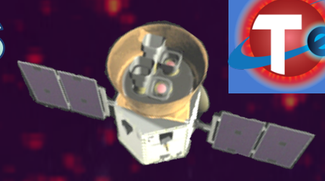
TESS Science Processing Operations Center Pipeline Status and Updates



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ABSTRACT

The past eighteen months have seen a number of important changes for the TESS Science Processing Operations Center (SPOC) and our archival data products as TESS embarked upon its first extended mission. First, the SPOC developed and deployed a new **20-sec cadence pipeline**, promising to unveil exciting new astrophysics at these short timescales for up to 1000 targets per observing sector. We also developed an **FFI light curve pipeline** that creates light curves and associated data products for up to 160,000 targets in each sector and archive these as High-Level Science Products (HLSP) at the Mikulski Archive for Space Telescopes (MAST). Soon we plan to perform transiting planet searches on these light curves and to release Data Validation reports and associated data products to the MAST. We also present results from the **first multi-year transiting planet search of sectors 1 through 36**. Finally, we discuss major changes to the SPOC pipeline that motivated the reprocessing of the first year of data, including the application of **target- and cadence-specific scattered light flags**, and an **update to the sky background correction algorithm** to mitigate bias in the original algorithm for dim and/or severely crowded stars.

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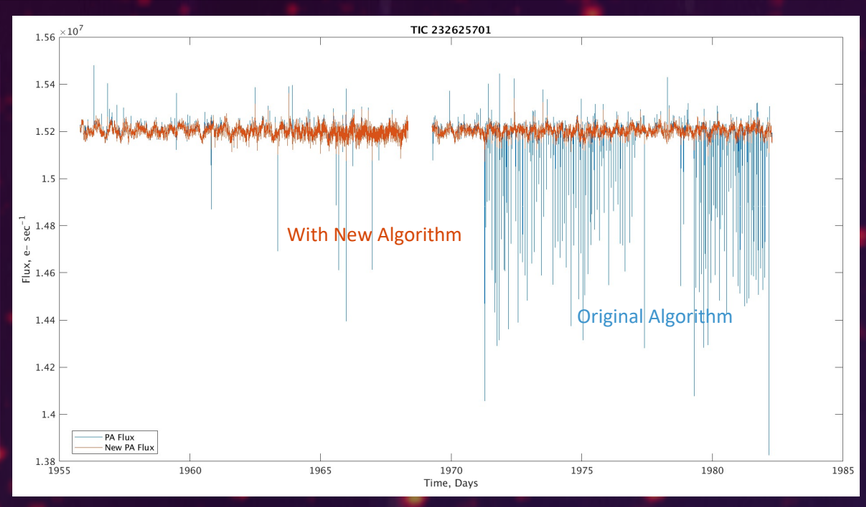
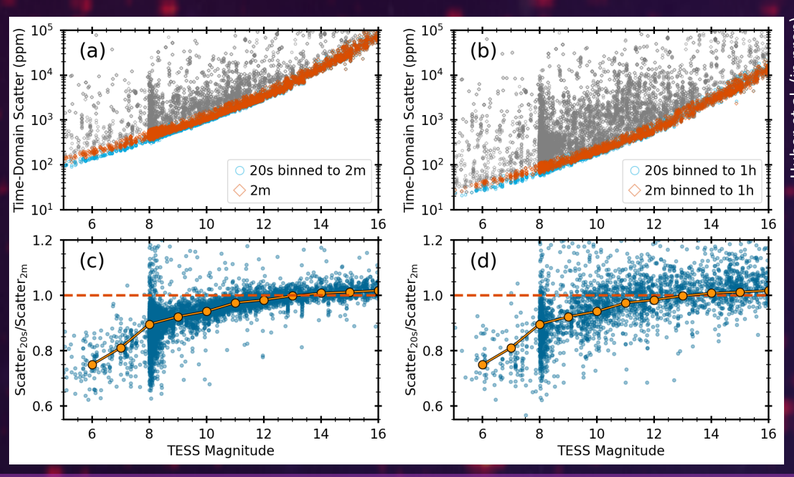
1. 20-Sec Cadence Mode

