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Abstract. A metrology system to measure the on-orbit movement of a ten meter mast has been built for the Nuclear Spectroscopic Telescope Array (NuSTAR) x-ray observatory. In this paper, the metrology system is described, and the performance is measured. The laser beam stability is discussed in detail. Pre-launch alignment and calibration are also described. The invisible infrared laser beams must be aligned to their corresponding detectors without deploying the telescope in Earth's gravity. Finally, a possible method for in-flight calibration of the metrology system is described. [DOI: 10.1117/1.OE.51.4.043605]

Subject terms: NuSTAR; metrology system; alignment.

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1 Introduction

The Nuclear Spectroscopic Telescope Array (NuSTAR) is a small explorer mission designed to measure hard x-ray emissions (6 to 80 keV) from black holes, characterize supernova remnants, and observe the most extreme objects in the Universe. The NuSTAR x-ray telescope consists of two co-aligned grazing incidence angle x-ray mirrors, coated with depth-graded multilayers, and focused onto two cadmium-zinc-telluride pixel detectors that are separated from the mirrors by ~10 meters. The two telescopes are operated independently and the sensitivity of the mission is achieved by combining exposures from the two telescopes. The long focal length required by the hard x-ray optics demands the use of a ~10 meters extendable mast. A rendering of the observatory is shown in Fig. 1.[1,2]

2 Metrology System

The data produced by NuSTAR must be capable of determining the origin (in celestial coordinates) of all detected x-ray photons during post processing. However, solar heating of the mast will cause lateral movement of the optics with respect to the detectors of several millimeters during each orbit. A metrology system for measuring and recording these relative movements is necessary to precisely determine the source position.

The metrology system includes both a star tracker and two laser-detector pairs illustrated in Fig. 1. (The second laser-detector pair is located at the back of the satellite as shown in the figure and is not visible.) The star tracker is

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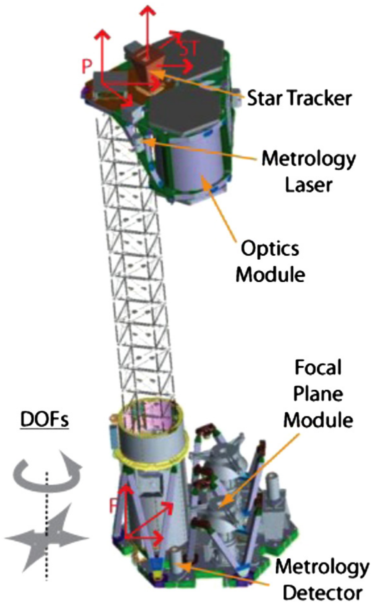

Fig. 1 Rendering of the NuSTAR Observatory.[3] DOF = Degrees of Freedom.

rigidly mounted to the optical bench and provides complete attitude information for the optical bench with respect to the celestial coordinate system (J2000); that is, the star tracker defines the attitude of the optical bench. There is also a 6-degrees of freedom (DOF) transformation between the optical bench and the focal plane bench. The metrology lasers are not required to measure all 6 DOFs. Because the distance (along the axis of the mast) between the two benches is ~10 meters and thermal variations predicted in this direction would introduce such a small error (less than ~0.1 arcseconds) it is not necessary to measure this distance. Also, because the error is expected to be very small (less than 1 milliarcsecond), the metrology lasers do not measure the angle of the focal plane bench relative to the optical bench (i.e., deviations from the nominal parallelism of the benches). Note that this does not imply that the absolute tip and tilt of the optics bench with respect to the stars is ignored. All such motion is detected by the star tracker mounted on the optics bench.

The metrology lasers measure only translation in 2 axes (those directions transverse to the laser beams) and a clocking angle (rotation about the mast axis). Only these 3 DOFs have the potential to introduce errors large enough to warrant measurement. The motions at the focal plane bench due to these DOFs are shown with arrows in Fig. 1. A metrology system with the described features can be implemented with a star tracker on either bench and any two independent fiducials tracked between the benches. NuSTAR has chosen to locate the star tracker on the optics bench, so it can be co-aligned with the telescopes, which is the optimal configuration.

When the observatory is commissioned after deployment of the mast on orbit, the observatory performs an in-flight calibration to establish launch shifts and the deployed position of the mast. This is done using two bright x-ray sources with known celestial coordinates (or the same bright x-ray source at different locations on the detector), and simultaneously logging star tracker data, laser metrology data, and x-ray detector data.

During operation, the positions of the laser beams on the position sensitive detectors (PSD) are continually recorded at a frequency much higher than that of the mast oscillations. Also, all star tracker updates are recorded along with the time and locations on the focal plane where the individual x-ray photons impinge. All this information is used to generate high-resolution images during on-ground post processing of data. It should be emphasized that the x-ray detectors are not integrating detectors; they detect single x-ray photons. The described metrology system would not work with an integrating detector [such as a charge-coupled device (CCD) chip] that does not register the arrival time of the individual photons, since the unique aspect solution of the observatory at a certain instant could not be applied to a given detector read-out. For details on operation of the metrology system refer to Ref. 3.

