Metrology System for Measuring Mast Motions on the NuSTAR Mission

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Abstract—A metrology system designed and built for the NuSTAR mission is described. The NuSTAR mission is an orbiting X-ray telescope with a 10 meter focal length. The system consists of two laser pointers mounted rigidly together with a star tracker and the X-ray optics. The focused laser beams illuminates two metrology detectors mounted rigidly with the X-ray detectors. The detectors and optics/lasers are separated by a ~10 meter deployable (and somewhat flexible) carbon fiber mast. Details about the implementation of the metrology system is discussed in this paper. [1 2]

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1. INTRODUCTION

NuSTAR (The Nuclear Spectroscopic Telescope ARray) is a Small Explorer mission (SMEX) to measure hard x-ray emission (6-80 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 angle incidence x-ray mirrors, coated with depth-graded multilayers, focusing onto two cadmium-zinc-telluride pixel detectors that are separated from the mirrors by ten 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-m extendable mast. A rendering of the observatory is shown in Figure 1 [1] – [2].

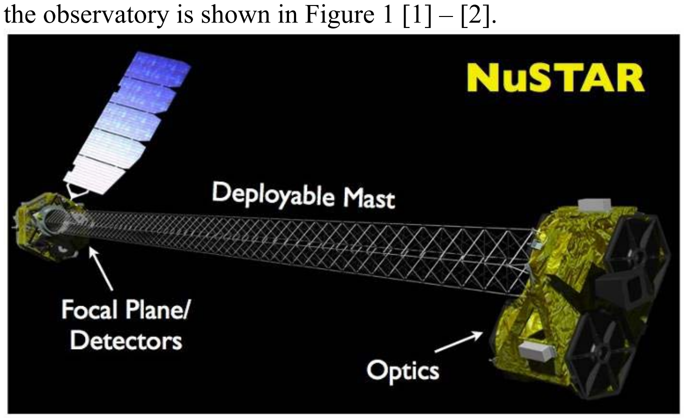

Figure 1. Rendering of the NuSTAR Observatory [1]

The observatory must determine the origin (in celestial coordinates) of all detected X-ray photons during post processing, in order to produce sharp images. This task is complicated by distortions due to thermal bending and

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external forces acting on the mast during orbit.

To track the motion of this mast, the observatory carries two metrology laser subsystems, which are mounted on the bench with the X-ray optics. The metrology lasers are focused on two metrology detectors mounted on the bench with the X-ray detectors. These metrology detectors are based on position sensitive detectors (PSD). To generate a unique aspect solution, the observatory also carries a star tracker camera on the optics (outboard) bench.

When the observatory is commissioned after launch, the observatory performs a one-time in-flight calibration of the observatory to establish launch shifts and the deployed position of the mast. This is done by observing a bright X-ray source (with known celestial coordinates), and simultaneously logging star tracker data, laser metrology data and X-ray detector data. A sketch of the metrology system diagrammed with the mast and a single telescope is shown in Figure 2.

During operation, the positions of the laser beams on the PSD detectors are continually recorded at a frequency much higher than the mast oscillations. Also, all star tracker updates are recorded and the positions (and times) on the focal plane where the individual x-ray photons impinge are recorded. 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 detect single incoming X-ray photons. That is, the X-ray detectors are not integrating. The described metrology system would not work with an integrating detector (such as a 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.

In this paper, the concept of operations and aspect generation of the entire metrology system will be described. In addition, the optical, electronics, mechanical, and thermal design of the laser metrology system, along with the space qualification process and test results, will be discussed in detail.

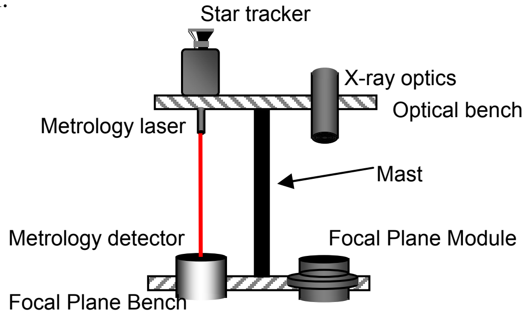

Figure 2. Simplified sketch of the NuSTAR observatory. The observatory contains two identical sets of optics, x-ray detectors and metrology systems. There is a single star tracker.

2. TRADE STUDIES

The NuSTAR metrology system is not required to measure the full 6 Degrees Of Freedom (DOFs) transformation from the optical bench to the focal plane bench. The longitudinal distance (along the axis of the mast) between the two benches is ~10 meters and thermal variations of a few mm in this direction would only introduce an error of ~0.5 microradians in the error budget. This is insignificant, and so deviations in the distance between the benches are not tracked. Also, the metrology system does not need to measure the angle of the focal plane bench relative to the optical bench (deviations from the nominal parallelism of the benches). Simulations show that this angle can change up to ~100 microradians. The corresponding error in determining the orientation of an X-ray photon is ~100 femtoradians and is therefore neglected.

