The Nuclear Spectroscopic Telescope Array (NuSTAR)

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ABSTRACT

The *Nuclear Spectroscopic Telescope Array (NuSTAR)* is a NASA Small Explorer mission that will carry the first focusing hard X-ray (5 – 80 keV) telescope to orbit. *NuSTAR* will offer a factor 50 – 100 sensitivity improvement compared to previous collimated or coded mask imagers that have operated in this energy band. In addition, *NuSTAR* provides sub-arcminute imaging with good spectral resolution over a 12-arcminute field of view. After launch, *NuSTAR* will carry out a two-year primary science mission that focuses on four key programs: studying the evolution of massive black holes through surveys carried out in fields with excellent multiwavelength coverage, understanding the population of compact objects and the nature of the massive black hole in the center of the Milky Way, constraining explosion dynamics and nucleosynthesis in supernovae, and probing the nature of particle acceleration in relativistic jets in active galactic nuclei. A number of additional observations will be included in the primary mission, and a guest observer program will be proposed for an extended mission to expand the range of scientific targets. The payload consists of two co-aligned depth-graded multilayer coated grazing incidence optics focused onto solid state CdZnTe pixel detectors. To be launched in early 2012 on a Pegasus rocket into a low-inclination Earth orbit, *NuSTAR* largely avoids SAA passages, and will therefore have low and stable detector backgrounds. The telescope achieves a 10.15-meter focal length through on-orbit deployment of an extendable mast. An aspect and alignment metrology system enable reconstruction of the absolute aspect and variations in the telescope alignment resulting from mast flexure during ground data processing. Data will be publicly available at GSFC's High Energy Astrophysics Science Archive Research Center (HEASARC) following validation at the science operations center located at Caltech.

Keywords: X-rays, gamma-rays, missions

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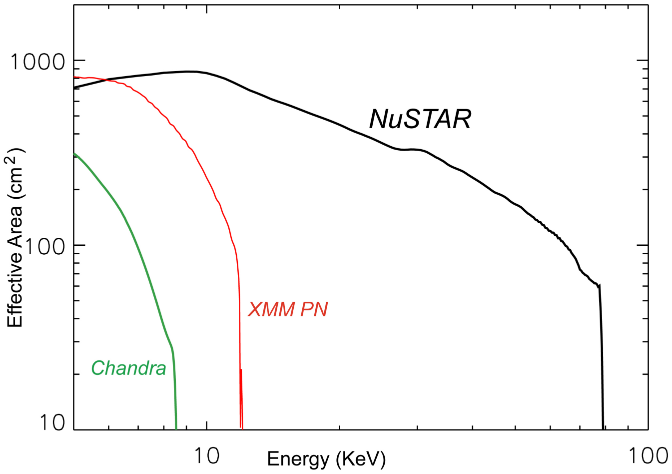

Figure 1. Effective area for two telescopes as a function of energy compared with the *Chandra* and *XMM* focusing telescopes. *NuSTAR* utilizes a low graze angle design combined with depth-graded multilayer coatings to extend sensitivity to 80 keV. Focusing in this band provides improvements in sensitivity by a factor 50 - 100 compared to hard X-ray collimated or coded mask experiments with larger collecting area

1. INTRODUCTION

The last decade has seen a major technological advance in hard X-ray/soft gamma-ray astronomy – the ability to focus efficiently – enabling instruments that improve sensitivity by orders of magnitude compared to the collimators and coded-mask cameras previously used to observe the cosmos at these energies. Focusing instruments achieve large concentration factors, such that their collecting area is significantly larger (by factors of 1000 or greater) than the detector area used to register the signal. In the hard X-ray band, where particle interactions result in high detector backgrounds, large concentration factors result in enormous improvements in the signal to background ratio over coded mask cameras, where telescope effective areas are typically less than (∼50%) of the detector area. Focusing telescopes operating at energies above 10 keV have recently been developed and deployed on balloon platforms,[1–3] and will be incorporated on two approved space experiments; *The Nuclear Spectroscopic Telescope Array (NuSTAR)* NASA Small Explorer, and the JAXA *Astro-H*[4] mission, as well as the proposed *New Hard X-ray Mission (NHXM)*.[5]

