Appendix SMEX-11 to the Explorers Program Plan

Nuclear Spectroscopic Telescope Array (*NuSTAR*)

Program Level Requirements

NATIONAL AERONAUTICS
and
SPACE ADMINISTRATION

Science Mission Directorate

DOCUMENT CHANGE LOG

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1. Scope

This appendix to the Explorers Program Plan identifies the mission, science and programmatic (funding and schedule) requirements imposed on the California Institute of Technology (Caltech), the Goddard Space Flight Center (GSFC) and the Jet Propulsion Laboratory (JPL) for the development and operation of the *Nuclear Spectroscopic Telescope Array* (*NuSTAR*) Project of the Explorers Program. Requirements begin in Section 4. Sections 1, 2, and 3 are intended to set the context for the requirements that follow.

This document serves as the basis for mission assessments conducted by NASA Headquarters during the development period and provides the baseline for the determination of the science mission success following the completion of the operational phase.

Program authority is delegated from the Associate Administrator of the Science Mission Directorate (AA/SMD) through the Explorers Program Manager within the Flight Projects Directorate at GSFC to Caltech and JPL.

The California Institute of Technology, under contract to the Explorers Program at GSFC, is responsible for the scientific success of the *NuSTAR* Project, using the set of approved co-investigators reflected in the proposal including any approved changes prior to the release of this appendix.

Caltech is responsible for design, development, test, mission operations, and data verification tasks and shall coordinate the work of all contractors and co-investigators. The *NuSTAR* Project is managed by the Jet Propulsion Laboratory.

Changes to information and requirements contained in this document require approval by the AA/SMD, NASA Headquarters.

2. Science Definition

2.1 *NuSTAR* Science Objectives

Significant portions of the sky have been mapped in exquisite detail at X-ray energies below 10 keV to depths enabling the study of objects far outside our Galaxy. At energies above this, the lack of focusing telescopes capable of sensitive observations has limited our knowledge of the Universe largely to bright objects within our own Galaxy, and a few dozen nearby extragalactic sources. *NuSTAR* employs technologies developed over the last decade in a system that extends the inherently low-background, high-sensitivity observations of a focusing telescope to X-ray energies up to 79 keV. *NuSTAR*'s primary science goal is to make the first deep observations of regions of the sky in the high-energy X-ray band (defined as 6 to 79 keV) in order to discover astrophysical objects that primarily radiate at these wavelengths, and to study energetic phenomena uniquely observable there. The following primary science objectives support this goal:

OBJECTIVE 1: Locate massive black holes in other galaxies at high energy X-ray energies (6 - 79 keV) that are dim at X-ray energies below 10 keV, measure their density on the sky, as well as the distribution of their high-energy X-ray apparent brightness, and correlate these properties with those found at other wavelengths.

OBJECTIVE 2: Locate the remnants of collapsed stars -- black holes, neutron stars, and white dwarfs -- in our Galaxy that radiate high-energy X-rays, measure their spatial distribution, and correlate their properties with those found at low-energy X-ray, radio, and infrared wavelengths.

OBJECTIVE 3: Measure the intensity and distribution of material in the remnants of stars that have exploded within the last ~ 500 years by using the radioactive tracer ^{44}Ti, which has key diagnostic decay lines at X-ray energies of 68 and 78 keV.

OBJECTIVE 4: Observe a sample of Very High Energy (VHE) gamma-ray sources and measure their high energy X-ray temporal, spatial and spectral properties in order to constrain the mechanisms responsible for the high energy emission.

OBJECTIVE 5: Observe any core collapse supernovae in the Local Group and/or any Type Ia supernovae identified by optical telescopes that are in or closer than the Virgo cluster that occur during the mission life. Although such an event is not guaranteed to happen within the mission lifetime, the scientific implications would be profound, and observations of such events are therefore included in the primary objectives.

2.2 Baseline Science Mission

The baseline science mission supports the NuSTAR primary science goal discussed in § 2.1 and shall address the complete set of primary science objectives listed there.

2.3 Threshold Science Mission

The threshold science mission supports the *NuSTAR* primary science goal discussed in § 2.1 and shall address a subset of the primary science objectives (1, 2, and 3) listed there.

