Capability improvements at Marshall Space Flight Center's x-ray and cryogenic facility

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ABSTRACT

The X-Ray & Cryogenic Facility (XRCF) at Marshall Space Flight Center is the world's largest x-ray optic calibration facility and NASA's premier cryogenic optical test facility. Built specifically to calibrate the Chandra telescope, the facility contributed to several other x-ray missions until 2005 when it became dedicated to normal incidence optical testing at cryogenic temperatures. Recently the facility's x-ray test capability has been returned to service and updated. New beam monitors, focal plane detectors, and test article and instrument positioning systems have been added. The x-ray data acquisition system has been updated. A real-time position monitoring metrology system is being developed that will enable calibration of large diameter optics via partial illumination in a diverging beam. The newly expanded x-ray test capabilities of the facility will be discussed.

1. INTRODUCTION

The X-Ray & Cryogenic Facility (XRCF) at NASA's Marshall Space Flight Center is an adaptable, multi-capable space simulation test facility which has been utilized extensively for 30+ years to enable technology maturation and pre-flight verification activities for instruments and observatories such as Chandra, Hinode, GOES Solar X-ray Imagers, and James Webb Space Telescope (JWST).

At the heart of this test complex is a large horizontal cylindrical thermal vacuum chamber that can achieve vacuum levels in the 10^{-8} millibar range and temperatures from -250C to 100C. At 6m diameter x 19m the test volume can accommodate almost any payload that can be launched today. Built specifically to perform the ground calibration and verification of the Chandra X-ray Observatory, the facility had a few specialized features built in – some of which are unique. To meet strict x-ray optics contamination control requirements, the chamber itself is extremely clean and opens into a 500m^2 ISO6 cleanroom. To enable optical testing, the chamber is equipped with a vibrationally insulated test bench and precision test article positioning systems inside the vacuum. And to enable proper full illumination of the Chandra x-ray mirrors, the chamber is connected to a 518m x 1.5m diameter evacuated beam line which make it the largest facility of this type in the world. Modifications after Chandra added the ability to optically evaluate structures and direct-incidence optics in relevant thermal environments from 300 to 20 Kelvin; these additional capabilities were utilized by James Webb Space Telescope from 2005 to 2015. Details of the facility's existing x-ray and cryogenic testing capabilities can be found in [1] and [2].

Since 2021, updates and upgrades to the x-ray test capabilities have been underway. The updates address the outdated beam monitoring, focal plane instrumentation, data acquisition, and other systems. The upgrades address enabling the optical evaluation of x-ray mirrors with apertures larger than the facility's x-ray beam; this sub-aperture illumination testing in a diverging beam and subsequent data stitching presents challenges that have been addressed in [3].

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To help orient the reader, a graphical layout of the XRCF depicting the relative positions of the x-ray source, beam monitors, chamber, and cleanrooms is shown in Figure 1; the interior of the thermal vacuum chamber is shown in Figure 2.

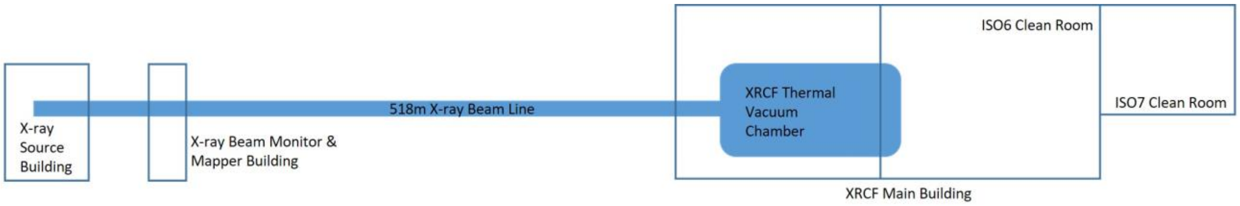

Figure 1. XRCF Graphical Layout.

