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*The Transiting Exoplanet Survey Satellite*

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# The Transiting Exoplanet Survey Satellite

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## ABSTRACT

The Transiting Exoplanet Survey Satellite (*TESS*) will search the solar neighborhood for planets transiting bright stars. *TESS* has been selected by NASA for launch in 2017 as an Astrophysics Explorer mission. The spacecraft will be placed into a highly elliptical 13.7-day orbit around the Earth. During its two-year mission, *TESS* will employ four wide-field optical CCD cameras to monitor at least 200,000 main-sequence dwarf stars with  $I_C \lesssim 13$  for temporary drops in brightness caused by planetary transits. Each star will be observed for an interval ranging from one month to one year, depending on the star's ecliptic latitude. The longest observing intervals will be for stars near the ecliptic poles, which are the optimal locations for follow-up observations with the James Webb Space Telescope. Brightness measurements of preselected target stars will be recorded every 2 min, and full frame images will be recorded every 30 min. *TESS* stars will be 10–100 times brighter than those surveyed by the pioneering *Kepler* mission. This will make *TESS* planets easier to characterize with follow-up observations. *TESS* is expected to find more than a thousand planets smaller than Neptune, including dozens that are comparable in size to the Earth. Public data releases will occur every four months, inviting immediate

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community-wide efforts to study the new planets. The *TESS* legacy will be a catalog of the nearest and brightest stars hosting transiting planets, which will endure as highly favorable targets for detailed investigations.

**Keywords:** Exoplanet, extrasolar planet, photometry, satellite, transit

## 1. INTRODUCTION

The study of exoplanets—planets orbiting stars outside our Solar System—is one of the most exciting and rapidly advancing fields of science. Especially valuable are systems in which a planet’s orbit carries it directly across the face of its host star. For such a “transiting” planet, it is possible to determine the planet’s mass and radius, its orbital parameters, and its atmospheric properties.<sup>1</sup>

Of particular interest are planets with sizes between those of the Earth and Neptune. Little is known about them, because there are no examples in the Solar System. NASA’s *Kepler* mission revolutionized exoplanetary science by revealing that such planets are abundant,<sup>2,3</sup> and seem to have a wide range of compositions<sup>4</sup> and interesting orbital configurations.<sup>5</sup> However, most of the *Kepler* stars are too faint for detailed follow-up observations.

The Transiting Exoplanet Survey Satellite, or *TESS*, will take the next logical step after *Kepler* by searching the nearest and brightest stars for transiting planets. The primary objective of *TESS* is to discover hundreds of transiting planets smaller than Neptune, with host stars bright enough for follow-up spectroscopy to measure planetary masses and atmospheric compositions. This objective will be achieved by conducting a two-year all-sky survey, during which differential time-series photometry will be performed for hundreds of thousands of stars. The main value of *TESS* data will not be statistical completeness, but rather the relative ease of following up on discoveries with current and planned instruments.

This paper provides an update of an earlier description<sup>6</sup> of the *TESS* mission, including current details relating: its history (§ 2), design considerations (§ 3), payload (§ 4), spacecraft (§ 5), orbit (§ 6), operations (§ 7), anticipated results (§ 8), institutional partners (§ 9), and broader context (§ 10).

## 2. HISTORY

The initial discussions leading to the *TESS* concept began at the Massachusetts Institute of Technology (MIT) and the Smithsonian Astrophysical Observatory (SAO) in late 2005. In early 2006, a proposal for a Mission of Opportunity was submitted to NASA to use the optical camera of the High Energy Transient Explorer<sup>7</sup> to perform a survey for transiting planets. This proposal was not selected.

Later in 2006 and early 2007, *TESS* was reformulated as a standalone small mission that would be privately funded. Seed funding was obtained through the Kavli Foundation, Google, and MIT, but attempts to raise the funds required for a full mission were not successful.

In 2008, *TESS* was reconceived as a Small Explorer Mission (SMEX), and proposed to a NASA program with a cost cap of \$100m. The *TESS* SMEX proposal was funded for a Phase A study during 2008-2009, but was not chosen to proceed into Phase B.

During the next two years, the *TESS* concept was gradually refined, and a new proposal was submitted to the NASA Explorer program in 2011. The larger cost cap (\$200m) enabled several key improvements, particularly the use of a high-Earth elliptical orbit, which provides a more stable platform for precise photometry than the low-Earth orbit that had been the basis of all the previous proposals. *TESS* was selected by NASA for a Phase A study as an Explorer mission in Fall 2011, and proceeded to Phase B in April 2013. The Preliminary Design Review (PDR) was completed in September 2014, and the Critical Design Review (CDR) was completed in December 2015.

## 3. DESIGN CONSIDERATIONS

This section describes some of the considerations that led to the current design of the *TESS* mission.

### 3.1 Sky coverage

Although many transiting planets have been found, relatively few of them orbit stars bright enough to enable follow-up measurements of planet masses and atmospheres. Therefore, a prime objective of *TESS* is to monitor bright stars. Since the brightest stars are nearly evenly distributed over the entire sky, the need for an all-sky survey is clearly indicated.

### 3.2 Period sensitivity

Ideally the mission would detect planets with a broad range of orbital periods, with  $P_{\min}$  near the Roche limit of a few hours, and  $P_{\max}$  of a year or longer. However, the choice of  $P_{\max}$  determines the mission duration and thereby has a disproportionate influence on cost. Furthermore, transit surveys are strongly and inherently biased toward short periods.\* Indeed, the period distribution of *Kepler* detections<sup>2</sup> reaches a maximum at  $\sim 10$  days, taking into account the period dependencies of both the transit detection efficiency and the occurrence rate of planets. Hence, even a value of  $P_{\max}$  as short as 10 days should yield many discoveries.

Choosing  $P_{\max}$  as short as 10 days rules out the detection of habitable-zone planets around Sun-like stars. However, it is possible to gain access to habitable-zone planets around M stars if at least a portion of the sky is observed with  $P_{\max} \gtrsim 40$  days.<sup>†</sup> And if there is a portion of the sky to be searched more extensively, it would be advantageous for that portion to coincide with the zones of longest continuous visibility with the *James Webb Space Telescope (JWST)*, which will likely be the best telescope in the near term for follow-up studies of planetary atmospheres. Those zones are centered on the ecliptic poles.<sup>10</sup>

Together these considerations led to the choices of  $P_{\max} \approx 10$  days in general, and  $P_{\max} \gtrsim 40$  days for as large an area as possible surrounding the ecliptic poles.

### 3.3 Type of stars monitored

While it would be interesting to survey all types of stars, it is logical to concentrate on main-sequence dwarfs with spectral types F5 to M5. Evolved stars and early-type dwarfs are large, inhibiting the detection of small planets. Dwarfs with spectral types earlier than F5 also rotate rapidly, broadening their spectral lines and preventing precise radial-velocity monitoring. M dwarfs are especially common in the Milky Way; about three-quarters of the stars in the solar neighborhood are M0–M5 dwarfs. Stars with spectral types later than M5 are rarer and optically faint. They could be observed advantageously at near-infrared wavelengths, but this would greatly increase the mission's cost, complexity, and risk. Furthermore, planets transiting the very latest-type stars can be detected with ground-based instruments, as demonstrated by the M<sub>Earth</sub><sup>11,12</sup> and TRAPPIST<sup>13,14</sup> surveys.