2.4 Science Instrument Summary Description

The baseline payload configuration consists of two focusing high-energy X-ray (6 - 79 keV) telescopes that are co-aligned to view the same field on the sky. The telescopes are comprised of two identical optics assemblies and associated focal plane modules that are maintained on-orbit at a 10-m focal length by a mast that extends after launch. The optics function like lenses, and the X-ray detectors like digital film. Two telescopes image the same field of view; the images are co-added on the ground in order to attain the full instrumental sensitivity. The detectors register the interaction position, time, and energy of individual X-rays, and images are built up on the ground by binning the X-ray counts into images.

3. Project Definition

3.1 Project Organization and Management

The Principal Investigator (PI) at Caltech is responsible for the overall success of the *NuSTAR* Project and is accountable to the AA/SMD for the scientific success, and to the GSFC/Explorers Program Manager for the programmatic success. The PI has delegated day-to-day management of the *NuSTAR* project to the *NuSTAR* Project Manager at the Jet Propulsion Laboratory. The Jet Propulsion Laboratory holds the Technical Authority (TA) for the *NuSTAR* mission. The GSFC/JPL Memorandum of Agreement concerning Program Managing Center/Project Managing Center/Instrument Provider responsibilities is applicable. The JPL Center Director is responsible for certifying *NuSTAR* flight readiness to NASA's Associate Administrator of the Science Mission Directorate with the concurrence of the Explorers Program Manager.

3.2 Project Acquisition Strategy

The payload development will be led by Caltech with systems engineering support and technical oversight from JPL. Major payload components will be subcontracted out as follows:

- Instrument Structure and Extendable Mast from ATK Space Systems
- Optics Modules from Columbia University
- Optics glass segments from GSFC
- Structures for focal plane assembly, electronics and laser metrology from the University of California at Berkeley

Caltech will develop the focal plane assembly and instrument electronics. JPL is responsible for developing the metrology system and the instrument integration and test. The spacecraft bus and observatory level integration and test will be procured from Orbital Sciences Corporation. The University of California at Berkeley will lead the development and implementation of the Mission Operations segment of the *NuSTAR* mission. The mission Science Operations and Data Analysis activities will be led by Caltech.

4. Mission Requirements

4.1 Baseline Mission Requirements

The *NuSTAR* baseline mission is defined as the nominal operation of the *NuSTAR* observatory (in the configuration specified at the time of confirmation for KDP B) for a nominal period of 25 months. It is comprised of two phases: an in-orbit checkout (IOC) period and the baseline science mission phase. The IOC phase represents the period during which the observatory is activated and brought to a state of nominal science operations and is expected to be ≤ 1 month in duration. The baseline science mission is defined as the period during which the *NuSTAR* science observing plan is executed; during this phase, the full set of mission science objectives (§ 2.2) shall be addressed, and the baseline mission science requirements (specified in § 4.1.1) shall be accomplished. The baseline science mission shall be a minimum of 24 months in duration. In addition to the baseline science mission, a mission extension may be approved to address an augmented set of science objectives, subject to appropriate review and approval by the AA/SMD.

4.1.1 Baseline Mission Science Requirements

As discussed in Section 2, *NuSTAR* will make sensitive maps of regions of the sky in the high-energy X-ray band from 6 to 79 keV. This section defines the science requirements imposed on *NuSTAR* corresponding to the complete set of mission scientific objectives described in § 2.1. These requirements are placed upon the baseline mission.

Scientific results obtained from other ground- and space-based observatories in the interim between approval of this document and *NuSTAR*'s launch may influence the mission's optimal observing strategy. In view of this fact and the exploratory nature of the *NuSTAR* mission, the requirements specified below reflect the current state of the field, and may be revised prior to launch to optimize the scientific return from *NuSTAR*. If this occurs, this appendix will be updated to reflect the changes and submitted for approval through the Astrophysics Division to the SMD AA.

Achievement of the baseline mission science objectives outlined in § 2.2 imposes the following baseline mission scientific requirements (BSR) on the mission:

BSR1: *NuSTAR* shall perform a minimum of two sky surveys in the hard X-ray band (E = 6 – 79 keV) of regions that have been previously surveyed in one or more wavelength bands to detect and accurately locate massive black holes in the nuclei of external galaxies that are obscured at soft X-ray energies (E < 10 keV). These surveys shall comprise the systematic mapping of at least one sky region with solid angle ≥ 200 square arcminutes and at least one sky region with solid angle ≥ 4 square degrees.