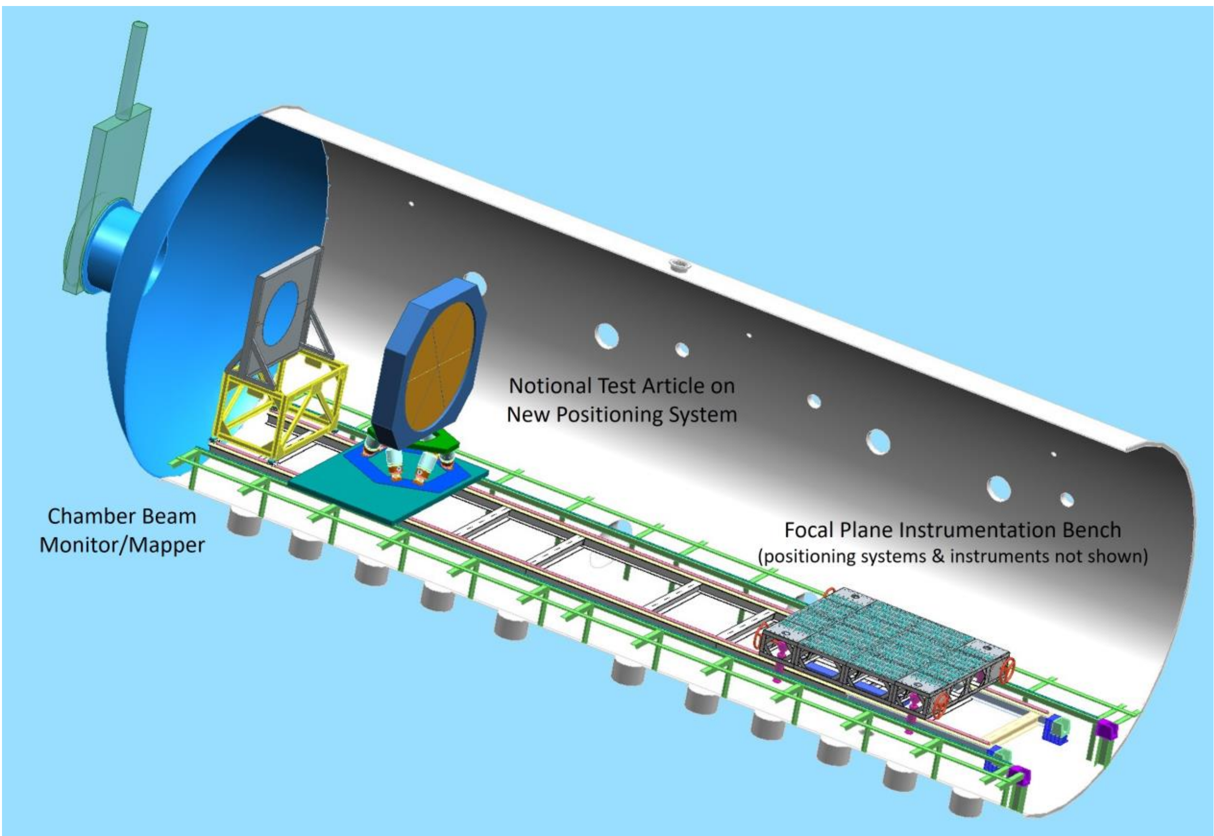

Figure 2. XRCF Chamber Interior.

2. X-RAY SOURCE AND INSTRUMENTATION

2.1 X-ray Source

The Chandra-era Electron Impact Point Source (EIPS) remains the primary x-ray source at the XRCF. Emitted x-rays traverse an evacuated 518-meter-long guide tube to the instrument chamber through a series of baffles designed to block unwanted reflections from the tube walls. The final baffle limits the divergence of the generated beam to 9.65 arcminutes resulting in a 1.45-meter beam diameter at the chamber entrance. The point source generates discrete x-ray lines and bremsstrahlung using various anodes with anode voltages between 0 and 40 KV. The emitted x-rays can be filtered using filters of 2 or 4 optical density, used alone or in combination. X-ray flux is dependent on the anode, the anode voltage and current, and the total optical density of filters used. Lines between 0.1 and 10 KV can be generated with total line and continuum fluxes at the instrument chamber up to 1000 photons/cm^2/second/mA using the available anodes and filters. The x-ray source spot size is 0.5 mm in diameter which subtends a 0.2 arcsecond angle at the instrument chamber. The x-ray source power supply settings are monitored and can be controlled by the recently updated X-ray Data Acquisition and Control System (XDACS). X-ray filters are operator-selected through XDACS and are mounted within a vacuum chamber in two independently controlled filter wheels each containing 32 filters. The filter wheel control system has also been recently updated along with the system controlling the filter chamber vacuum valves.