### 3.4 Detector and bandpass

The best astronomical detectors in the optical and very near infrared bands are silicon charge-coupled devices (CCDs), which have excellent linearity and dynamic range for bright objects, and a long spaceflight heritage. A wide bandpass is preferred to reduce photon-counting noise. However, very wide bands present challenges in constructing a wide-field and well-focused optical system. Enhanced sensitivity to red wavelengths is desired because small planets are more easily detected around small stars, which are cool and red.

These considerations led to the choice of a 600–1000 nm bandpass. The red end represents the redmost limit of silicon CCD sensitivity, and the width of 400 nm was the largest practical choice for the optical design. This bandpass is centered on the traditional  $I_C$  band but is much wider (see Fig. 1). It is similar to the union of the  $R_C$ ,  $I_C$ , and  $z$  bands.

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\*As shown in Refs. 8,9, in an idealized imaging survey limited only by photon-counting noise, the effective number of stars that can be searched for transiting planets of period  $P$  varies as  $P^{-5/3}$ .

<sup>†</sup>For an M0 star with  $T_{\text{eff}} = 3800$  K, the range of orbital distances receiving a bolometric insolation within a factor of two of the Earth's insolation corresponds roughly to  $P = 25\text{--}75$  days.

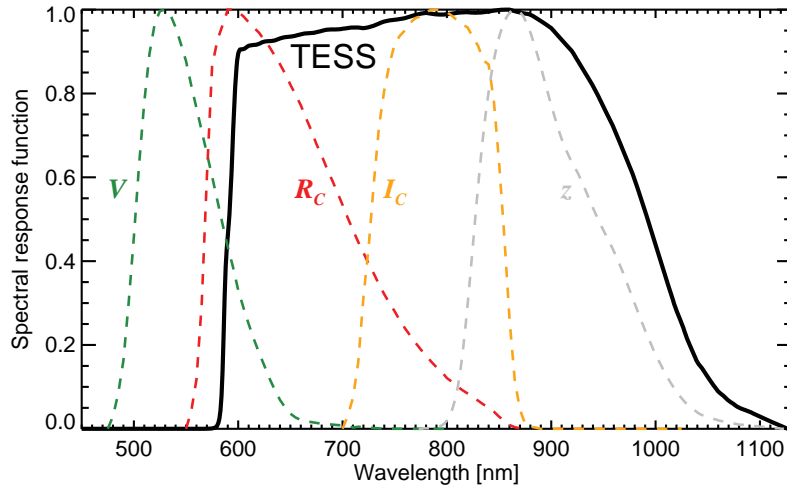


Figure 1. The *TESS* spectral response function (black line), defined as the product of the long-pass filter transmission curve and the detector quantum efficiency curve. Also plotted, for comparison, are the Johnson-Cousins  $V$ ,  $R_C$ , and  $I_C$  filter curves and the SDSS  $z$  filter curve. Each of the functions has been scaled to have a maximum value of unity.

### 3.5 Number of stars monitored

*Kepler*'s transit detection rate<sup>2</sup> for “super-Earths” ( $1.25\text{--}2 R_{\oplus}$ ) with  $P < 10$  days was about 0.2%. This represents the product of the occurrence rate ( $\sim 5\%$ ) and the geometric transit probability ( $\sim 5\%$ ). Therefore, *TESS* needs to monitor at least 500 stars for each super-Earth detection. The desire to find hundreds of such planets leads to the requirement to monitor  $\gtrsim 10^5$  stars.

According to Galactic star count models,<sup>15</sup> the brightest  $10^5$  dwarf stars have a limiting apparent magnitude of  $I_C \approx 10$ . In fact the *TESS* design employs a larger catalog ( $\gtrsim 2 \times 10^5$  stars) selected according to transit detectability rather than strictly on apparent magnitude. This leads to a limiting magnitude of  $I_C \lesssim 10\text{--}13$ , depending on spectral type. The faint M dwarfs, for example, have such small sizes that they can still be usefully searched for small planets.

### 3.6 Aperture size

Stars must be monitored with sufficient photometric precision to detect planetary transits. This leads to requirements on the collecting area and other properties of the cameras, although the derivation of those requirements is not straightforward because of the wide variation in the characteristics of the transit signals. As reviewed in Ref. 1, the transit depth varies with the radii of the star ( $R_{\star}$ ) and planet ( $R_p$ ),

$$\delta = (337 \text{ ppm}) \left( \frac{R_p}{2 R_{\oplus}} \right)^2 \left( \frac{R_{\star}}{R_{\odot}} \right)^{-2}, \quad (1)$$

and the transit duration ( $T$ ) depends on the stellar mean density ( $\rho_{\star}$ ) as well as the orbital period ( $P$ ) and dimensionless transit impact parameter ( $b$ ),

$$T = (3.91 \text{ hr}) \left( \frac{\rho_{\star}}{\rho_{\odot}} \right)^{-1/3} \left( \frac{P}{10 \text{ days}} \right)^{1/3} \sqrt{1 - b^2}. \quad (2)$$

In these equations the fiducial case is a transiting planet with  $R_p = 2 R_{\oplus}$  in a 10-day circular orbit around a Sun-like star ( $R_{\star} = R_{\odot}$ ,  $\rho = \rho_{\star}$ ).

Monte Carlo simulations were performed<sup>16</sup> to establish the requirements for detecting a certain number of transiting planets, taking into account the likely distribution of stellar apparent magnitudes and radii; the occurrence of planets of various sizes and orbits; as well as noise due to sky background, instrumental readout, and other sources. The results of this study, summarized in § 8, indicate that an effective collecting area of  $50 \text{ cm}^2$ , or effective aperture diameter  $D \sim 10 \text{ cm}$ , is sufficient to detect hundreds of super-Earths.

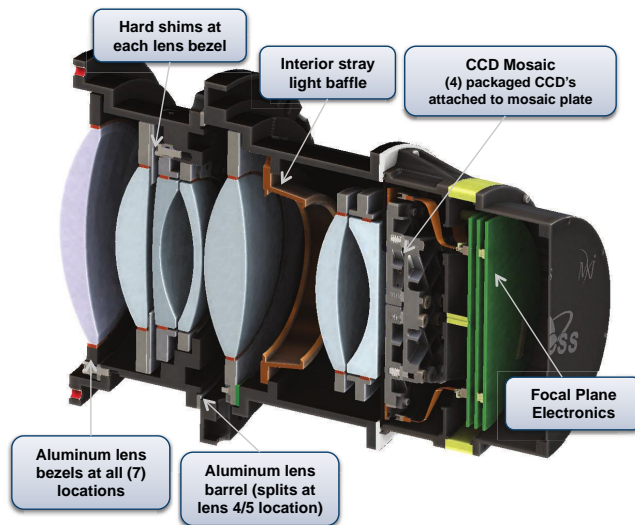


Figure 2. Diagram of the *TESS* lens assembly, CCD focal plane, and detector electronics.

### 3.7 Time sampling

Since the typical transit durations are measured in hours, the time sampling of the photometric observations should be substantially less than an hour. The timescale of the partial transit phases (ingress and egress) is  $\sim T(R_p/R_\star)$ , which is typically several minutes for planets smaller than Neptune. Therefore, to avoid excessive smearing of the partial transit signals, a time sampling of a few minutes or shorter is preferred. For *TESS* the brightness measurements of the preselected stars will be recorded every 2 min, which is consistent with these requirements and also enables asteroseismology (see § 8.3).