3 Implementation

The detectors for the metrology lasers are based on a 20-mm square PSD. The two-dimensional PSD is a large photodiode that is able to detect the centroid of a light spot falling on its surface in two dimensions. It is possible to get PSD chips with dimensions up to 45 mm on a side, but a trade study on the maximum travel distance for the mast determined that only a ~20-mm PSD chip was required. The metrology system must operate over a relative movement range at the PSD of $\pm \sim 6$ mm in any one axis. To attenuate background signals in the detector, stray light baffles are located above the detector and a laser bandpass filter is mounted in front of the PSD detector. To remove any remaining background signals, the laser beam is toggled on and off for a short period four times a second, and a background measurement is made. The latest background measurement is then subtracted from the corresponding laser signal measurement.

The metrology laser can emit up to 200 mW at 830 nm. It is focused to a spot size of a few millimeters on the PSD detector that is located at a distance of ~10 meters from the metrology laser. This is achieved utilizing a single aspherical lens and a 6 mm aperture. Figure 2 shows a picture of the laser spot on the PSD. Figures 3 and 4 are photos of the flight metrology detectors and a flight metrology laser. For details on the design and fabrication of the metrology system, see Ref. 4.

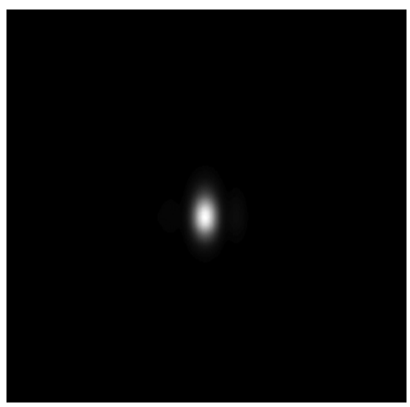

Fig. 2 Image of the laser spot from the metrology laser at ~10 meters distance. The black area of the image represents 20×20 mm (same as the PSD chip).

Fig. 3 Picture of the flight metrology detectors. The big black cylinder on top is the sun stray light baffle.

Figure 5 is a sketch of a metrology laser/detector pair. The metrology laser, mounted on a rigid optical bench, is shown on the left, illuminating a metrology detector on the right. The observatory (laser) optical bench is defined by 3 points: $(X_{\mathrm{ob1}}, Y_{\mathrm{ob1}}, Z_{\mathrm{ob1}})$, $(X_{\mathrm{ob2}}, Y_{\mathrm{ob2}}, Z_{\mathrm{ob2}})$ and $(X_{\mathrm{ob3}}, Y_{\mathrm{ob3}}, Z_{\mathrm{ob3}})$. These points are defined by spherical mounted retroreflectors (SMR). The optics bench coordinate system (CS) axes can be defined as follows: the X axis is the unit vector from point 2 to point 1 on the optical bench; the Y axis is defined as the unit vector going from point 2 to point 3 on the optical bench; the Z axis is the cross product of the X and Y vectors; and the origin is at point 2. The center of the metrology detector is located at $(X_{\mathrm{dc}}, Y_{\mathrm{dc}}, Z_{\mathrm{dc}})$.

Technically, the most challenging aspect of the metrology system design is to keep the laser beam sufficiently stable (to make sure that the point $(X_{\mathrm{dc}}, Y_{\mathrm{dc}}, Z_{\mathrm{dc}})$ does not change its x and y value with respect to the metrology laser coordinate system). Because the distance between the laser lens and the laser diode is so small (∼2 cm) compared to the focal length of the telescope (∼10 meters), any relative movement in the lens/diode assembly results in a comparatively large movement of the spot on the PSD chip. The requirement for laser beam stability is ∼100 microns. In other words, the lateral stability between the laser and the laser optics has to be $100\ \text{microns}/10\ \text{meters} \cdot 2\ \text{cm} = 200\ \text{nm}$. The following steps have been taken to ensure that this stability requirement is satisfied: the metrology laser housing is primarily manufactured from Invar 36 to minimize movement due to temperature changes. Thermal labyrinths and two thermal shields stabilize the structure and minimize thermal gradients. In addition, active thermal controls are employed to keep the unit stable to ∼1 °C on orbit.

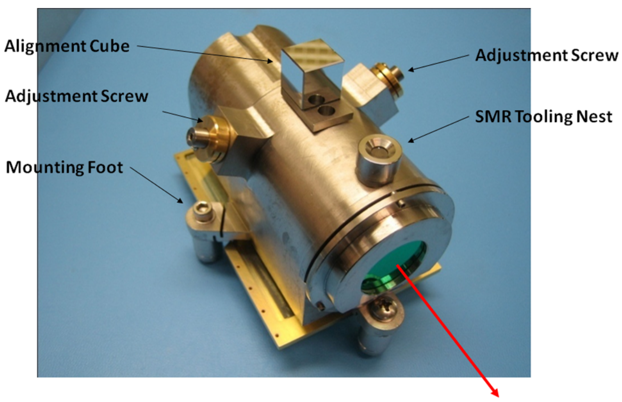

Fig. 4 Picture of a flight metrology laser. Alignment cube and SMR tooling nest are the features on the top. The two screws are adjustment screws for the beam pointing. The laser beam exits though the green-tinted band pass filter at the front of the housing. The alignment cube and SMR tooling nests are used for developmental testing. They are not used during the final alignment procedure described later in this paper.

