Upping the Ante: The TESS Mission Shortens Full Frame Images to 10 Minutes and Introduces a Twenty-Second Data Collection Mode

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INTRODUCTION

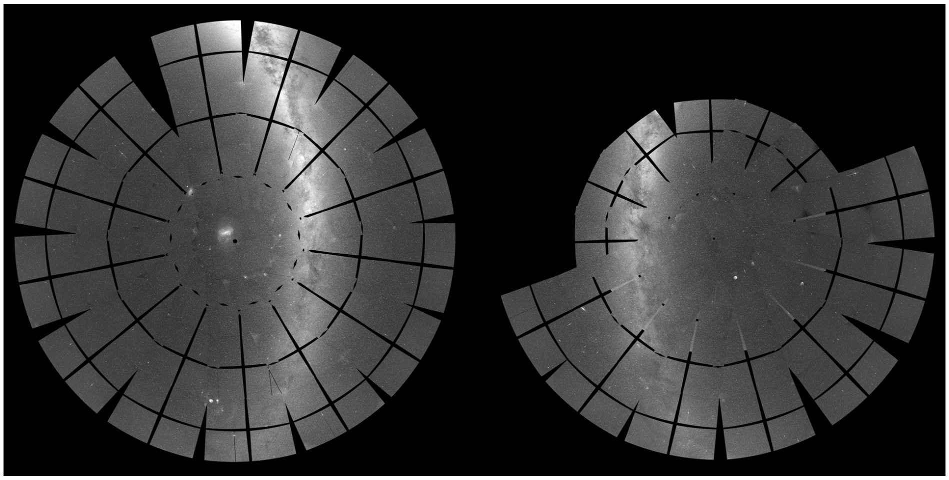


Image credit: Roland Vanderspek/MIT

Panorama of the sky TESS observed over the course of its 2-year prime mission from a montage of FFI images. The Southern celestial hemisphere is featured on the left-hand side, while the Northern hemisphere appears on the right-hand side. Since the Earth and Moon were in or near the field-of-view (FOV) of Camera 1 (the camera imaging the lowest latitudes) for ~6 months, the FOV was tilted upward towards the pole by ~31° in the Northern hemisphere to minimize data loss due to excessive contamination on Cameras 1 and 2. (See the TESS Observations Page (https://tess.mit.edu/observations/) for more information.)

A Busy 2020

The year 2020 has been an exceptionally busy year for the Transiting Exoplanet Survey Satellite (TESS) mission and the TESS Science Processing Operations Center as we completed the 2-year prime mission and prepared for the extended mission that began 5 July 2020.

During this year, TESS completed its survey of the northern celestial hemisphere (as indicated on the background of this iPoster), covering ~75% of the sky over its first two years in flight. TESS detected over 2000 planet candidates in its initial survey and identified 74 confirmed planets (and counting). TESS also unveiled a plethora of exciting non-exoplanet astrophysics results, such as asteroseismology, asteroids, and supernova.

There are some big changes in the extended mission:

1. TESS is collecting full frame images (FFIs) at 10-minute intervals rather than at 30-minute intervals, as was the case for the two-year primary mission.
2. TESS is also collecting and providing photometry for up to 600 20-sec targets in addition to the 20,000 target star postage stamps collected at 2-min intervals. There are a total of 1000 20-second targets, with 400 (100 per camera) reserved for bright, unsaturated targets used for registering each frame to sky coordinates and to probe the performance of the instrument. (See section "20-second Light Curves in the Extended Mission".)
3. The extended mission will also feature a five-month interval in which the 24°x96° field of view (FOV) will be rotated by 90° from its normal North-South orientation to observe a swath of the ecliptic plane.

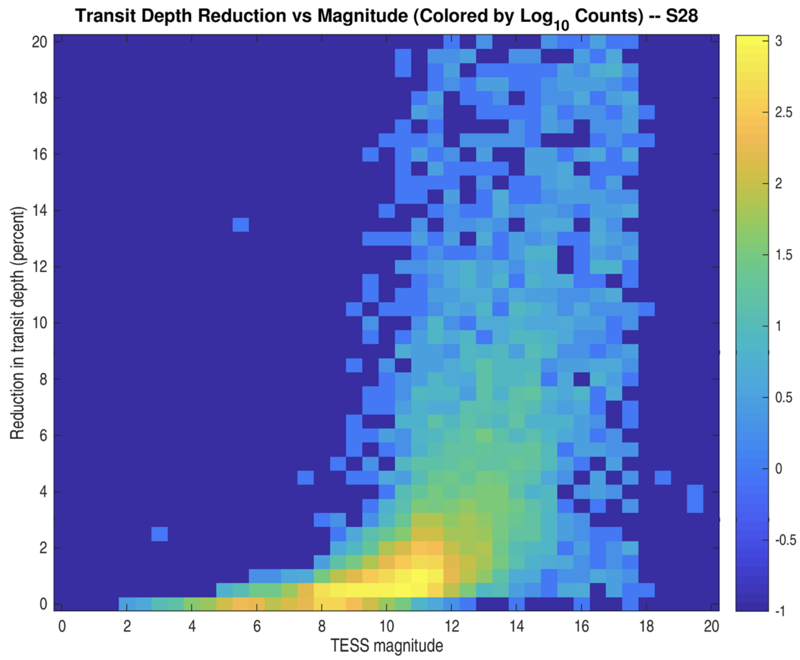
The FOVs for the remainder of the extended mission will also be offset in latitude from those of the prime mission to help fill in the gaps in the full sky coverage.