Extending focusing to the hard X-ray band requires a combination of low graze-angle and/or depth-graded multilayer-coated optics combined with imaging detectors utilizing high-atomic-number materials. For grazing-incidence X-ray optics, the graze angle (angle at which X-rays are reflected from a shell) range for which efficient reflectance can be achieved scales approximately inversely with energy. To achieve high-energy (10 – 60 keV) response with traditional metal coatings the optics design must utilize graze angles of a few arcminutes or less, which requires small-radius, tightly-nested optics shells. Since the field of view of a grazing incidence telescope is approximately equal to the average graze angle, metal-coated optics will have small fields of view at high energy. To overcome this limitation, a number of future astronomical telescopes will employ depth-graded multilayer coatings,[6] which exploit the principal of Bragg reflection to increase the graze angles at which significant reflectance can be achieved. This enables high throughput with moderate ($\sim 10'$) FoV.

The *NuSTAR* Small Explorer mission will be the first astronomical telescope on-orbit to utilize the new generation of hard X-ray optics and detector technologies to carry out high-sensitivity observations at X-ray energies significantly greater than 10 keV. *NuSTAR*, based in large part on the technologies developed for the *High-Energy Focusing Telescope (HEFT)*[1] balloon experiment, was selected after a competitive Phase A study for implementation, and the mission is now in Phase D with a launch scheduled for the first part of calendar year 2012. This paper describes *NuSTAR*'s two-year primary science program, the implementation of the science instrument, the mission design, and plans for data distribution and archiving.

Table 1. Key instrument performance parameters.

Energy range	5 – 80 keV
Angular resolution (HPD)	$45''$
Angular resolution (FWHM)	$9.5''$
FoV (50% resp.) at 10 keV	$10'$
FoV (50% resp.) at 68 keV	$6'$
Sensitivity (6 - 10 keV) [10^6 s, 3σ, ΔE/E = 0.5]	2×10^{-15} erg/cm^2/s
Sensitivity (10 - 30 keV) [10^6 s, 3σ, ΔE/E = 0.5]	1×10^{-14} erg/cm^2/s
Background in HPD (10 - 30 keV)	6.8×10^{-4} cts/s
Background in HPD (30 – 60 keV)	4.0×10^{-4} cts/s
Spectral resolution (FWHM)	500 eV at 10 keV, 1.2 keV at 80 keV
Strong source ($> 10\sigma$) positioning	$1.5''$ (1-σ)
Temporal resolution	2 μsec
Target of Opportunity response	< 24 hours

2. SCIENTIFIC PERFORMANCE

NuSTAR will fly two co-aligned focusing hard X-ray telescopes consisting of multilayer-coated, grazing-incidence optics and shielded solid state CdZnTe pixel detectors with a 10.15-meter focal length. Figure 1 shows the total effective area for both telescopes as a function of energy, with a comparison to *Chandra* and *XMM*. The energy band extends from about 5 keV to 80 keV, being limited at the low-energy end by the optics thermal cover and shield entrance window, and at the high energy end by the K-edge (at 78.4 keV) in the Platinum mirror coatings.

Table 1 provides the current best estimates of the key instrument performance parameters. The $45''$ angular resolution is projected based on mechanical metrology of the first flight optic, which is currently more than 75% complete, combined with a model of contributions from on-orbit thermal distortions and aspect reconstruction. The field of view is energy-dependent due to changes in multilayer reflectance as a function of energy and optics shell radius, which results in overall loss of reflectance and more vignetting at high energy (see Figure 2). The spectral resolution is 500 eV at energies below ~30 keV, and increases to 1.2 keV at the upper end of the energy range. The 2 μsec temporal resolution, determined by the bit rate allocated in the telemetry stream for time tags, is more than adequate to meet scientific requirements. The intrinsic temporal resolution of the detector is better than 1 μsec. The target of opportunity (ToO) response time is required to be less than 24 hours, however, on average the turnaround will be faster, with targets typically acquired within 6 hours.

3. BASELINE MISSION SCIENCE PLAN

Table 2. Core science program.