2.2 Beam Monitors

The x-ray beam is monitored within the guide tube and in the instrument chamber, 37m and 524m from the point source respectively, using fixed and mapping x-ray detectors at both locations. The mapping detectors are mounted on 2-D motion stages with ranges of motion exceeding the beam size at the mapper's location and sub-micrometer position resolution. The beam mapping detectors at the guide tube location include an Amptek Silicon Drift Detector (SDD) and the original Chandra-era Flow Proportion Counter (FPC) with selectable 1,4,12, or 36 mm diameter apertures. An additional fixed position Amptek SDD replaces the original Chandra-era germanium (Ge) Solid-State Detector (SSD) at the same location. Two additional Amptek detectors are used in the instrument chamber to map and monitor the x-ray beam. The detectors can be used to measure the x-ray beam flux, energy distribution, spatial uniformity, and temporal stability, and the beam can be monitored as the test optic is illuminated. The Amptek detectors have silicon nitride (Si_3N_4) windows with an aluminum coating, a response range between 0.26 and 30 KeV, and 0.5 cm^2 area circular apertures. The FPC uses a 90:10 mixture of argon and methane gases (P10) at 400 Torr, a polyimide ($C_{22}H_{10}O_4N_2$) window with an aluminum coating, and has a response range between 0.15 and 10 KeV.

2.3 Focal Plane Instrumentation

X-ray detectors at the focal plane of the test optic include another Amptek Silicon Drift Detector (SDD) and a Princeton Instruments PI-MTE3 camera with an external shutter and optional visible light blocking filters. The camera's detector is a back-illuminated, scientific grade, 6 cm x 6 cm Charge-Coupled Device (CCD) array with 4096 x 4096 - 15 um square pixels. The Amptek detector replaces the Chandra-era focal plane FPC and SSD, and the camera is used in place of the original High-Speed Imager (HSI) microchannel plate. The instruments are currently mounted on a Chandra-era 3-D motion stage with sub-micrometer resolution and are used to characterize such test optic performance parameters as the Point Spread Function (PSF), the Half-Energy Width (HEW), and the Effective Area (EA).

3. X-RAY DATA ACQUISITION AND CONTROL SYSTEM

Since much of the Chandra era X-ray data acquisition and control system (XDACS) hardware is obsolete, hardware and software updates have recently been installed and verified for the control, data acquisition, monitoring, analysis and logging functions of the X-ray Source and Detection Systems. The XDACS consists of the computers, hardware devices/controllers, software, and isolated network required to perform these functions. See Figure 3.

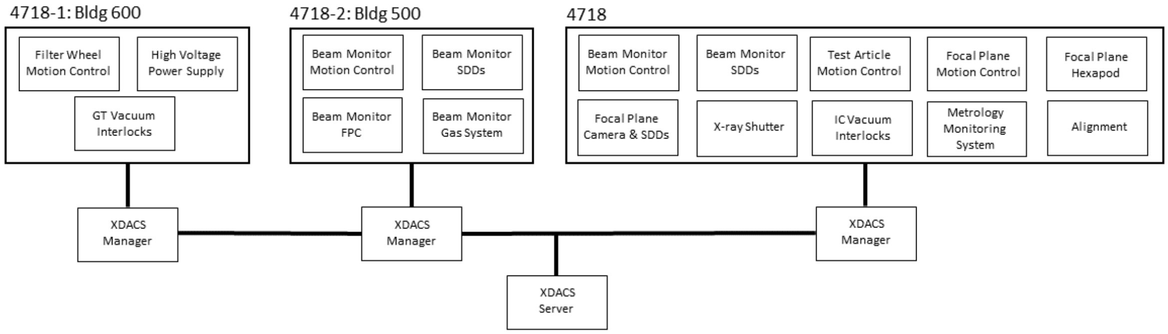

Figure 3. XDACS Block Diagram.

4. ALIGNMENT AND METROLOGY MONITORING SYSTEM

The XRCF maximum beam diameter is ~1.46m at the optic under test. To characterize and calibrate optics with larger apertures, it is necessary to develop the capability to perform sub-aperture testing. Sub-aperture illumination testing in a diverging beam and subsequent data stitching requires precise knowledge of the optic and detector positions during the calibration. See [3].

