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TESS Data Release Notes:
Sector 50, DR72

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Acknowledgements

These Data Release Notes provide information on the processing and export of data from the Transiting Exoplanet Survey Satellite (TESS). The data products included in this data release are full frame images (FFIs), target pixel files, light curve files, collateral pixel files, cotrending basis vectors (CBVs), and Data Validation (DV) reports, time series, and associated xml files.

These data products were generated by the TESS Science Processing Operations Center (SPOC, Jenkins et al., 2016) at NASA Ames Research Center from data collected by the TESS instrument, which is managed by the TESS Payload Operations Center (POC) at Massachusetts Institute of Technology (MIT). The format and content of these data products are documented in the Science Data Products Description Document (SDPDD)[1]. The SPOC science algorithms are based heavily on those of the Kepler Mission science pipeline, and are described in the Kepler Data Processing Handbook (Jenkins, 2020).[2] The Data Validation algorithms are documented in Twicken et al. (2018) and Li et al. (2019). The TESS Instrument Handbook (Vanderspek et al., 2018) contains more information about the TESS instrument design, detector layout, data properties, and mission operations.

The TESS Mission is funded by NASA's Science Mission Directorate.

This report is available in electronic form at
https://archive.stsci.edu/tess/

[1] https://archive.stsci.edu/missions/tess/doc/EXP-TESS-ARC-ICD-TM-0014-Rev-F.pdf
[2] https://archive.stsci.edu/kepler/manuals/KSCI-19081-003-KDPH.pdf

1 Observations

TESS Sector 50 observations include physical orbits 107 and 108 of the spacecraft around the Earth. Data collection was paused for 0.90 days between the orbits to download data. Data collection was also paused for four hours in orbit 107 (between TJD 2672.2512 and 2672.4206) to test data downlink near spacecraft apogee, in preparation for operation changes scheduled for 2022 September. In total, there are 25.17 days of science data collected in Sector 50.

Table 1: Sector 50 Observation times

	UTC	TJD[a]	Cadence #
Orbit 107 start	2022-03-26 18:20:52	2665.26598	1035224
Orbit 107 end	2022-04-08 21:36:51	2678.40208	1044682
Orbit 108 start	2022-04-09 19:14:51	2679.30347	1045331
Orbit 108 end	2022-04-22 00:10:51	2691.50902	1054119

[a] TJD = TESS JD = JD - 2,457,000.0

The spacecraft was pointing at RA (J2000): 221.8575°; Dec (J2000): 41.7577°; Roll: 329.7340°. See the TESS project Sector 50 observation page[3] for the coordinates of the spacecraft pointing and center field-of-view of each camera. Fields-of-view for each camera can be found at the TESS Guest Investigator Office observations status page.[4] The detailed target list for both 2-minute and 20-second data, as well as the Guest Investigator target lists, can be found at the Sector 50 observation page and the observations status page.

1.1 Notes on Individual Targets

There are no issues with missing light curves in the 20-second data products. There were 1223 targets chosen for 20-second cadence observations, including 400 PPA stars. TIC 551711135 and 441804565 are blended with comparably bright stars—the contaminating flux for these objects is very large, and the resulting photometry is expected to be unreliable.

For the 2-minute cadence data, three bright stars (Tmag $\lesssim$ 1.8) with large pixel stamps were not processed in the photometric pipeline. The target pixel files with original and calibrated pixel data are provided, but no light curves were produced. Note that the TPF files do not include a background correction for stars without light curves. The affected TIC IDs are 459832522, 411188061 and 219827143.

One additional target (1101424611) is blended with a brighter saturated star. No optimal aperture was assigned in this case. A target pixel file with the original and calibrated pixel data is provided, but no light curve was produced.

Six target stars (441804565, 341873045, 321539985, 1551711135, 1102093580, 1000665296) are blended with comparably bright stars—the contaminating flux for these objects is very large, and the resulting photometry is expected to be unreliable.

One target (198187877) has a pixel stamp that does not fully capture the bleed trails.