With feedback from the community, we identified several issues with the data products that motivated the reprocessing of Sectors 14-19 while Sectors 20-26 were being collected and processed. Section "Quality Flag Updates" discusses changes to the Quality Flags in the TESS archival data products.

The SPOC has begun generating light curves for up to 160,000 targets in the FFIs, as discussed in Section "SPOC FFI Target Pixel Files, Light Curves, and Cotrending Basis Vectors". These data products are available as High Level Science Products (HLSP) at the MAST under the project name TESS-SPOC.

All northern hemisphere sectors (14-26 have been processed with a uniform codebase (SPOC R4.0) and the reprocessing of sectors 1-13 has commenced with an update to the background estimation algorithm, described in the section titled "Updating the Sky Background Algorithm" as part of release SPOC R5.0.

UPDATING THE SKY BACKGROUND ALGORITHM



False Color Image of a Histogram of the Reduction in Transit Depth for the 2-minute targets from Sector 28 vs. TESS magnitude due to the bias in the original sky background algorithm. The overwhelming majority of stars are not significantly impacted by the background bias. Note that the counts are in $\log_{10}$ units.

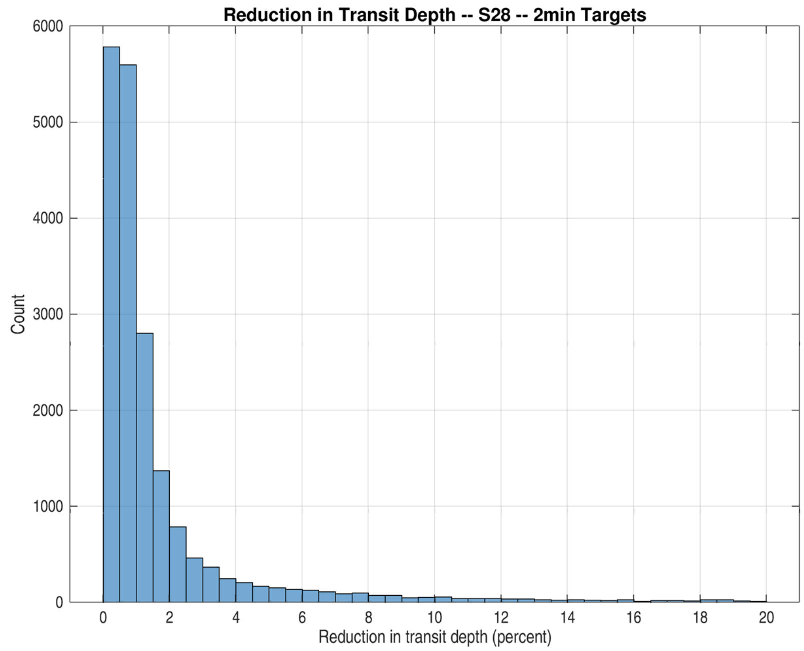
Estimating the Sky Background

SPOC release 5.0 includes an update to the sky background estimation algorithm to improve the background estimates for dim and/or crowded stars. The original algorithm performed a trimmed mean on dim pixels selected in the neighborhood of the target star to avoid star images. For relatively dim and/or crowded stars the trimmed mean was often overestimated by this algorithm leading to overestimated background levels and thus, underestimating the baseline flux level. The relative changes in flux for such stars will also be overestimated, affecting the imputed fractional transit depth for detected transit signals.

The new algorithm inspects the background pixels after the initial sky background estimate has been removed, and adjusts the background level so that the third dimmest pixel's average value is centered on zero. This results in much less bias for the affected targets.

This algorithm is part of SPOC Release R5.0 for the extended mission and will be applied to all new observations in the extended mission, as well as to the reprocessing of the year 1 data set.

Although it is important to adjust the sky background bias to better serve dim and/or crowded stars, the vast majority of stars are not significantly affected by the bias in the original sky background algorithm, as indicated in the figure at the top of this box, and the following figure.



Histogram of the reduction in transit depth for the Sector 28 2-minute targets vs. TESS magnitude. Note that the vast majority would experience an apparent reduction in the transit depth of less than 2%.

Procedure for Correcting the Background Bias in Year 1

Users who wish to remove the sky background bias from year 2 light curves can do so using the following approach.