Key science goal	**Observations**
Locate massive black holes	Deep and wide-field surveys in GOODS, COSMOS, XBootes
Study the population of compact objects in the Galaxy	Galactic survey centered on Sgr A*
Understand explosion dynamics and nucleosynthesis in core collapse and Type Ia SNe	Pointed observations of Cas A, SN1987A, Tycho ToO observations of Ia SNe
Constrain particle acceleration in relativistic jets in supermassive black holes	Contemporaneous multiwavelength observations of GeV and TeV blazars

The two-year *NuSTAR* baseline science mission begins after a 1-month on-orbit checkout period. During the baseline mission *NuSTAR* will focus on a set of four key objectives (Table 2). If the currently estimated performance is achieved on-orbit, completing these objectives will require about eighteen months of observation

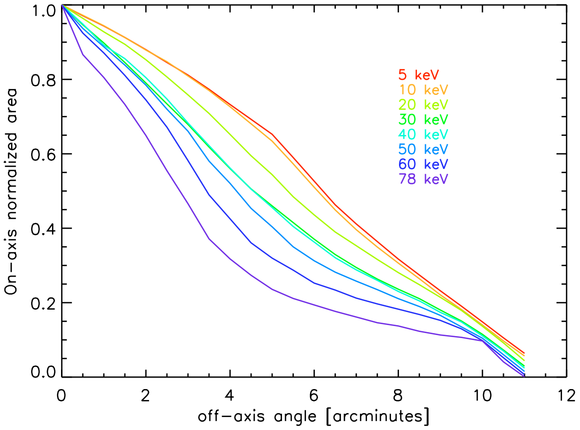

Figure 2. Effective area as a function of off-axis angle, as a fraction of on-axis area, for several energies.

time. The remaining six months will be used to perform additional targeted programs. Although survey fields and specific sources for the key programs have been identified, the detailed designs of the observations are not yet complete. The science team is also in the process of prioritizing the additional science objectives. The final baseline science observing plan will be determined six months prior to launch, although alterations may be made after launch as a result of measured on-orbit performance or preliminary data analysis.

Table 2 summarizes the key objectives and the associated observations. The primary extragalactic science objective is to understand the physical processes that drive the evolution of supermassive black holes and galaxies at redshift $z \lesssim 1$. *NuSTAR's* specific contribution will be to measure the evolution of obscured active galactic nuclei (AGN), study the characteristics of the galaxies that host them, and determine if they evolve similarly to the well studied unobscured population. In addition, *NuSTAR* will undertake simultaneous observations of blazar AGN with *Fermi* and the TeV gamma-ray telescopes Veritas and HESS, as well as with ground-based optical and radio telescopes in order to study particle acceleration in jets. In the Galaxy, *NuSTAR* will advance the understanding of explosion dynamics and nucleosynthesis in supernovae by mapping Cas A in the radioactive decay of ^{44}Ti (68 keV). Other remnants that will be studied include SN 1987A, Tycho, and G1.9+03. *NuSTAR* will also survey regions of the Galaxy, with the primary survey field being the few square degrees centered on Sgr A*, a region that contains 1% of the stellar mass, but 10% of the massive young stars. The Galactic surveys will identify hundreds of compact stellar remnants even in obscured regions, and will map diffuse features associated with molecular cloud complexes. The *NuSTAR* mission is designed to have access to 80% of the sky at any time, and has ToO capability to enable follow-up of any Type Ia supernova out to Virgo and any core collapse in the local group that occurs during the mission life.

A wide variety of programs are being considered to fill the science reserve time. These include observations of the Sun to search for micro flares believed to heat the corona, high signal to noise spectroscopy of bright AGN, surveys and ToO observations of known magnetars, mapping non-thermal emission in galaxy clusters, and imaging of nearby starburst galaxies. While a number of these programs will be accomplished in the two-year baseline mission, others will be good candidates for Guest Observer (GO) proposals undertaken in an extended mission. *NuSTAR* has no consumables, and the expected orbit lifetime is in excess of five years. The team expects to propose a GO program to the NASA Senior Review that will broaden the scientific return and enable broader community participation.

