SURF 2010

NuSIM

Prepared for: SURF Committee

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Abstract

The NuSTAR (Nuclear Spectroscopic Telescope ARray) spacecraft, set to launch in February 2012, will be capable of performing some of the most detailed X-Ray astronomical observations ever made in the 5-80 keV energy range. The source positioning accuracy of the telescope is limited by the ability to correct for thermal distortions and movement of the optics relative to the focal plane, as well as the overall aspect of the optics bench. These are more than average for space-based observatories, because a ten meter deployable mast, utilized to reduce the size of the launch vehicle, allows for significant thermal distortions. In order to predict the on-orbit performance of the instrument, the NuSTAR team has developed NuSIM, a software based simulation of NuSTAR. My SURF has consisted mainly of the generation of parametrically-changing databases of the mast geometry in order to interrogate the robustness of the on-orbit accuracy of the science system's data reconstruction algorithms within NuSIM. This method has been used to test the Finite Element Model (FEM) simulation results of the observatory's structure, by using a conceptual model of the mast geometry. Furthermore, I have explored additional possible sources of error, such as calculating light scattering from the simulated optics. This project has contributed to the verification of key science requirements of NuSTAR in advance, most notably the level one requirement on localization of a point source in celestial coordinates.

Background

When fully deployed, NuSTAR will observe X-Ray sources using a pair of co-aligned grazing angle incidence x-ray mirrors, each coated with depth-graded multilayers, separated from a pair of cadmium-zinc-telluride pixel detectors by a ten meter mast, which will deploy in space. By combining the exposures of the two long focal length telescopes, it can achieve unparalleled sensitivity. In theory, it should have an angular resolution of 43" (HPD), 7.5" (FWHM), an an energy resolution of 1.2 keV at 68 keV (FWHM).

NuSIM is a software-based simulation of NuSTAR. Using all known parameters concerning the functioning of the NuSTAR spacecraft, NuSIM is meant to be used to verify that NuSTAR's structural distortions during the mission will in fact produce a level of scientific performance predicted by the pointing error budget, the level of expected "noise" in the system due to factors that cannot be compensated for.

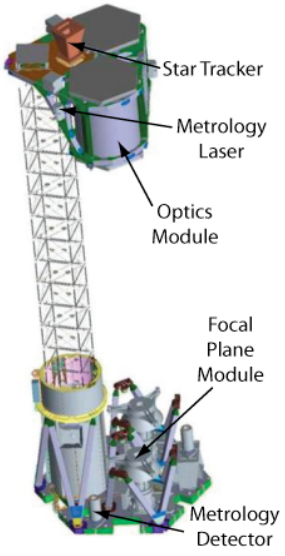


Figure 1: A Rendering of NuSTAR

NuSIM's Objectives

The goal of NuSIM is to verify and validate NuSTAR's scientific capabilities to the greatest extent possible prior to launch. In this case, verification refers to ensuring correspondence between the component algorithms of NuSIM and mathematical models of the real world, while validation refers to testing the correspondence between the simulator's behavior and expected or real-world behavior. Because many science requirements of NuSTAR cannot be tested directly prior to launch in controlled situations (such as distortions in the ten meter mast under zero gravity conditions), it is up to NuSIM to verify all possible science requirements in advance, most notably the pointing budget.

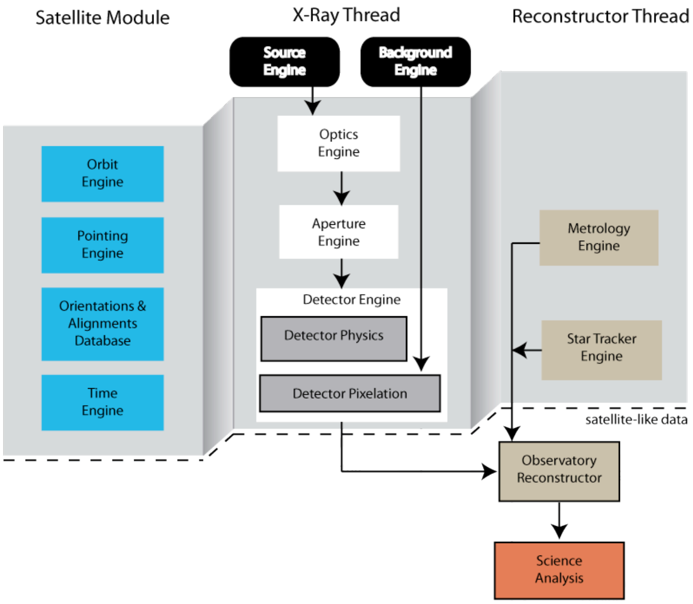


Figure 2: NuSIM architecture

Architecture

NuSIM is capable of emulating all physical motions of NuSTAR, as well as all interactions of X-Rays with optical components, and data output behavior. The basic software architecture can be seen in figure 2.