### 3.8 Orbit

The ideal orbit for the *TESS* spacecraft would allow for continuous observations lasting for weeks, and would be stable to perturbations over the multi-year duration of the survey. It would offer a low-radiation environment, to avoid high trapped-particle fluxes and resulting degradation of the CCDs and flight electronics. It would also offer a stable thermal environment and minimal attitude disturbance torques, to provide a stable platform for precise photometry. The orbit would be achievable with a moderate  $\Delta V$ , avoiding the need for a costly secondary propulsion unit. Furthermore, to facilitate data transfer, the spacecraft would be close to the Earth during at least a portion of the orbit. As explained in § 6, these requirements were met by choosing an elliptical orbit around the Earth, with approximate perigee and apogee distances of 17 and 59  $R_\oplus$ , and a period of 13.7 days.

## 4. PAYLOAD

The *TESS* payload consists of four identical cameras and a Data Handling Unit (DHU). Each camera consists of a lens assembly with seven optical elements, and a detector assembly with four CCDs and their associated electronics. All four cameras are mounted onto a single plate. These components will now be discussed in turn.

Each of the four identical *TESS* lenses is an  $f/1.46$  custom design consisting of seven optical elements, with an entrance pupil diameter of 10.5 cm (see Figs. 2–4 and Table 1). For ease of manufacture, all lens surfaces are spherical except for two mild aspheres. There are two separate aluminum lens barrels that are fastened and pinned together. All optical elements have antireflection coatings. The surface of one element also has a long-pass filter coating to enforce the cutoff at 600 nm. The red limit at 1000 nm is set by the quantum-efficiency curve of the CCDs (see Fig. 1).

Each lens forms a  $24^\circ \times 24^\circ$  unvignetted image on the four-CCD mosaic in its focal plane. The optical design was optimized to provide small image spots of a consistent size across the field of view (FOV). At nominal focus and flight temperature ( $-75^\circ\text{C}$ ), the 50% ensquared-energy half-width is 15  $\mu\text{m}$  (one pixel or 0.35 arcmin)

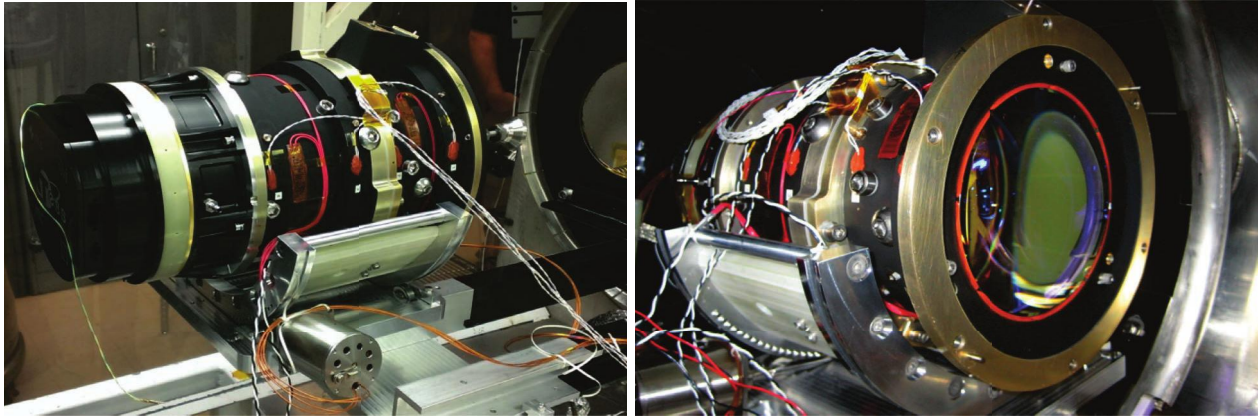


Figure 3. Side and front views of a single *TESS* engineering model camera undergoing thermal-vacuum testing at MIT.

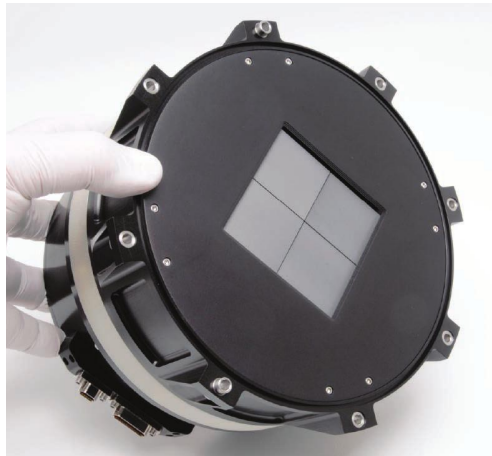


Figure 4. The detector assembly for the *TESS* engineering model camera. The light-sensitive area of the 4 CCD focal plane array is centered in the housing; the frame-store regions of the CCDs are covered by a black metal shield.

averaged over the FOV. Each lens is equipped with a lens hood, which reduces the effects of scattered light from the Earth and Moon.

Table 1. Characteristics of the *TESS* lenses. Ensquared energy is the fraction of the total energy of the point-spread function that is within a square of the given dimensions centered on the peak.

Field of view of each lens	$24^\circ \times 24^\circ$
Combined field of view	$24^\circ \times 96^\circ = 2300 \text{ sq. deg.}$
Entrance pupil diameter	10.5 cm
Focal ratio ( $f/\#$ )	$f/1.46$
Wavelength range	600–1000 nm
Ensquared energy	50% within $15 \times 15 \mu\text{m}$ (one pixel, or $0.35 \times 0.35 \text{ arcmin}$ ) 90% within $60 \times 60 \mu\text{m}$ ( $4 \times 4$ pixels, or $1.4 \times 1.4 \text{ arcmin}$ )

#### 4.1 Detector assembly

The focal plane consists of four back-illuminated MIT Lincoln Lab CCID-80 devices. Each CCID-80 consists of a  $2048 \times 2048$  imaging array and a  $2048 \times 2048$  frame-store region, with  $15 \mu\text{m}$  square pixels. The frame-store region allows rapid shutterless readout ( $\approx 20 \text{ ms}$ ). On each CCD there are four regions of 512 columns, each of which has a dedicated output register. The full well capacity is approximately 200,000 electrons, and when the



well is exceeded the electrons are not lost; they spill into neighboring pixels, allowing for precise photometry of saturated images.<sup>17</sup> The four CCDs are abutted with a 2 mm gap, creating an effective  $4096 \times 4096$  imaging array contained within a  $62 \times 62$  mm square (see Fig. 4).

The CCDs have an operational temperature of  $-75$  °C to reduce the dark current to a negligible level. The read noise is  $<10 e^-$ . The detector electronics are packaged onto three compact double-sided printed circuit boards, each 12 cm in diameter, which are located beneath the CCD focal plane and transmit digitized video data over a serial LVDS link to a Data Handling Unit.

## 4.2 Data Handling Unit

The *TESS* Data Handling Unit (DHU) is a Space Micro Image Processing Computer (IPC-7000) which consists of eight boards: the Image Processing Computer (IPC), which contains two Virtex-7 field-programmable gate arrays (FPGAs) that serve as interfaces to the four cameras, and perform high-speed data processing; the Proton 400K computer, which is responsible for commanding, communicating with the spacecraft master avionics unit, and interfacing with the Ka-band transmitter; two 192 GB solid-state buffer (SSB) boards for mass data storage; an analog I/O power switch board to control instrument power; and three power supply boards.

The CCDs produce a continuous stream of images with an exposure time of 2 sec. These are received by the FPGAs on the IPC, and summed into consecutive groups of 60, giving an effective exposure time of 2 min. During science operations, the DHU performs real-time processing of data from the four cameras, converting CCD images into the data products required for ground post-processing. A primary data product is a collection of subarrays (nominally  $10 \times 10$  pixels) centered on preselected target stars. The Proton 400k extracts these subarrays from each 2 min summed image, compresses them and stores them in the SSB prior to encapsulation as CCSDS packets for the Ka-band transmitter. Full frame images are also stacked every 30 min and stored in the SSB. Data from the SSB are downlinked every 13.7 days at perigee.