4.1 Initial Alignment

The facility is equipped with an alignment telescope assembly (ATA) and an alignment laser (AL) located near the x-ray source. A co-aligned telescope, the auxiliary alignment telescope (AAT), is located on-axis in the cleanroom. Using the x-ray source limiting apertures these telescopes and the laser can be coaligned with the x-ray axis (XRA) to provide a visual reference for the facility's x-ray axis [the facility optical axis, FOA].

The plan being developed and demonstrated first aligns the focal plane instrumentation to the FOA and thus the XRA. Next, the test article (mirror) is aligned to the focal plane instrumentation. Tools enabling this activity are described below:

<u>Permanent Reference Structure (PRS)</u>

The PRS is a stable, fixed point inside the vacuum chamber that has a retroreflector and an optical flat. These components will be coaligned to the FOA prior to test article installation.

<u>Test Article Reference (TAR)</u>

The TAR is a retroreflector and an optical flat set that defines the test article's optical axis and has been co-aligned and installed on the test article by the test article owner.

<u>Centroid Alignment Tools (CATs)</u>

The CATs system is located on the focal plane instrumentation bench and consists of a laser and position sensing detectors (PSD). The CATS will illuminate both the PRS retro and flat and monitor the return on the PSDs to align the focal plane instrumentation bench to the FOA in shear and rotation respectively. Similarly, the CATs will illuminate the TAR retro and flat to align the test article to the focal plane instrumentation. The concept for CATs system is shown in Figure 4.

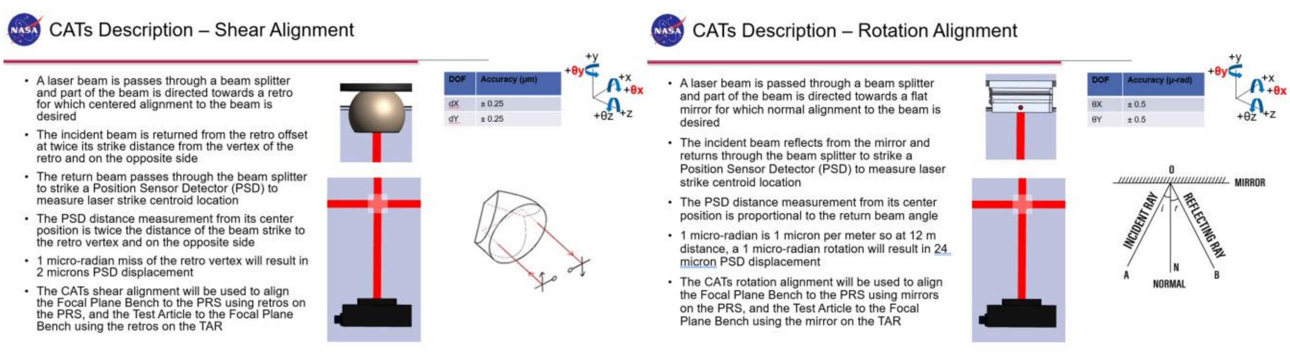

Figure 4. Centroid Alignment Tools. Credit: Kratos SRE.

4.2 Positioning Monitoring

Once initial alignment is complete, monitoring the relative position of the mirror with respect to the focal plane instrumentation in six degrees of freedom (6DOF) during test operations will be accomplished by creating a virtual hexapod. Rather than controlling 6DOF motion by changing leg length as in done in traditional hexapods, the virtual hexapod calculates relative 6DOF changes in position by measuring changes in “leg” length. Only six “legs” are required but for redundancy and improved accuracy, nine discrete displacement measuring interferometers (DMIs) between three reference points on the focal plane instrumentation bench and three points on the test article are used as shown in Figure 5. The DMIs are unique in that the laser beams can be steered before entering their respective reference optics without loss of continuous measurement of “leg” length to the test article targets. The steering capability allows for needed range of motion of the test article while tracking its 6DOF motion relative to the focal plane instrumentation. Injecting steerable DMI’s into a vacuum chamber to monitor test article motion is derived from heritage testing performed on the JWST backplane at the XRCF as well as legacy ties to instrumentation used to track the position of the JWST Optical Telescope Element for many weeks during optical testing at Johnson Space Center.