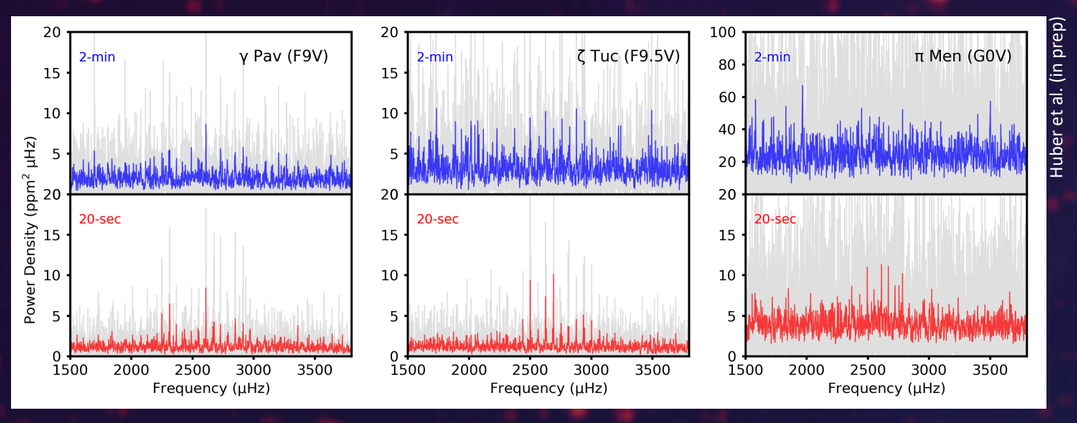
The first TESS Extended Mission features a new cadence mode: up to 1000 targets may be collected at 20-sec integration intervals to permit investigation of short-timescale phenomena such as micro-flaring, high-frequency oscillations (such as from white dwarfs), pressure-mode oscillations of later stars than was permitted with 2-min integrations, and other phenomena. Unlike the FFI and 2-min target data, 20-sec data must be corrected for cosmic rays in ground processing.

We developed a new algorithm for identifying and correcting for cosmic rays using the quaternions and the background flux time series for each target to model the pixel time series. The new algorithm also conditions detections on whether they lead to smoother aperture flux time series, to guard against mistaking pointing-induced brightness variations for cosmic rays.





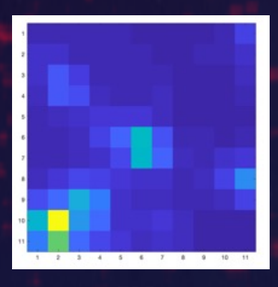
Panel (a): Time-domain scatter as a function of TESS magnitude for stars observed in 20-second cadence from Sectors 27 to 36. Symbols show 20-second light curves binned to 2-minute cadence (cyan circles) and original 2-minute light curves (red diamonds) for each sector. Grey points mark stars likely dominated by stellar variability. Panel (b): Same as panel (a) but binning light curves to 1-hour cadence. Panel (c): Ratio of the time-domain scatter for the two datasets shown in panel (a), retaining only stars not dominated by stellar variability (i.e. each point in panel c is the ratio of a cyan and red point in panel a). The dashed line marks unity and orange circles show median bins. Panel (d): Same as panel (c) but for the binned light curves shown in panel (b).



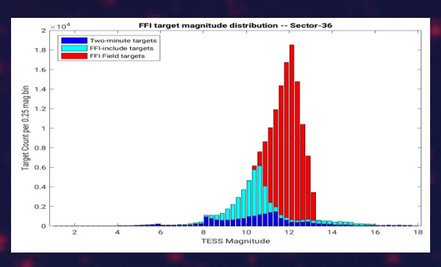
The S/N of the oscillation mode detection dramatically increases for the 20-sec cadence data

2. TESS Light Curves From Full Frame Images ("TESS-SPOC")

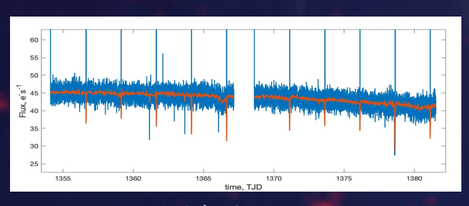
- Data include SPOC-formatted light curves, target pixel files and cotrending basis vectors
- Up to 160,000 targets per sector are chosen that are reasonably bright and uncrowded
- RNAAS published
- These are being released to MAST as High Level Science Products: https://archive.stsci.edu/hlsp/tess-spoc



