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. The large, lightweight, deployable primary mirror, and the cryogenic operating environment make optical testing of NGST OTA (Optical Telescope Assembly) extremely challenging. A telescope of the complexity of NGST has never been built and tested on the ground in 1-g environment. A brief summary of the preliminary metrology test plan at the mirror component and telescope system level is presented.

Keywords: Next Generation Space Telescope, NGST, optical testing

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). Additionally, due to rocket shroud limitations the primary mirror has to be segmented. NGST has to be assembled in space and be highly reliable. The baseline orbit for NGST is L2. The deep orbit limits the amount of weight and thus system redundancy and also rules out servicing. Therefore to achieve its science requirements it has to be much more reliable than Hubble Space Telescope (HST) that has required servicing missions to keep it operational. The NGST optical test program has to demonstrate that the optical system meets its performance requirements on orbit and is reliable. However, NGST is a cost capped mission, therefore 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 validation of the optics is such an essential part of the NGST program, the 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 team responsible for the study includes the authors of this paper.

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.

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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 are 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)[3] is a three mirror anastigmat which provides a real, accessible pupil and permits the use of a 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.

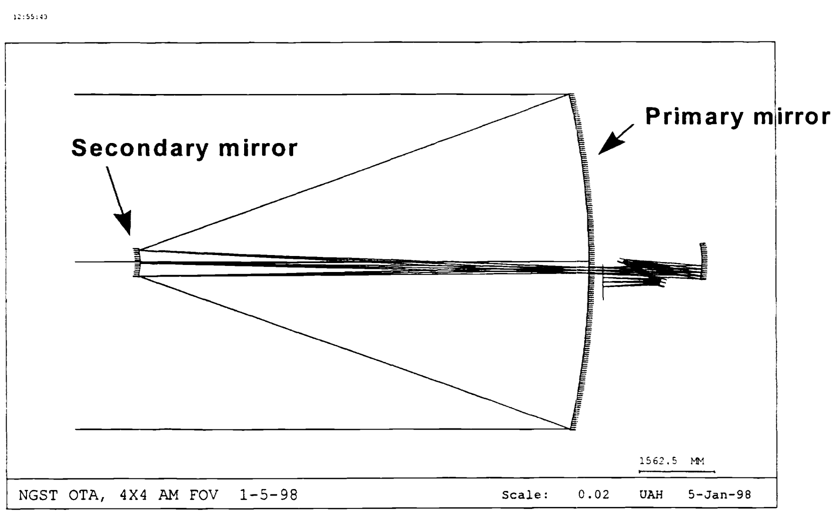

Figure 1. Optical layout of the baseline OTA.

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 roughly 2.2 m long and 1.8 m wide 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(s) 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.

The surface figure requirements also drive the requirements for the mount for each optic, with the goal being minimal figure distortion due to mounting and cryogenic cycling. Each flight optical components must be tested in its mount at cryogenic temperature prior to installation into the OTA assembly due to the difficulty in producing a cryogenic mount and to allow an as-built model to be developed based on each element's performance.

3.1. Component Level Testing

3.1.1. Primary Mirror

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. There are three main options for the null corrector: diffractive, reflective and refractive two element Offner type. Since the primary mirror is nearly parabolic, the two element Offner type is the most likely candidate. In the cryogenic temperature test the interferometer and the null lens would be outside the cryogenic chamber.

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)[4]. 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.