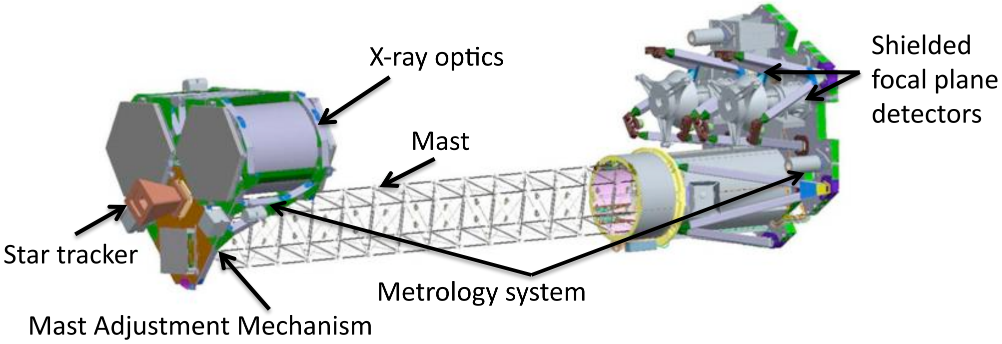

Figure 3. Diagram of the *NuSTAR* instrument showing the principal elements.

4. SCIENCE INSTRUMENT IMPLEMENTATION

The *NuSTAR* science instrument (see Figure 3) consists of two co-aligned grazing incidence optics focusing on to two shielded solid state CdZnTe pixel detectors. The instrument is launched in a compact, stowed configuration, and after launch a 10-meter mast, manufactured by ATK Space Systems, Goleta, is deployed to achieve a focal length of 10.15 m. Because the absolute deployment location of the mast is difficult to measure on the ground, due to complications associated with complete gravity offloading, an adjustment mechanism is built into the last section of the mast to enable a one-time alignment to optimize the location of the optical axes on the focal plane. This mechanism provides two angular adjustments as well as rotation. The mast is not perfectly rigid, but undergoes thermal distortions particularly when going in and out of Earth shadow (the mission is deployed in a low-Earth orbit) that translate into changes in telescope alignment of $1 - 2'$. These mast alignment changes are measured by the combination of an optics bench-mounted star tracker and a laser metrology system. The same combination of sensors also provides the absolute instrument aspect. In order to limit the FoV open to the detectors, and therefore the diffuse cosmic background, an aperture stop consisting of three rings deploys with the mast. The aperture stop is shown in stowed configuration in Figure 3. In deployed configuration the top will be 0.83 m above the focal plane surface.

Table 3. Optics configuration summary.

Parameter	**Value**	**Parameter**	**Value**
Focal length	10.15 m	Shell length	22.5 cm
# shells	133	Min. graze angle	1.34 mrad
# azimuthal segments	6 (inner)/12 (outer)	Max. graze angle	4.7 mrad
Inner radius	5.44 cm	Coating (outer)	W/Si
Outer radius	19.1 cm	Coating (inner)	Pt/C

The *NuSTAR* optics utiliThe foe a conical approximation to a Wolter-I design in a highly nested configuration, with 133 shells per optic with graze angles ranging from 4.6 – 16 arcminutes. The shells are fabricated from segmented thermally formed glass, and the segments are coated with depth-graded multilayers optimized to achieve significant high energy response for this graze angle range.[7] The coatings employ a combination of W/Si bilayers on the outer shells, and Pt/C on the inner shells. The high-energy effective area cutoff results from the K-shell absorption in Platinum. Hailey *et al.* (2010) describe the optics implementation in detail, and Table 3 provides a summary of the primary configuration parameters.

