Appendix EX-2 to the Explorers Program Plan

Transiting Exoplanet Survey Satellite (TESS)

Program Level Requirements

NATIONAL AERONAUTICS
and
SPACE ADMINISTRATION

Science Mission Directorate

DOCUMENT CHANGE LOG

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CONTENTS

1. Scope

This appendix to the Explorers Program Plan identifies the mission, science and programmatic (funding and schedule) requirements imposed on the Massachusetts Institute of Technology (MIT), and the Goddard Space Flight Center (GSFC) for the development and operation of the Transiting Exoplanet Survey Satellite (TESS) Project of the Explorers Program. Requirements begin in Section 4. Sections 1, 2, and 3 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 SMD Astrophysics Division Explorer Program Director to the Explorers Program Manager within the Flight Projects Directorate at GSFC to MIT.

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

MIT is responsible for design, development, test, mission operations, and data verification tasks and shall coordinate the work of all co-investigators and all MIT subcontractors. The TESS Project is managed by GSFC.

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

2. Science Definition

2.1 Science Objectives

TESS's science goal is to detect transiting exoplanets orbiting nearby, bright stars. A sample of hundreds of thousands of stars must be searched in order to detect a large sample of exoplanets, with an emphasis on discovering Earth-sized and super-Earth planets in the solar neighborhood. Specifically, the stars to be searched are dwarfs of spectral classes F, G, K, and M. The sample of stars will have a limiting I-band apparent magnitude of approximately 10-14, depending on spectral class.

To accomplish this goal, TESS will monitor the brightness of a large sample of stars distributed over the celestial sphere, looking for dips in brightness characteristic of transiting planets. Because the TESS target stars are, on average, much brighter than Kepler targets, it will be much easier to follow up TESS discoveries with ground-based spectroscopy to measure the planet masses, and with space-based spectroscopy to characterize their atmospheres.

The following science objectives support this goal:

OBJECTIVE 1: Identify a diverse sample of transiting exoplanets with radii less than 2.5 R_{Earth} and orbital periods of up to 10 days orbiting the brightest stars in the solar neighborhood.

OBJECTIVE 2: Identify a sample of transiting exoplanets with radii less than 2.5 R_{Earth} and orbital periods 120 days or more orbiting bright stars situated near the ecliptic poles, locations that are optimal for JWST followup.

OBJECTIVE 3: Establish the masses of a sample of TESS-located transiting planets with sizes less than 4 R_{Earth} by means of analytical techniques and/or precise radial velocity measurements.

2.2 Baseline Science Mission

The baseline science mission supports the TESS science goal discussed in §2.1 and shall fully satisfy the complete set of baseline mission science requirements listed in §4.1.1.

2.3 Threshold Science mission

The threshold science mission minimally supports the TESS science goal discussed in §2.1 and shall satisfy the set of threshold mission science requirements listed in §4.2.1.

2.4 Science Instrument Summary Description

The baseline instrument configuration consists of four identical wide-field photometers, each with a FOV of 24°x24°, aligned to image a 96° x 24° sector of the sky. The cameras each consist of a four-CCD array at the focus of a refractive optic, operating in the spectral band 0.6-1.0 microns. The CCDs are clocked so as to generate a contiguous set of two-second images; the images are co-added on board the spacecraft to reduce data storage and downlink requirements.

Pixel subarrays ("postage stamps"), notionally 10x10 pixels, are extracted from regions centered on target stars. Subarray data are processed on the ground to generate calibrated light curves for each target star, in a manner very similar to the processing done for Kepler. In addition, stacked full-frame images (FFIs) from each camera will be downlinked at 30 minute intervals, providing both diagnostic and science data.

3. Project Definition

3.1 Project Organization and Management

The Principal Investigator (PI) at MIT is responsible for the overall success of the TESS 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 TESS project to the TESS Project Manager at the GSFC. The GSFC holds the Technical Authority (TA) for the TESS mission. The GSFC Center Director is responsible for certifying TESS 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 TESS observatory development will be led by MIT with Project Management from GSFC. Responsibility for major TESS observatory components is assigned as follows:

- MIT Kavli Institute and MIT Lincoln Laboratory, for instrument development and integration.
- Orbital Sciences Corporation (OSC), for spacecraft bus and observatory level integration and testing.

The Mission Operations Center (MOC) will be the responsibility of OSC at Dulles, VA. Science Operations will be the responsibility of MIT . The Space Telescope Science Institute will assist MIT by serving as the archive facility, and the Ames Research Center (ARC) will assist MIT by providing data processing support.