## 5. SPACECRAFT

*TESS* uses the Orbital LEOStar-2/750 bus equipped with a Ka-band transmitter and a monopropellant (hydrazine) propulsion system. The bus has a three-axis controlled, zero-momentum attitude control system, and two deployed solar array wings. To achieve fine pointing, the spacecraft uses four reaction wheels and high-precision quaternions produced by the science cameras. The transmitter has a body-fixed high-gain antenna with a diameter of 0.7 m, a nominal power of 1 W and a data rate of  $100 \text{ Mb s}^{-1}$ . This is sufficient to downlink the science data during each perigee.

The cameras are bolted onto a common plate that is attached to the spacecraft, such that their fields of view are lined up to form a rectangle measuring  $24^\circ \times 96^\circ$  on the sky (see Figs. 5 and 8). Four elliptical holes in the plate allow shimless alignment of the four cameras at the desired angles.

## 6. ORBIT

The *TESS* orbit is elliptical, with nominal perigee and apogee of  $17 R_\oplus$  and  $59 R_\oplus$ , and a 13.7 day period in 2:1 resonance with the Moon's orbit. The *TESS* orbit is inclined from the ecliptic plane, thereby eliminating lengthy eclipses by the Earth and Moon. The spacecraft orbit is operationally stable as a result of the Moon leading or lagging the spacecraft apogee by  $\approx 90^\circ$ , averaging out the lunar perturbations.<sup>18</sup> The orbit remains above the Earth's radiation belts, leading to a relatively low-radiation environment with a total ionizing dose of  $<300 \text{ rad yr}^{-1}$  behind  $5 \text{ g cm}^{-2}$  Al-equivalent shielding. The nearly constant thermal environment ensures that the CCDs will operate near  $-75$  °C, with temperature variations  $<0.1$  °C  $\text{hr}^{-1}$  for 90% of the orbit, and  $<2$  °C  $\text{hr}^{-1}$  throughout the entire orbit.

This orbit can be reached efficiently using a small supplemental propulsion system ( $\Delta V \approx 3 \text{ km s}^{-1}$ ) augmented by a lunar gravity assist. The specific path to the orbit will depend on the launch date and launch vehicle. In a nominal scenario (illustrated in Fig. 6), *TESS* is launched on a SpaceX Falcon 9 FT rocket from Cape Canaveral directly into an elliptical transfer orbit with an equatorial inclination of  $28.5^\circ$ . The apogee is raised to 400,000 km after two additional burns by the spacecraft hydrazine system, one at perigee of the first



Figure 5. *Left.*—Diagram illustrating the orientations of the four *TESS* cameras, lens hoods, and mounting platform. *Right.*—Artist's conception of the *TESS* spacecraft and payload.

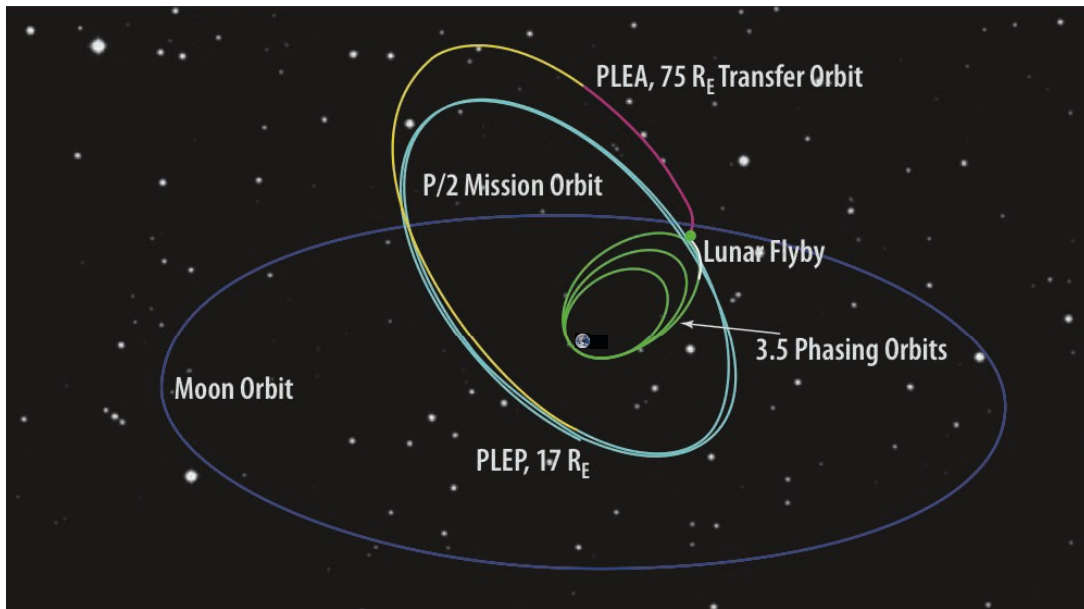


Figure 6. Maneuvers and scenario for achieving the *TESS* mission orbit. PLEP is post-lunar-encounter perigee, and PLEA is post-lunar-encounter apogee.

phasing orbit, and another at perigee of the second phasing orbit. An adjustment is made at third perigee, before a lunar flyby raises the ecliptic inclination to about  $40^\circ$ . A final period-adjust maneuver establishes the desired apogee and the 13.7 day period. The final orbit is achieved about 60 days after launch.

The orbital period and semimajor axis are relatively constant, with long-term exchanges of eccentricity and inclination over a period of order 8-12 years (driven by a Kozai-like mechanism<sup>18</sup>). There are also short-term oscillations with a period of six months caused by solar perturbations (see Fig. 7). The orbit is stable on the time scale of decades, or more, and requires no propulsion for station-keeping. Table 2 lists a number of advantages of this type of orbit for *TESS*.

## 7. SURVEY OPERATIONS

### 7.1 Star selection

A catalog of preselected stars will be monitored at a cadence of 2 min or better. Ideally the catalog will include  $\gtrsim 200,000$  main-sequence FGKM stars that are sufficiently bright and small to enable the detection of

Table 2. Characteristics of the *TESS* spacecraft orbit and comparisons to a low-Earth orbit.

Extended and unbroken observations: $>300 \text{ hr orbit}^{-1}$
Thermal stability: $<40 \text{ mK hr}^{-1}$ with passive control only
Earth/Moon stray light: $\sim 10^6$ times lower than in low-Earth orbit
Low radiation levels: no South Atlantic Anomaly or outer belt electrons
Frequent launch windows: $>3$ days per lunation
High data rates at perigee: $\sim 100 \text{ Mb s}^{-1}$
Excellent pointing stability: no drag or gravity gradient torques
Simple operations: single 5–7 hr downlink & reposit every 2 weeks
Long lifetime: several decades above GEO ( $>6.6 R_{\oplus}$ )