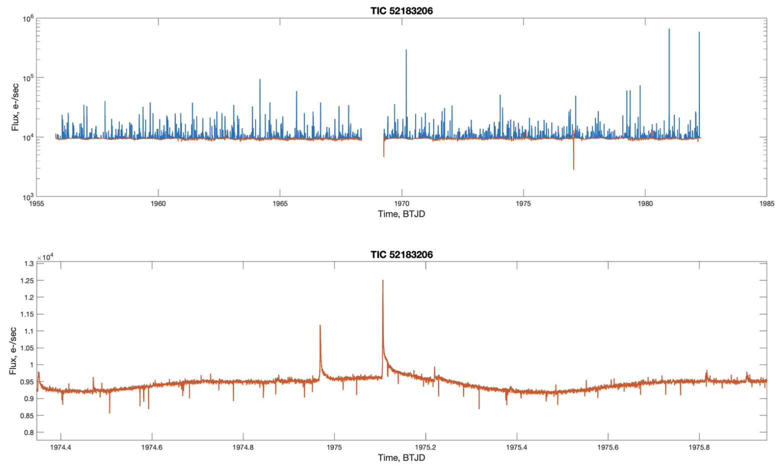
First, determine an estimate for the background bias, bgbias, from the offset of the background-corrected pixels used to determine the background correction and zero. Note that the APERTURE image extension in the LC and TPF FITS files indicates which pixels were assigned to the background pixels and to the optimal aperture. See section 6.2 of the Science Data Products Description Document (Rev-F) (https://archive.stsci.edu/missions/tess/doc/EXP-TESS-ARC-ICD-TM-0014-Rev-F.pdf) for more information.

Next, scale bg_{bias} by the number of pixels in the optimal aperture, N_{pixels}, and then add this value to the SAP_FLUX time series. To adjust the PDCSAP_FLUX, scale bg_{bias} by both the number of pixels in the optimal aperture and the ratio of the crowding metric to the flux fraction correction, and then add this value to the PDCSAP_FLUX:

$$f''_{\mathrm{PDCSAP\_FLUX}}(n) = f_{\mathrm{PDCSAP\_FLUX}}(n) + bg_{bias}\, N_{optimal\ aperture}\, \frac{CROWDSAP}{FLFRCSAP}$$

where $f''_{\mathrm{PDCSAP\_FLUX}}$ is the background bias-adjusted PDCSAP_FLUX.

20-SEC LIGHT CURVES IN THE EXTENDED MISSION



An example of cosmic ray cleaning for a flare star observed at the new 20-sec data mode. The blue curve in the top panel is the simple aperture flux time series when cosmic ray cleaning is disabled. The red curve is the resulting time series with cosmic ray cleaning enabled. The bottom panel is a zoom on some short, small-amplitude flares in the same flux time series.

The TESS mission is offering a new 20-second data mode in the extended mission to open the TESS mission's science space to high frequency astrophysical phenomena on synoptic time scales. Six hundred 20-second target stars are available for the community to propose targets to be flown in extended mission. Another 400 target slots are reserved for bright, unsaturated and uncrowded target stars to be used for image registration and computing the World Coordinate System coefficients generated for each TPF and LC FITS file.

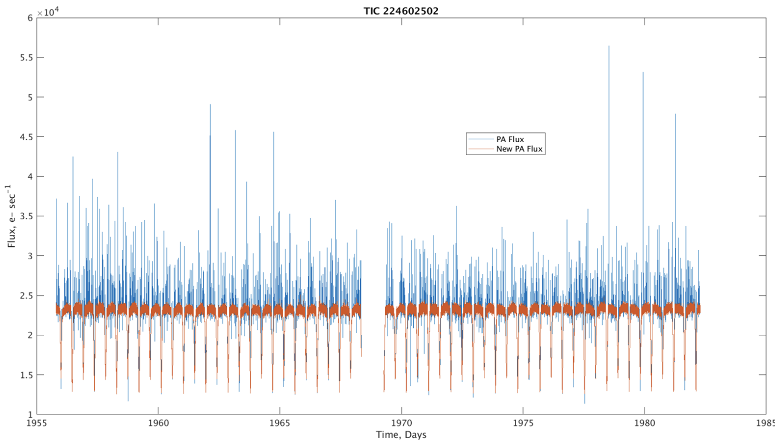
Unlike the FFI and 2-min data, the 20-sec postage stamps are not screened for cosmic rays during data collection on board the spacecraft. Instead, this task must be accomplished in ground software. This is a challenging task as the TESS spacecraft sometimes experiences brief (<2 sec) pointing excursions of up to ~1 pixel (21 arcsec) that cause both negative and positive outliers in the pixel time series. These can imbalance the flux sum in the photometric aperture and lead to negative and positive outliers in the resulting flux time series. To exacerbate the situation, the positive motion-induced outliers can be mistaken for cosmic rays at the pixel level, introducing additonal negative outliers in the light curve.