Many of the laser parts are bonded together using epoxies. Because very small movements of the laser components can cause a large displacement of the laser beam at the detector, the positional stability of these epoxy bonds was a concern and special fixtures and procedures were developed to minimize this. The laser lens is first bonded to its supporting cylindrical barrel, cured according to the manufacturer's specifications, then thermally cycled to reduce subsequent movement. The laser diode is separately bonded into its boron nitride mount (to provide thermal conductivity and electrical isolation) and then into a focusing sleeve. After a complete cure, the diode and lens assemblies are focused in a jig, bonded, and clamped until the epoxy cures. The laser remains powered on during the bonding and curing steps, and the focus is verified before and after curing. At different points during assembly and environmental testing, the laser subassemblies and the complete unit are subjected to thermal cycles to ensure that the epoxy is fully cured. Finally, during integration of the laser to the NuSTAR spacecraft, the metrology laser is exposed to room humidity for a period of ∼1 year.

To investigate the stability of the laser spot position with time, a kinematic mounting fixture was designed and fabricated. The laser was placed on the fixture at various points in the test and assembly flow, and the position of the spot at a distance of 10 meters was recorded. The result of 7 measurements for one laser and 10 measurements for a difficult laser are shown in Fig. 6. The data points are $(X_{\mathrm{dc}}, Y_{\mathrm{dc}})$ in a metrology laser coordinate system.

In Fig. 6, it is observed that the laser beam can shift as much as 3 mm during a TVAC cycle. A 3-mm shift of the laser beam at ∼10 meters corresponds to a lateral shift of the laser diode of 5 microns relative to the lens. Three mm is the maximum shift acceptable given the size of the metrology detector from this specific error contribution. We believe that the bulk of this movement is the result of water taken up by the epoxy after a TVAC cycle, which causes lateral movement of the lens within its Invar cylinder. It should be emphasized that one of the first tasks to be undertaken when the observatory is commissioned is an in-flight calibration to quantify this and other shifts. The issue of the hygroscopic properties of epoxy and the in-flight calibration will be described later in this paper. During flight there is no humidity and a stable thermal environment is maintained within ∼1 °C; therefore, it is not expected to cause problems. The shape of the laser spot has also been examined, but its shape does not change with time. To further investigate laser beam pointing stability, a series of measurements were conducted at various temperatures. The laser beam spot position was measured at a

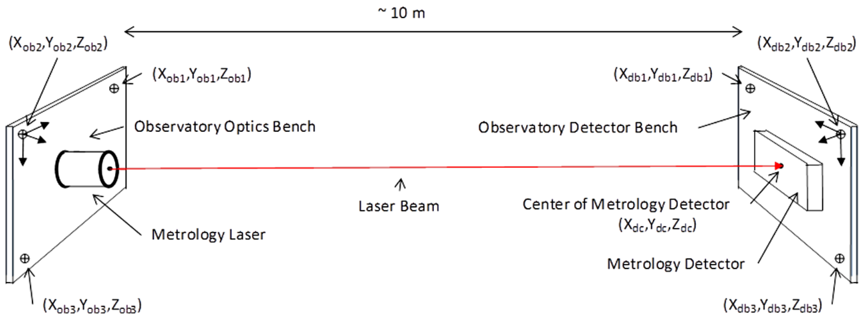

Fig. 5 Sketch of a metrology laser-detector pair and coordinate systems in flight configuration.

distance of ∼10 meters from the metrology laser. In separate trials, two metrology lasers were heated from ∼19 °C to ∼28 °C (flight nominal temperature is 17 ± 1.5 °C at the adjustment screws). The results of these tests are shown in Fig. 7. Again, the data points are (X_{dc}, Y_{dc}) in a metrology laser coordinate system.

In Fig. 7, it is observed that the laser spot position changes ∼300 microns when the temperature is changed ∼9 °C, or approximately 35 microns/°C. The laser spots moved in different directions because: (1) the actual epoxy bond between the lens and structure is different in each assembly, and (2) the details of the interaction of the tip of the adjustment screws with the bearing surface of the inner barrel differs in each unit.

During the tests, the metrology lasers were heated using the internal operational heaters, and the units were thermally connected to a very large aluminum structure. The thermal gradients are likely to be different than an actual flight scenario. Thermal simulations show that the temperature of the metrology laser adjustment screw will change ±0.5 °C over the orbit. This corresponds to ∼20 microns, well within the total requirements allocation of ∼100 microns.