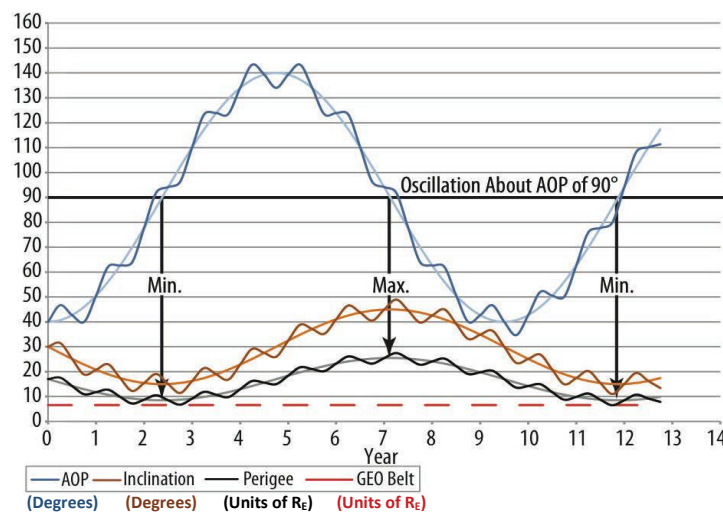


Figure 7. Calculated time variations in the elements of the nominal *TESS* mission orbit. The units of each curve are specified in the legend. AOP is the argument of perigee. GEO is geosynchronous Earth orbit.

transiting planets smaller than Neptune. This corresponds to approximately  $I_C < 12$  for FGK stars and  $I_C < 13$  for M dwarfs.<sup>16</sup> These stars are bright enough that it should be possible to assemble a list using currently available all-sky surveys. A draft catalog has been constructed using the 2MASS,<sup>19</sup> Tycho-2,<sup>20</sup> and UCAC4<sup>21</sup> catalogs, supplemented with smaller catalogs of nearby M dwarfs. For the M stars, infrared magnitudes allow for discrimination between dwarfs and giants.<sup>22</sup> G and K dwarfs are distinguished from giants through their relatively rapid reduced proper motion.<sup>23</sup> It may also be possible to use trigonometric parallaxes measured by the ongoing European *Gaia* mission, if they become available early enough for *TESS* mission planning.

## 7.2 Scanning strategy

The four cameras act as a  $1 \times 4$  array, providing a combined FOV of  $24^\circ \times 96^\circ$  or 2300 square degrees (see Fig. 8). The north and south ecliptic hemispheres are each divided into 13 partially overlapping sectors of  $24^\circ \times 96^\circ$ , extending from an ecliptic latitude of  $6^\circ$  to the ecliptic pole. Each sector is observed continuously for two spacecraft orbits (27.4 days), with the bore sight of the four-camera array pointed toward  $54^\circ$  in ecliptic latitude, and approximately anti-solar in ecliptic longitude. After two orbits, the FOV is shifted eastward in ecliptic longitude by about  $27^\circ$ , to observe the next sector. Observing an entire hemisphere takes one year, and the all-sky survey takes two years.<sup>‡</sup>

<sup>‡</sup>A video illustrating the *TESS* survey strategy, along with the pathway to the spacecraft orbit, can be seen at <https://www.youtube.com/watch?v=mpViVE0-ymc>.

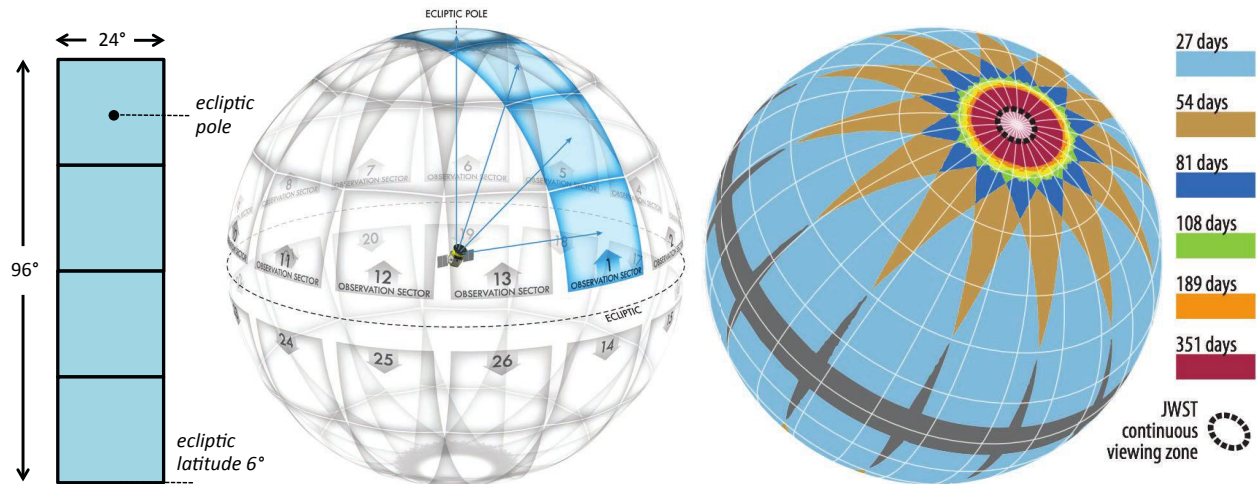


Figure 8. *Left.*—The instantaneous combined field of view of the four *TESS* cameras. *Middle.*—Division of the celestial sphere into 26 observation sectors (13 per hemisphere). *Right.*—Duration of observations on the celestial sphere, taking into account the overlap between sectors. The dashed black circle enclosing the ecliptic pole shows the region which *JWST* will be able to observe at any time.

The overlap of the sectors is illustrated in Fig. 8. Approximately 30,000 square degrees are observed for at least 27 days. Close to the ecliptic poles, approximately 2800 square degrees are observed for more than 80 days. Surrounding the ecliptic poles, approximately 900 square degrees are observed for more than 300 days.

### 7.3 Data Downlink and Housekeeping Operations

At perigee, science operations are interrupted for no more than 16 hours to point *TESS*'s antenna toward Earth, downlink data, and resume observing. This includes a 5–7 hr period for Ka-band science data downlink using NASA's Deep Space Network. In addition, momentum unloading is occasionally needed due to the  $\sim 1.5$  N m of angular momentum build-up induced by solar radiation pressure. For this purpose *TESS* uses its hydrazine thrusters.

### 7.4 Ground-based data analysis and follow-up

The *TESS* data will be processed with a data reduction pipeline based on software that was developed for the *Kepler* mission.<sup>24</sup> This includes pixel-level calibration, background subtraction, aperture photometry, detrending with respect to weighted ensembles of target star light curves, and searching for transits with a wavelet-domain matched filter.

Once the data are processed and transits are identified, selected stars will be characterized with ground-based imaging and spectroscopy. These observations are used to establish reliable stellar parameters, confirm the existence of planets, and establish the sizes and masses of the planets. Observations will be performed with committed time on the Las Cumbres Observatory Global Telescope Network,<sup>25</sup> OHP SOPHIE,<sup>26</sup> and the M<sub>Earth</sub> Observatory.<sup>11,12</sup> In addition the *TESS* science team members have access to numerous other facilities (e.g., Keck, Magellan, Subaru, HARPS, HARPS-North, Euler CORALIE, Lick Observatory APF;<sup>27</sup> see review by Pepe et al.<sup>28</sup>) through the usual telescope time allocation processes at their home institutions. The *TESS* team includes a large group of collaborators for follow-up observations and welcomes additional participation.

