Southern Horizons in Time-Domain Astronomy
Proceedings IAU Symposium No. 339, 2019
E. Griffin, ed.

doi:10.1017/S1743921318002648

Getting Ready for TESS: an On-hand Software Tutorial

WORKSHOP 3

J. Burt[1] **and T. Barclay**[2]

[1]Massachusetts Institute of Technology, Cambridge, MA, USA
email: jennburt@mit.edu

[2]NASA Goddard Space Flight Center, Greenbelt, MD, USA

Abstract. The launch of NASA's next exoplanet mission, the Transiting Exoplanet Survey Satellite (*TESS*), took place successfully on 2018 April 18, and has now commenced science operations. *TESS* is specifically designed to search for exoplanets transiting the closest and brightest stars using high-cadence photometric measurements. The images employed for detecting those planets can also be used for a wide variety of time-domain astronomy, especially when considering the full-frame images that *TESS* takes every 30 minutes. This (pre-launch) workshop familiarised participants with the details of how *TESS* will operate, described the expected data products and how to access them, introduced the software suite `PyKE`, which can be used to analyse *TESS* data, and highlighted ways for participants to request additional *TESS* targets.

Keywords. Methods: data analysis, techniques: photometric

1. Introduction

The *TESS* mission builds on the success of NASA's *Kepler* spacecraft but focuses specifically on observing exoplanets that are amenable to follow-up observations (namely, those orbiting bright, nearby stars), and represents the next crucial step in our efforts to understand exoplanet formation and evolution. By surveying first the southern and then the northern ecliptic hemisphere in a series of 30-minute Full Frame Images (FFIs) combined with more targeted 'postage stamp' images with a cadence of 2 minutes, the mission is expected to detect some 3,000 exoplanets smaller than Neptune, and 17,000 giant exoplanets (Sullivan *et al.* 2015) around stars within 300 pc of the Earth. Much thought has already gone into optimising *TESS*'s exoplanet science, but as the spacecraft gets closer to launch we are now also thinking about the wealth of non-exoplanet science that could come from its data products.

One obvious such application of the *TESS* data is the area of time-domain astronomy. For example, photometry from *TESS* could be used to determine the oscillation frequencies of hundreds of white dwarfs, provide precursor light-curves of supernovæ, detect EM counterparts of gravitational wave events, or expand our astroseismic view of the Milky Way to encompass thousands of dwarf stars and hundreds of thousands of giant stars. With those goals in mind, we developed this Workshop so as to walk participants through the design, survey strategy and expected photometric performance of *TESS* in a way that enabled them to plan and design how to best use the upcoming mission results to facilitate time-domain science. This report summarises the results of that Workshop. Comments and questions from the participants have been worked into the text.

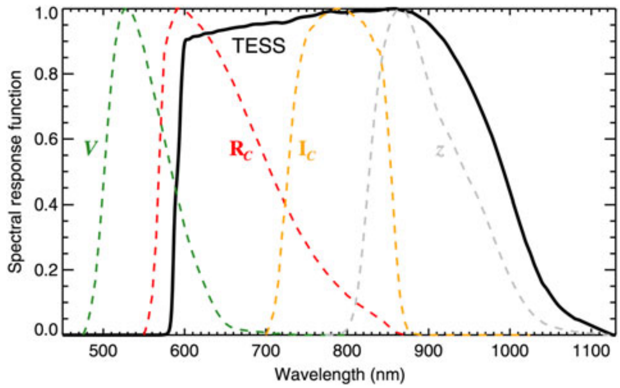

Figure 1. The *TESS* bandpass combines broad wavelength coverage, to reduce photon-counting noise, and a red/NIR centre, to improve photometry results on cool M dwarfs stars that allow for the detection of smaller exoplanets in transit.

2. TESS Overview

Cameras: The *TESS* spacecraft contains four identical cameras, each using the same custom $f/1.4$ design consisting of seven optical elements with a 10.5-cm entrance pupil. Each camera forms an unvignetted $24° \times 24°$ image across a 4-CCD mosaic (2×2 grid) in its focal plane (see Fig. 2). The camera optics were designed to form small consistently sized images across the FOV, and to produce images that are undersampled in the same way as the *Kepler* images. For observing, the four *TESS* cameras are arranged in a 1×4 array, providing a combined FOV of $24° \times 96°$, or $2300°^2$ (Ricker *et al.* 2015).