Epoxy is hygroscopic, and has a typical expansion coefficient of 3,200 ppm/% (mass) of absorbed humidity. Epoxy can absorb up to ∼3.5% (of mass) humidity*.[5] Therefore, dry epoxy can expand ∼1% when saturated with humidity. Humidity expansion and thermal expansion of epoxy acts somewhat similarly. A typical thermal expansion coefficient of epoxy is 100 ppm/C. In other words, heating epoxy 100°C will cause the same expansion as saturating dry epoxy with moisture. In Fig. 7, the thermal motion was estimated to be ∼35 microns/°C. Therefore, the laser beam will shift its position by ∼3.5 mm when heated to 100°C or completely saturated by humidity. This is consistent with the observations presented in Fig. 6, where shifts during TVAC (removing moisture) of ∼3 mm were observed. Due to this phenomenon, metrology laser exposure to humidity is limited before alignment and calibrations, and they are stored in nitrogen dry boxes. After launch, the water vapor will evaporate and move the laser beam back to the original position.

4 Metrology Detector Calibration

Because the laser beam spot is not a point as it approaches the edge of the PSD chip, a portion of the spot will fall outside the active area of the PSD chip and the calculated centroid of the spot will be shifted towards the center of the PSD chip. In addition, the response of the PSD chip is not completely linear. Both of these issues require that each detector be calibrated with its corresponding laser. It is required that the position of the centroid of the spot be measured to better than 70 microns.

A metrology laser/detector pair is calibrated by mounting a detector on a precision X-Y stage on a rigid structure.

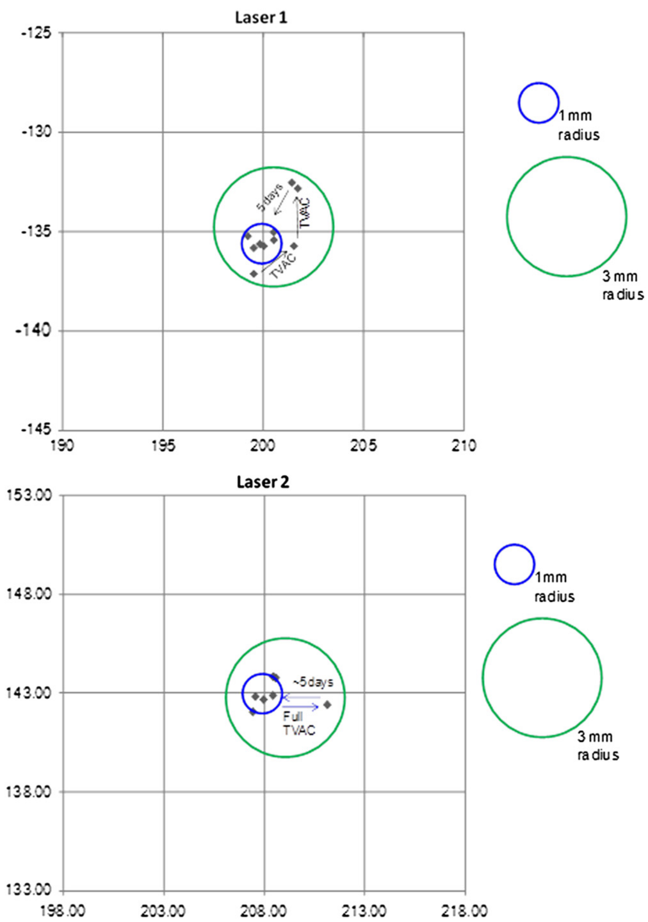

Fig. 6 Graph showing the laser beam pointing of a metrology laser over a period of ∼6 weeks. The units on the axes are in mm. The absolute numbers are arbitrary. It is observed that the laser spot converges towards an equilibrium position. The measurement uncertainty is ∼0.5 mm. When the laser is subjected to a Thermal Vacuum (TVAC) cycle the laser spot moves ∼3 mm (moisture is removed during TVAC). The laser beams appear to return to the equilibrium position when it has absorbed moisture again.

*The moisture uptake and thermal expansion is for a representative epoxy. No data was available from the specific vendor of the flight qualified epoxy.

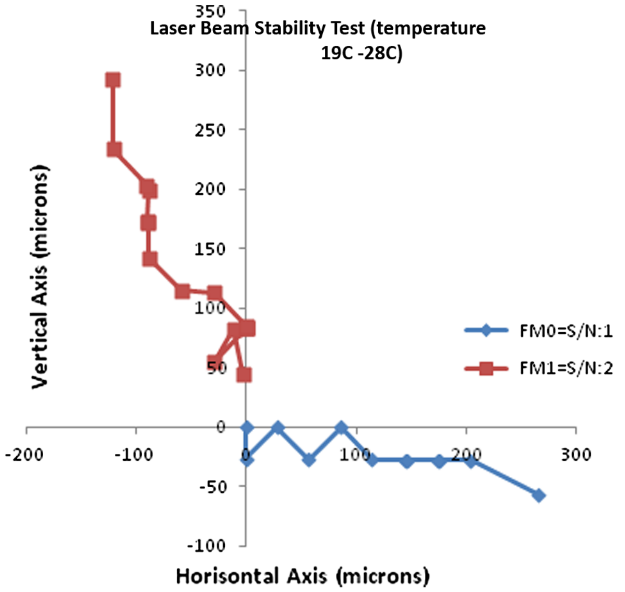

Fig. 7 Laser positions at ~10 meters when the temperature is increased from ~19°C to ~27 °C.