Each focal plane consists of four CdZnTe pixel sensors coupled to a custom low-noise ASIC.[9] Each hybrid contains a 32×32 array of 600 μm pixels with a resulting plate scale of $12.3''$/pixel, so that the mirror point spread function is over-sampled. The sensors are placed in a two-by-two array with a minimal (~ 500 μm) gap

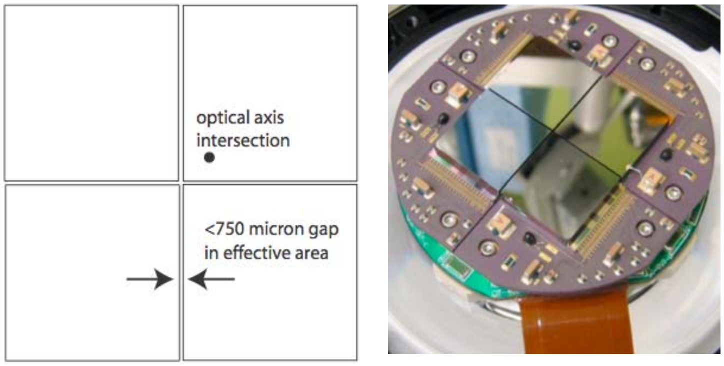

Figure 4. The *NuSTAR* focal plane configuration and photograph of an engineering test module.

between them to fill a total subtended field of view of 13′ on a side (Figure 4). Table 4 summarizes the primary characteristics of the focal plane.

Table 4. Focal plane configuration summary.

Parameter	**Value**	**Parameter**	**Value**
Pixel size	0.6 mm/12.3″	Max processing rate	400 evt/s
Focal plane size	13′ × 13′	Max flux meas. rate	10^4/s
Pixel format	32 × 32	time resolution	2μsec
Threshold	2.5 keV (each pixel)	Dead time fraction (weak source)	2%

To achieve a low energy threshold and good spectral performance, the detector readout is designed for very low noise. The electronic noise contribution (including detector leakage current) to the energy resolution is 400 eV, and the low-energy threshold is 2.5 keV for an event registering in a single pixel. Over most of the energy range the detector spectral resolution is limited by charge collection uniformity in the CdZnTe crystal. At low energies, between 5 and 30 keV, the average spectral resolution for a typical flight detector is 500 eV FWHM, while at 60 keV it is 1.0 keV, and at 86 keV it is 1.2 keV. The focal plane will be passively cooled in flight to between 0° and 5° C. The passive cooling is enabled by the low-power dissipation of the detector readout chip (50 μW/pixel). At in-flight operating temperatures, the detector leakage current is a negligible contributor to the resolution. In addition to measuring the deposited energy and arrival time for each event, the readout architecture enables a depth of interaction measurement which can be used both to maximize photo peak efficiency at high energy, where charge trapping effects can lead to a low-energy 'tail' on the energy resolution, and in addition reject background from the back portion of the detector.

The readout of each focal plane module is controlled by an FPGA-embedded microprocessor. Because each pixel triggers independently, and the electronics shaping time is short, there are no pile-up issues equivalent to the CCD focal planes on *XMM* and *Chandra*. The maximum rate that events can be processed is 400 cps in each telescope; however, pulse pileup does not occur until substantially higher rates ($\sim 10^5$ cps). The readout system is designed so that source fluxes can be measured up to count rates of 10^4 cps. At the nominal faint-source count rates, the readout dead time is $\lesssim 2\%$.

The focal plane is surrounded by an active 2 cm thick CsI(Na) shield and incorporates a deployable aperture stop. The CsI shield extends 20 cm above the detector, and has an opening angle of 16 degrees, while the passive aperture stop defines a much narrower opening of 4 degree diameter. Figure 5 shows the expected background counts per unit detector area as calculated using the GEANT-based MGGPOD[10] Monte Carlo suite. At low energies the background is dominated by diffuse leakage through the portion of the aperture stop FoV not blocked by the optics bench. The spectral features between 25 and 35 keV are fluorescence from the CsI shield. The