The *TESS* bandpass is centred on the traditional I_C bandpass in an effort to increase the mission's sensitivity to M-dwarf stars, which emit the majority of their light in the red–optical or NIR wavelength regions. It was actually broadened to be much wider than the I_C band in order to reduce photon-counting noise. With a top-hat shape stretching from 600–1000 nm, the Tessmag bandpass is comparable to a filter that combines the R_C, I_C and z bands (Fig. 1).

Orbit: *TESS* orbits the earth in an elliptical 13.7-day orbit that places the spacecraft into a 2:1 resonance with the Moon. The orbit is inclined from the ecliptic, thus removing the possibility of long-period eclipses with the Earth or Moon that would hinder stellar observations. The northern and southern surveys of *TESS* are each divided into thirteen partially overlapping sectors of $24° \times 96°$ that extend from an ecliptic latitude of 6° up to 6° past the ecliptic pole. The spacecraft will point anti-solar, and will spend two orbits (27.4 days total) on each sector. Once per orbit, at perigee, *TESS* will transmit its most recent set of observations to Earth. This process will require a pause in science operations (lasting for ∼20 hours) while the spacecraft downlinks data to NASA's Deep Space Network and unloads angular momentum built up from solar radiation pressure during the observations acquired during that orbit.

After two full orbits and downlinks have been completed for a given sector, the camera array's FOV will be shifted ∼27° east in ecliptic longitude, and observations of the next sector will begin. In both hemispheres, camera #4 will rotate on top of the ecliptic pole to provide continuous coverage of objects within ∼6° of the pole throughout the year. Objects with lower ecliptic latitudes will be observed for shorter amounts of time, as they are not covered by the overlap regions between different sectors. In fact, most of the sky (∼65%) will be covered for only 27 days (Ricker *et al.* 2015). Extended missions are currently being discussed (see, e.g., Bouma *et al.* 2017), as *TESS*'s orbit should remain

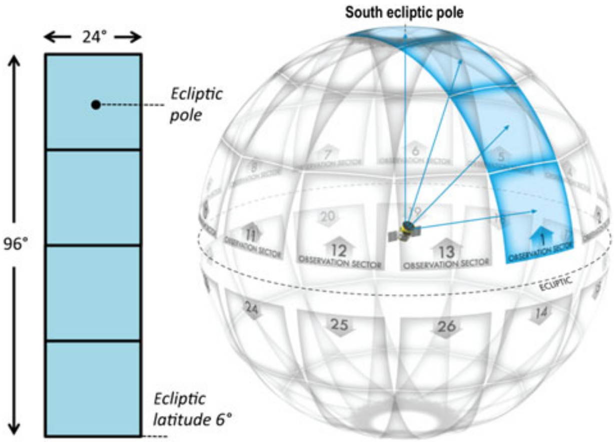

Figure 2. Survey design of *TESS*. The FOVs of the four cameras are stacked into a 1 × 4 array, forming a 24° × 96° sector on the sky. This sector stretches from an ecliptic latitude of 6° to up and over the ecliptic pole, resulting in a continuous viewing zone that extends ∼ 6° out from the pole. Each sector is observed for two orbits (27.4 days) before the camera array's FOV is shifted ∼ 27° east in ecliptic longitude and observations of the next sector begin.

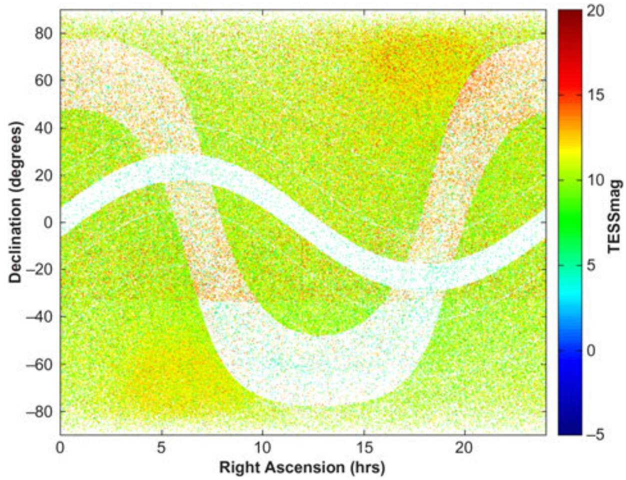

Figure 3. The top 400,000 *TESS* targets from CTL-6. The TESS Target Selection Working Group expects an updated version of the full documentation to be available on the arXiv in late January or early February 2018. The full, machine-readable version of the current CTL is available at http://astro.phy.vanderbilt.edu/∼oelkerrj/tic6_ctl_20180108.tar.gz as a CSV file.

stable for at least two decades thanks to its 2:1 lunar resonance and the lack of propulsion required for station keeping.