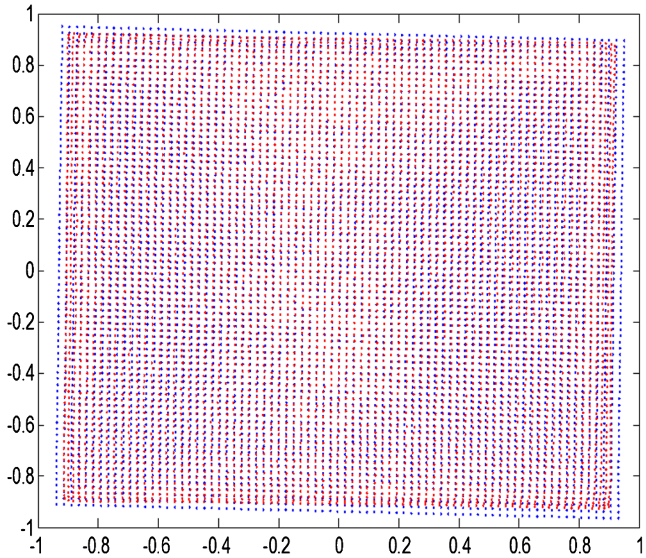

Fig. 8 Result of accuracy testing of the metrology detector. The metrology system is calibrated over an area of ±9.5 mm. The red dots are the measured positions. The blue dots are model points that are fitted to the data. For details on the calibration, see Ref. 6.

The corresponding laser is mounted on another rigid structure ten meters away and the beam is focused on the PSD chip. The *X-Y* stage then steps the detector in a rectangular grid pattern, recording the position of the spot every 0.25 mm. After every 100 measurements, the detector is returned to the home position at the center of the chip to detect any shifts in the setup.

During these tests the laser beam travels a distance of 10 meters in air and it is subjected to air turbulence. A test was conducted where the position of the stationary laser spot was recorded with a sampling frequency of 1 KHz at a distance of 10 meters. When the laser spot position was averaged over a period of 1 second, the laser spot centroid noise was less than 7 microns due to atmospheric turbulence. Therefore, each data point is averaged over 1 second for the calibration. This error can be ignored compared to the overall calibration residual.

Figure 8 shows a picture of the measured laser beam positions recorded on a grid with a spacing of 0.25 mm. The measured uncalibrated position is better than 80 microns over the central ±7 mm. More formally, the metrology laser coordinate system is fixed and the detector bench coordinate system defined by (X_{ob1}, Y_{ob1}, Z_{ob1}), (X_{ob2}, Y_{ob2}, Z_{ob2}), and (X_{ob3}, Y_{ob3}, Z_{ob3}) is moved in the x and y coordinate. Based on the data shown in Fig. 8, X and Y correction functions are constructed based on interpolation. The X correction function corresponding to Fig. 8 is shown in Fig. 9.

5 Laser Beam Alignment

The metrology laser beam must intercept the center of the metrology detector (X_{dc}, Y_{dc}) to achieve maximum operational range. Alignment of the system is complicated by the fact that the infrared laser beam is invisible to the human eye and not eye safe, and because the NuSTAR observatory 10-meter mast cannot be deployed during alignment due to gravity. Therefore, the laser beam has to be aligned without any direct verification of the alignment accuracy.

According to the mechanical computer aided design (CAD) model of the NuSTAR observatory, the coordinates for the three SMR targets on the optics bench are: (X_{ob1}), (X_{ob2}, Y_{ob2}, Z_{ob2}), and (X_{ob3}, Y_{ob3}, Z_{ob3}). The laser is supposed to point at the point with the following coordinate: (X_{dc}, Y_{dc}, Z_{dc}) in an optical bench coordinate system. Deployment tests in a simulated zero-g environment (not described in this paper) have experimentally shown that the detector actually deploys to the position described in the mechanical CAD model.

Special support equipment that can measure the position of the laser beam spot has been constructed (see Fig. 10). A PSD chip is mounted on a rigid aluminum plate, which is in turn mounted on a precision *X-Y* stage. Four SMRs are also mounted on the aluminum plate. The position of the four SMRs with respect to the PSD chip is precisely determined by surveying the plate using an optical coordinate measuring machine. The *X-Y* stage is manipulated to bring the laser spot to the center of the PSD chip and the position of the four SMRs[†] is then recorded using a laser tracker.[‡]

The actual alignment is performed by following these steps:

1. The laser tracker measures the position of (X_{ob1}, Y_{ob1}, Z_{ob1}), (X_{ob2}, Y_{ob2}, Z_{ob2}) and (X_{ob3}, Y_{ob3}, Z_{ob3}).[7] This is shown in step 1 in Fig. 11.