BSR2: *NuSTAR* shall perform a survey of the region in the direction of the center of the Milky Way Galaxy to detect and locate compact objects (black holes, neutron stars, and white dwarfs) in accreting binary systems and correlate their hard X-ray characteristics with those observed at soft X-ray, infrared, and radio wavelengths. This survey shall comprise a systematic mapping of a region of extent ≥ 1 square degree concentrated towards the direction of the Galactic Center.

BSR3: *NuSTAR* shall investigate the process of nucleosynthesis of the elements via observations of selected supernova remnants in the Milky Way Galaxy and neighboring Local Group galaxies by measuring the spatial distribution, intensity, and spectrum of material ejected in the supernova explosion. At a minimum, *NuSTAR* shall observe the supernova remnants Cassiopeia A and SN1987A over the hard X-ray band with the goal of detecting (or setting stringent upper limits upon) the emission of ^{44}Ti from the ejecta.

BSR4: *NuSTAR* shall observe and determine the temporal and spectral properties of the hard X-ray emission from gamma-ray sources that are bright at very high energies (GeV and TeV; commonly referred to as "VHE gamma-ray sources") to provide new constraints on the energy release mechanism(s) of these objects. A minimum of four VHE gamma-ray sources selected from GeV and TeV catalogs shall be observed with *NuSTAR*. Coordinated observations with radio, optical, and gamma-ray observatories shall be conducted for at least three of these sources.

BSR5: *NuSTAR* shall investigate the process of explosive nucleosynthesis in the nearby Universe through Target of Opportunity (ToO) observations in response to the onset of a core collapse and/or Type Ia supernova identified within the Local Group or out to the distance of the Virgo Cluster, respectively, during the baseline science mission. *NuSTAR* shall respond to such events on a timescale of ≤ 48 hours after receipt of the target coordinates and shall observe them for a minimum of 14 days.

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4.1.2 Baseline Mission Technical Requirements

In order to address the *NuSTAR* primary science objectives described in § 2.1 and satisfy the corresponding baseline mission science requirements specified in § 4.1.1, the *NuSTAR* mission shall meet the following baseline technical requirements (BTR):

BTR1: The *NuSTAR* observatory and associated ground support system shall be designed and fabricated to sustain science operations at the level required to achieve the baseline mission science requirements defined in § 4.1.1.

BTR2: The *NuSTAR* observatory shall collect data from astrophysical targets for ≥ 40% of the baseline science mission duration. This accounts for all sources of observing inefficiency, including loss of S/C attitude, Earth occultation, SAA passage, data errors, and instrument electronic dead time.

BTR3: The *NuSTAR* observatory shall have the capability to respond to Targets of Opportunity (ToO) anywhere on the sky, subject to viewing constraints (sun/earth/moon avoidance), on a timescale of ≤ 48 hours after receipt of the target coordinates.

BTR4: The *NuSTAR* observatory shall provide the following detection sensitivity (field averaged) for studies of point sources:

(a) *Continuum*: The *NuSTAR* observatory shall detect, at a confidence level of 99.7%, sources that have an X-ray continuum flux $S \geq 6 \times 10^{-15}$ erg/cm^2/s (6 - 10 keV) averaged over a 64 square arcminute field of view, $S \geq 5 \times 10^{-14}$ erg/cm^2/s (10 - 40 keV) averaged over a 16 square arcminute field of view, and $S \geq 4 \times 10^{-13}$ erg/cm^2/s (40 - 79 keV) averaged over a 4 square arcminute field of view. These detection levels are defined for a net observation time of 10^6 s for sources with photon spectral index $\alpha = 1.7$.

(b) *Lines*: The *NuSTAR* observatory shall detect, at a confidence level of 99.7%, line emission at E = 68 keV that has a flux $\geq 1.8 \times 10^{-6}$ ph/cm^2/s over a 4 square arcminute field of view. This detection level is defined for a net observation time of 10^6 s.

