson/Ball Aerospace, C. Atkinson /TRW, M. Krim/Lockheed-Martin and M. Steir/ Raytheon.

In order to protect the proprietary character of the industry concepts, we have based our study on the so-called "Yardstick design" developed by the government team as a reference architecture. Although this is not the concept that will be built, its characteristics are generic enough to serve for the required feasibility demonstration.

2. Reference Design

The optical system for NGST must support a wide range of science observations. The science requirements determine mirror specifications and test requirements. The primary performance requirements for NGST are shown in Table 1. The detailed requirements are under development. The image quality criteria is discussed in Ref. 1.

Table 1. Fundamental NGST performance requirements.

	Requirement
Wavelength Range	0.6 to 10 μm
Resolution	Diffraction limited at 2 μm
Aperture Diameter	8 m
Sensitivity	Zodiacal light limited up to 10 μm
Mission Lifetime	>5 years

The baseline configuration for our study is the Yardstick design[2]. In this design the Optical Telescope Assembly (OTA) is a three mirror anastigmat which provides a real, accessible pupil and permits the use of relatively fast primary mirror to minimize telescope length. This design provides excellent imaging over a large field with relatively loose alignment tolerances. The primary mirror f/number is 1.25 and the OTA f/number is 24.

The primary is an 8 meter diameter segmented concave ellipsoidal mirror with partially filled aperture. The aperture consist of seven subaperture mirrors residing in two radial zones. The central hexagonal segment is 2.5 m from edge to edge. The outer annular zone consist of six elongated hexagonal mirrors adjoining the sides of the central hexagon. The secondary is a 0.66 meter diameter hyperbolic convex mirror. The tertiary is a 0.95 meter elliptical concave mirror of which only half is used. The mirror parameters are given in Table 2.

Table 2. Mirror parameters.

MIRROR	RADIUS OF CURVATURE	CONIC CONSTANT	APERTURE	TESTING f/NUMBER
Primary	20 m	-0.9984	8.0 m	2.5
Secondary	1.678 m	-1.3699	0.66 m	2.54
Tertiary	2.864 m	-0.7209	0.95 m	3.01

3. Optical Testing

The objective of the NGST optical testing program is to verify that the optical system meets performance requirements on orbit. The NGST OTA includes the primary, secondary, tertiary, deformable and fast steering mirror as well as the metering structure and mounts that hold each optic. Each optical component will be tested as it is fabricated to determine whether it meets its surface figure and surface roughness requirements. Characterization of mirror surfaces at all spatial frequencies is important for optimum performance of the instrument. Ideally the characterization will include the transfer of optimized alignment of each element to reference surfaces to facilitate system level alignment.

Component Level Testing

The primary mirror segment and assembled mirror figure can be measured interferometrically at center of curvature with null corrector both at ambient and cryogenic temperature. The mirror segments will be fabricated to match the wavefront generated by the null corrector.

To avoid a problem like in the primary mirror of the Hubble Space Telescope (HST) that was made to the wrong shape because of errors in the null corrector, University of Arizona has developed a technique to certify null correctors using small, highly accurate computer generated holograms (CGHs)[3]. To implement the test, a CGH is manufactured that has a ring pattern on a flat substrate that diffracts light exactly like it was reflected from a much larger, perfect mirror. The CGH is placed in front of the null corrector and measured. Any error in the null corrector will show up directly when testing the hologram. Figure 1 shows the optical layout of certifying a null lens using a computer generated hologram and for measuring the figure of a primary mirror using a null lens.