Targets: To learn more about the stars that *TESS* currently plans to target with a 2-minute cadence (Fig. 3), one can access the now publicly available TESS Input Catalog (TIC) Candidate Target List (CTL) 6 at https://filtergraph.com/tess_ctl (Stassun *et al.* 2017). CTL-6 is a compilation of several catalogues, including (among others) 2MASS, Gaia DR1, UCAC-4 & 5, Tycho-2, and APASS DR9, and is currently the best effort to identify those stars most suitable for exoplanet transit detection with *TESS*. Stars are considered for the CTL if they are (1) identified as RPMJ dwarfs with a 2σ confidence, and (2) meet one of the following temperature/magnitude criteria: TESSmag < 12 or

https://doi.org/10.1017/S1743921318002648 Published online by Cambridge University Press

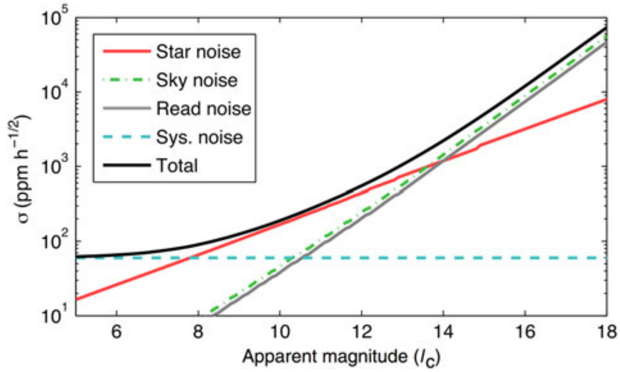

Figure 4. Expected performance of *TESS* as a function of I_C. In one hour of binned observations, *TESS* will obtain 1% photometry at 16$^{\rm th}$ magnitude and better than 10% photometry at 18$^{\rm th}$ magnitude.

TESSmag $<$ 13 and $T_{\rm eff} <$ 5500 K. Additionally, a star is included in the CTL, regardless of the above criteria, if it is a member of the bright-star list (TESSmag $<$ 6) or is on the specially curated cool-dwarf list.

Images: Each *TESS* camera exposes at a native resolution of 2 seconds, but the images will be binned in one of two modes before being downlinked to Earth. A catalogue of ∼170,000 stars will be observed at a 2-minute cadence, and are referred to as 'postage stamp' stars as TESS will downlink only the pixels covering and immediately surrounding the star on the CCD. These stars will chiefly be FGKM dwarfs that are sufficiently bright and small enough to enable the detection of transiting planets smaller than Neptune (or stars identified through the guest-investigator or FFT programmes as needing a 2-minute cadence). Additionally, the entire 24° x 24° FOV of each camera will be captured as 'full frame images' (FFIs) every 30 minutes, yielding 1300 successive FFIs per 2300 degree^2 sky segment. Each FFI will provide precise photometry (∼5 mmag) for ∼one million bright galaxies and stars ($I_C < 15$), resulting in 20 million bright objects surveyed at a 30-minute cadence over *TESS*'s two year primary mission.

Precision: When taking into account the effects of photon-counting noise from the star and the background (zodiacal light and light from faint unresolved background stars), read-out noise, and a term representing additional systematic errors that cannot be corrected by co-trending, the expected 1σ photometric precision of the *TESS* cameras around the brightest target stars is better than 0.1% (Fig. 4). On the fainter end, in one hour *TESS* will obtain 1% photometry at 16$^{\rm th}$ magnitude and better than 10% photometry at 18$^{\rm th}$ magnitude. In 12 hours, *TESS* will be able to reach 10% photometry for objects at magnitude 19.5. Applying this sensitivity curve to a variety of time-domain astronomy subjects, we predict that *TESS* will be able to provide interesting coverage of classical novæ out to the Andromeda galaxy, intermediate luminosity red transients out to the Virgo Cluster, and core-collapse supernovæ out to the Coma Cluster.