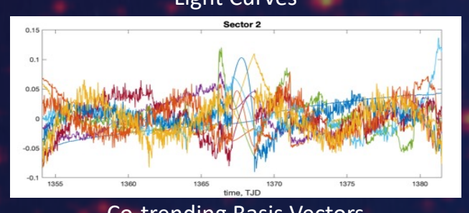
TPFs



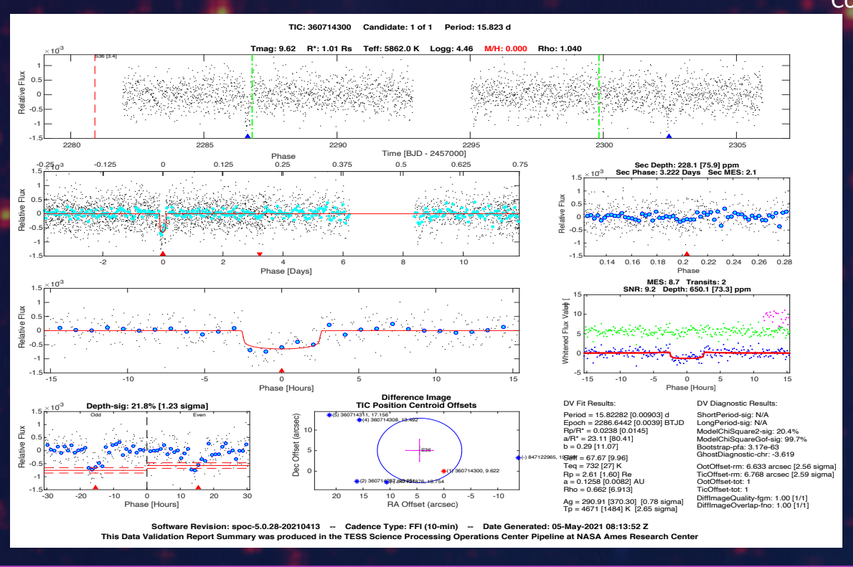
Histogram of FFI Targets



Light Curves

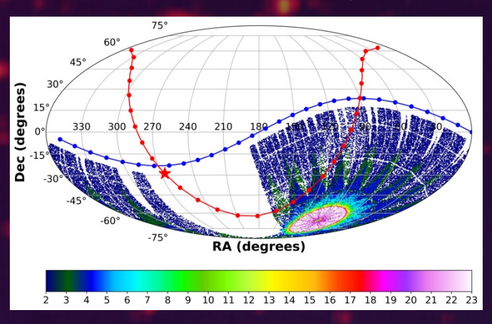


Co-trending Basis Vectors

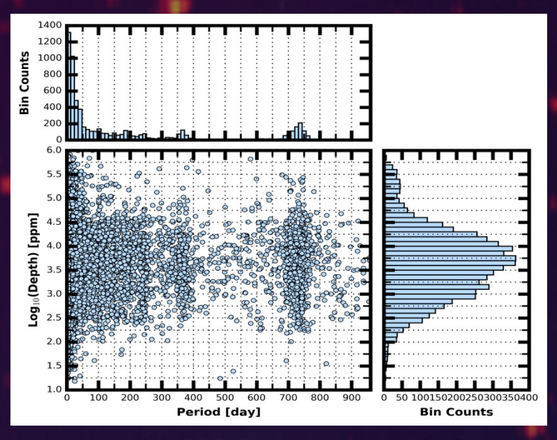


- Sectors 1-6, 14-32 are available on MAST
- We are searching the FTL light curves for transiting exoplanet signatures
- Example on left is a very good-looking candidate
- Coming soon to a MAST near you!

3. Multi-Year, Multi-Sector Search of Sectors 1-13 + 27-36



Left Figure: Right Ascension and Declination for TESS 2-min targets included in this multi-sector search, color-coded by the number of sectors in which that target was observed. The galactic and ecliptic planes are indicated by the red and blue lines, respectively.



A total of 57,515 stars were searched
More info in DRN 53

Right Figure: Lower Left Panel: Transit depth as a function of orbital period for the 12466 TCEs identified for the Sectors 1 – 36 multi-sector search. For enhanced visibility of long-period detections, TCEs with orbital period<3.0 days are not shown. Reported depth comes from the DV limb-darkened transit fit depth when available (or the DV trapezoid model fit depth if the limb darkened transit fit is not available). Top Panel: Orbital period distribution of the TCEs shown in the lower left panel. Right Panel: Transit depth distribution for the TCEs shown in the lower left panel.