[3] https://tess.mit.edu/observations/sector-50

[4] https://heasarc.gsfc.nasa.gov/docs/tess/sector.html

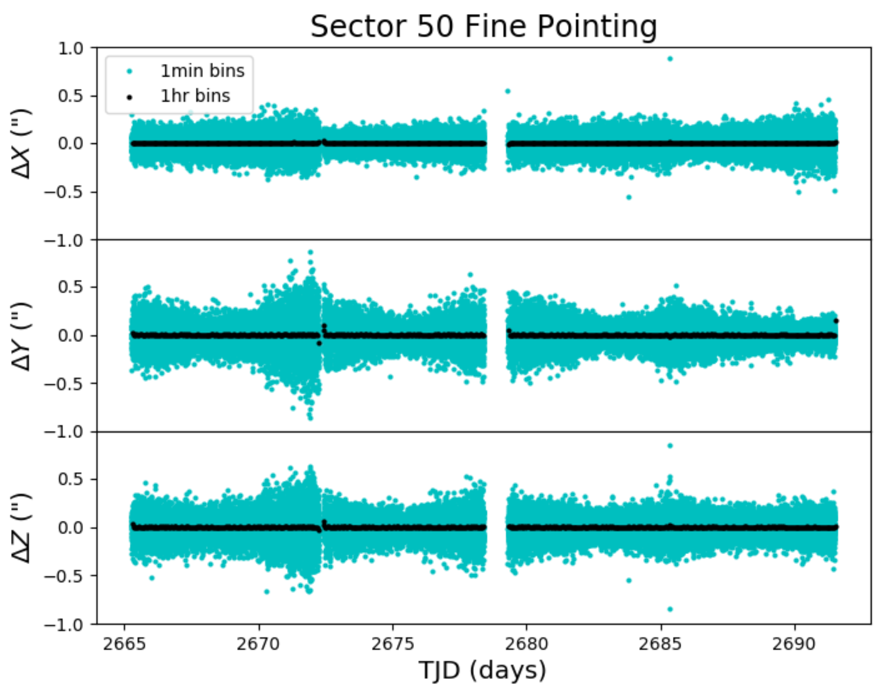

Figure 1: The delta-quaternions from each camera have been converted to spacecraft frame, binned to 1 minute and 1 hour. The figure for Sector 50 only shows quaternions from Camera 4. Long-term trends (such as those caused by differential velocity aberration) have also been removed. The ΔX/ΔY directions represent offsets along the detectors' rows/columns, while the ΔZ direction represents spacecraft roll.

1.2 Spacecraft Pointing and Momentum dumps

Sector 50 consists of observations of the northern ecliptic hemisphere, with Camera 4 pointed near the north ecliptic pole. Camera 4 alone was used for guiding in the first half of orbit 107. After the data downlink at apogee, guiding with both Cameras 1 and 4 was enabled. This introduced a small shift in the spacecraft attitude in the second half of orbit 107. Some `SAP_FLUX` light curves may show discontinuities before and after the data gap at these times. However, cotrending with PDC removes this offset in most cases. Camera 4 alone was used for guiding in all of orbit 108.

One momentum dump was performed in each of the orbits 107 and 108. In orbit 107, the momentum dump took place during the data downlink at apogee and does not affect any science data. Figure 1 summarizes the pointing performance over the course of the sector based on Fine Pointing telemetry.

1.3 Scattered Light

Figure 2 shows the median value of the background estimate for all targets on a given CCD as a function of time. Figure 3 shows the angle between each camera's boresight and the Earth or Moon—this figure can be used to identify periods affected by scattered light and the relative contributions of the Earth and Moon to the image backgrounds.

At the start of orbit 107, the Earth crosses through Cameras 1 and 2, saturating the CCD detectors and/or causing strong glints. At the start of orbit 108, the Earth and then the Moon moves through Camera 1, saturating the detectors and causing strong glints and scattered light signals in both Cameras 1 and 2 (see Figure 3).