3. Accessing *TESS* Data and Using `PyKE`

Data access: *TESS* data have no proprietary period, and will be available publicly on the STScI MAST archive within 2 months (6 for the first sector) of observation, after being processed by the Science Processing Operations Center (SPOC) at NASA Ames. The archive will be searchable via target name, TESS ID, location (RA and Dec), and release date, among other criteria. The data products for a specific 'postage stamp' star will include a calibrated light-curve and the target pixel files used to create it. The FFIs will also be hosted on MAST and available for downloading.

https://doi.org/10.1017/S1743921318002648 Published online by Cambridge University Press

A TESS Object of Interest (TOI) includes planet candidates, and anything else of specific astrophysical interest such as eclipsing binaries, unusual light-curves like those of Tabby's star, or potentially disintegrating comets. The TESS Science Office will deliver lists of TOIs on a regular schedule, with dispositions and information documenting the vetting process for each object. An up-to-date catalogue containing all identified TOIs will be maintained on the public TESS website at MIT (https://tess.mit.edu). The TOI catalogue will be mirrored on the MAST archive.

PyKE: After downloading the relevant data products for their targets, users can perform efficient analyses by making use of the `PyKE` software suite, developed by NASA's *Kepler* office (Still & Barclay 2012, Vinícius *et al.* 2017). PyKE is a set of data analysis tools which offer a user-friendly way to inspect and analyse pixels and light-curves obtained by NASA's Kepler, K2 and TESS missions. A user running a working version of Python 2 or 3 can simply install the latest stable release of `PyKE` using `pip`. `PyKE` is comprised of a large set of functions (called tasks) that include tools to perform Box Least-Square searches for periodic exoplanet transits, construct dynamic power spectra from *Kepler* time-series data, display a portion of a Full Frame Image (FFI) and define custom target apertures, and plot, create or edit custom target masks for target pixel files (among many others). For the user's convenience, many of these tasks can be called both as python functions and as command-line utilities.

A large section of this workshop was spent walking through real-time demonstrations of how to use different `PyKE` tasks to extract and analyse *TESS* data. In lieu of recreating those steps here, we strongly suggest that interested readers visit the `PyKE` website (https://pyke.keplerscience.org) for instructions on how to get started, along with polished tutorials that cover many basics, such as aperture photometry on a *K2* target, separating a background eclipsing binary from a foreground star, identifying stellar astrophysics signals, quarter stitching and removing spacecraft artefacts, and fitting pixel response functions in *K2* target pixel files.

4. *TESS* Target Requests

The *TESS* Guest Investigator programme has been implemented to allow astronomers from the community to participate in *TESS* science investigations that fall outside the core mission science goal of detecting small exoplanets. The programme enables applicants to propose new targets that should be monitored in the 2-minute cadence mode (40,000 of the 170,000 total 'postage stamp' objects are allocated to GI targets), and provides funding for US teams to analyse data from both the 'postage stamp' stars and from the FFIs. Applications are open to all investigators, including those from non-U.S. countries, under NASA's no-exchange-of-funds policy, but at least 70% of the work effort should be focused on exploiting TESS data products. The first programme cycle (corresponding to targets in the southern hemisphere) has already closed, but the second programme cycle (for northern hemisphere targets) will open in 2018 and a solicitation will be posted on the NSPIRES website. For more information and a variety of useful tools for crafting a GI proposal, visit the *TESS* Science Support Center website (https://heasarc.gsfc.nasa.gov/docs/tess).

An additional 40,000 stars (1,500 per sector) may be allocated as Director's Discretionary Targets (DDTs). The purpose of the DDT programme is to enable observations that address emerging scientific topics or areas missed in the proposal review process, specifically those that respond to targets of opportunity, e.g. newly-discovered exoplanets or supernovæ, that yield high-impact science from TESS, and/or which enhance existing GI programmes with additional critical data. More details of the DDT programme will be posted at https://heasarc.gsfc.nasa.gov/docs/tess/ddt.html when

https://doi.org/10.1017/S1743921318002648 Published online by Cambridge University Press

it is launched; it is anticipated that this will be in time for selection of targets for Sector 3 observations.

5. Acknowledgements

The research described in this paper makes use of Filtergraph, an online data visualisation tool developed at Vanderbilt University through the Vanderbilt Initiative in Data-Intensive Astrophysics (VIDA).

References

Bouma, L. G., Winn, J. N., Kosiarek, J., & McCullough, P. R. 2017, arXiv:1705.08891
Ricker, G. R., *et al.* 2015, *J. Astron. Telescopes, Instruments, and Systems*, 1, 014003
Stassun, K. G., *et al.* 2017, arXiv:1706.00495
Still, M., & Barclay, T. 2012, *Astrophys. Source Code Library*, 1208.004
Sullivan, P. W. 2015, *ApJ*, 809, 1
Vinícius, Z., Barentsen, G., Gully-Santiago, M., Cody A. M., Hedges, C., Still, M., & Barclay, T. 2017, doi:10.5281/zenodo.835583