The metrology system is required to measure the translation in 2 axes (those directions transverse to the laser beams) and the clocking angle (rotation around the observatory boresight). Only these 3 DOFs have the potential to introduce errors large enough that they must be measured. In Figure 3 is shown a sketch of the DOFs that need to be measured.

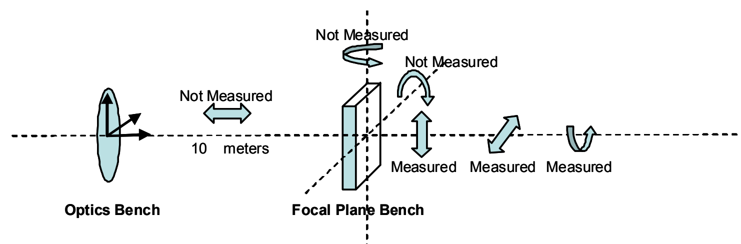

Figure 3. The DOFs that are required to be measured by the metrology system. The sketch is utilizing a coordinate system that is fixed on the optical bench (where the star tracker is mounted)

A metrology system with the described requirements can be implemented with at least 4 different architectures, based on optical fiducial tracking. The 4 different configurations are shown in Figure 4. More complicated metrology systems utilizing mirrors in combination with the configurations shown in Figure 4 have also been considered. Finally, a GPS only system was considered but not selected.

The disadvantage of locating the star tracker on the focal plane bench is that the star tracker can not be co-boresighted with the X-ray telescopes due to occultation by the optics bench. A star tracker typically has a roll accuracy that is 10 times lower than the cross boresight accuracy. In other words, the accuracy of the star tracker in the direction that the X-ray telescope is pointing will be lower in a sideward pointing configuration. In the side-mounted orientation, a separate sun exclusion orientation from the X-ray telescope would also be created. For these reasons, architectures (3) and (4) were not chosen for the NuSTAR metrology system. In architectures (1) and (2), the star tracker is mounted on the optical bench, and co-boresighted with the X-ray telescopes.

To measure a total of 3 DOFs, it is necessary that 2 independent fiducials be tracked in addition to the star tracker. The laser metrology system could either be implemented with two laser pointers on the optical bench illuminating 2 focal planes on the focal plane bench (as in architecture 1), or with two light sources (e.g. LEDs) on the focal plane bench being imaged by two target tracking cameras mounted on the optics bench (as in architecture 2). Due to cost constraints, architecture (1) was selected. In this configuration the focal plane does not have optics in front of it, making it simpler to implement. The disadvantage of this architecture is the high demands on the beam pointing stability of the metrology lasers.

3. METROLOGY SYSTEM DESIGN AND REQUIREMENTS

Architecture 1 in Figure 4 was chosen for the metrology system. The PSD detectors in the metrology detectors measure the positions of the laser beams. To attenuate the background, a narrow bandpass filter is mounted in front of the PSD detector. However, there are still residual background signals that may disturb the measurement from e.g. sun stray light on the baffle knives, dark current, the moon in the FOV etc. To remove this background the laser beam is turned off 4 times a second and a background measurement is made. The latest background signal is always subtracted from the laser signal measurement.

There is some uncertainty associated with the mast deployment, but the observatory has a mast adjustment motor to correct any static deployment errors. The requirement on the metrology system is that the metrology system is operating within specifications when the laser beam illuminates its detector inside a circle of ~6 mm in diameter relative to the nominal laser position.

A block diagram of the metrology system is shown in Figure 5 [3].