## 8. ANTICIPATED RESULTS

### 8.1 Photometric performance

Figure 9 shows the anticipated photometric performance of the *TESS* cameras. The noise sources in this model are photon-counting noise from the star and the background (zodiacal light and faint unresolved stars), dark

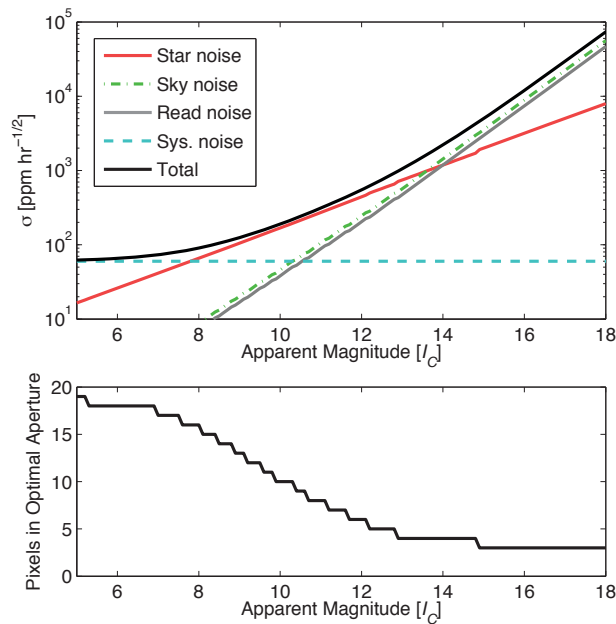


Figure 9. *Top.*—Expected  $1\sigma$  photometric precision as a function of stellar apparent magnitude in the  $I_C$  band. Contributions are from photon-counting noise from the target star and background (zodiacal light and unresolved stars), detector read noise ( $10 e^-$ ), and an assumed 60 ppm of incorrigible noise on hourly timescales. *Bottom.*—The number of pixels in the photometric aperture that optimizes the signal-to-noise ratio.

current (negligible), readout noise, and a term representing additional systematic errors that cannot be corrected by detrending. The most important systematic error is expected to be due to random pointing variations (“spacecraft jitter”). Because of the non-uniform quantum efficiency of the CCD pixels, motion of the star image on the CCD will introduce changes in the measured brightness, as the weighting of the image PSF changes, and as parts of the image PSF enter and exit the summed array of pixels.

## 8.2 Transit detections

Monte Carlo simulations are used to verify that the science objectives can be met and to anticipate the properties of the detected planetary systems.<sup>16</sup> These simulations are based on a model of the local neighborhood of main-sequence FGKM stars.<sup>15</sup> Simulated stars are populated randomly with planets, and “observed” by *TESS*. Those for which transits are observed with a sufficiently high signal-to-noise ratio are counted as detections. In addition, the simulated star catalog is populated with eclipsing binaries that may be blended with brighter stars to produce transit-like signals; the detections of these “false positives” are also recorded.

Among the features of the current simulations are: (1) a realistic distribution of stars and eclipsing binaries based on local census data; (2) probability distributions for planetary occurrence and orbital properties taken from the *Kepler* results;<sup>3</sup> (3) variation in stellar surface density and zodiacal light with position on the celestial sphere; (4) variation in the duration of *TESS* observations depending on ecliptic coordinates; (5) effects of solar and galactic cosmic rays.

Figures 10 and 11 illustrate some of the simulation results. *TESS* is expected to find thousands of planets smaller than Neptune, including hundreds of super-Earths ( $1.25\text{--}2 R_{\oplus}$ ) and tens of planets comparable in size to Earth. These will be accompanied by a roughly equal number of false positives, a majority of which are background eclipsing binaries. Some false positives will be identifiable using *TESS* data alone, based on the detection of secondary eclipses, ellipsoidal flux modulation, or transit-specific image motion. In other cases ground-based observations will be required to check for composite spectra, large radial-velocity variations, color-dependent transit depths, and resolved companions that are indicative of false positives.

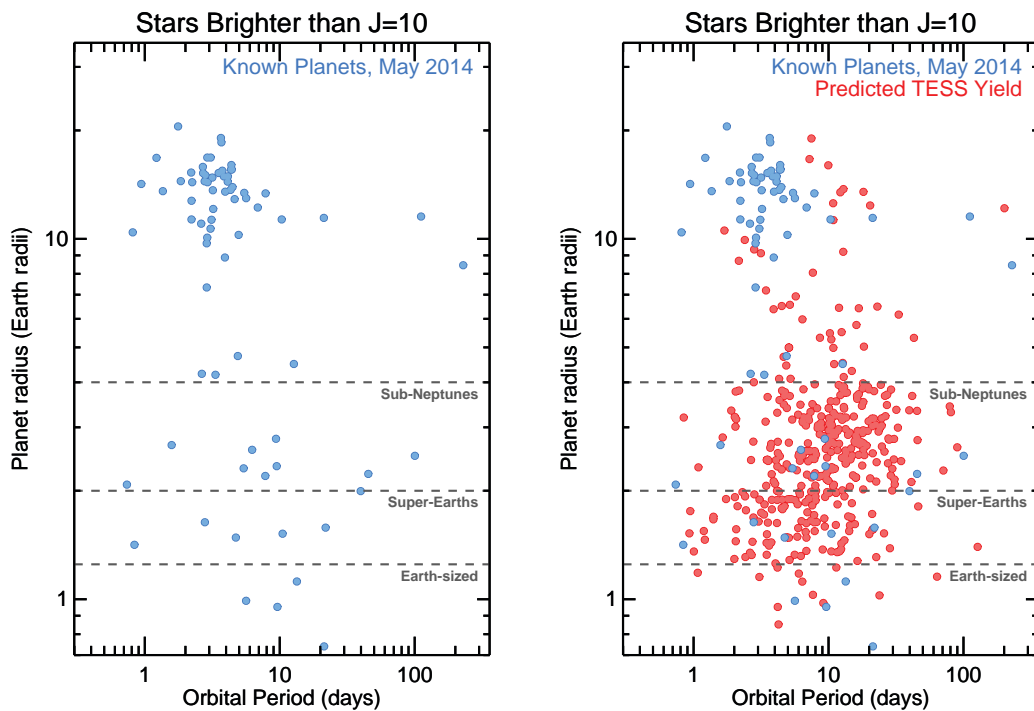


Figure 10. Sizes and orbital periods of planets with host stars brighter than  $J = 10$ . *Left*.—Currently known planets, including those from the *Kepler* and *CoRoT* missions as well as ground-based surveys. *Right*.—Including the simulated population of *TESS* detections.

### 8.3 Asteroseismology

Observing photometric variations due to stellar oscillations (“asteroseismology”) provides sensitive diagnostics of the stellar mass, radius, and internal dynamics. Based on the *Kepler* experience with mode amplitudes as a function of stellar parameters,<sup>29</sup> *TESS* can be expected to detect  $p$ -mode oscillations on about 6,000 stars brighter than  $V = 7.5$ , including (a) the majority of all stars brighter than  $V = 4.5$ , (b) about 75 stars smaller than the Sun, (c) about 2,000 upper-main-sequence and subgiant stars, and (d) virtually all the giant stars. Stars that are not suitable for planet searching but are appropriate for asteroseismology (such as giants) can be added to the *TESS* input catalog at minimal cost.

The key features enabling *TESS*’s advances in this area are all-sky coverage and fine time sampling. Compared to similar stars studied by *CoRoT* and *Kepler*, the *TESS* stars will be more numerous, brighter, and nearer to the Earth. *TESS* stars will have accurately known parallaxes, will be much more amenable to interferometric and radial-velocity studies, and are themselves among the likely targets for future, imaging-based missions to study exoplanets.