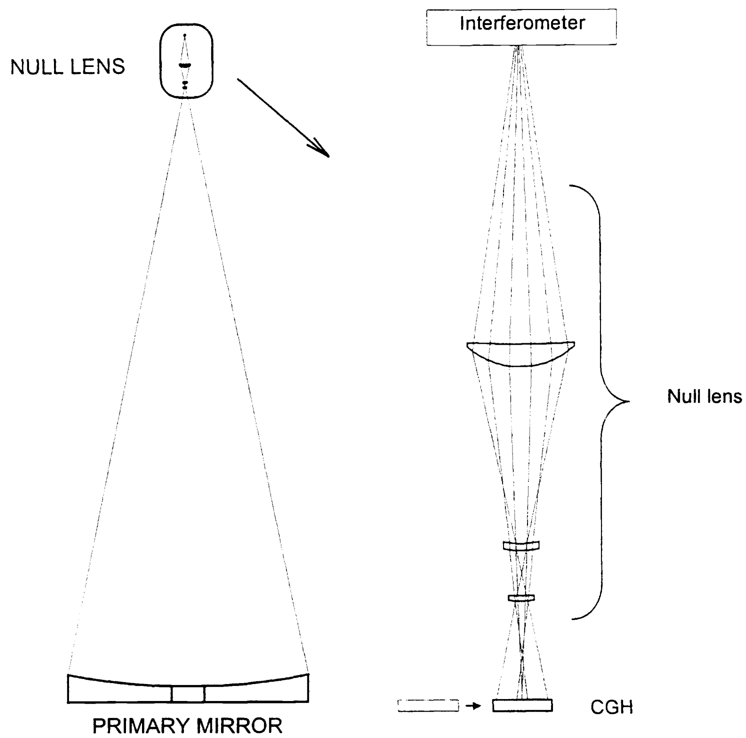

Figure 2. Certification of a null lens using a computer generated hologram. For measuring the primary mirror, the null corrector is held a large distance from the mirror (twice the focal length). The CGH is much smaller since it is placed where the light from the null corrector comes to focus. The CGH 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.

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

A distance measuring interferometer can be used for radius of curvature measurement both at ambient and cryogenic temperature. Currently a simple time of flight insrument is bring used to monitor the radius of curvature of the NGST Mirror System Demonstrator (NMSD) and Subscale Beryllium Mirror Demonstrator (SBMD) as they undergo testing at cryogenic temperature at Marshall Space Flight Center (MSFC) X-ray Calibration Facility (XRCF). Current instrument accuracy is 3.0 mm, however, another version of the instrument has a 10 micrometer capability, however, this accuracy was not required for NMSD or SBMD measurements. Radius of curvature matching of the segments can be verified interferometrically.

3.1.2. Secondary Mirror

There are two tests under consideration for testing the convex hyperbolic secondary mirror, the Simpson-Hindle test and the diffractive test plate. Testing at cryogenic temperature requires that the test setups including all the optical components are calibrated at cryogenic temperature.

The Simpson-Hindle[5] 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.

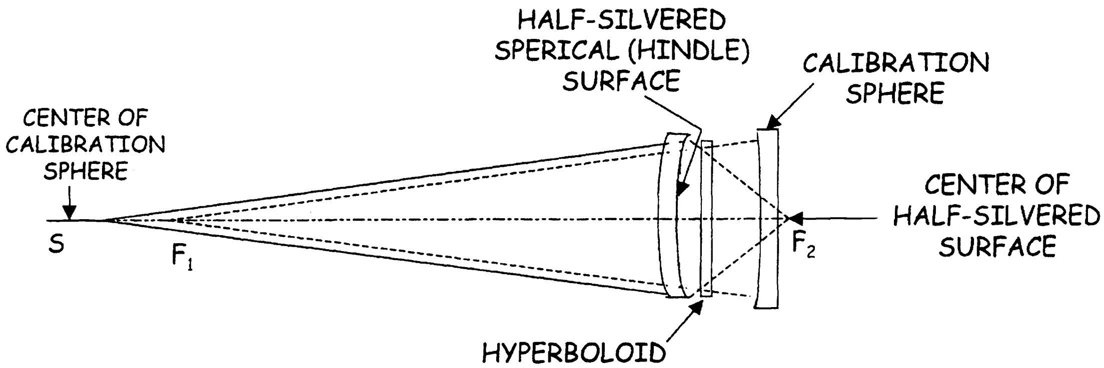

Figure 3. Testing of the secondary mirror using refractive Hindle's sphere.