Verification

It is often impossible or infeasible to test a piece of software such as the components of NuSIM against all possible inputs and predict reasonable outputs against which to verify them. As such, in many cases, extensive *ad hoc* testing much be used. In these cases, a variety of sample inputs, including many testing near or at the physical or theoretical limitations of the simulation are tried, and their outputs checked against predicted or observed results to ensure software correctness.

In all cases, verification of any one component shall fall under one of three classifications as outlined in "NuSIM Validation Plan," from least to most preferable:

1. Verification of polarity is any test that interrogates the direction, sign, polarity, frequency, or other uni-dimensional projection of an output or set of outputs.
2. Verification of form is any test that interrogates (principally visually) the shape, size, layout, or other qualitative form of an output or set of outputs.
3. Quantitative verification is any test that compares the actual values of outputs with their expected values, using hand calculations, a parallel algorithm, or inspection of the data.

Validation

Validation shall take place in a modular fashion. Any single algorithm shall be verified prior to integration with any engine or module, just as any engine or module shall be verified before it becomes part of a simulation. When possible, the simulation will be checked against the test results of actual flight hardware, and adapted if it does not match.

This is analogous to testing the simulation of vibrations in the mast for correctness prior to placing it in a simulation in which it effects the mirror movements.

All data used as inputs for the simulator shall be independently verified for an appropriate level of accuracy before being used to validate any software itself.

Mast Distortions

My work over the summer of 2010 has centered upon experimenting with the effects of displacement between the Focal and Optics Benches due to distortions in the ten meter mast between the two. NuSIM requires an Orientations and Alignments database to run. This database sets the parameters for the coordinate system transformations (as a three dimensional translation and a quaternion rotation) between NuSTAR's various modules. By altering these transformations, the simulator is simulating NuSIM under various nonideal conditions. To facilitate this and similar future tests, I constructed NuSIM Database Transformer, a library for the procedural generation of parametrically varying Orientations and Alignments databases. For example, databases were constructed in which the optics bench was translated relative to the focal bench by a total of a centimeter over the course of a thousand time steps. Similar tests were run with various rotations of the benches.

Thermal Mast Distortions

The Thermal Mast Distortion Data prepared for JPL details the effects on the mast under the thermal effects of sunlight. In particular, it provides x and y offsets of the focal plane intersections with the beams from the optics, as well as the twisting of the mast itself (ROTZ). These effects are most pronounced for a 170 degree angle of the mast toward the sun. To more fully model the effects of thermal mast bending on NuSTAR, an Orientations and Alignments database had to be constructed for the mast in the configurations predicted for a full orbit.

In developing an analytical model, I operated under the following assumptions:

- The twist in the mast is small enough that its effect on the bend of the mast is not worth calculating, which is to say it can be interpreted as one of the benches at either end having been rotated about the mast.
- The mast bend in x and y dimensions can be interpreted as separate arcs, and the displacement from each is additive, as the mast is square and is likely to bend more or less independently in each direction along these small angles.
- The beams from the optics modules are meant to move exactly parallel to the mast, centered at the center of the OM coordinate system. (supported by the coordinate systems IDEAL reference documentation).

- Over these small angles, second order approximations of cosine are acceptable.

First, to counteract the twist in the mast, input offsets were rotated about the mast by ROTZ, in order to find the offset due to bending alone.

For each of the dimensions x and y, the mast is essentially an arc (of radius *r,* and length *m*) with the optics module and the exact point on the focal plane meant to receive the beam each on what amount to radial lines perpendicular to the arc of the mast extending out by a distance *x*. The line from the center of the arc to the optics module emitting the beam (length *r* + *x*) is a leg of a right triangle, with the other leg being the beam itself and the hypotenuse being the line from the center of the arc to the point where the beam hits the detector, which is offset by *Δx* from where it hits under ideal conditions (length *r* + *x* + *Δx*). Using the second order Cosine approximation, it is possible to solve for the arc angle, and thus the angle between the benches.

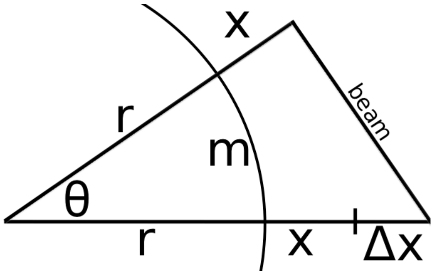


Figure 3: modeling the mast as an arc

$$\theta \approx \frac{-m+\sqrt{m^2+8x\Delta x+8\Delta x^2}}{2\left(x+\Delta x\right)}$$

An Orientations and Alignments database was generated for each of the bent mast positions using the NuSIM Database Transformer library. Without ROTZ, which is to say when given data in which the mast itself was not twisted, the model proved accurate, displaying small, linear error to be expected with the second order cosine approximation.