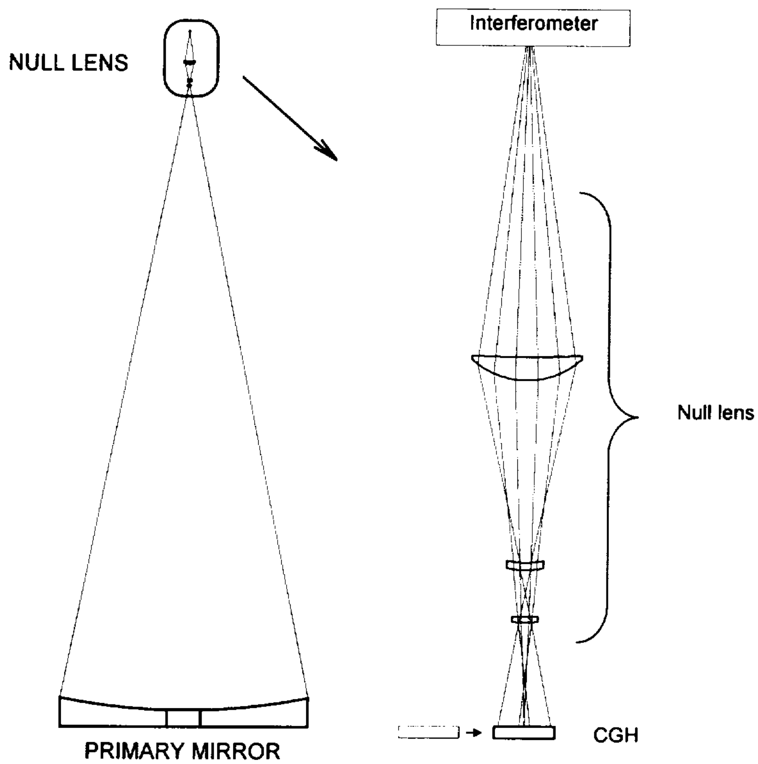


Figure 1. Certification of a null lens using a computer generated hologram. For measuring the primary mirror, the null corrector is held a large distance from the mirror (twice the focal length). The CGH is mush smaller since it is placed where the light from the null corrector comes to focus. The CGH diffracts light that appears to the null corrector as if it was reflected by a perfect primary mirror.

The CGH can be made much more accurately than the null corrector. The hologram is small, only 16 cm for the f/1.25 NGST primary mirror (from the NASA yardstick). The CGH is manufactured on a flat substrate, which is easy to make and certify. The ring pattern that creates the diffraction is made using advanced lithographic methods. This test has been used at University of Arizona and by industry to calibrate numerous null correctors as fast as F/1.

Two methods have been identified for testing of the convex secondary mirror. The Simpson-Hindle[4] test requires a meniscus test shell somewhat larger than the secondary mirror. In addition a reflective sphere is needed to calibrate the transmitted wavefront for the shell. Cryogenic temperature complicates the test. The cryo distortion of the test shell and the reflective sphere need to be calibrated and taken into account in mirror measurements.

The convex secondary mirror can also be measured at ambient and cryogenic temperatures using interferometry with a holographic test plate[5]. This technique is similar to test plate interferometry for spherical surfaces, but the aspheric departure of the secondary mirror is compensated with a computer-generated hologram that is written onto the concave spherical surface of the test plate. This test has been used for measuring numerous aspheric mirrors, both at the University of Arizona and in industry.

The test can be done at cryogenic temperature. The cryo distortion of the test plate can be minimized using homogenous fused silica, and it can be calibrated by direct measurement, and then backed out of the mirror measurement.

The tertiary mirror can be tested using the test approach as for the primary mirror.

The mid frequency errors at spatial periods 1 – 10 cm can be measured by subaperture interferometry on primary mirror segments, secondary and tertiary mirrors on several locations across the mirrors. The wavefront may need to be corrected with a null corrector or a CGH compensator. The measurements can be performed at ambient temperature. However, it may be necessary to sample the mirror at cryogenic temperature depending on the spacing of the actuators and other features in the back of the mirror.

The microroughness error at spatial periods of micron to cm can be measured using commercial interferometric microscopes. The accuracy of these interferometers in the 0.1 nm range. In order to reduce risk to the mirror the surface will be replicated with RTV and the replicas will be measured. Microroughness measurements are necessary only at ambient temperature.

Distance measuring interferometer can be used for radius of curvature measurement both at ambient and cryogenic temperature.