The convex secondary mirror can also be measured at ambient and cryogenic temperatures using interferometry with a holographic test plate[6]. 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.

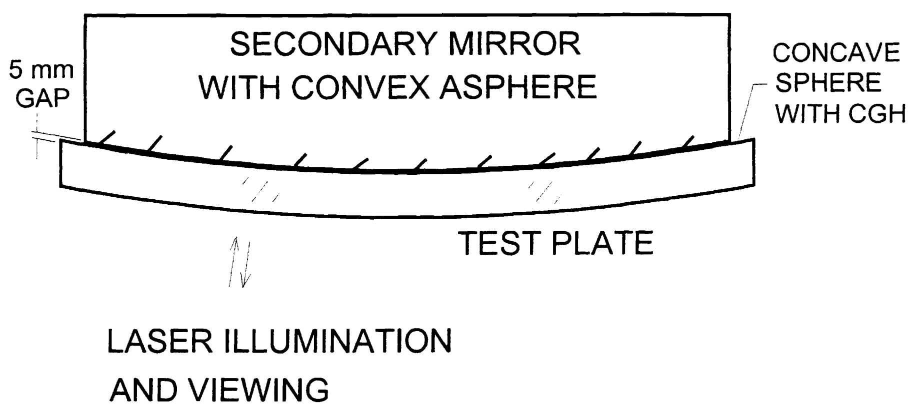

Figure 4. Diffractive test plate test.

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.

3.1.3. Tertiary Mirror

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

3.1.4. Mid-frequency Error and Microroughness

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 aspheric departure of the mirror 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 a micron to a cm can be measured using commercial interferometric microscopes. The accuracy of these interferometers is 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.

3.2. Full OTA System Test

Ideally, some demonstration of diffraction limited performance of the active optical system will be necessary at ambient and cryogenic temperature on the ground before launch. A wide range of test options exists for this demonstration and runs gamut from a full aperture cryogenic test of the OTA with dummy scientific instrument to a sub-aperture test of the system at ambient with validated models used to predict performance. In the first instance, a direct measurement is required with either a large aperture collimator or telescope. For the case where analysis using validated models supplemented with component and system level test results is used to predict performance, a shortcoming of this approach is the lack of fidelity of models in matching measured performance data. Obviously, somewhere in between the two extremes outlined above is probably the best compromise balancing the need to demonstrate performance conclusively with the need to save cost and schedule. Primary mirror architecture and material choice play a large role in determining exactly what tests should be performed at the system level.

3.2.1. Full Aperture Test

The integration of the OTA components will be performed at ambient temperature utilizing standard metrology techniques to align each component. The full system level test could be a full aperture test both at ambient and cryogenic temperatures. The performance test would be performed in a large cryogenic vacuum chamber. Testing of the OTA would include wavefront measurements, encircled energy, Strehl, throughput and verification of the wavefront sensing, 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. Cost will be a critical issue for the full aperture test and full aperture system test even at ambient will be expensive.

One option for the full aperture test is an autocollimation test. Full aperture autocollimation test requires a large 8m diameter flat. An 8 m flat presents extremely difficult qualification issues and would require another large optic to calibrate the flat. Another problem is self-distortion due to the flat's own weight and orientation. Second option is a star test with a collimator. This test requires an 8 m diameter collimator. A large collimator is easier to make than a large flat. Mirrors of this size have been made and their surface figures can be measured interferometrically at center of curvature with a null corrector.