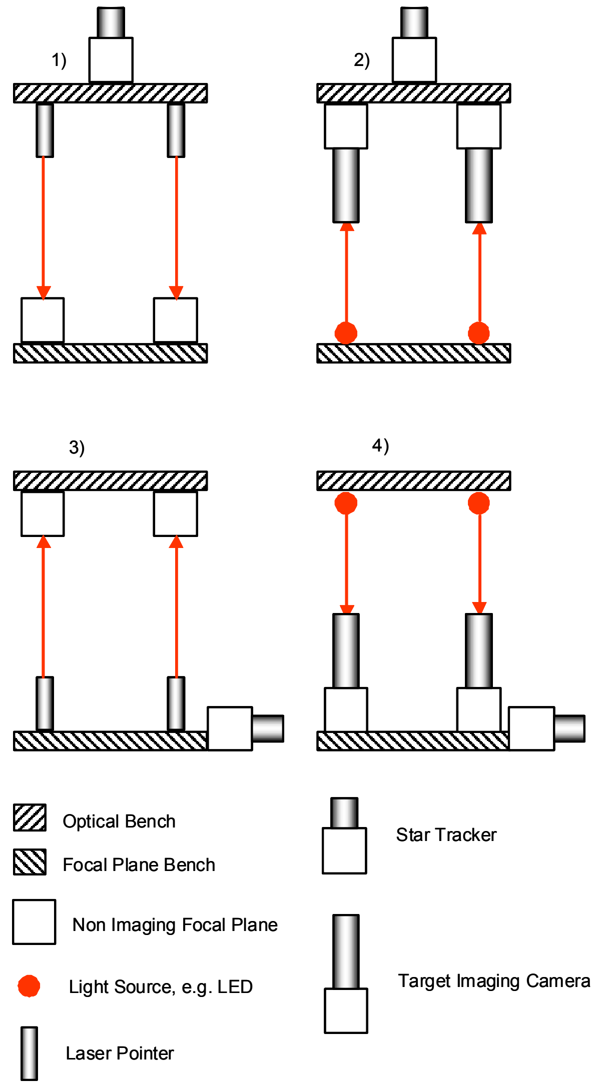

Figure 4. Different architectures for the metrology system

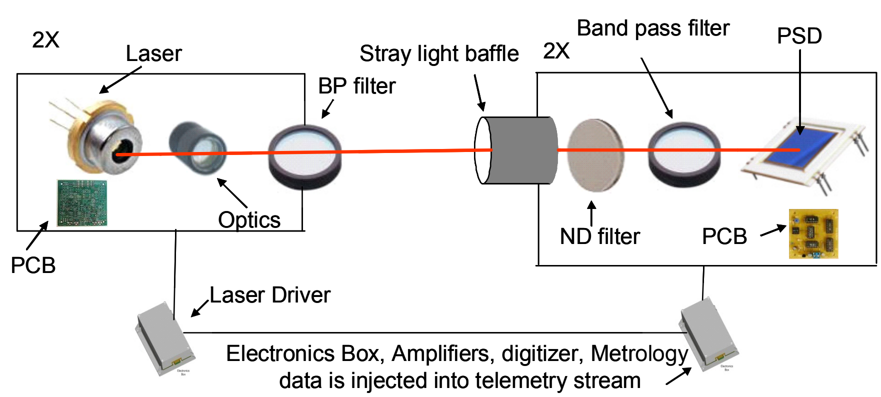

Figure 5. Block diagram of the metrology system

The science requirement for the NuSTAR observatory that governs the metrology system performance is that the celestial coordinates of a detected bright X-ray source be determined to an accuracy of ~10 arcseconds. The NuSTAR project has developed a number of pointing error budgets that shows that the X-ray source position requirement can be met. For the metrology system, the following pointing requirements apply[3]:

- *The metrology laser position 10 meters away shall be stable to better than 130 microns*
- *The metrology detectors shall be stable to better than 40 micron*
- *The error in determining the x-y position of a metrology laser spot shall be better than 100 microns*

The first of these requirements is on dynamic laser stability, and the second is on dynamic detector stability; these two error sets are driven primarily by thermal distortions in the observatory. The third requirement is on the detector read; this error set is driven by noise and algorithm. In order to meet those 3 requirements, 3 independent error budgets were generated. The requirements can be met with comfortable margin.

4. LASERS

The fundamental requirements for the laser diodes are on:

- Power – sufficient to generate a bright laser signal relative to sun reflections in the baffle, or relative to other objects like the moon or earth in the field of view of the metrology detector. A radiometry budget showed it was required to operate the laser diodes to at least 50 mW. To accelerate lifetime testing and derate for flight, the laser diode rating should be at least 200 mW.

- Reliability – the Failure In Time (FIT)[4] should be lower than 11400.

- Wavelength – within the range in which the silicon based detector is sensitive to light. The project did not want to engage in any technology development, and therefore the project was limited to selecting a laser diode technology that was commercially available. 830 nm, 200 mW laser diodes were baselined for the design for heritage reasons (JPL has flown 830 nm laser diodes successfully to Mars [4]).

Both lasers in the two independent metrology systems need to operate simultaneously in order to provide complete information for all 3 measured DOFs (cross boresight translations and clocking around the boresight)[5]. To maximize the probability of success of the metrology system, a decision was made to fly two lasers from different laser manufacturers. This will maximize the probability that at least one laser will survive (in the unlikely event that one of the lasers has a fatal flaw not uncovered during the space qualification process).

The two lasers are interchangeable seen from an electrical, optical and mechanical point of view. An image of a laser is shown in Figure 6. Laser vendor "A" custom packaged and space qualified 60 lasers for this project; 60 commercial off-the-shelf lasers were procured from laser vendor "B". The lasers have been space qualified though a process of destructive physical analysis (DPA) from the lot to verify physical dimensions, solderability, bond strength and die shear (and solder type, coatings, materials and internal architecture in the case of the commercial laser from vendor B). Also, the lasers went though temperature cycling and a stress test to weed out infant mortality failures. Lasers from the lot were selected as flight lasers and the remaining lasers went through lifetime testing. For details on this specific laser qualification and selection process, refer to [5].

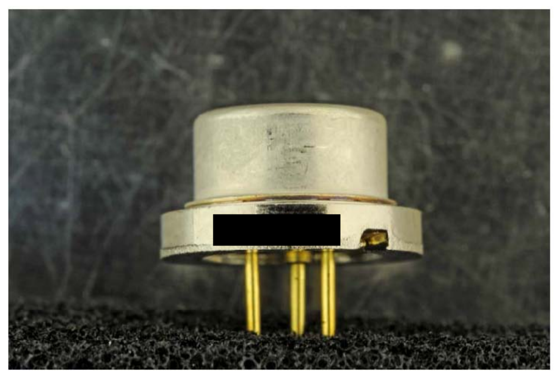

Figure 6. Photograph of diode laser from Vendor "B".