BTR5: The *NuSTAR* observatory shall provide the following imaging capability for studies of cosmic X-ray sources:

(a) *Angular Resolution*: The *NuSTAR* observatory shall have an angular resolution with half power diameter ≤ 60 arcseconds.

(b) *Positional Accuracy*: The *NuSTAR* observatory shall determine the celestial coordinates of X-ray sources to an accuracy of 10 arcseconds (at a confidence level of 99.7%) for sources detected at a signal to noise ratio ≥ 15.

BTR6: The *NuSTAR* observatory shall provide the following spectroscopic capability for studies of cosmic X-ray sources:

(a) *Spectral Response*: The *NuSTAR* observatory shall have the capability to measure the continuum and line emission from cosmic X-ray sources over the energy band E = 6 – 79 keV.

(b) *Spectral Resolution*: The *NuSTAR* observatory shall measure the centroid and width of spectral lines to an accuracy of ≤ 0.2 keV (confidence level of 99.7%) and resolution

$\delta E < 1.6$ keV (FWHM), respectively. This shall apply to lines detected with a signal to noise ratio ≥ 15 over the energy range from 60 to 79 keV.

4.1.3 Baseline Mission Data Requirements

In order to address the mission science objectives described in § 2.1 and satisfy the corresponding baseline mission science requirements specified in § 4.1.1, the *NuSTAR* mission shall meet the following data requirements (BDR):

BDR1: The NuSTAR science operations system shall collect and make available to the Science Operations Center (SOC) > 95% of all data collected by the observatory.

BDR2: Beginning 6 months after the completion of IOC, the NuSTAR science operations system shall validate all science data delivered to the SOC within two months of receipt.

BDR3: All data files, calibration files, and software tools required for analysis of the NuSTAR science data shall be delivered to the High Energy Astrophysics Science Archive Research Center (HEASARC) within one week of validation by the NuSTAR science operations system. The data will be accessible to the broader astrophysical community immediately upon receipt by the HEASARC with no proprietary period.

BDR4: The NuSTAR SOC shall compile a comprehensive set of the high-level science data products (e.g., sky maps, source light curves and spectra, etc.) for archiving at the HEASARC. The final, fully-calibrated NuSTAR science data set shall be delivered to the HEASARC within one year following the end of the mission.

4.1.4 Baseline Mission Success Criteria

The baseline mission success criteria shall be met when the Baseline Mission Science Requirements (BSR1 – BSR4) are satisfied and BSR5 is satisfied if a qualifying event occurs during the baseline science mission.

4.2 Threshold Mission Requirements

The *NuSTAR* threshold mission is defined as the nominal operation of the *NuSTAR* observatory (in the actual launch configuration) for a nominal period of 19 months. It is comprised of two phases: an in-orbit checkout (IOC) period and the threshold science mission phase. The IOC phase represents the period during which the observatory is activated and brought to a state of nominal science operations and is expected to be

≤ 1 month in duration. The threshold science mission is defined as the period during which the *NuSTAR* science observing plan is executed; during this phase, the subset of mission science objectives (§ 2.3) shall be addressed, and the threshold mission science requirements (specified in § 4.2.1) shall be accomplished. The threshold science mission shall be a minimum of 18 months in duration. In addition to the threshold science mission, a mission extension may be approved to address an augmented set of science objectives, subject to appropriate review and approval by the AA/SMD.

4.2.1 Threshold Mission Science Requirements

As discussed in Section 2, *NuSTAR* shall make sensitive maps of selected regions of the sky in the high-energy X-ray band (E = 6 - 79 keV). This section defines the science requirements imposed on *NuSTAR* corresponding to the threshold mission scientific objectives as outlined in § 2.3. These requirements are placed upon the threshold science mission.

Scientific results obtained from other ground- and space-based observatories in the interim between approval of this document and *NuSTAR*'s launch may influence the mission's optimal observing strategy. In view of this fact and the exploratory nature of the *NuSTAR* mission, the requirements specified below reflect the current state of the field, and may be revised prior to launch and/or fine-tuned during the threshold science mission to optimize the scientific return from *NuSTAR*. If this occurs, this appendix will be updated to reflect the changes and submitted for approval through the Astrophysics Division to the SMD AA.