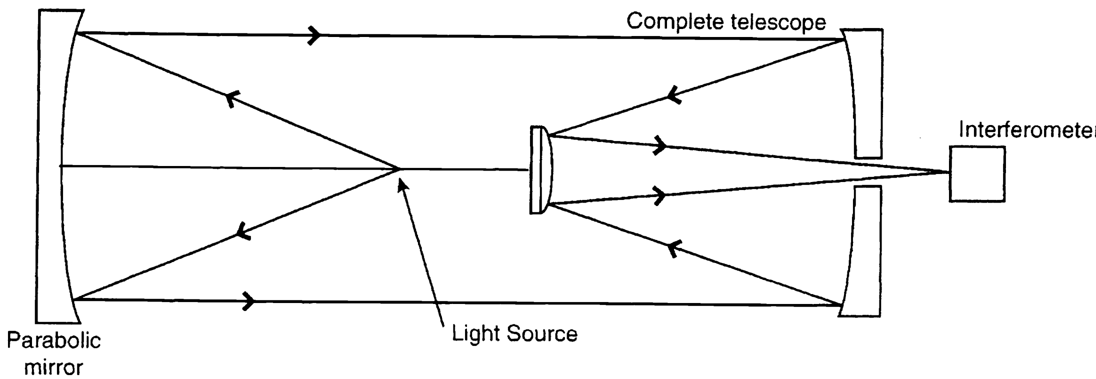

Figure 5. Star test with a collimator.

3.2.2. Sampled Aperture Test

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 6.

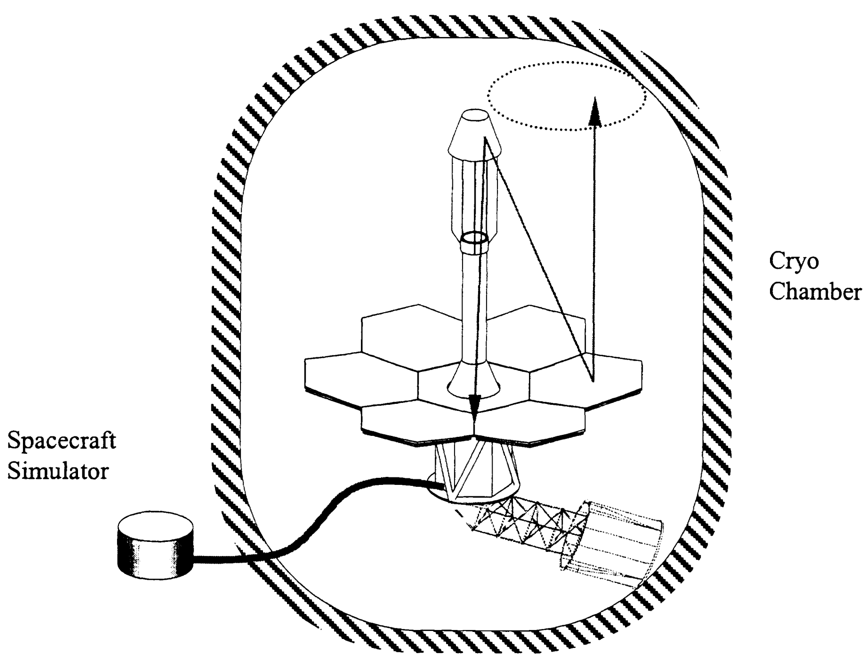

Figure 6. Full OTA system test with subaperture flat.

4. INSTRUMENTATION DEVELOPMENT

To test the NGST mirrors and the telescope interferometric methods and noninterferometric methods will be used. Long optical path lengths, large apertures, and high noise test environment require development of metrology instrumentation that minimizes vibration sensitivity. The instrument development efforts underway include Wavescope®, Instantaneous Phase Interferometer (IPI) and Vibration Compensated Phase Shifting Interferometer.