4. Mission Requirements

4.1 Baseline mission requirements

The TESS baseline mission begins at launch plus 2 months, and shall be 36 months in duration, spanning Phases E and F of the mission lifecycle. Phase E shall begin after a 2 month orbital checkout of the TESS observatory, and consist of 24 months of TESS observatory and groundbased science operations. Phase F shall consist of a 12 month closeout of the TESS mission and associated ground-based science observations. During the 24 months of TESS observatory and ground-based science operations, and the 12 months of subsequent closeout, the full set of mission science objectives (§2.1) shall be addressed and the baseline mission science requirements (§4.1.1) shall be accomplished. The TESS baseline mission is designed to yield at least 200 exoplanets between 2.5 and 4 R_{Earth}, as predicted by models based upon the current best understanding of exoplanet populations. By discovering a sample of this size, the TESS follow-

up program will be able to choose a set of planets that reflect a diversity of characteristics (orbital parameters, planetary size, stellar type, etc.). In addition to the TESS baseline 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, or as delegated to the SMD Astrophysics Division.

4.1.1 Baseline Mission Science Requirements

As discussed in Section 2, TESS will monitor the brightness of nearby, bright F, G, K, and M stars in the sky in order to search for transiting planets. This section defines the science requirements imposed on the TESS mission to fully satisfy the complete set of scientific objectives described in §2.1.

Scientific results obtained from other ground- and space-based observatories in the interim between approval of this document and TESS 's launch may influence the mission's optimal observing strategy. In view of this fact and the exploratory nature of the TESS 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 TESS. 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: TESS shall perform a wide-field sky survey sensitive to transiting planets with orbital periods of less than 10 days. In this survey, TESS shall monitor >200,000 stars spread over the celestial sphere with a photometric sensitivity sufficient to permit detection of transiting planets with a radius $\geq 2.5\ R_{Earth}$.

BSR2: TESS shall perform a concurrent sky survey sensitive to transiting planets with periods of 120 days or more. In this survey, TESS shall monitor >10,000 stars in regions centered on the ecliptic poles with a photometric sensitivity sufficient to permit detection of transiting planets with a radius $\geq 2.5\ R_{Earth}$.

BSR3: The TESS team shall assure that the masses of fifty (50) planets with radii less than 4 R_{Earth} are determined.

4.1.2 Baseline Mission Technical Requirements

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

BTR1: The TESS observatory and associated ground support system shall be designed and fabricated to sustain all aspects of spacecraft operations for a period of 26 months, the time period necessary to fully execute an all-sky survey of transiting planets around nearby, bright F, G, K, and M stars.

BTR2: The TESS observatory shall collect data from each exoplanet target for at least 20 days during each 27 day observing session. This accounts for all sources of observing inefficiency, including repointing for data downlink, interruptions due to Earth/Moon in a camera FOV, and eclipses.

BTR3: The TESS cameras shall have an effective instrumental effective area, defined as the product of the geometric area of the entrance pupil, the CCD QE over the 0.6-1.0 μm bandpass, the transmissivity of the optics, and the transmissivity of the bandpass filter, of at least 50 cm^2.

BTR4: The TESS observations shall achieve a systematic noise floor of 60 ppm or better, on a timescale of one hour, for stars brighter than I-band apparent magnitude 8.

BTR5: The TESS observations shall provide a temporal resolution of 2 minutes or better for the brightest 100,000 target stars.

BTR6: The TESS data analysis and ground-based follow-up observing program shall be sufficient to ensure that the masses of fifty (50) planets with radii less than 4 R_{Earth} can be determined within Phases E and F.

4.1.3 Baseline Mission Data Requirements

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

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

BDR2: Six (6) months after the in-orbit checkout is complete, the TESS SOC shall begin delivering science data products to the permanent science data archive. These products will include raw pixel data, calibrated pixel data and FFIs, ancillary data, calibration files, and other processed science data. The initial delivery will comprise data from the first four (4) months of survey observations. Subsequent deliveries will occur at four month intervals, and will consist of data taken up to 6 months prior to delivery.

BDR3: The final, fully-calibrated set of TESS science data products shall be delivered at the end of Phase F.

BDR4: All TESS data products will be made publicly available at the permanent science data archive with no proprietary period.

4.2 Threshold Mission Requirements

The TESS threshold mission is defined as the nominal operation of the TESS observatory if the observatory performance (e.g. observatory lifetime, reduced solid angle coverage or sensitivity) compromises the mission's ability to fully achieve the Baseline Mission Requirements defined in §4.1. The threshold science mission phase is defined as the period during which the TESS science observation plan is executed. During this phase, the full set of mission science objectives (§2.1) shall be minimally addressed and the threshold mission science requirements (§4.2.1) shall be accomplished. The threshold science mission shall observe a minimum of 50% as many

stars as could the baseline mission, still assuring a yield of at least 100 exoplanets with radii between 2.5 and 4 R_{Earth}. 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, or as delegated to the SMD Astrophysics Division.