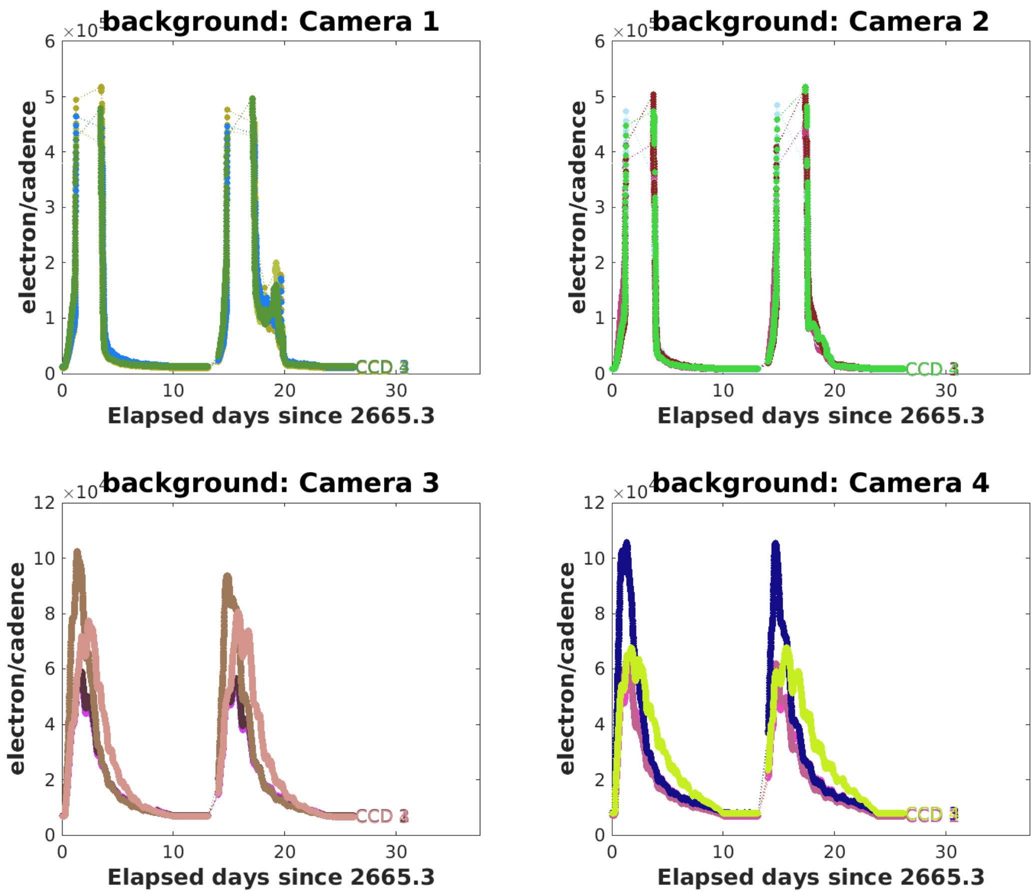

Figure 2: Median background flux across all targets on a given CCD in each camera. The changes are caused by variations in the orientation and distance of the Earth and Moon. In Sector 50, the Earth and Moon pass through the camera fields of view, saturating the detectors.

2 Data Anomaly Flags

See the SDPDD (§9) for a list of data quality flags and the associated binary values used for TESS data, and the TESS Instrument Handbook for a more detailed description of each flag.

The following flags were not used in Sector 50: bits 1, 2, and 9 (Attitude Tweak, Safe Mode and Discontinuity).