Cosmic rays are identified and corrected by the Photometric Analysis module in target pixel time series as follows. Pixel values for every cadence are predicted by a model based on delta-quaternions and the measured background flux. After subtracting the model, the residual time series for each pixel is detrended with a moving median to remove long timescale stellar variations. Candidate cosmic ray hits are identified with an adaptive threshold based on noise estimates in a sliding window. For Sectors 25–28, the cosmic ray detection threshold was set to 5 σ to limit the opportunity for triggering on astrophysical signatures such as flares. After reviewing the results, the cosmic ray threshold is set to 4 σ for Sector 29 onward. Estimates of the flux deposited by cosmic rays are obtained from the detrended residuals between the pixel time series and pixel model when the residuals exceed the detection threshold. Candidate cosmic ray detections in the photometric aperture are only accepted on cadences where

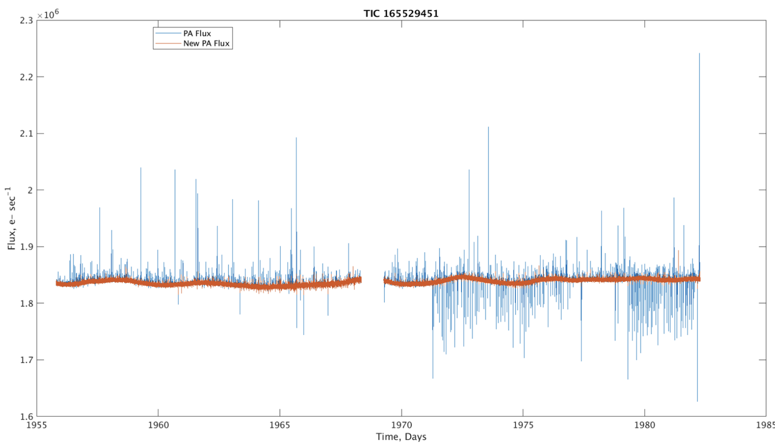
1. the aperture sum improves the smoothness of the flux time series (measured as the distance from each flagged data point to a local median), and
2. cosmic ray hits do not occur in the optimal aperture on three or more consecutive cadences; all candidate cosmic ray hits outside the photometric aperture are (currently) accepted.

Cosmic rays corrected by the pipeline are tabulated in a FITS extension in the 20-second cadence Target Pixel and Collateral Pixel Files. The tables give the cadence, CCD row, CCD column, and estimated charge deposited by the detected cosmic rays. Uncorrected pixel data can be reconstructed by adding the values in the COSMIC_RAY column of the TPF TARGET COSMIC RAY table to the appropriate pixel and cadence. The Data Anomaly Flags in the light curves identify cadences where cosmic ray hits were identified in the optimal aperture or collateral pixels that intersect the rows or columns of the optimal aperture. (See Section "**Quality Flag Updates**" for more information on the quality flags.)

More examples of early results for the 20-sec data are given below.

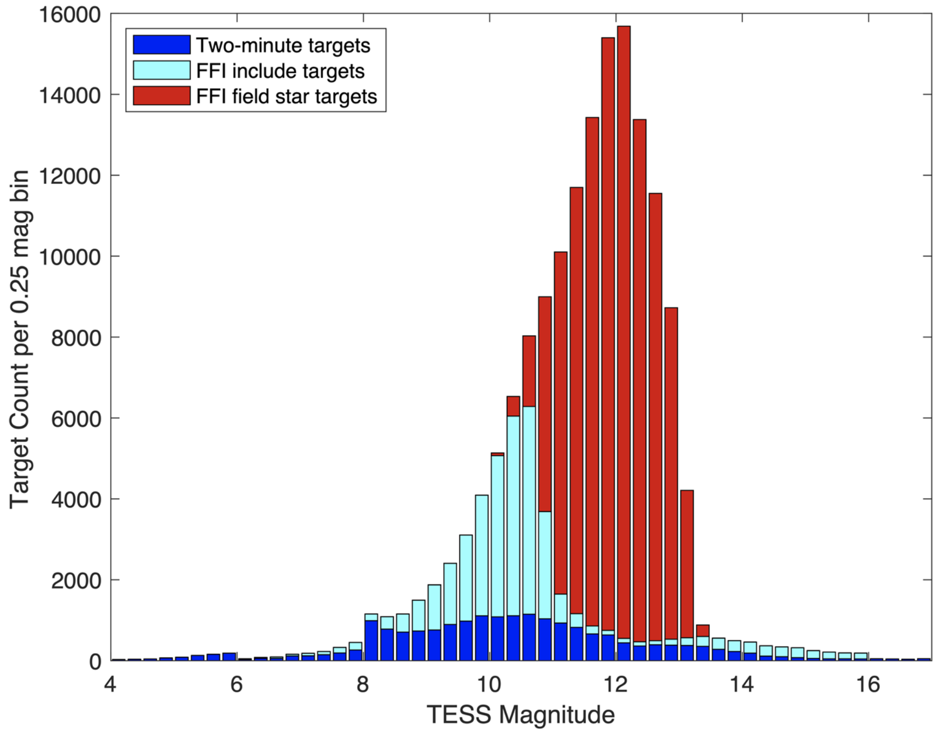


An example of cosmic ray cleaning for an eclipsing binary observed at the new 20-sec data mode. The blue curve in the top panel is the simple aperture flux time series when cosmic ray cleaning is disabled. The red curve is the resulting time series with cosmic ray cleaning enabled.