Full OTA System Test

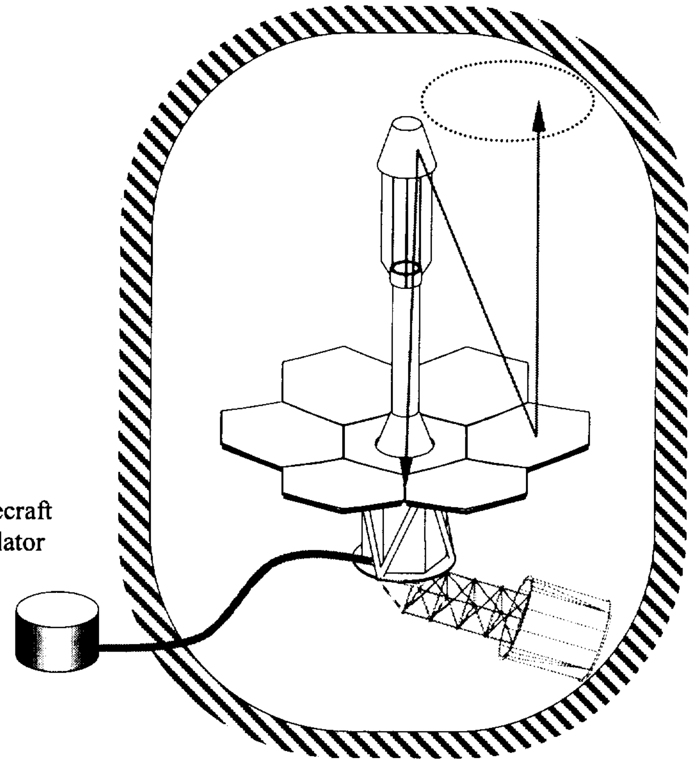
The integration of the OTA components will be performed at ambient temperature utilizing standard metrology techniques to align each component. The wavefront quality of the assembled OTA would be measured at ambient temperature to verify performance. The testing could measure wavefront quality, encircled energy or Strehl. The full system test may be either a full aperture or sampled aperture test.

The cyrogenic performance of the NGST OTA would be performed in a large cryogenic vacuum chamber. Candidate test configurations include a full aperture test or subaperture test with a large autocollimation flat. Testing of the OTA would include wavefront measurements, encircled energy, Strehl, throughput and verification the wavefront sensing and control hardware and software. A dummy science instrument would be required to allow closed loop operation of the control system, with a dispersed fringe sensor or alternate means of measuring piston. All aspects of the OTA performance should be tested at this level of assembly to verify performance prior to system level integration.

Full aperture autocollimation test requires a large 8m diameter flat. It also requires another large optic to calibrate the flat. Another option is a star test with a collimator. This test requires an 8 m diameter collimator.

Sampled aperture test requires a smaller test mirror which would be easier to calibrate. For the "Yardstick design" a three meter aperture would be desired at a minimum. The difficulty comes in patching together the subapertures into a full aperture wavefront map. A reasonable overlap of the subapertures is required for fidelity. The larger the overlap the more data sets required. The more data sets, the longer the time required for testing. The longer the testing time, the greater the possibility that some change will take place in the setup, relative mirror positions, individual mirror figures etc. These changes may result from moving the test mirror around to the different test positions. Slight variations in temperature can result in erroneous data as the mirror configuration is changed. Layout of a full OTA system level test with subaperture flat is shown in Figure 2.

Another test which only obtains data across a diameter is the scanning penta-prism. This test is used to measure any residual spherical aberration. It does not give a full aperture wavefront map.



Figire 2. Full OTA system test with subaperture flat.

4. Instrumentation Development

Because of long optical path lengths in the test setups, large apertures and test facility limitations, it is necessary to develop interferometric test equipment that minimize vibration sensitivity. The efforts underway include Wavescope, Instantaneous Phase Interferometer (IPI) and Vibration Compensated Phase Shifting Interferometer.

Wavescope is a Shack-Hartman wavefront sensor built by Adaptive Optics Associates Inc. (AOA)[6]. The light from the image point of the test optic is collimated and directed to the lenslet array. The collimating lens also images the pupil of the test optic onto the lenslet array. Point images formed by the the lenslet array are re-imaged onto the CCD. The difference in spot locations from the reference beam and the optic under test is related to the wavefront. The wavescope was selected for use at Marshall Space Flight Center (MSFC) X-Ray Calibration Facility (XRCF) for NGST Mirror System Demonstrator (NMSD) testing because mechanical vibrations ruled out the use of commercial Fizeau phase shift interferometers.

The MSFC Wavescope employs a high resolution CCD (1024 x 1024) coupled to a 150 x 150 lenslet array 15 mm square. It avoids the XRCF vibration problems by using very fast integration times on the CCD (e.g. down to 1/8000 of a sec).