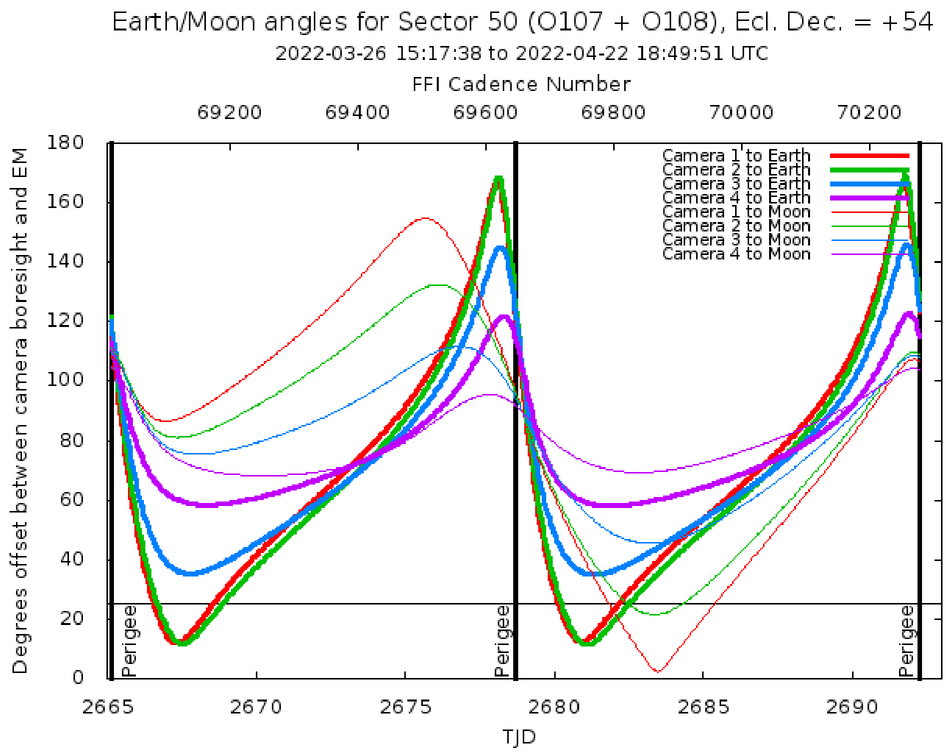

Figure 3: Angle between the four camera boresights and the Earth/Moon as a function of time. When the Earth is within $\sim 25^{\circ}$ of a camera's boresight, transiting planet searches may be compromised by high levels of scattered light. At larger angles, up to $\sim 35^{\circ}$, scattered light patterns and complicated structures may be visible. At yet larger angles, low level patchy features may be visible. Scattered light from the Moon is generally only noticeable below $\sim 35^{\circ}$. This figure can be used to identify periods affected by scattered light and the relative contributions of the Earth and Moon to the background. However, the background intensity and locations of scattered light features depend on additional factors, such as the Earth/Moon azimuth and distance from the spacecraft.

Cadences marked with bits 3, 4, 6, and 12 (Coarse Point, Earth Point, Reaction Wheel Desaturation Event, and Straylight) were marked based on spacecraft telemetry. The cadences during the data downlink at apogee (1040253 to 1040376) are marked with bit 4 (Earth Point).

Cadences marked with bit 5 and 10 (Argabrightening Events and Impulsive Outlier) were identified by the SPOC pipeline. Bit 5 marks a sudden change in the background measurements. In practice, bit 5 flags are caused by rapidly changing glints and unstable pointing at times near momentum dumps. Bit 10 marks an outlier identified by PDC and omitted from the cotrending procedure.

The 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.