Achievement of the threshold science mission objectives imposes the following threshold scientific requirements (TSR) upon the mission:

TSR1: *NuSTAR* shall perform a minimum of two sky surveys in the hard X-ray band (E = 6 – 79 keV) of regions that have been previously surveyed in one or more wavelength bands to detect and accurately locate massive black holes in the nuclei of external galaxies that are obscured at soft X-ray energies (E < 10 keV). These surveys shall comprise systematic mapping of at least one sky region with solid angle ≥ 200 square arcminutes and at least one sky region with solid angle ≥ 4 square degrees.

TSR2: *NuSTAR* shall perform a survey of the region in the direction of the center of the Milky Way Galaxy to detect and locate compact objects (black holes, neutron stars, and white dwarfs) in accreting binary systems and correlate their hard X-ray characteristics with those observed at soft X-ray, infrared, and radio wavelengths. This survey shall comprise a systematic mapping of a region of extent ≥ 1 square degree concentrated towards the direction of the Galactic Center.

TSR3: *NuSTAR* shall investigate the process of nucleosynthesis of the elements via observations of supernova remnants in the Milky Way Galaxy and neighboring Local Group galaxies by measuring the spatial distribution, intensity, and spectrum of material ejected in the supernova explosion. At a minimum, *NuSTAR* shall observe the supernova remnants Cassiopeia A and SN1987A over the hard X-ray band with the goal of detecting (or setting stringent upper limits upon) the emission of ^{44}Ti from the ejecta.

4.2.2 Threshold Mission Success Criteria

The threshold mission success criteria shall be met when the set of Threshold Mission Science Requirements (TSR1 – TSR3) are satisfied.

4.3 Launch and Orbit Requirements

NuSTAR shall be launched into a circular, low Earth ($h \geq 525$ km altitude), low inclination ($i \leq 28^{\circ}$) orbit by a suitable launch vehicle. The launch vehicle and launch services shall be provided by the NASA Kennedy Space Center (KSC). Potential launch sites capable of meeting the NuSTAR orbital inclination requirement include Kennedy Space Center ETR and Kwajalein Atoll; the substantially lower inclination attainable from the latter ($i \leq 5^{\circ}$) would provide both a significantly enhanced science return (for a given mission lifetime) and more benign radiation environment. The *NuSTAR* launch readiness date is nominally planned for no later than 31 August 2011. The latter is predicated upon availability of funding according to the nominal budget profile as specified at KDP-B.

5. NASA Mission Cost Requirements

5.1. Cost Cap

NuSTAR project funding is capped at $99 M FY08 Dollars for design, development, mission operations, and data analysis and archiving. Launch and associated launch vehicle integration and accommodation costs are not included under this cap.

5.2. Cost Management and Scope Reduction

Provided that Program Level Requirements are preserved, and that due consideration has been given to the use of budgeted contingency and planned schedule contingency, the *NuSTAR* project shall pursue scope reduction and risk management as a means to control cost. The *NuSTAR* Mission Implementation Plan shall include potential scope reductions and the time frame in which they could be implemented. If other methods of cost containment are not practical, the reductions identified in the *NuSTAR* Mission Implementation Plan may be exercised. Any reduction in scientific capability below the baseline requirements shall be implemented only after consultation with, and approval by, the signers of this document.

6. Multi-Mission NASA Facilities

The *NuSTAR* project shall use the following NASA facilities:

- Kennedy Space Center ETR launch facilities (as required)
- Goddard Space Flight Center Spectrum Management for NTIA licensing using government frequencies
- TDRSS facilities for commanding and data retrieval

7. External Agreements

The following agreements with non-U.S. entities will be required to carry out the *NuSTAR* mission:

(1) Caltech and the Danish National Space Center (DNSC) for multilayer coating for the optics and calibration facilities and support

(2) Caltech and the Agenzia Spaziale Italiana (ASI) for use of the Malindi ground station

8. Public Outreach and Education

The *NuSTAR* project shall develop and execute an Education and Public Outreach Plan consistent with information provided as a part of the NASA Headquarters SMD Confirmation Review. Science images shall be made available for outreach purposes within one month of the end of in-orbit checkout.

9. Approvals

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