4.1. Shack-Hartman Wavefront Sensors

Wavescope® is a Shack-Hartman wavefront sensor developed and built by Adaptive Optics Associates Inc. (AOA)[7]. The instrument utilizes a Shack-Hartman wavefront sensor to measure the slope of the wavefront under test. The converging light from the incoming wavefront under test is focused and then collimated by a lens. The collimating lens also images the exit pupil of the test wavefront onto an array of micro-lenslets. Test spot images formed by the lenslet array are re-imaged onto the CCD by a relay lens. A reference beam can be inserted at the focal spot position to calibrate the spot centroid locations in the CCD focal plane for a perfect reference wavefront. When the test wavefront is measured, the difference in spot locations between the reference wavefront and the test wavefront is directly related to the slope of the wavefront for each subaperture measurement point. The instrument is sold with a powerful data analysis software package that allows the user to reconstruct the wavefront and perform other optical calculations. The instrument works with either monochromatic or white light and can achieve an absolute accuracy of less than 1/20 wave at 633 nm.

The Wavescope® was selected for use at 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 (with array of 1024 x 1024 pixels) coupled to a 150 x 150 lenslet array with 15 mm square subapertures. Vibration problems within the XRCF are avoided by using very fast integration times on the CCD (e.g. down to 1/8000 of a sec).

4.2 Interferometry

Interferometric measurements of optical components can be made using many different interferometers such as Fizeau interferometer, Twyman-Green interferometer, and common path interferometer such as Point Diffraction Interferometer (PDI), and shearing interferometers. In any interferometric measurement to acquire stable fringes, the vibration between the two arms of the interferometer must be minimized. Common path interferometers such as PDI are not sensitive to piston vibration , however, they cannot be phase shifted accurately, therefore the spatial resolution is limited to the number of fringes across the surface of the optic under test. Fizeau interferometers are quite sensitive to vibration. To test the NGST optics two vibration compensated phase shifting Twyman-Green interferometers are under development.

Instantaneous Phase Interferometer (IPI) is polarization based Twyman-Green unequal path interferometer developed by ADE Phase Shift[8]. 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[9]. 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 times. 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[10] 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 is polarization based Twyman-Green interferometer that uses an Electro-Optics modulator to compensate for error in phase due to piston and tilt vibration. A breadboard instrument was built and used successfully for a 2-m NMSD mirror testing in a non-isolated tower. The instrument is being redesigned for NGST testing to improve performance and robustness. It will also have the 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.

The NMSD and SBMD mirrors are tested at the XRCF (Figure 7) test facility at MSFC at cryogenic temperatures down to 35K. This facility will also be used to test the mirrors developed under Advanced Mirror System Demonstrator program. NGST primary mirror segment level testing at cryogenic temperatures could be done at XRCF, however, it is not large enough for full primary mirror testing.

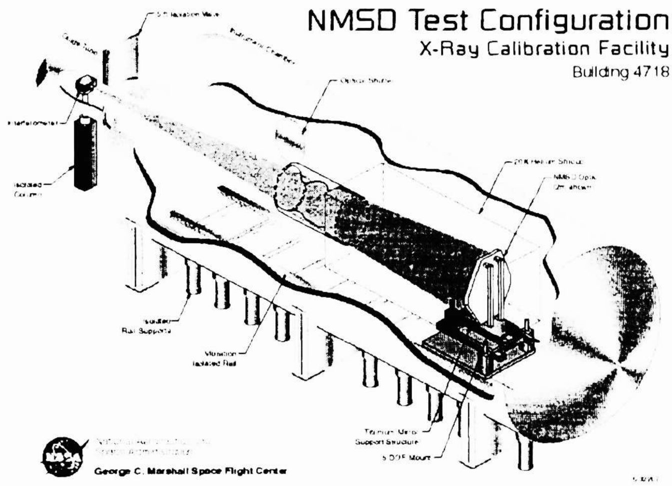

Figure 7. NMSD mirror test configuration.

A survey[11] 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 major risk and cost uncertainty to the NGST program. 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. This includes development of interferometric test equipment that minimizes vibration sensitivity in the high noise test environment, and assessment of test facilities. Facility development/modification will be required for full primary mirror/OTA testing at cryogenic temperature.

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