5. OPTICS

The optical components in front of the laser must focus the laser to a spot of a few millimeters on a PSD detector that is located at a distance of ~10 meters from the metrology laser. This is achieved utilizing a single aspherical lens with a focal length of ~20 mm, f/# ~1.0. Commercial lenses were available, but a custom lens was manufactured to get the materials traceability required for space flight. An example of an actual focused laser spot is shown in Figure 7.

[3] The requirements shown in this paper are representative for the metrology system capability. The actual NuSTAR requirements are not shown due to International Traffic in Arms Regulations (ITAR) concerns

[4] FIT = Device failures for 10^9 operating hours

[5] It actually may be possible to derive some metrology data (primarily cross boresight translations) from a single laser-detector system even if one of the lasers should fail, provided that reliable characterization of observatory thermal behavior can be performed during some initial period on-orbit.

Figure 7. Focused laser spot on a beam profiler. The black area covers an area of ~1 x ~1 cm

6. PSD DETECTORS

The metrology detector is a ~20 mm Position Sensing Detector (PSD)[6]. The two-dimensional PSD is a large photodiode that is able to detect the centroid of a light spot on its surface in two dimensions. The PSD has four terminals; two are on the back side of the photodiode and two are on the front side, with those on the back oriented perpendicularly to those on the front [6]. See Figure 8. The photoelectric current generated by the incident laser spot flows through the device and can be seen as two input currents, X_{1M} and X_{2M}, and two output currents, Y_{1M} and Y_{2M}. Based on the currents, it is possible to calculate the centroid position utilizing the equations below:

$$y = \frac{PSD_{Dimension}(Y_1 - Y_2)}{2(Y_1 + Y_2)} \quad and \quad x = \frac{PSD_{Dimension}(X_1 - X_2)}{2(X_1 + X_2)}$$

where X_1, X_2, Y_1 and Y_2 are currents flowing to/from the PSD. It is observed that the intensity of the incident light spot does not affect the calculation of the laser centroid. This means that potential degradation of the diode laser output, molecular contamination or other decrease in the laser light will not require a new calibration of the metrology system during flight[7]. There is an additional background signal from sources such as sun stray light in the baffles, dark current in the PSD, the Moon or Earth in the FOV etc. Therefore the laser is turned off 4 times a second and the background signals: X_{1B}, X_{2B}, Y_{1B} and Y_{2B} are measured. The values X_1, X_2, Y_1 and Y2 used in the above equation are therefore not the measured values, but the measured value minus the background currents. X_1=X_{1M}-X_{1B} etc.

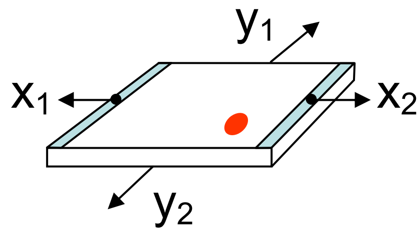

Figure 8. PSD Terminal locations and current readouts

It is possible to get PSD chips with dimensions up to 45 mm, but a trade study on the maximum travel distance for the mast determined that only a ~20 mm PSD chip was required. The operation range requirement is that the metrology system shall be able to operate over the range of ~6 mm in any one axis (+/- ~3 mm). A total of 20 custom packaged PSD detectors were procured. A few of the chips were subjected to DPA. All chips were then subjected to temperature extremes and bias voltage for a month, with continuous monitoring of the dark current. The PSD chips with the lowest and most stable dark currents were selected as flight candidates. Another metric in the acceptance testing was the linearity of the optical response of the PSD chip. A picture of the PSD chip mounted on its circuit board and base mechanical structure is shown in Figure 9.

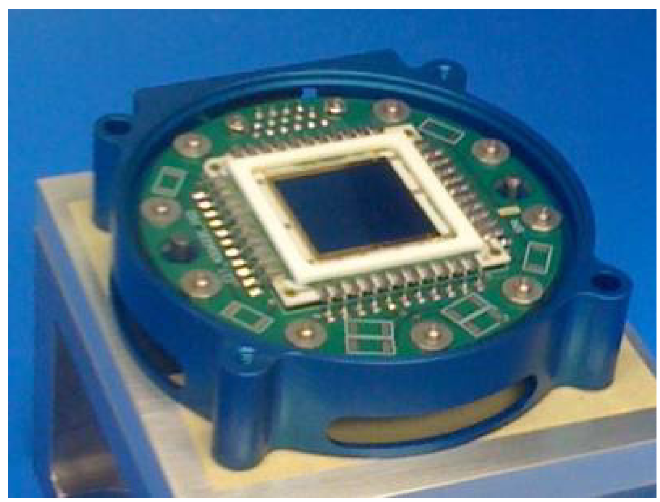

Figure 9. Picture of the PSD chip mounted on the PCB and the base mechanical structure