An interferometric instrument under development is Instantaneous Phase Interferometer (IPI) built by ADE Phase Shift[7]. IPI is an updated version of Simultaneous Phase Shift Interferometer (SPSI) that has been used successfully for testing of 8 m class mirrors with surface errors in the 12 nm range[8]. It is polarization based Twyman-Green unequal path interferometer. It utilizes four individual focal planes, each phase shifted by $\lambda/4$ by polarization techniques. This allows the four frames required for one data set to be taken simultaneously at 0.1 millisecond exposure. The CCD cameras have to be aligned to sub-pixel tolerances.

The simultaneous short exposure makes this interferometer immune to vibration in the 10 Hz to 30 Hz range of the measured ground vibration. The IPI is baselined for Advanced Mirror System Demonstrator (AMSD) testing at MSFC.

Another interferometer under development is vibration compensated phase shift interferometer[9] built by University of Arizona. It can measure and actively compensate vibration to allow interferometric measurements to be made with $\lambda/100$ accuracy in high vibration environment. It measures and compensates vibration at 4000 Hz. The second generation instrument was built and used successfully for 2-m NMSD mirror testing in non-isolated tower. The third generation instrument proposed for NGST testing will have improved system design for better performance and robustness. It will also have possibility of adding two-wavelength capability for measuring segment phase.

5. Facilities

The NGST primary mirror is a subsystem that must be demonstrated to reliably deploy, phase mirror segments, adjust radius of curvature errors and not drift from its phased configuration over large temporal periods of operation. The full primary mirror and the OTA testing requires a large cryogenic test facility.

A survey[10] of large existing test facilities was conducted in the beginning of 1999. The assumptions included testing at < 40K temperature in high vacuum environment and non deployed primary mirror installation. Key factors considered in the study were facility size, vibration isolation, operational cost, cost to modify for NGST, existing GHe refrigeration capability, and installation of special test equipment. The most promising existing facilities were considered to be AEDC Mark1, Lewis SPF, Johnson A, TRW Space Park M-4, Kodak, Lockheed Sunnyvale, ROSI Danbury. All of these facilities require modifications for NGST testing. Cost to modify for NGST was estimated to be from < $8 million to $25 million depending on the facility. A cost for a new facility was estimated to be $30 - $70 million.

6. Summary

Because of large, lightweight optics and cryogenic operating environment validation of the NGST optical components and the full OTA on the ground is very challenging and a big cost driver. Therefore it is important to develop detailed test concepts early in the program to arrive at an optical testing approach that is technically sound and cost effective and demonstrates that the optical system performance meets science requirements at the cryogenic operating environment.

References

1. P.Y. Bely, "Large Space Optics", these proceedings.
2. J.B. Hadaway, M.E. Wilson, D.C. Redding, and R.A. Woodruff, "Lessions learned in the optical design of the Next Generation Space Telescope (NGST)", Proc. SPIE 3356, 114-121, (1998).
3. J. H. Burge, "Certification of null correctors for primary mirrors", Proc. SPIE 1994, 248-259 (1993).
4. D. Malacara, "Optical Shop Testing", 2nd ed., John Wiley & Sons Inc. 1992.
5. J. H. Burge, "Measurement of large convex aspheres," in Optical Telescopes of Today and Tomorrow, A. Ardeberg Ed., Proc. SPIE 2871, 362-373 (1996).
6. Adaptive Optics Associates Inc., 54 Cambridge Park Dr., Cambridge, MA 02140.
7. ADE Phase Shift, 3470 E. Universal Way, Tucson, AZ 85706.
8. W. S. Smith, J. F. Hraba and G. Jones, "Manufacturing and Testing of an 8.3 meter Astronomical Mirror", Proc. SPIE, Vol. 3782 (1999).
9. G.C. Cole, J.H.Burge, L.R. Dettmann, "Vibration stabilization of a phase-shifting interferometer for large optics", Proc. SPIE Vol. 3134, p. 438-446, Optical Manufacturing and Testing II, H. Philip Stahl; Ed. (1997).
10. D. Johnston, "Potential NGST Test Faclities", presentation at MSFC, 3/16/99.