An example of cosmic ray cleaning for a relatively quiet star with variations on timescales of days observed at the new 20-sec data mode. The blue curve in the top panel is the simple aperture flux time series when cosmic ray cleaning is disabled. The red curve is the resulting time series with cosmic ray cleaning enabled.

SPOC FFI TARGET PIXEL FILES, LIGHT CURVES, AND COTRENDING BASIS VECTORS



Distribution of selected FFI targets in TESS magnitude from Sector 14 shown as a stacked histogram. The FFI target list includes 156,217 total targets with 20,000 targets from the 2-minute list (blue), 31,175 FFI include targets (cyan), and 105,042 FFI field star targets selected by magnitude (red).

New FFI Data Products

During the second year of TESS science operations, the SPOC developed a complete FFI photometry pipeline and is currently delivering Target Pixel Files (TPFs), Light Curve files (LCs), and Cotrending Basis Vector (CBVs) files to the MAST as High Level Science Products as of October 2020. The FFI pipeline was originally completed in order to compare FFI processing against 2-min data processing to ensure the two pipelines were providing consistent results.

After noting keen community interest in SPOC FFI light curves and CBVs, we implemented an FFI target list (FTL) selection module to identify up to 160,000 target stars (10,000 per CCD) that are reasonably bright and uncrowded for FFI light curve generation, as illustrated above for Sector 14.

The philosophy behind our FFI target selection was to use the simplest approach possible within the constraints of the pipeline infrastructure design, while still selecting a set of targets that could prove useful for diverse scientific goals. In order to minimize the impact to operations, the FFI target lists need to be generated automatically based on criteria to the pipeline, including the TESS Input Catalog (TIC – Stassun et al. 2019 (http://doi.org/10.3847/1538-3881/ab3467)) and the pipeline-calculated crowding metric (Bryson et al. 2017). FFI target selection is done in three steps:

1. Select all two–minute targets (nominally 20,000 per sector)

2. Select potentially high value FFI include targets

- with H magnitude ≤ 10 or distance ≤ 100 pc (to include IR bright or nearby stars, which are valuable for exoplanet follow-up)
- crowding metric ≥ 0.5 (at least 50% of the flux in the photometric aperture is from the selected target)
- TESS magnitude ≤ 16 (only TIC objects brighter than 16 are nominally available to the pipeline modules)

3. Select additional FFI field star targets in order of TESS magnitude with

- TESS magnitude ≤ 13.5
- log surface gravity ≥ 3.5 (select dwarfs and sub-giants)
- crowding metric ≥ 0.8 (select stars that dominate the flux in their aperture)

The SPOC now produces target pixel files, light curve files, and cotrending basis vector files which are being submitted to the MAST as HLSP products under the project TESS-SPOC. These files are designed to be consistent with the corresponding 2-min target data products. Some examples of the data in these files are illustrated in the figures below.