[†]An SMR target is a steel sphere (typical 0.5 inch diameter). Inside the sphere is mounted a corner cube that will reflect red laser light. The center of the corner cube is always the same, independent of the angular position of the sphere. The sphere can be attached to a magnetic tooling nest. The repeatability of mounting the SMR is very high.

[‡]A laser tracker is a surveyor's instrument. It is a heavy instrument that can be placed arbitrary in a room on a tripod. It needs a clear line of sight to the SMRs to be measured. The laser tracker is either manually or automatically aimed at the SMR that needs to be measured. The laser tracker then measures the distance to the SMR and the azimuth/elevation of the SMR. The laser tracker has sophisticated software that makes it possible to transform measurement points between different coordinate systems.

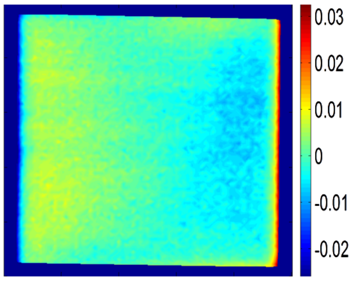

Fig. 9 The correction function for the x-coordinate of the PSD reading. The picture covers an area of −10 mm to +10 mm in both axes. This is a false color scale. Red means that a large number should be added to the measured X-position. Blue means that a large number should be subtracted from the measured X-position. The reason this function is not more symmetric in the X `and Y direction is that this is the correction function for X. When the laser beam "falls" of the PSD chip on the top or bottom, it will shift the Y coordinate, but there is no significant shift in the X-correction function. The Y correction function looks very similar to this figure but rotated 90 deg.

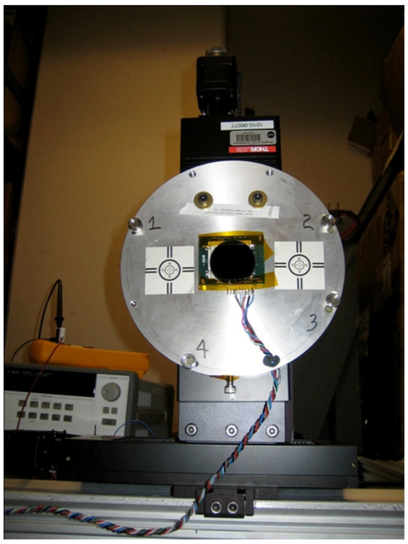

Fig. 10 The special alignment tool for measuring the interception of a laser beam. The black circle in the center of the tool is a neutral density filter covering the PSD chip to attenuate the laser signal. The mechanical features labeled 1, 2, 3, and 4 are tooling nests for the four SMRs.

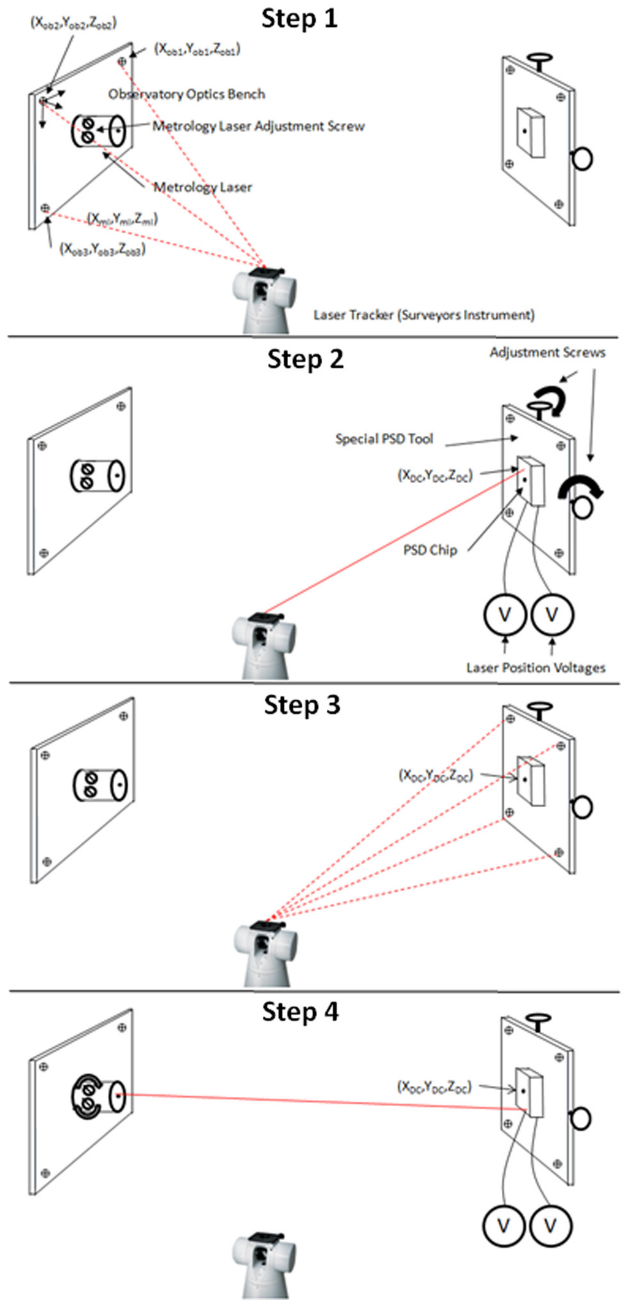

Fig. 11 Sketch of the process used to align the laser beam of the metrology laser to a virtual target.