### 8.4 Full Frame Images

In addition to monitoring 200,000 pre-selected stars with a 2 min cadence, *TESS* will return a nearly continuous series of full frame images (FFI) with an effective exposure time of 30 min. As *Kepler* has shown, a 30 min cadence still allows for the efficient discovery of transiting planets. The FFIs will expand the transit search to any star in the fields of view that is sufficiently bright, regardless of whether it was selected ahead of time. This will reduce the impact of any imperfections in the target star catalog, and allow the search sample to extend beyond the FGKM dwarfs that are the focus of the mission. In addition, the transit candidates that are identified in the FFIs during the baseline *TESS* mission could be selected for shorter-cadence observations during an extended mission.

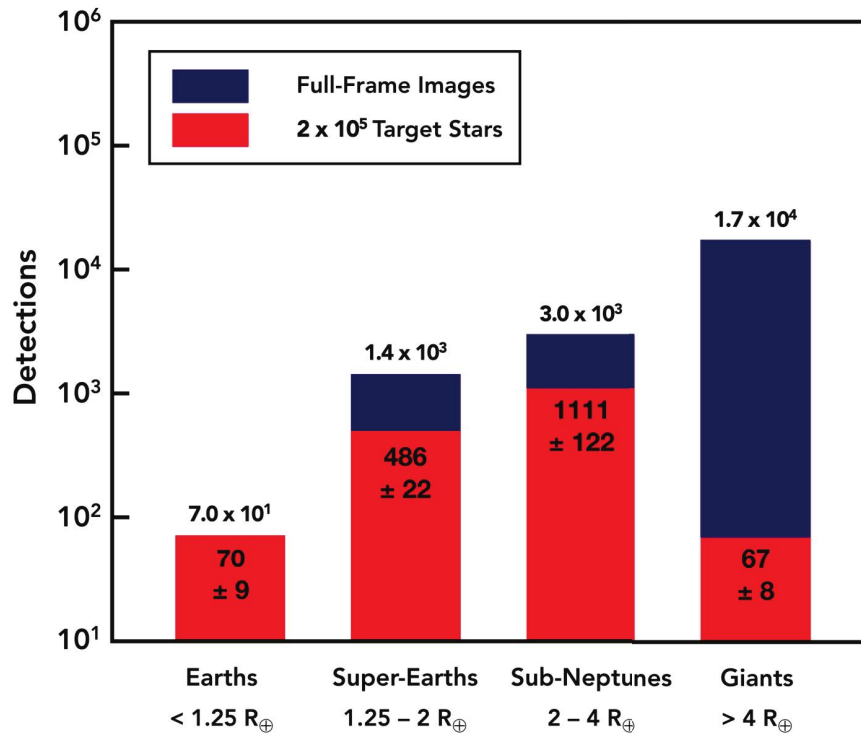


Figure 11. Mean numbers of planets that are detected in simulations of *TESS* exoplanet yields.<sup>16</sup> Results are shown for the 200,000 target stars that are observed with 2-minute time sampling as well as stars in the full-frame images that are observed with 30-minute sampling. The statistical error from Poisson fluctuations and the input planet occurrence rates are shown.

The FFIs will also enable a wide variety of other scientific investigations, such as the detection and monitoring of nearby supernovae and gamma-ray burst afterglows, bright AGN outbursts, near-Earth asteroids, eclipsing and close binaries, novae, flaring stars, and other variable stars. Each 30 min FFI will provide precise ( $\approx 5$  mmag) photometry for approximately  $10^6$  bright galaxies and stars ( $I_C < 14-15$ ) within a  $2300 \text{ deg}^2$  field. Over two years, the *TESS* all-sky survey will provide such data for approximately 30 million objects *brighter* than 16th magnitude, including  $\sim 20$  million stars and  $\sim 10$  million galaxies. Many of the stars and nuclei of galaxies will exhibit short-term variability. Thus, the *TESS* FFIs will provide broad-ranging fundamental data for time-domain astronomy. In particular, *TESS* will complement the Large Synoptic Survey Telescope (LSST), which is limited to observing objects *fainter* than 16th magnitude.<sup>30</sup>

### 8.5 Sky Map of Anticipated Planet Yields

During the initial and definition study phases for the *TESS* mission, an extensive series of anticipated exoplanet yield calculations were carried out by the *TESS* Science Team.<sup>16</sup> The top panel of Figure 12 maps the simulated planet detections in ecliptic coordinates from the most recent *TESS* simulations paper.<sup>16</sup> Detections among the target stars (red points) are enhanced in the vicinity of the ecliptic poles because of the overlapping pointings they receive. Apart from that conspicuous feature, the detections are nearly uniformly distributed across the sky. The detections from stars that are only observed in the full-frame images (blue dots) show a strong enhancement near the galactic plane. This is due to the vast number of faint and distant stars around which giant planets can be detected.

### 8.6 Extended Mission

The baseline mission duration of *TESS* is currently set at two years to accomplish the primary scientific goals. However, the science instruments and spacecraft should be fully capable of operating for several additional years

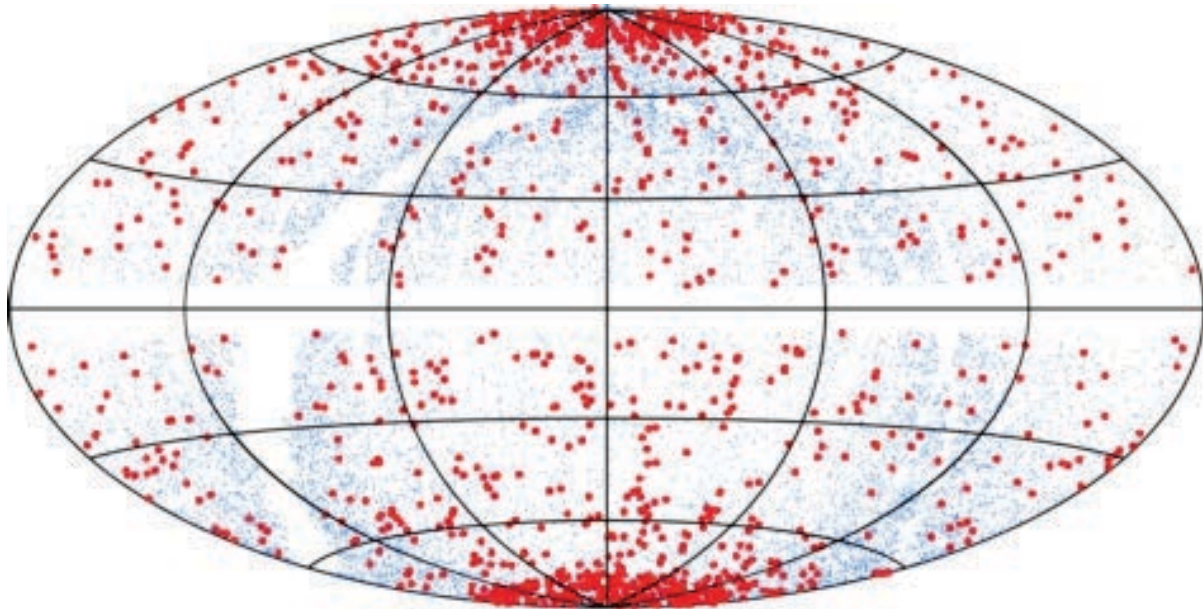


Figure 12. Sky maps of the simulated *TESS* exoplanet detections<sup>16</sup> in equal-area projections of ecliptic coordinates. The lines of latitude are spaced by  $30^\circ$ , and the lines of longitude are spaced by  $60^\circ$ . Red points represent planets detected around target stars (2-minute cadence). Blue points represent planets detected around stars that are only observed in the FFIs (30-minute cadence). Note the enhancement in the planet yield near the ecliptic poles, which *TESS* observes for the longest duration. The planet yield is small in the densest portions of the Galactic Plane due to source confusion. Note also that a band within  $6^\circ$  of the ecliptic is not observed.