7. ELECTRONICS

A block diagram of the electronics is shown in Figure 10. The lasers are driven by a processor, through analog laser drivers. The PSD detector is mounted on a printed circuit board along with 4 operational amplifiers. The 4 signals for each channel are routed to the main instrument processor where the signal is low pass filtered and multiplexed into a 14 bit A/D converter. The electronics components are space qualified. The electronics power cycle the lasers and make a background measurement 4 times a second to subtract out the background signal produced by dark current, the moon

[6] A PSD is often confused with a quad cell. A quad cell is a different technology, not used here.
[7] Particulate contamination or other change in the spot intensity distribution on the detector face may degrade performance.

or the earth in the FOV, sun stray light, etc.

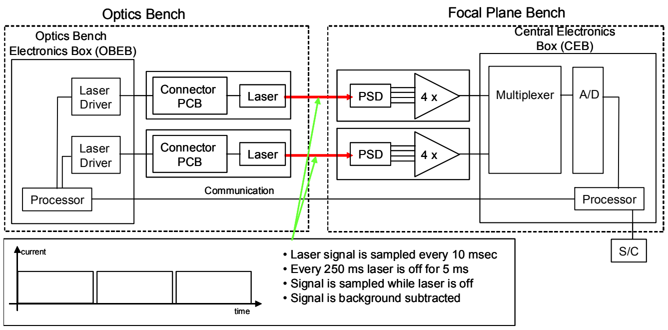

Figure 10. Electronics Block Diagram

8. MECHANICAL DESIGN

A picture of the metrology detector is shown in Figure 11 and a picture of the metrology laser is shown in Figure 12. A sketch of the metrology detector is shown in Figure 13 and a sketch of the metrology laser is shown in Figure 14.

Figure 11. Photograph of the metrology detector

Figure 12. Photograph of the metrology laser being assembled

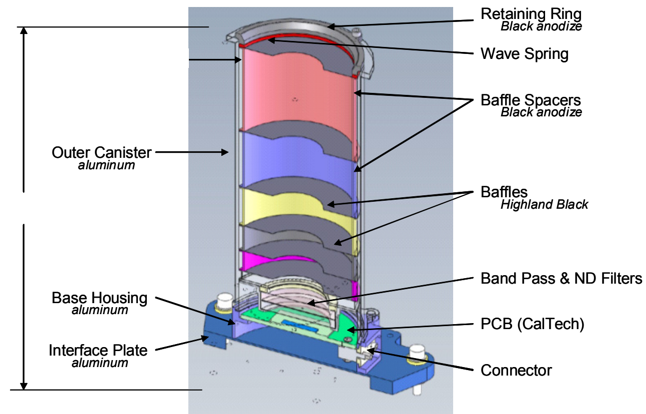

Figure 13. Sketch of the metrology detector

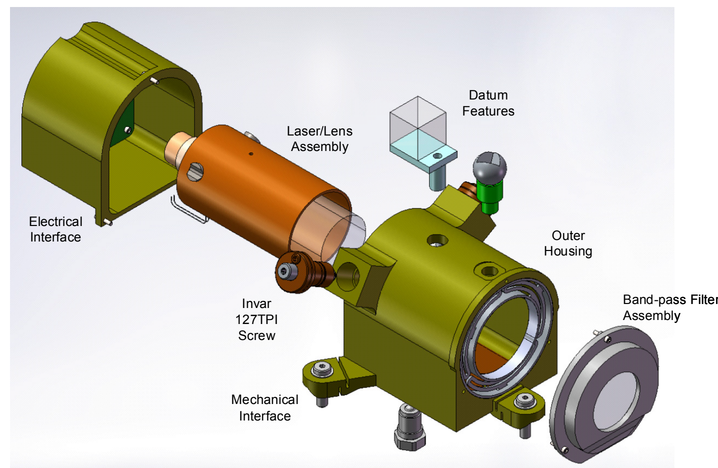

Figure 14. Sketch of the metrology laser.

The metrology detector structure is constructed with aluminum. There are only requirements on the mechanical stability in terms of translation (not rotation). Mounted in a canister above the detector face are a stray light baffle, a Neutral Density filter and bandpass filter.

The mechanical requirements on the metrology laser mechanical construction are more demanding. It is required that the beam pointing of the metrology laser does not change more than ~130 microns (at ~10 meters) over all observatory orientations and orbits following the initial one-time calibration. (In other words, under all sun illumination circumstances). Thermal stability is the key to achieving this requirement. To minimize the effect of the sun, the structure is primarily made of Invar 36, which has a low CTE. The laser is mounted behind the optics in an invar barrel. This barrel is placed inside another invar barrel to mechanically hold it, to serve as a thermal shield, and to spread the thermal variation from the sun. To further minimize the impact of the sun, the entire metrology laser is mounted inside yet another aluminum thermal shield. Its function is to spread the effect of the sun shining on one side of the metrology laser. Also, the metrology laser has a narrow band pass filter. This filter has no optical effect on the laser, but prevents sun light from shining inside the structure – a process which would otherwise generate undesirable thermal gradients. While on ground, it is possible to adjust the pointing of the metrology laser by turning on 2 fine pitch invar screws that impinge upon the inner invar barrel (for alignment purposes).