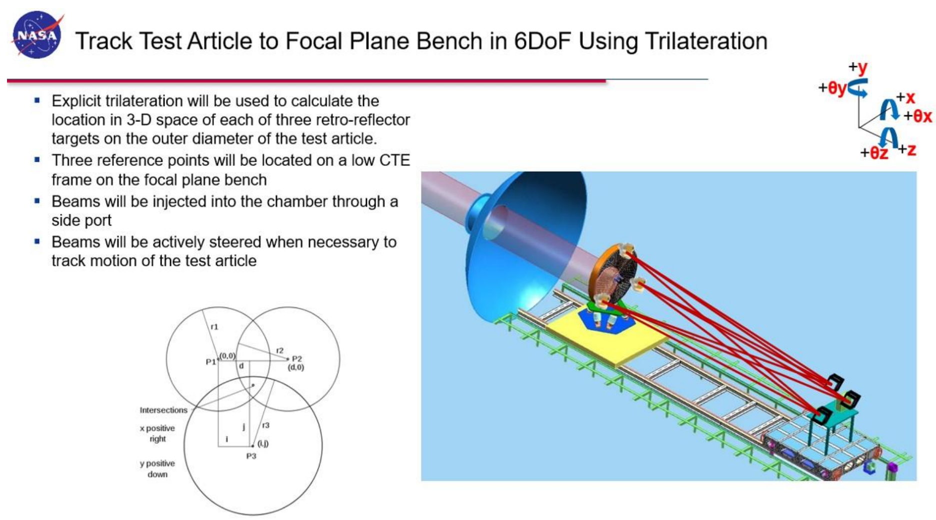

Figure 5. Virtual Hexapods. Credit: Kratos SRE.

5. FOCAL PLANE INSTRUMENTATION POSITIONING SYSTEM

While the Chandra-era focal plane instrumentation positioning system will be retained at the XRCF, a new system with increased range is being acquired. The focal plane instrumentation and position monitoring metrology will be mounted on a common bench in the focal plane. This bench will in turn be mounted on motion stages to accommodate the anticipated large range necessary for multiple sub-aperture measurements and the resolution necessary for precise x-ray measurements. These motion stages will consist of a 3-Axis linear mount and a commercially available hexapod. This positioning system is being provided by Moog, Inc. in Golden, Colorado. A concept of this positioning system is shown in Figure 6.

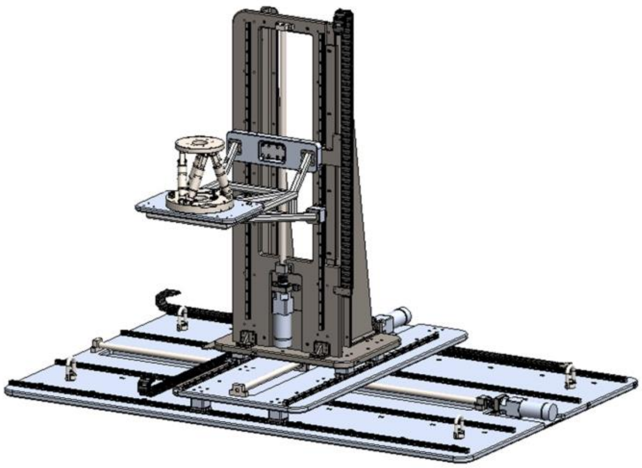

Figure 6. Focal Plane Positioning System Concept. Credit: Moog, Inc.

5.1 3-Axis Mount

The base of the focal plane instrumentation bench will be a 3-Axis Mount. This mount enables the large range of motions required in focus (X), horizontal (Y), and vertical (Z). The ranges and step sizes for these axes is given in Table 1 below:

Table 1. Focal Plane 3-Axis Mount Range and Minimum Step Sizes.

Axis	Range	Minimum Step Size
Focus (X)	1 m	500 µm
Horizontal (Y)	2 m	500 µm
Vertical (Z)	1 m	500 µm

5.2 Focal Plane Hexapod

A commercially vacuum-compatible hexapod is proposed to perform precision motions for the focal plane instrumentation bench. The hexapod is model H-850.H2V by PI (Physik Instrumente) USA. The ranges and step sizes for these axes is given in Table 2 below:

Table 2. Focal Plane Hexapod Range and Minimum Step Sizes.