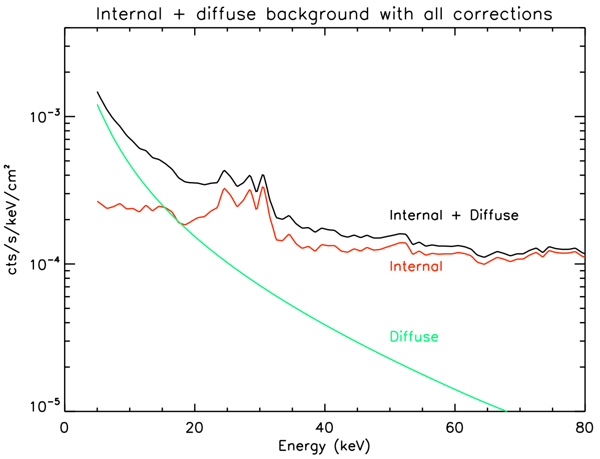

Figure 5. Predicted detector background count rate per unit area as a function of energy.

background level shown in Figure 5 assumes the use of the depth-of-interaction measurement to reject interactions in the back of the detector, which results in about a factor two background reduction at 60 keV.

The instrument components are in a mature state, with flight hardware fabrication underway, and delivery to integration and test beginning in Fall 2010.

5. MISSION DESIGN

NuSTAR will be launched on a Pegasus XL rocket into a 6° inclination, 575 × 600 km low Earth orbit. The low inclination, achieved by using a near-Equatorial launch site at Kwajalein Island, significantly reduces internal detector backgrounds because the orbit avoids the intense region of the SAA (which it still skims on some orbits). The orbit altitude leads to an expected mission life in excess of five years. The telescope will not re-orient during Earth occultations, and the total expected observing efficiency is 50% for typical targets, with higher efficiency (approaching 90%) for targets near the poles. The spacecraft, manufactured by Orbital Sciences Corp., is three-axis stabilized with a single articulating solar panel and relies predominantly upon a multi-head star camera (the DTU microASC) for aspect. This enables 80% of the sky to be accessed at any given time, which both allows ToO viewing with few restrictions, and aids in mission planning.

The satellite will be operated out of the Mission Operations Center (MOC) at U.C. Berkeley. Command uplinks and data downlinks will be through a ground station, operated by the Agenzia Spaziale Italiana, located in Malindi, Kenya. Most science targets will be viewed for a week or more, so that after a 30-day in-orbit checkout and commissioning period, commanding will be rare. The turnaround time for ToO observations depends largely on timing relative to the ground station passes. The Malindi station is visible once per 90 minute orbit, but commands can take up to 12 hours to prepare given that the MOC is not staffed 24 hours/day. The spacecraft slews at an average rate of 1.2°/minute, so a typical slew will take less than 90 minutes.

6. GROUND DATA SYSTEM

The science data will be transferred from the U.C. Berkeley MOC to a Science Operations Center (SOC) located at Caltech. The SOC will process and validate the data, and distribute products to the science team. All science data will be converted to FITS format conforming to Office of Guest Investigator Programs (OGIP) standards, and analysis software will adopt the FTOOLS approach and environment. The *NuSTAR* science data has no proprietary period, and after a six-month interval during which the instrument calibration will be understood and the performance verified, data will enter the public science archive, located at the HEASARC at Goddard Space Flight Center, within two months of completion of an observation (the two-month period being required for ground data processing and validation).

7. SUMMARY AND CONCLUSIONS

With a launch scheduled for early 2012, *NuSTAR* will be the first of a new generation of focusing hard X-ray telescopes, and will provide two orders of magnitude improvement in sensitivity over previous hard X-ray missions, combined with good spectral resolution and sub-arcminute imaging. In the first two years *NuSTAR* will focus on four key science objectives. However, the mission life is limited only by the orbit decay, and an extended mission will be proposed to allow a substantial guest investigator program to expand the scientific reach. The scientific performance expectations are largely based on measurements made on prototype and flight hardware, giving confidence in current projections for sensitivity, spectroscopic and imaging performance.

NuSTAR will incorporate a number of recently developed technologies. At the heart of the instrument are novel depth-graded multilayer optics focusing onto CdZnTe pixel detectors developed originally for the *HEFT* balloon experiment. *NuSTAR* will be the first X-ray telescope to utilize a long (10-meter) extendable mast, and will demonstrate the application of this technology as well as the requisite metrology system. While the instrument contains new elements, the spacecraft is based on a heritage design, and the mission operations approach is simple. These elements enable a highly capable science mission on a Small Explorer platform.

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