in the *TESS* high earth orbit, depending only on continued mission funding support. For such an extended mission, a number of possible mission observing plans for *TESS* are being considered,<sup>31</sup> including:

1. Repeat the primary mission survey, to enhance the signal-to-noise and period sensitivity for detections from the baseline survey. The sectors would likely be shifted by  $13^\circ$  in longitude to cover the inter-sector gaps in the sky coverage for the two year primary coverage.
2. Dwell entirely on a single hemisphere for two years (Fig. 13, left). The observing time per sector could be doubled to 56 days.
3. Dwell on a single  $24^\circ \times 96^\circ$  field for as long as possible (consistent with mission requirements for the orientation of the spacecraft solar panels, etc.).
4. Focus on one of the ecliptic poles (Fig. 13, center). The combined field of view would be centered on one of the ecliptic poles, and the long axis of the field of view would be advanced in ecliptic longitude by  $28^\circ$  every lunar month.
5. Focus on the ecliptic plane (Fig. 13, right), which is not covered during the primary mission (Fig. 8, rightmost panel). The long direction of the combined field of view would be oriented along the ecliptic, and approximately centered in the anti-solar direction.

## 9. PARTNERS AND THEIR ROLES

The lead institution for *TESS* is the Massachusetts Institute of Technology (MIT), which hosts the Principal Investigator, Dr. George Ricker. The MIT Lincoln Laboratory is responsible for the CCD focal planes, lenses and lens hoods, and the camera array mounting assembly. The MIT Kavli Institute is responsible for the camera electronics, calibration, and testing, as well as instrument management. NASA's Goddard Space Flight Center provides overall project management, systems engineering, and safety and mission assurance. Orbital ATK builds



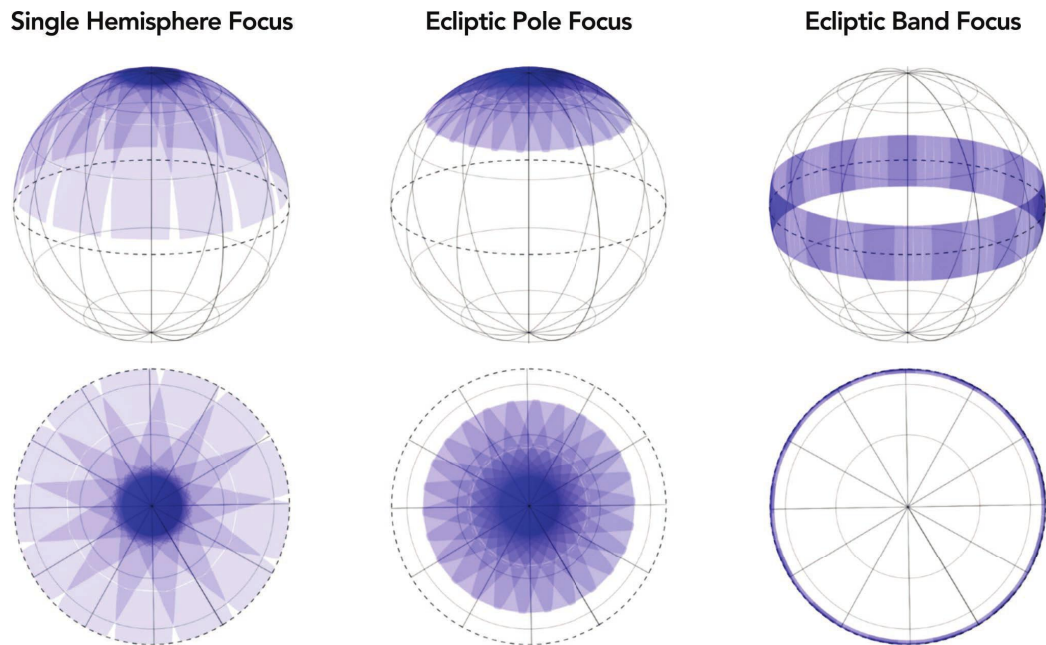


Figure 13. Tilted (top) and polar (bottom) projections for several possible extended mission observing plans<sup>31</sup> for *TESS*, shown in ecliptic coordinates on the celestial sphere. Lines of constant latitude in the polar projections correspond to ecliptic latitudes of  $60^\circ$ ,  $30^\circ$  and  $0^\circ$ , proceeding radially outward from an ecliptic pole. *Left.*—Focus on a single hemisphere. *Center.*—Focus on an ecliptic pole, advancing the long axis of the field of view every lunar month. *Right.*—Orient all cameras along the ecliptic plane.

and operates the spacecraft. The mission is operated from the Mission Operations Center (MOC) at Orbital ATK in Dulles, Virginia.

The *TESS* Science Office and Science Operations Center, which analyze the science data and organize the co-investigators, collaborators, and working groups (with members from many institutions) is a partnership among MIT's Physics Department and Kavli Institute for Astrophysics and Space Research, the Smithsonian Astrophysical Observatory, and the NASA Ames Research Center. The raw and processed data are archived at the Mikulski Archive for Space Telescopes, at the Space Telescope Science Institute.

## 10. DISCUSSION

*Kepler* has revealed the vast numbers of small planets that exist in the Galaxy. *TESS* will find them around stars in the local neighborhood, which will be easier to study with current and planned instruments, including the *JWST*. The *TESS* launch is currently scheduled for late 2017, and the all-sky survey for 2018-2019. An extended mission of several years is a realistic possibility, and is compatible with the supply of consumable materials and the stability of the spacecraft orbit. An extended mission would increase the number of planet detections, especially those with longer orbital periods, including planets in the habitable zones of their host stars.

A broad community effort will be needed to harvest all of the scientific potential of the survey. Following its launch, *TESS* will serve as the "People's Telescope," with public data releases every four months to stimulate community-wide effort and optimize target selection for subsequent studies. The *TESS* team will establish an electronic clearinghouse to exchange information and coordinate these efforts.

One of the most scientifically productive—and challenging—types of follow-up observations is precise radial-velocity (PRV) monitoring. PRV monitoring is used to confirm the planetary nature of *TESS* detections, provide constraints on planetary densities and possible interior compositions, and inform the interpretation of planetary atmosphere studies with *JWST* and other instruments. PRV monitoring is likely to be the rate-limiting step in realizing the full benefits of *TESS* for exoplanetary science. Even though *TESS* stars are relatively bright

and favorable for study, the expected number of new and interesting PRV targets will greatly exceed the time budgets of currently available observatories. Many groups are aiming to rectify this situation by building new PRV instruments. Among the new instruments being planned with *TESS* targets in mind are ESPRESSO,<sup>32</sup> NRES,<sup>33</sup> IRD,<sup>34</sup> CARMENES,<sup>35</sup> HPF,<sup>36</sup> HRS,<sup>37</sup> SPIRou,<sup>38</sup> MAROON-X,<sup>39</sup> CODEX,<sup>40</sup> G-CLEF,<sup>41</sup> HARPS-3,<sup>42</sup> SHREK,<sup>43</sup> ExTrA,<sup>44</sup> MINERVA,<sup>45</sup> WISDOM,<sup>46</sup> iLocater,<sup>47</sup> and VELOCE.<sup>48</sup>

The *TESS* legacy will be a catalog of the nearest and brightest stars hosting transiting planets, which will likely be the most favorable targets for detailed investigations in the decades or even centuries that follow.

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