2. The optical bench coordinate system is established by the laser tracker, by calculating the transformation between the native coordinate system of the laser tracker and the optical bench coordinate system given by the mechanical CAD model of the NuSTAR instrument.
3. The point (X_{dc}, Y_{dc}, Z_{dc}) is transformed to the laser tracker native coordinate system.
4. The laser tracker is commanded to point its red visible laser beam towards the (X_{dc}, Y_{dc}, Z_{dc}) point. This is shown in step 2 in Fig. 11.
5. At this point, the position of the special PSD tool is adjusted so the red beam from the laser tracker is centered exactly on the PSD chip. This is done by nulling out the voltages from the PSD chip. This is also shown in step 2 in Fig. 11.
6. The four SMRs of the special PSD tool are read. The position of the metrology laser interception point is calculated. Any necessary adjustments are performed. This is sketched in step 3 in Fig. 11.
7. The red laser tracker beam is turned off.
8. The metrology laser is turned on and adjusted (with the adjustment screw) so it points exactly to the same center on the PSD chip as the laser tracker did. This is done by monitoring 2 voltmeters from the special PSD tool while adjusting the 2 adjustment screws on the laser. This is sketched in step 4 in Fig. 11.

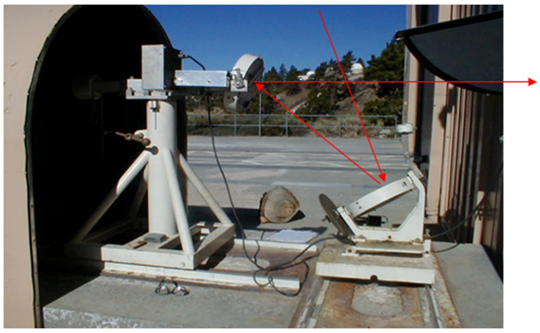

Fig. 12 Coelostat mirrors. Red arrows show the path that the sun rays traverses.

Utilizing this procedure, it was possible to point the laser beam so the error on (X_{dc}, Y_{dc}) was (−0.3 , 2.4 mm) for one laser and (−1.1 , 1.5 mm) for the other laser. The error sources for this alignment procedure are (most important first): (1) shift in pointing direction of the metrology laser when the adjustment screws are secured; (2) limited resolution of the adjustment screws on the metrology laser (it is not possible turn the adjustment screws less than a few degrees); (3) limited accuracy of the special alignment tool; and (4) limited accuracy of the laser tracker.

6 Measurement of the Sun Exclusion Angle

The sun is very bright. If the sun were illuminating the PSD chip directly, it would shift the laser centroid significantly. Therefore, the metrology detector has a sun exclusion baffle. The Field Of View (FOV) of the metrology detector is pointing in the same direction as the star tracker. The star tracker cannot operate when the sun is within 18 deg of the boresight. Therefore, it is not required that the metrology system operate within 18 deg of the sun.

A sun exclusion angle test was conducted utilizing a coelostat. The coelostat is a two-mirror device controlled by analog electronics which tracks sidereal motion and redirects sunlight into a room where the metrology detector was exposed to this constant sunlight. The walls of the room are painted back to minimize sun light reflections inside the room. Figure 12 shows a photograph of the coelostat seen from the outside. The metrology detector was mounted on a gimbal inside the coelostat room.

The signal levels generated by the sun were recorded for a number of different gimbal angles. The metrology detector was mounted at three different clocking angles relative to the gimbal motion. An example of the sun signal as function of sun angle is shown in Fig. 13.

It is observed that the stray light signal generation is below 3% (the requirement) when the gimbal is outside an angle on $\sim\pm 11$ deg. This meets the requirement on 18 deg.

7 In-Flight Calibration

As mentioned earlier, the laser beam may shift on orbit due to thermal flexing of the mast. Also, other mechanical relationships may shift during launch. As an example, the metrology detector may shift slightly relative to the metrology detector mounting feet, and the orientation of the star tracker may shift relative to the metrology lasers, etc. The NuSTAR spacecraft has a motor which can adjust the orientation of the mast's deployed position. This feature will be used in the beginning of the mission to make sure that the metrology lasers are accurately striking the metrology detectors, should the mast deployment be out of specifications. In other words, when the spacecraft is launched, commissioned, and begins to acquire data, the metrology system accuracy will be unknown, and so will the celestial coordinates of an x-ray source.