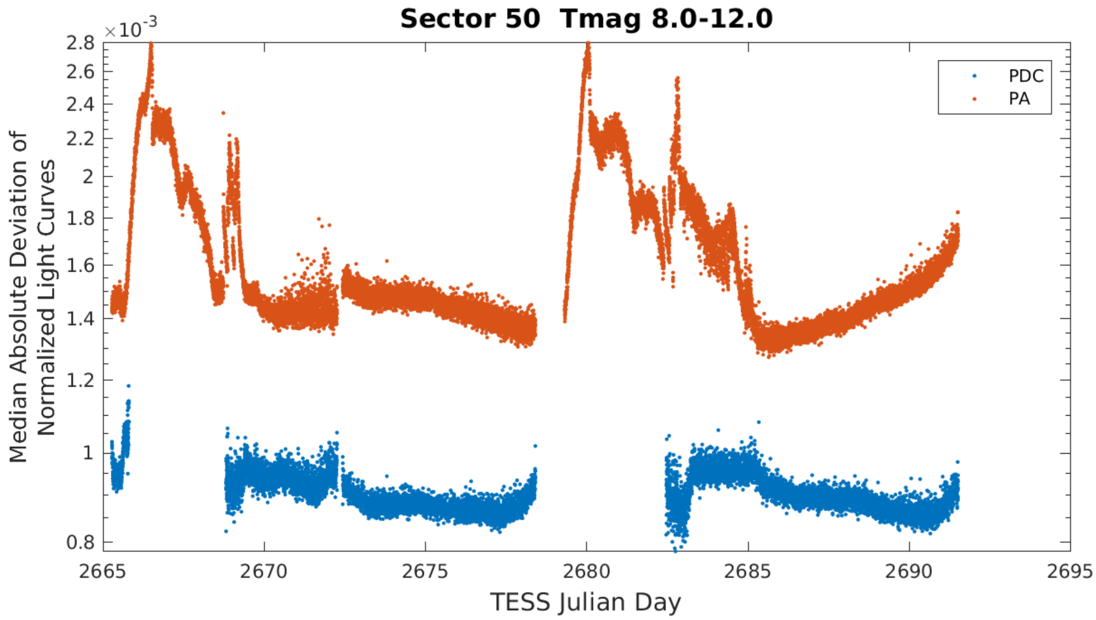

Figure 4: Median absolute deviation (MAD) for the two-minute cadence data from Sector 50, showing the performance of the cotrending after identifying Manual Exclude data quality flags. The MAD is calculated in each cadence across stars with flux variations less than 1% for both the PA (red) and PDC (blue) light curves, where each light curve is normalized by its median flux value. The scatter in the PA light curves is much higher than that for the PDC light curves, and the outliers in the PA light curves are largely absent from the PDC light curves due to the use of the anomaly flags.

Cadences marked with bit 8 (Manual Exclude) are ignored by PDC, TPS, and DV for cotrending and transit searches. In Sector 50, these cadences were identified using spacecraft telemetry from the fine pointing system. All cadences with pointing excursions >7 arcsec (0.3 pixel) were flagged for manual exclude. Figure 4 also shows an assessment of the performance of the cotrending based on the final set of manual excludes.

The predicted stray light flag (bit 12, value 2048) is marked in the FFIs and flags times when the Earth/Moon are near the camera FOVs and may interfere with guiding or saturate the detectors. 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 quality of data usable for analysis.

The predicted stray light flag (bit 12) is disabled for the 2-minute and 20-second data products. The scattered light exclude flag (bit 13, value 4096) identifies cadences at which individual targets are affected by scattered light

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").

FFIs were only marked with bits 3, 6, 8, 12, and 15 (Coarse Point, Reaction Wheel Desaturation Events, Manual Exclude, Straylight, and Bad Calibration Exclude). Only one FFI is affected by each momentum dump. There are no WCS coordinates for FFIs that coincide with momentum dumps.

3 Anomalous Effects

Smear Correction Issues

The following columns were impacted by bright stars in the science frame, and/or upper buffer rows, and/or lower science frame rows, which bleed into the upper serial register resulting in an overestimated smear correction.

- Camera 1, CCD 2, Column 1345 - Star TYC 887-783-1
- Camera 1, CCD 4, Column 481 - Star HX Bootes
- Camera 2, CCD 1, Column 232 - Star HD 133460
- Camera 2, CCD 1, Column 499 - Star HD 132408
- Camera 2, CCD 1, Column 745 - Star HD 131411
- Camera 2, CCD 1, Column 1535 - Star Sigma Bootes
- Camera 2, CCD 1, Column 1792 - Star HD 127066
- Camera 2, CCD 2, Column 327 - Star HD 124186
- Camera 2, CCD 3, Column 1471 - Star HD 122503
- Camera 3, CCD 1, Column 1645 - Star TYC 3868-796-1
- Camera 3, CCD 3, Column 875 - Star X Hercules
- Camera 3, CCD 4, Column 917 - Star HD 132465
- Camera 3, CCD 4, Column 1491 - Star HD 128729
- Camera 4, CCD 1, Column 712 - Star HD 157663
- Camera 4, CCD 1, Column 1754 - Star HD 163214
- Camera 4, CCD 2, Column 624 - Star TYC 4212-1074-1
- Camera 4, CCD 4, Column 1046 - Star HD 161178