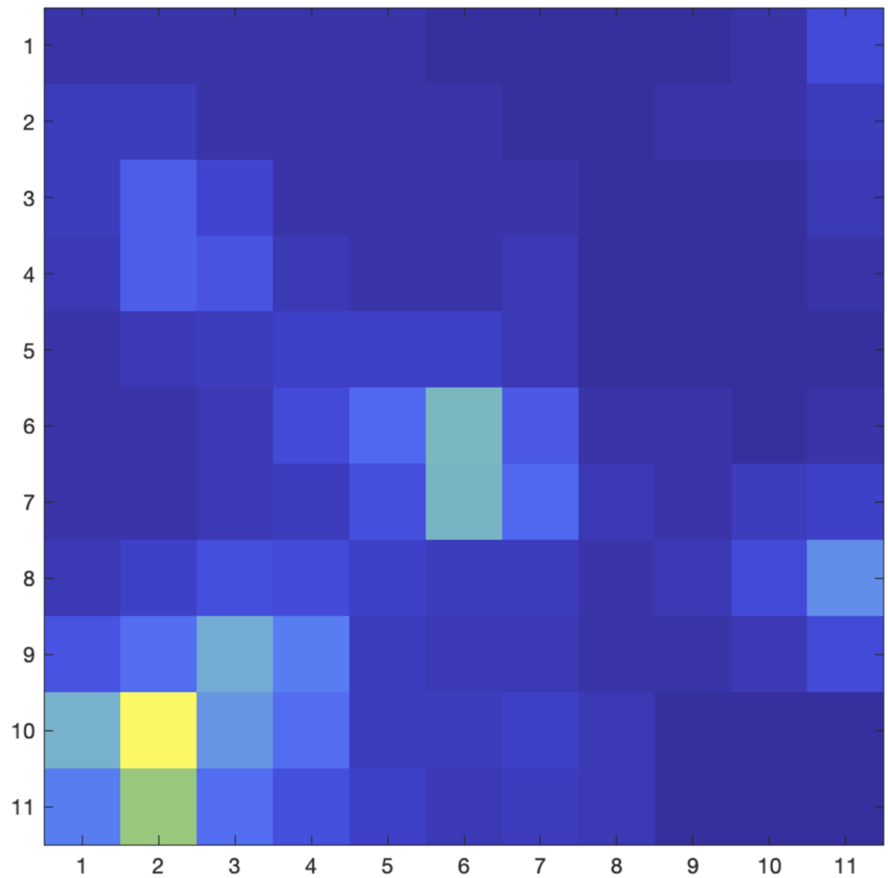
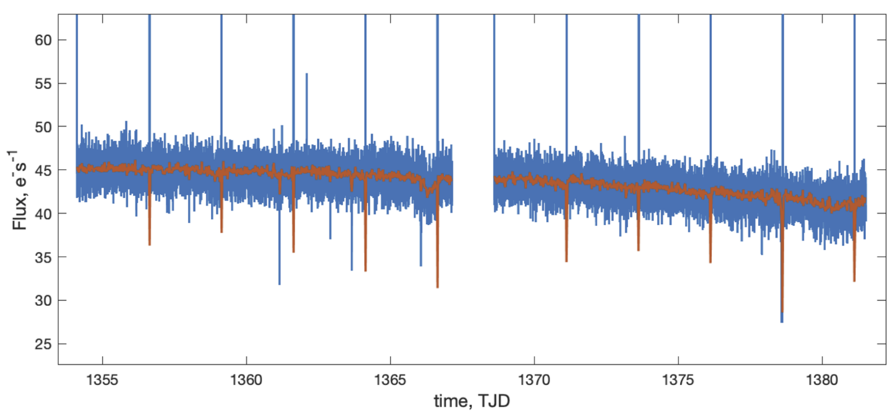
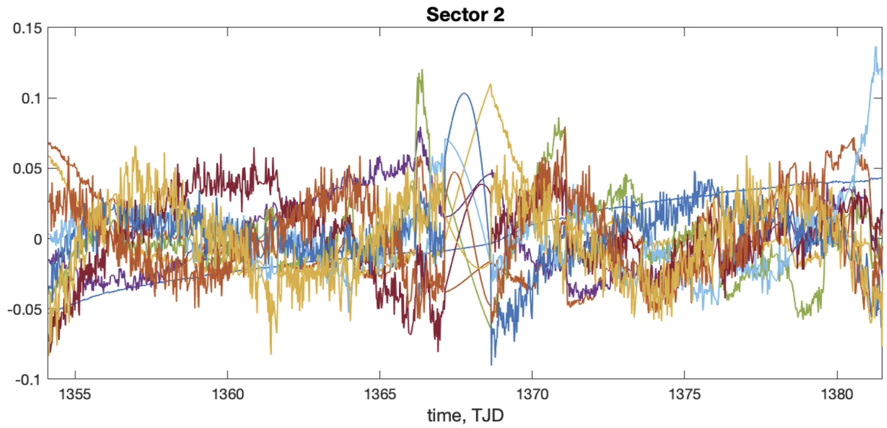


Image of one frame from a Target Pixel File for an FTL target star.



Flux time series at 2-minutes (blue curve) and at 30-minutes (red curve) for a target star vs. time.

The two time series are consistent with one another when the 2-minute data are binned to the cadence interval of the FFI-derived light curve at 30 minutes, except for timesteps when the reaction wheel desaturation operations were performed, as expected.



Single scale cotrending basis vectors derived from the ensemble of FTL targets on a CCD from a test run on Sector 2 vs. time. The community will have access to CBVs derived on the native timescale for FFI light curves for use in identifying and removing signatures of instrumental systematic errors.