Structural analysis was performed on the metrology system. The metrology laser has flexures on its mounting feet and puts 0 N force into its mounting interface. The structure has a lowest vibration frequency of >150 Hz and can survive Pegasus launch loads with acceptable margins.

9. THERMAL DESIGN

It is required that the metrology system survive a non-operating temperature range of -45ºC to 60ºC. This has been verified experimentally in a thermal vacuum chamber. The operating temperature range of the metrology detector is 17ºC ± 5ºC. Requirements on thermal gradients are that the metrology laser thermal gradient between the flexure and the adjustment screws shall be less than 5ºC and that the temperature difference between the two adjustment screws shall be less than 1ºC. The temperature control is cold biased by radiators and actively controlled by operational heaters that are powered and monitored by the instrument electronics. For this purpose, each metrology laser and metrology detector has a thermistor and a kapton strip heater. The metrology detector heater runs at ~10 Watts and the metrology laser heater runs at ~3 Watts. Both units also have thermostats and survival heaters. A thermal simulation of the metrology laser is shown in Figure 15.

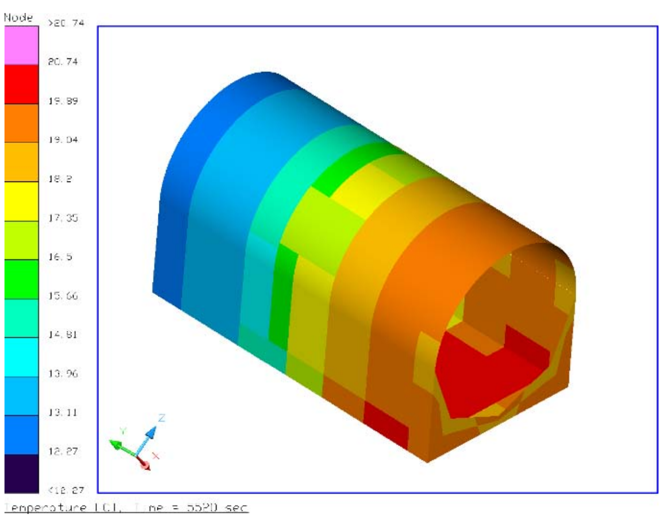

Figure 15. Thermal map of the metrology laser. This is worse case orientation for largest thermal gradients

10. SOFTWARE

The metrology lasers are driven by an instrument electronics box with a processor located on the optical bench. The currents from the PSD are digitized by the instrument electronics box located on the focal plane bench. The instrument electronics are based on several small processors that are implemented in FPGA chips. The software for the metrology system was written in FORTH and has the following parameters that can be set and changed:

- Set the laser current while laser is on
- Set the laser current while laser is off (the reason this is not zero is to minimize the thermal excursions of the laser chip)
- Set the length of high laser current
- Set the length of low laser current
- Set the detector sampling pattern
- Set an over-sampling mode to reduce random noise
- Set the temperature set point for the metrology lasers
- Set the temperature set point for the metrology detectors
- Set the gain for the heater control loops
- Output raw data in diagnostics mode
- Output compressed data

Other commands can also be uploaded.

During normal operational mode, the instrument electronics will output time tagged centroid positions (as calculated by the equation in section 6) along with housekeeping data such as temperatures, intensities etc.

11. ASSEMBLY

The metrology laser and detector are assembled utilizing standard processes for assembling flight hardware with travelers, quality assurance witnesses, full traceability of all materials, requirements verification etc. Machining of the invar parts requires special heat treatments to maximize stability. Many of the assembly operations require bonding operations. JPL did not have a bonding strength database for a low viscosity epoxy and invar or glass-silicone-invar. Therefore, a special program was conducted to measure adhesive shear strength. A number of coupons were manufactured and temperature cycled. The shear strengths were measured. Surface preparation before bonding plays a key role in the bond's strength.

The most critical assembly tolerance is the distance from the laser to the optics. It is necessary to situate the laser relative to the optics to an accuracy of a few microns, and then secure the focus utilizing epoxy. When the epoxy has cured, the assembly is subjected to a full temperature cycle to make sure that the focus does not shift to a different position. Also, the focused (only engineering model, not flight models) laser is X-rayed to confirm that there are no voids in the epoxy. The focus setup is shown in Figure 16.