Figure 4: Mast Bending Projection vs. Ideal: ROTZ=0 (Projection on Focal Plane, axes in mm)

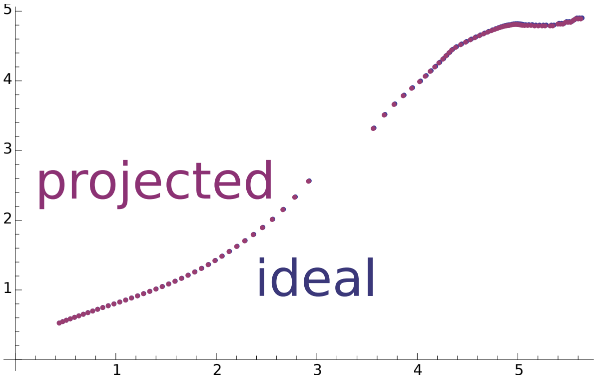
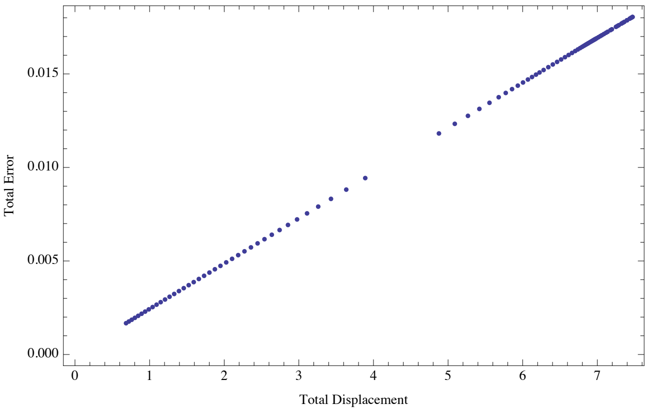


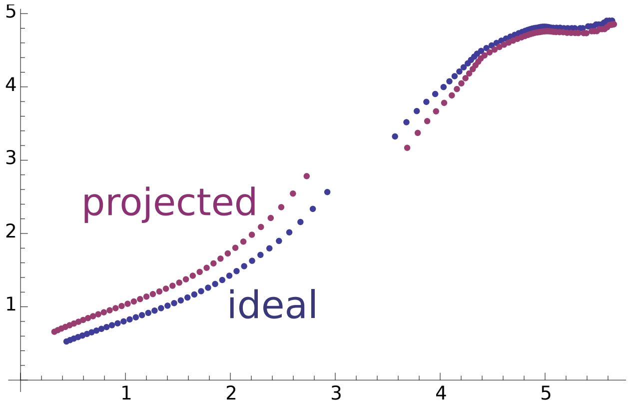
Figure 5: Total Error vs. Total Displacement: ROTZ=0 (all measurements in mm)



The mast bending model itself can thus be said to be quantitatively verified, with only extremely small error when given the largest likely thermal mast bending figures. The twisting model however, a simple rotation of the focal plane by ROTZ about the mast, proved to be only accurate in form.

Further investigation shall have to be conducted to hone this algorithm down to a more accurate solution, modeling the twisting of the mast in a more accurate manner than a simple rotation of the focal plane.

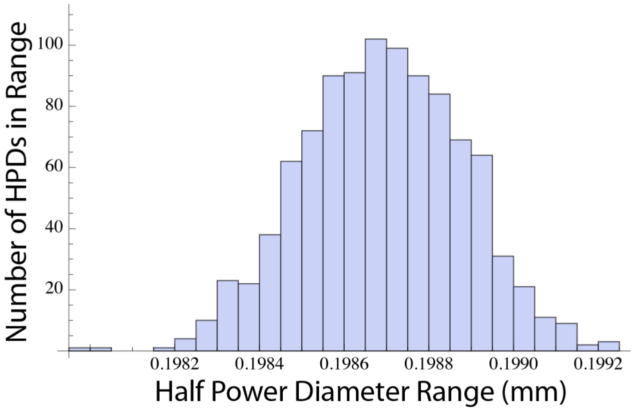
Figure 6: Mast Bending Projection vs. Ideal With ROTZ (Projection on Focal Plane, axes in mm)



Light Scattering

An important part of NuSIM's mission is to determine how sharp an image can be made. Even accounting for all known displacements in the optics, the optics themselves produce light scattering. How much light scatters can be characterized by the average half power diameter (the diameter of the smallest circle containing half of the photons) of a light beam from a distant source, which ought to focus to a single point if optics could be made perfect. I ran a thousand tests of NuSIM's ray tracing engine with a beam of ten million 30KeV photons, and found the half power diameter of such a beam to be 0.19869 ± 0.00019 mm. This shall serve as a baseline for future resolution calculations.