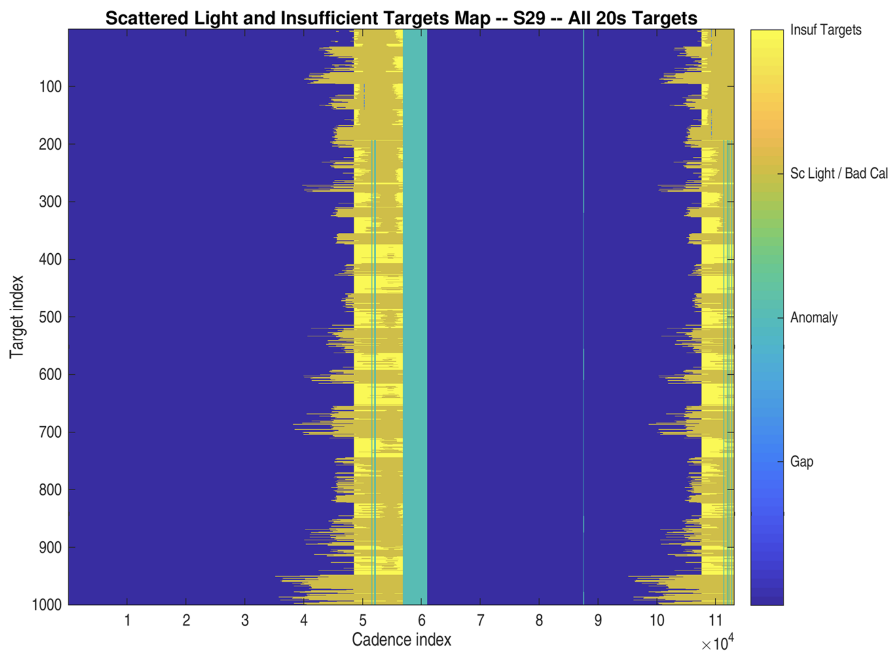
QUALITY FLAG UPDATES

Table I: Data Quality Flags

Bit	Value	FFI	Description
1	1	Y	Attitude Tweak
2	2	N	Safe Mode
3	4	Y	Spacecraft is in Coarse Point
4	8	N	Spacecraft is in Earth Point
5	16	Y	Argabrightening Event
6	32	Y	Reaction Wheel Desaturation Event
7	64	N	Cosmic Ray in Optimal Aperture
8	128	N	Manual Exclude. The cadence was excluded because of an anomaly
9	256	N	Discontinuity corrected between this cadence and the following one
10	512	N	Impulsive outlier removed before cotrending
11	1024	Y	Cosmic ray detected on collateral pixel row or column
12	2048	Y	Straylight from Earth or Moon in Camera FOV (predicted)
13	4096	N	Scattered light exclude (spoc-4.0.5 and later)
14	8192	N	Planet search exclude (spoc-4.0.5 and later)
15	16384	Y	Bad calibration exclude (spoc-4.0.14 and later)
16	32768	N	Insufficient targets for error correction exclude (spoc-4.0.14 and later)

There have been a number of updates to the Quality Flags reported in the FFI, target pixel, and light curve files starting with Sector 20 (DRN27), as described below. The new flags have been applied to the reprocessed sectors released to the public (14-19) and to all data sets going forward starting with Sector 20. They are also being applied to the reprocessing of year 1 data currently underway.

Scattered light flags were originally applied to every target on a CCD at a given cadence. However, scattered light caused by the Earth and Moon creates a complicated spatial pattern in the camera, and not every target on a CCD is affected at the same time or to the same degree. In DR30, each individual target now has a unique set of cadences marked with the “Scattered light flag” (bit 13, value 4096). Cadences for a given target are flagged for periods of time when the measured background rises above the baseline background level by a factor of two and when the measured background exceeds a specified fraction of the target flux (typically 0.25). The figure below illustrates the new quality flags for all 1000 20-sec targets in Sector 29.



The target- and cadence-specific flags are illustrated in this example for all the 20-sec targets from Sector 29 observations. The scattered light/bad calibration flags are cadence- and target-specific. Manual excludes, or anomaly flags are set for specific cadences and apply to all targets. The insufficient target flags are defined in the text below.

For reprocessed data, the predicted stray light flag (bit 12, value 2048) is disabled in two-minute and in 20-second data products because the scattered light exclude flag (bit 13, value 4096) better identifies cadences affected by scattered light. The predicted stray light flag (bit 12) continues to mark FFIs during times when the Earth/Moon are near the camera FOVs and the image quality may be degraded. We strongly recommend that users inspect the FFI data before removing images marked with bit 12, because this bit is set based on predictions from mission planning and is known to be conservative with respect to the actual image quality.

If the Earth/Moon interference is strong enough to saturate the detector, all targets on a CCD slice will be affected and the data are unusable. Cadences with bad calibrations due to saturation are now explicitly marked with bit 15 (value 16384, “Bad Calibration Exclude”). For some cadences, the majority of targets on a CCD may be flagged for scattered light and not enough valid data remains to derive cotrending basis vectors in PDC. No systematic error correction can be applied at these times. This situation is identified by bit 16 (value 32768, “Insufficient Targets for Error Correction Exclude”).

The new 20-second data mode includes cadences marked with bit 7 and 11 (Cosmic Ray in Optimal Aperture and Cosmic Ray in Collateral Pixel). These flags indicate cadences affected by cosmic rays that are removed by the pipeline, and can be found in both the TPF and LC files. The data provided in the archive products are corrected for cosmic rays, and a FITS table extension in the TPF and Collateral Pixel File details the cosmic rays identified and removed by the pipeline at the pixel level. The cosmic ray mitigation algorithm implemented in the SPOC pipeline is described in Section "20-sec Light Curves in the Extended Mission".