4.2.1 Threshold Mission Science Requirements

As discussed in Section 2, TESS will monitor the brightness of nearby, bright F, G, K, and M stars in the sky in order to search for transiting planets. This section defines the science requirements imposed on TESS to minimally satisfy the complete set of scientific objectives described in §2.1. These requirements are placed upon the threshold mission. Scientific results obtained from other ground- and space-based observatories in the interim between approval of this document and the TESS launch may influence the mission's optimal observing strategy. In view of this fact and the exploratory nature of the TESS 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 TESS . 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: TESS shall perform a wide-field sky survey sensitive to transiting planets with orbital periods of less than 10 days. In this survey, TESS shall monitor >100,000 stars with a photometric sensitivity sufficient to permit detection of transiting planets with a radius ≥ 2.5 R_{Earth}.

TSR2: TESS shall perform a concurrent sky survey sensitive to transiting planets with periods of 60 days or more. In this survey, TESS shall monitor >5,000 stars in regions centered on one or both of the ecliptic poles with a photometric sensitivity sufficient to permit detection of transiting planets with a radius ≥ 2.5 R_{Earth}.

TSR3: The TESS team shall assure that the masses of thirty-five (35) planets with radii less than 4 R_{Earth} are determined.

4.2.2 Threshold Mission Technical Requirements

In order to minimally address the TESS science objectives described in §2.1 and satisfy the corresponding threshold mission science requirements specified in §4.2.1, the TESS mission shall meet the following threshold technical requirements (TTR):

TTR1: The TESS observatory and associated ground support system shall be designed and fabricated to sustain all aspects of spacecraft operations operations. for a period of time necessary to execute a survey of transiting planets around >100,000 of nearby, bright F, G, K, and M stars.

TTR2: The TESS observatory shall collect data from each exoplanet target for at least 20 days during each 27 day observing session. This accounts for all sources of observing inefficiency,

including repointing for data downlink, interruptions due to Earth/Moon in a camera FOV, and eclipses.

TTR3: The TESS cameras shall have an effective instrumental effective area, defined as the product of the geometric area of the entrance pupil, the CCD QE over the 0.6-1.0 μm bandpass, the transmissivity of the optics, and the transmissivity of the bandpass filter, of at least 40 cm^2.

TTR4: The TESS observations shall achieve a systematic noise floor of 80 ppm or better, on a timescale of one hour, for stars brighter than I-band apparent magnitude 8.

TTR5: The TESS observations shall provide a temporal resolution of 5 minutes or better for the brightest 50,000 target stars.

TTR6: The TESS data analysis and ground-based follow-up observing program shall be sufficient to ensure that the masses of thirty-five (35) planets with radii less than 4 R_{Earth} can be determined during Phases E and F.

4.2.3 Threshold Mission Data Requirements

The TESS threshold mission data requirements are the same as the baseline mission data requirements stated in 4.1.3.

4.3 Mission Success Criteria

A successful TESS mission shall:

4.3.1. Identify a set of transiting exoplanets with periods of $\leq$ 10 days and radii of $\geq$ 2.5 R_{Earth} distributed over the area of the sky surveyed during the TESS mission.

4.3.2. Identify a set of transiting exoplanets with periods of $\geq$ 60 days and radii of $\geq$ 2.5 R_{Earth} distributed over the area of the sky surveyed during the TESS mission.

4.3.3. Deliver a high quality data set of raw and processed observations of all TESS targets for public use. Included with this archive shall be documentation describing the data, their analysis, and any instrumental effects or data processing artifacts known to remain, sufficient to enable any competent scientist familiar with astronomical photometry to successfully exploit the TESS archive.

4.4 Launch and Orbit Requirements

TESS shall be launched into a high Earth elliptical orbit (nominally 17 x 59 Earth radii), with an initial 35°– 45° inclination with respect to the Earth-Moon plane. The launch vehicle and launch services shall be provided by the NASA Kennedy Space Center (KSC).

The Agency TESS launch readiness date is June 2018.

5. NASA Mission Cost Requirements

5.1 Cost Cap

TESS project funding is currently capped at $228.3 M RY Dollars for design, development, mission operations, and data analysis and archiving, and will be updated consistent with the KDP-C budget decision, as required. 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 TESS project shall pursue scope reduction and risk management as a means to control cost. The potential scope reductions and the time frame for implementation will be reviewed as part of the KDP-C decision process. 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 TESS project shall use the following NASA facilities:

- Kennedy Space Center ETR launch facilities, or other launch facilities, as identified.
- Goddard Space Flight Center for engineering development support (as required).
- Ames Research Center for support in data processing.
- DSN/TDRSS facilities for commanding and data retrieval.

7. External Agreements (Not applicable)

8. Public Outreach and Education (Not applicable)

E/PO is not included in the TESS Project per NASA SMD Astrophysics Division policy.

9. Concurrence

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