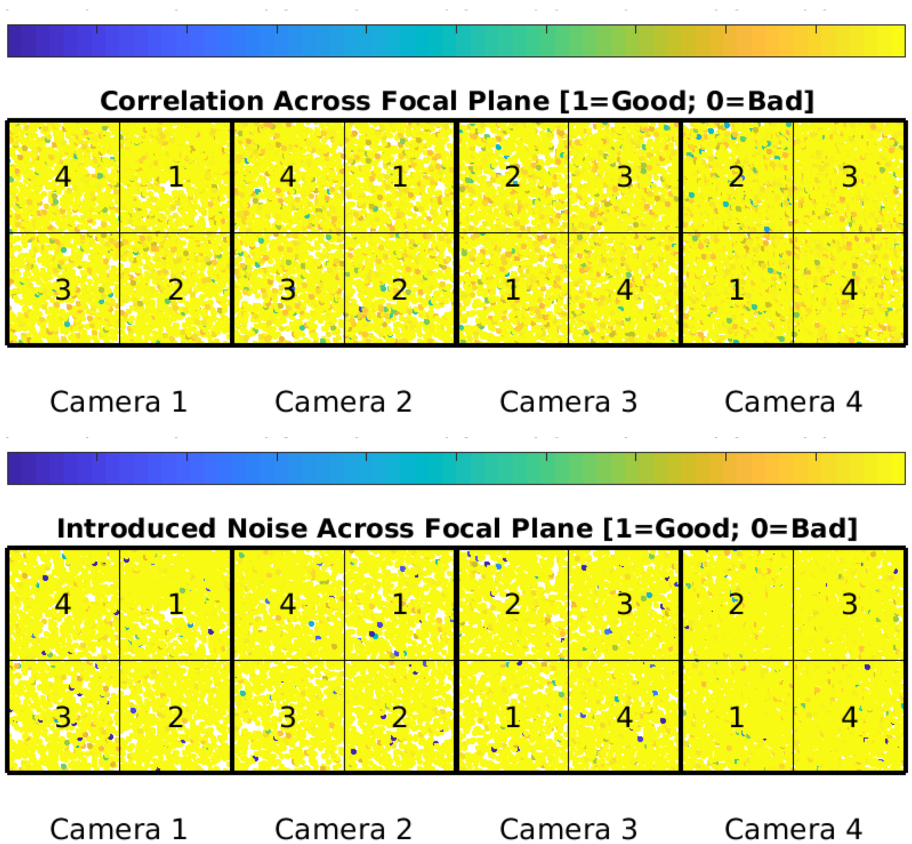

Figure 5: PDC residual correlation goodness metric (top panel) and PDC introduced noise goodness metric (bottom panel) for the two-minute cadence data. The metric values are shown on a focal plane map indicating the camera and CCD location of each target. The correlation goodness metric is calibrated such that a value greater than 0.8 means there is less than 10% mean absolute correlation between the target under study and all other targets on the CCD. The introduced noise metric is calibrated such that a value greater than 0.8 means the power in broad-band introduced noise is below the level of uncertainties in the flux values.

4 Pipeline Performance and Results

4.1 Light Curves and Photometric Precision

Figure 5 gives the PDC goodness metrics for the two-minute cadence data, with residual correlation goodness and introduced noise goodness shown on a scale between 0 (bad) and 1 (good). The performance of PDC is very good and generally uniform over most of the field of view. Figure 6 shows the achieved Combined Differential Photometric Precision (CDPP) at 1-hour timescales for all two-minute targets.