Axis	Range	Minimum Step Size
Focus (X)	100 mm	1 µm

Horizontal (Y)	100 mm	1 µm
Vertical (Z)	50 mm	1 µm
Theta X (roll)	30 deg	5 µrad
Theta Y (pitch)	30 deg	5 µrad
Theta Z (yaw)	60 deg	5 µrad

6. TEST ARTICLE POSITIONING SYSTEM

As with the focal plane systems, the Chandra-era test article positioning system will also be retained at the XRCF. A new system with increased range and capacity is being acquired to accommodate larger diameter test articles. The new test article positioning system will consist of a transportation base plate used to transfer the test article and associated motion stages into the vacuum chamber, a single axis linear translation stage used to position the test article in the x-ray beam, and a hexapod for precision movements of the test article in the x-ray beam. The hexapod, by CSA Engineering (now Moog, Inc.), was originally utilized by the James Webb Space Telescope test program and is being repurposed for use at the XRCF. This test article positioning system which has a capacity of over 4,000 kg is being provided by Moog, Inc. in Golden, Colorado. A concept of this positioning system is shown in Figure 7.

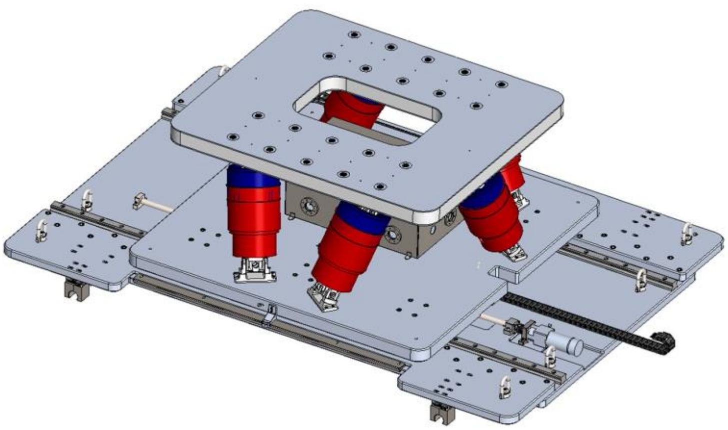

Figure 7. Test Article Positioning System Concept. Credit: Moog, Inc.

6.1 1-Axis + Transporter

The 1-Axis + Transporter will interface to the chamber's rail system and accommodate installation of the test article into the vacuum chamber. The 1-Axis motion stage atop the transporter will allow for gross positioning of the test article in the x-ray beam. This 1-Axis stage will have a range of 1.5m with a minimum step size of 500 µm.

6.2 Hexapod

This vacuum-compatible hexapod originally designed and built for the JWST program is being repurposed for use in the XRCF as a test article positioning system. Details of the JWST hexapod can be found in [4]. It incorporates a new, larger top deck that will interface to test articles and can support 4,000 kg. The range and step size of this hexapod is shown in Table 3.

Table 3. Test Article Hexapod Range and Minimum Step Sizes.

Axis	Range	Minimum Step Size
Focus (X)	300 mm	1 µm

Horizontal (Y)	300 mm	1 µm
Vertical (Z)	170 mm	1 µm
Theta X (roll)	4 deg	5 µrad
Theta Y (pitch)	4 deg	5 µrad
Theta Z (yaw)	≥ 4 deg	5 µrad

7. CONCLUSION

Over the past 18 months, several updates and upgrades have been completed and functionally demonstrated. Outstanding items include the commissioning of the new focal plane and test article positioning systems in conjunction with the demonstration of the metrology systems. Once completed, the XRCF capabilities will be ready to enable characterization and calibration of future large aperture x-ray missions.

REFERENCES

[1] Eng, Ron, "Newly Modified Cryogenic Optical Test Facility at the Marshall Space Flight Center," Proc. SPIE 4131, (2000).
[2] Kegley, Jeff, "Improved cryogenic testing capability at Marshall Space Flight Center's X-ray Cryogenic Facility," Proc. SPIE 6265 (2006).
[3] Madsen, Kristin, "Simulations of the ATHENA performance verification testing at XRCF," Proc. SPIE 12181 (2022).
[4] Sneed, Ryan, "Six degrees of freedom, sub-micrometer positioning system for secondary mirrors," Proc. SPIE 7733 (2010).