Figure 7: Histogram of 1,000 Half Power Diameters



NuSIM's Future

NuSIM is still very much a work in progress. Many aspects, from thermal vibrations to equipment calibration remain yet to be tested. Work shall continue to hone corrective algorithms and verify all possible mission requirements before NuSTAR's launch in February 2012. As components of NuSTAR come together, additional validation and updates to NuSIM's parameters will be possible. At this time, however, NuSIM's results are well within the expected range for the science requirements of NuSTAR to be met.

Methods

NuSIM Database Transformer

NuSIM Database Transformer is a Python library written as a tool to ease the generation of Orientations and Alignments databases. It is written in functional style, allowing one to create a database object, and input a function which controls the coordinate system transformations between the various parts of NuSTAR with each time step. This is done so that in the future anyone wishing to test any series of configurations of NuSTAR will be able to program them without having to be intimately familiar with the database structure.

Because NuSIM is very much a work in progress, database structures are continuously changing, at least in terms of the details of formatting. NuSIM Database Transformer is built to adapt to these changes without the user having to input formatting details. Instead, it takes as input a database of NuSIM in its ideal configuration, and extrapolates the default configuration values and formatting from there.

Internal Software Development

Over the course of this project, I have made some contributions to the development of the NuSIM software itself.

My installation of NuSIM was the first attempted on mac OSX 10.6, and as such there were some compatibility issues with the updated OS. Attempting various builds of NuSIM and its prerequisite libraries (from HEAsoft and ROOT), took quite some time. The problem is that HEAsoft is built to only properly compile in 32-bit mode, in part due to its use of Fortran libraries that are not written to be 64-bit compatible. ROOT, on the other hand, was compiled on my own system, as was NuSIM, and OSX 10.6 is the first Mac OS to make compilation 64 bit by default, causing NuSIM to be incompatible with the HEAsoft libraries. Upon discovering this source of the compilation errors, Makefiles and configuration files had to be changed to force NuSIM to compile in 32-bit mode (ROOT has precompiled binaries available). NuSIM has now been made to successfully run on OSX 10.6 machines. I have written a guide for future installations under these circumstances.

NuSIM outputs photon detections from the simulated optics into a custom data file. For many purposes, however, it is useful to have this in a standard FITS table file. I have therefore written a binary, FITSConverter, which accomplishes this task using the CFITSio library (part of HEASoft). In order to accommodate the regularly changing format of NuSIM's output files, FITSConverter also takes as input a format file that should be simple for future users to adapt.

Whilst investigating errors in my mast bending tests, it became necessary to check through the coordinate system conversions within NuSIM. The checks verified that the ray tracing and projection engines do indeed behave as theoretically predicted under standard conditions.

All code I have written for NuSIM as well as NuSIM Database Transformer is fully documented, complete with use manuals.

References

1. California Institute of Technology, Pasadena, CA, USA, “NuSTAR home page.” <http://www.nustar.caltech.edu/>, accessed 2/18/2010.
2. “NuSTAR NuSIM Architecture Document.” D. Isaiah Harp, NuSIM Team. 8 Dec. 2009, <https://pdms.jpl.nasa.gov>.
3. “NuSTAR NuSIM Architecture and Validation Plan” D. Isaiah Harp, NuSIM Team. 19 Feb. 2010, <https://pdms.jpl.nasa.gov>.
4. “NuSTAR Coordinate Systems Description Document” Christian Liebe, Jason Willis, Fiona Harrison, Isaiah Harp, et al. 12 Oct. 2009, JPL D-41871 Rev 1.1 <https://pdms.jpl.nasa.gov>.
5. “HEASoft” NASA HEASARC. 29 Mar. 2010 <https://heasarc.gsfc.nasa.gov/lheasoft/>.
6. “ROOT” The ROOT Team, 31 Mar. 2010 <http://root.cern.ch/drupal/>.
7. “Development of the HEFT and NuSTAR Focusing Telescopes” Harrison, F.A., Christensen, F.E., Craig, W., Hailey, C., Baumgartner, W., Chen, C. M. H., Chonko, J., Cook, W.R., Koglin, J., Madsen, K.-K., Pivavoroff, M., Boggs, S., & Smith, D. 2005, Experimental Astronomy, 20, 131.
8. “Measuring Mast Motions on the NuSTAR Mission” Liebe, C.C., Burnham, J., Cook, R., Craig, W., Decker, T., Harp, D.I., Kecman, B., Meras, P., Raffanti, M., Scholz, C., Smith, C., Waldman, J., & Wu, J. 2010, IEEE, in press.

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