The first activity after mast deployment is the acquisition of a bright x-ray calibration source. There are ∼20 on the sky that can be used for this activity. The celestial coordinates of the bright x-ray sources are accurately known, and there is a high flux of x-ray photons from them (100 s of x-ray photons per second). The objective of this operation is to establish the direction cosine rotation matrix from the star tracker coordinate system to the x-ray telescope coordinate system. The star tracker is observing multiple stars and solves the

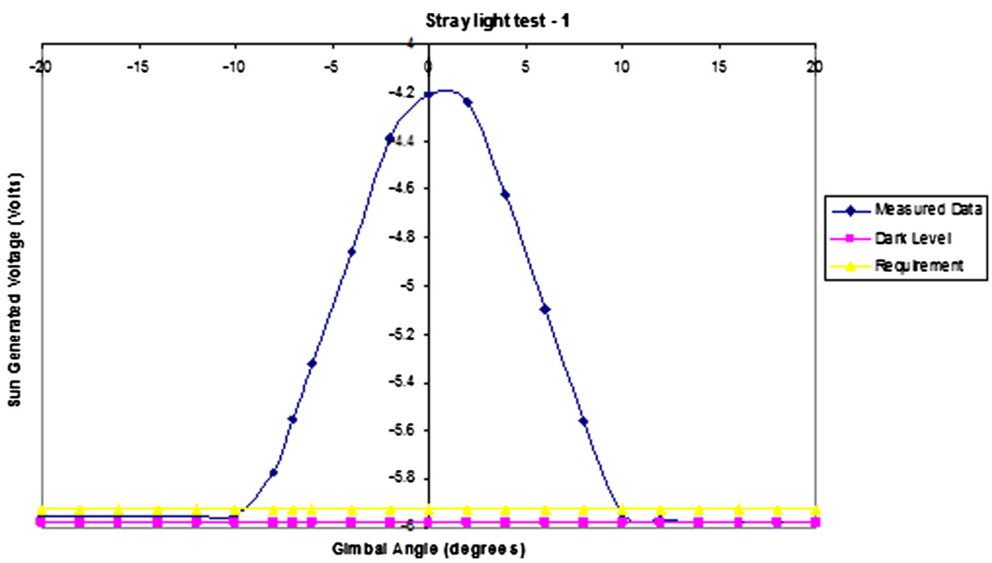

Fig. 13 Sun signal as function of sun angle.

Table 1 Key metrology system specifications.

Parameter	Value
Mass of laser/detector pair	∼1.5 kg
Uncalibrated residual of metrology detector (over central 14 mm of the detector)	∼80 microns
Laser beam shift from build to on-orbit	∼3 mm
Laser beam stability over orbit	∼50 microns
Operational range	±8 mm
Alignment accuracy	∼2 mm
Sun exclusion angle	∼11 deg

three axis attitude. However, just looking at a single x-ray source (with known celestial coordinates) establishes just one vector and one vector is not enough to establish a rotation matrix. Therefore, the bright x-ray source has to be observed at the edge of the FOV of the telescope. When the observation is complete, the observatory must be slewed to the other side of the FOV and the same x-ray has to be observed again. Based on the two vector observations, it is possible to calculate the direction cosine rotation matrix from the star tracker to the x-ray telescope. For details see the TRIAD algorithm.[8]

In this discussion, it has been assumed that the on-ground calibration as shown in Fig. 8 is still valid. It is valid, as long as the spot shape shown in Fig. 2 remains the same. No changes in the spot shapes have been observed with the flight metrology lasers. However, should a change occur in the laser spot, a backup plan has been developed for generating a new calibration on orbit. The back-up plan is as follows. The NuSTAR observatory is pointed at a bright x-ray source so a steady stream of x-ray photons hits the x-ray detector at approximately the same position on the x-ray detector. (There are statistical variations due to the point spread function of the x-ray optics.) At the same time, the metrology laser beam spot will hit the metrology detector at approximately the same location. The telescope is left in this position a few minutes until a large number of photons, say, 10,000, have been collected. The centroid of the x-rays is plotted on a model of the x-ray detectors and the average laser position on the PSD detectors is plotted on a model of the PSD detectors. The mast adjuster is then stepped to another position and this procedure is repeated. Based on many of these measurements, it is possible to reconstruct the metrology system calibration as shown in Figs. 8 and 9. Currently, there are no plans to perform this in-flight calibration.

8 Summary

This paper has discussed the metrology system on the NuSTAR x-ray observatory. The metrology system is implemented as two lasers sitting on a rigid optical bench illuminating two position sensitive detectors mounted on a rigid detector bench ∼10 meters away. The metrology lasers, used in conjunction with a star tracker, will measure the mast motion. The measured specifications of the metrology system are shown in Table 1. It has been shown that the pointing of the metrology lasers can change several millimeters when they absorb moisture before launch. The method of calibrating and aligning the lasers has been discussed in details. Finally, the sun exclusion angle has been measured.

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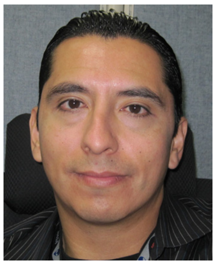

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