New Scattered Light Flags

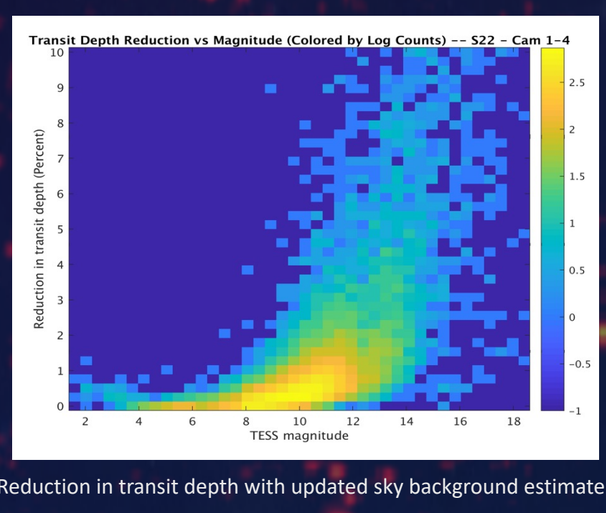
Bit	Value	FFI	Description
1	1	Y	Attitude Tweak
2	2	N	Safe Mode
3	4	Y	Spacecraft is in Coarse Point
4	8	N	Spacecraft is in Earth Point
5	16	Y	Argabrightening event
6	32	Y	Reaction Wheel desaturation Event
7	64	N	Cosmic Ray in Optimal Aperture pixel
8	128	N	Manual Exclude. The cadence was excluded because 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).

- Data Quality Flags are bit-encoded – each bit represents a separate event/issue
- Note that StrayLight (bit 12) indicates when a particular camera is not used for guiding the pointing – it does not indicate the data are necessarily bad!
- New Scattered Light Flag (bit 13) – Indicates scattered light too severe for pipeline photometry
- New Planet Search Exclude Flag (bit 14) – indicates a target was excluded from the transit search
- New Bad Calibration Exclude Flag (bit 15) – indicates scattered light corrupted the calibration of a target
- New Insufficient targets for error Correction (bit 16) – Indicates there was an insufficient number of targets on a cadence for PDC to correct systematic errors

Algorithm Update: Sky Background Correction

Starting with Sector 27 the sky background has been updated to mitigate bias in the original algorithm. The new algorithm applies to all data from sector 27 onwards as well as to the reprocessed data from Year 1 (Sectors 1-13). The Data Release notes for Sector 27 (DRN 38) documents how one can identify and correct for the sky background bias in the Year 2 light curve files (Sectors 14-26).

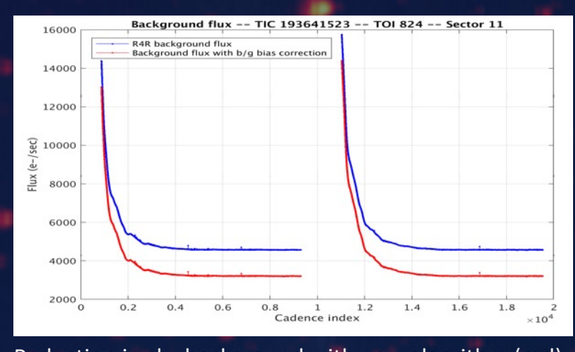
- The original algorithm tended to over-estimate the sky background flux, especially for dim and/or heavily crowded stars
- This sky background bias then caused the fractional transit depth to be overestimated
- For uncrowded stars brighter than Tmag=14, the typical bias in the transit depth was less than ~2%



Reduction in transit depth with updated sky background estimate

Case Study: TOI-824
- SPOC fitted transit depth was ~1900 ppm
- Ground-based observations showed it was ~1500 ppm

Problem traced to overestimation of the sky background:
- Dimmest background-corrected, calibrated pixels in postage stamp were ~-180 $e^- s^{-1}$
- Adjusting the sky background so that the third dimmest pixel is centered on zero after BG subtraction mitigates most of the bias



Reduction in sky background with new algorithm (red) compared to original algorithm (blue)

One can correct for the sky background bias in Year 2 data by working with the target pixel file (TPF) and the light curve file (LC) for a particular target.

1. Inspect the pixel time series of the background-corrected, calibrated background pixels from the postage stamp (bit 3 is set in the Aperture Image Mask extension) to determine the sky background bias, bg_{bias}. (If sky background bias is present, the dimmest pixels will have negative median flux rates)

2. Multiply the background bias by the number of pixels in the optimal aperture, $N_{optimal\ aperture}$, the crowding metric, CROWDSAP (from the LC FITS binary table header), and divide by the flux fraction in the optimal aperture, FLFRCSAP (from the LC FITS binary table header).

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

Check out the TESS documentation at MAST!