Please note that the quality flags can only be properly interpreted by inspection of the specific bit for each flag – comparing the numerical value of a particular flag against the data quality time series will produce erroneous results when two or more flags are set in the same cadence.

THE SPOC TEAM

Our lean extended mission operations team at the Science Processing Operations Center consists of the following individuals:

- Jon M. Jenkins, Science Lead and Manager
- Eric B. Ting, Lead Operations Engineer
- Joseph D. Twicken, Lead Data Scientist
- Peter Tenenbaum, Lead Software Engineer
- Douglas A. Caldwell, Support Scientist
- Jeffrey C. Smith, Data Scientist

The SPOC is supported as well by Pipeline Scientists from MIT:

- Michael Fausnaugh
- Chris Burke

ABSTRACT

The Transiting Exoplanet Survey Satellite (TESS) recently completed its initial two-year, near all-sky survey, identifying over 79 exoplanets and over 2000 exoplanet candidates. The mission is well on its way to find at least 50 small, nearby exoplanets for which masses can be ascertained and whose atmospheres can be characterized by ground- and space-based follow-on observations. TESS has unveiled a plethora of exciting non-exoplanet astrophysics results, such as asteroseismology, asteroids, and supernova. In the extended mission, TESS is collecting full frame images (FFIs) at 10-minute intervals rather than at 30-minute intervals, as was the case for the two-year primary mission. TESS is also collecting and providing photometry for up to 1000 20-sec targets in addition to the 20,000 target star postage stamps collected at 2-min intervals. The extended mission will also feature a five-month interval in which the 24°x96° field of view (FOV) will be rotated by 90° from its normal North-South orientation to observe a swath of the ecliptic plane. The FOVs for the remainder of the extended mission will be offset in latitude from those of the prime mission to help fill in the gaps in the full sky coverage. We discuss the performance and behavior of the data products generated by the TESS Science Processing Operations Center (SPOC) at NASA Ames Research Center and highlight the new 20-sec data mode and the 10-min FFIs.

The TESS Mission is funded by NASA's Science Mission Directorate as an Astrophysics Explorer Mission.

REFERENCES

Bryson, S. T., Jenkins, J. M., Klaus, T. C., et al. 2017, Kepler Data Processing Handbook (KSCI-19081-003 (http://archive.stsci.edu/kepler/manuals/KSCI-19081-003-KDPH.pdf)): Target and Aperture Definitions: Selecting Pixels for Kepler Downlink, Tech. rep., NASA Ames Research Center

Jenkins, J. M. 2020, Kepler Data Processing Handbook (KSCI-19081-003) (http://archive.stsci.edu/kepler/manuals/KSCI-19081-003-KDPH.pdf): Overview of the Science Operations Center, Tech. rep., NASA Ames Research Center

Jenkins, J. M., Twicken, J. D., McCauliff, S., et al. 2016, Kepler Data Validation I—Architecture, Diagnostic Tests, and Data Products for Vetting Transiting Planet Candidates (http://doi: 10.1117/12.2233418),in Proc. SPIE, Vol. 9913, Software and Cyberinfrastructure for Astronomy IV, 99133E

Li, J., Tenenbaum, P., Twicken, J. D., et al. 2019, Kepler Data Validation II–Transit Model Fitting and Multiple-planet Search (https://iopscience.iop.org/article/10.1088/1538-3873/aaf44d), PASP, 131, 024506

Stassun, K. G., Oelkers, R. J., Paegert, M., et al. 2019, "The Revised TESS Input Catalog and Candidate Target List (http://doi.org/10.3847/1538-3881/ab3467)," AJ, 158, 138

Twicken, J. D., Catanzarite, J. H., Clarke, B. D., et al. 2018, Kepler Data Validation I—Architecture, Diagnostic Tests, and Data Products for Vetting Transiting Planet Candidates (http://doi.org/10.1088/1538-3873/aab69), PASP, 130, 064502

Twicken, J. D., D. A. Caldwell, J.M. Jenkins, et al. 2020, TESS Science Data Products Description Document (EXP-TESS-ARC- 14 Rev F) (https://archive.stsci.edu/missions/tess/doc/EXP-TESS-ARC-ICD-TM-0014.pdf), Tech. Rep., NASA Ames Research Center

Vanderspek, R., Doty, J., Fausnaugh, M., et al. 2018, TESS Instrument Handbook (https://archive.stsci.edu/files/live/sites/mast/files/home/missions-and-data/active- missions/tess/_documents/TESS_Instrument_Handbook_v0.1.pdf) , Tech. rep., Kavli Institute for Astrophysics and Space Science, Massachusetts Institute of Technology