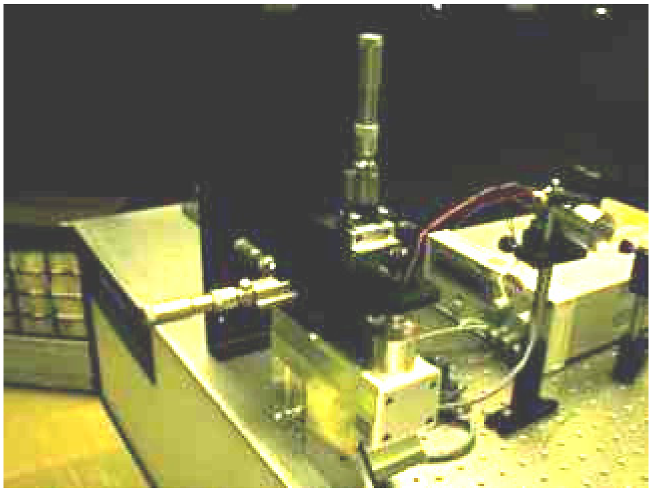

Figure 16. GSE used to focus the laser relative to the optics. There are 3 micrometer screws to adjust the focus. When focus is achieved, epoxy is injected with a syringe

Another critical assembly step is centering the PSD detector in the metrology detector base. The PSD detector is first mounted on top of a PCB. The whole PSD chip is then centered on the housing utilizing a liquid pinning operation. This is done by adjusting the position of the PSD PCB until the center of the PSD chip is at the center of the mechanical structure. That positioning is verified in an optical Coordinate Measuring Machine (CMM), and the PCB is moved by pushing it with an orange wood. This method makes it possible to position the PSD to an accuracy better than ~50 microns. A detail from the liquid pinning process is shown in Figure 17.

Figure 17. The PSD PCB is being manually pushed (using an orange stick) into position to an accuracy better than 50 microns under an optical CMM

12. TEST

The accuracy of the metrology detector to determining the position of a laser beam is measured by placing the metrology detector on a ridged aluminum structure with 2 accurate translation stages. The metrology laser is placed on another ridged aluminum structure ~10 meters from the detector and the laser beam is pointed towards the center of the PSD chip. The metrology detector is then moved in a rectangular grid by the translation stages. The detected position of the laser beam is recorded along a grid with 1 mm spacing. Between every measurement, the translation stages are moved back to a home position, in order to compensate for drift in the set-up or the building itself. The measurements last ~8 hours and are always done in the middle of the night when thermal conditions are most stable and no other personnel are in the building to disturb the setup. Photographs of the test setup are shown in Figure 18 and Figure 19. In Figure 20 is shown a picture of the true position of the laser beam (as reported by the accurate translation stages) and the measured laser position with the PSD chip. The measured accuracy is ~35 microns (3σ).

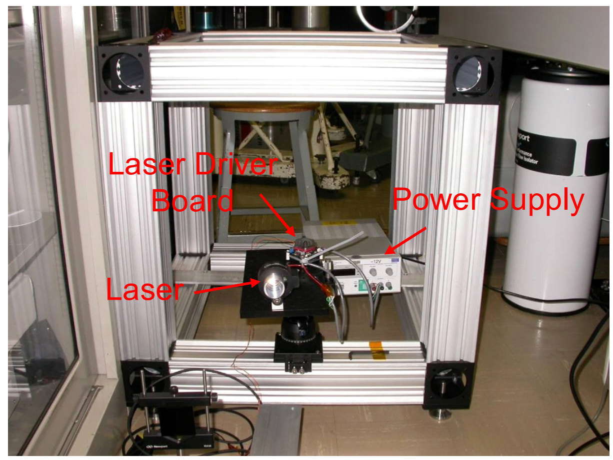

Figure 18. The ridged aluminum structure with the metrology laser

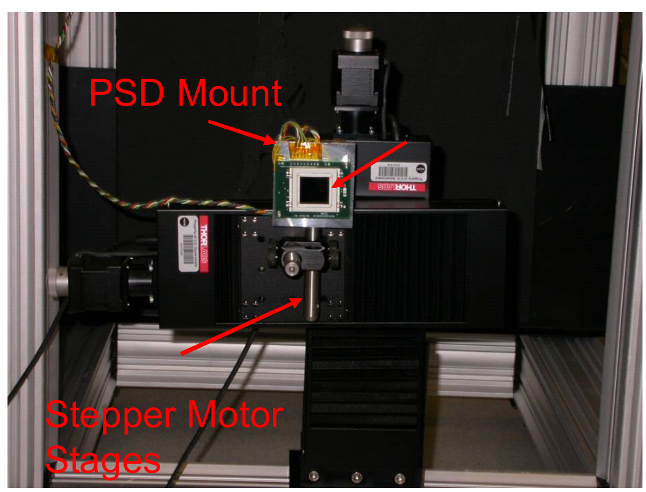

Figure 19. Picture of setup used for accuracy testing

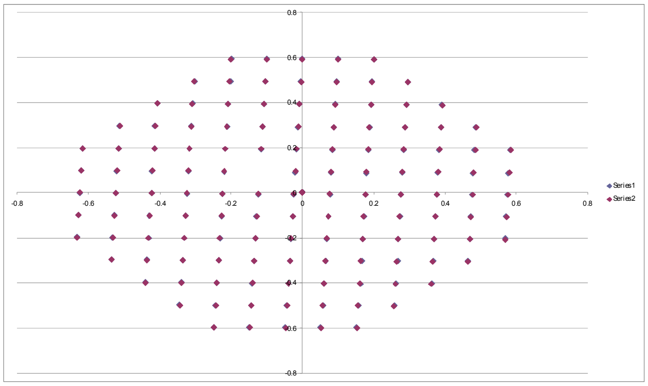

Figure 20. Result of accuracy testing of the metrology detector

It was determined that verifying the metrology laser beam stability experimentally inside a thermal vacuum chamber would be logistically infeasible. It was therefore decided to prove the beam stability analytically. To accomplish this, a number of thermal maps (e.g. Figure 15) are transferred to a NASTRAN model. The NASTRAN model then calculates the laser lateral motion relative to the optics.

The metrology system is also vibration tested and functionally tested during a thermal vacuum test. Before and after the environmental tests, a baseline test is performed. If the results of this baseline test are the same before and after the environmental test, then it is concluded that nothing changed and the environmental test was successful.

For the metrology detector, the baseline test is performed in a large ridged aluminum structure. The metrology detector is mounted in a fixed position. A collimated 830 nm laser beam is also mounted on the aluminum structure, shining down on the PSD detector inside the metrology detector assembly. If the position of the laser beam does not change while the metrology detector has been subjected to environment tests, it is concluded that nothing moved and the detector survived the environmental test. On the metrology detector, the laser position changed less than 20 microns during vibration testing and less than 10 microns during TVAC testing. It was not possible to establish if this shift was do to the test setup or the metrology detector actually moved. However, there is enough margin in the metrology detector budgets that these small errors can be absorbed.

The metrology laser has an alignment cube and a Spherical Mounted Retroreflector (SMR) target (similar fiducials are mounted on the test fixture). To test the stability of the metrology laser structure, the laser is first turned on and a laser tracker[8] is used by a surveyor to measure these two fiducials in order to establish a coordinate system fixed on the metrology laser chassis. Special support equipment that can measure the interception of an invisible 830 nm laser beam has also been constructed. This support equipment is positioned at 9 different positions from 8 meters to 12 meters from the metrology laser. Based on these 9 laser beam interception points, it is possible to establish the equation of the laser line in a coordinate system that is fixed on the metrology laser chassis. The intersection of a point at a distance of ~10 meters is interpolated. The same procedure is repeated after the environmental test. If no changes are observed, it is concluded that the environmental test was successful for the metrology laser. At the time of this writing, this test has not been completed yet.

Finally, the stray light rejection of the metrology detector stray light baffle is also tested. This is done by bringing the metrology detector to a heliostat. The sun bundle from the heliostat is routed into a room where the walls are covered with black honeycomb. The metrology detector is mounted in the sun bundle and rotated the sun rejection angle away from the sun bundle. Measurements are taken when the stray light baffle is shaded and when it is not shaded by moving a small plate into the beam. The difference between these two measurements is the contribution from sun stray light.

13. SUMMARY

The metrology system specifications are shown in Figure 21.

Parameter	CBE
Mass (laser – detector pair)	~ 1.5 kg
Sun Exclusion Angle	< 15 degrees
Detector centroiding error	~ 50 microns
Detector translation	~ 25 microns
Pointing stability	~ 80 microns
Update rate	100 Hz
Operating range	~ 6 mm

Figure 21. Metrology system specifications

A laser metrology system has been built for the NuSTAR observatory. The laser metrology system acquires data that is used to compensate for mast motion during post processing of observatory data. By combining this data with data from an outboard star tracker, the unique aspect solution of the observatory can be generated. The laser metrology system is implemented as two laser pointers mounted on a bench with the optics. The laser pointers are

[8] A laser tracker is a modern surveyor's instrument that fires a laser at a retro-reflector target that then returns the beam. The laser tracker pointing is adjusted until the incoming beam is collinear with the outgoing beam. The following can then be measured with respect to a local coordinate system centered on the laser tracker: (1) the azimuthal angle to the target, (2) the elevation angle to the target (relative to the plum line), and (3) the distance to the target (determined using interferometry). Thus, a laser tracker generates the polar coordinates (r,θ,ϕ) for a retro-reflector in the local frame of the tracker.

illuminating 2 PSD detectors mounted ~10 meters away on a bench with the X-ray detectors. The implementation of the metrology system has been discussed in this paper. The metrology subsystem meets its requirements and is currently being built for flight.

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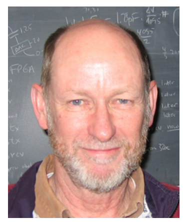

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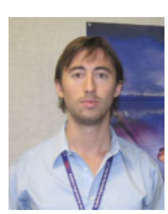

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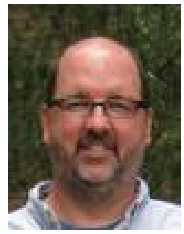

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