4.2 Transit Search and Data Validation

In Sector 50, the two-minute light curves of 19996 targets were subjected to the transit search in TPS. Of these, Threshold Crossing Events (TCEs) at the 7.1 σ level were generated for

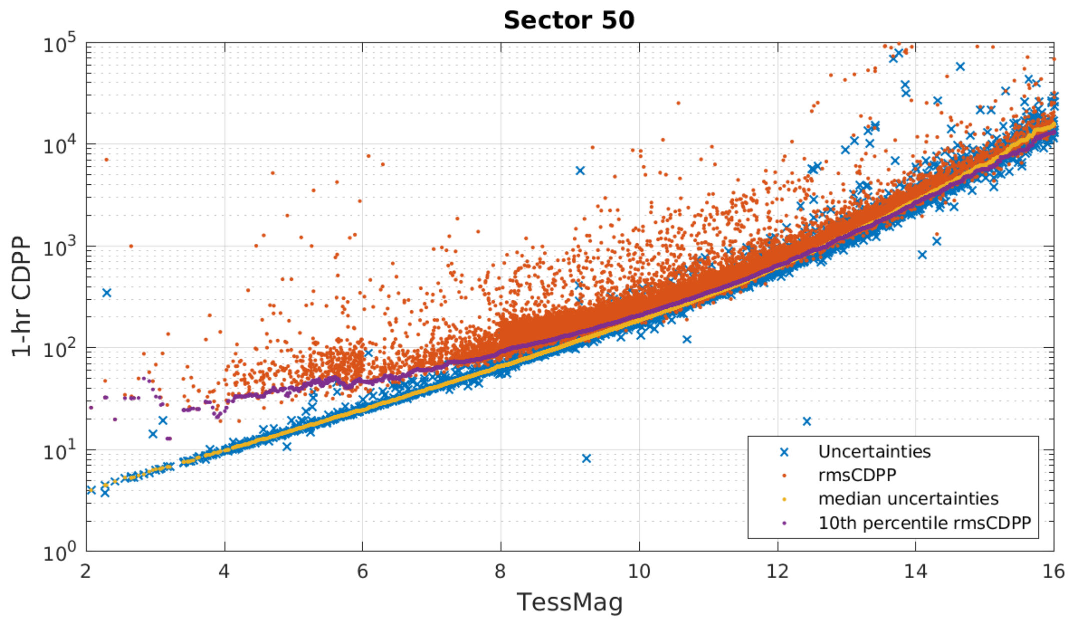

Figure 6: 1-hour CDPP. The red points are the RMS CDPP measurements for the 19996 light curves from Sector 50 plotted as a function of TESS magnitude. The blue x's are the uncertainties, scaled to 1-hour timescale. The purple curve is a moving 10th percentile of the RMS CDPP measurements, and the gold curve is a moving median of the 1-hr uncertainties.

732 targets.

We employed an iterative method when conducting the Sector 50 transit search. The top panel of Figure 7 shows the number of TCEs at a given cadence that exhibit a transit signal from an initial run of TPS. The 3-σ peaks were used to define de-emphasis weights for a second run of TPS, the results of which are shown in the bottom panel of Figure 7. The final set of TCEs and the results reported here are based on the second run of TPS. The values of the adopted de-emphasis weights are provided in the DV timeseries data products for targets with TCEs.

The top panel of Figure 8 shows the distribution of orbital periods for the final set of TCEs found in Sector 50. The bimodal nature of the period distribution is due to a large number of two-transit detections with periods ranging from 8 to 20 days, many of which are likely false positives. Two-transit TCEs can be identified with the `NTRANS` keyword in the headers of the dv-timeseries FITS files. The vertical histogram in the right panel of Figure 8 shows the distribution of transit depths derived from limb-darkened transiting planet model fits for TCEs. The model transit depths range down to the order of 100 ppm, but the bulk of the transit depths are considerably larger.

A search for additional TCEs in potential multiple planet systems was conducted in DV through calls to TPS. A total of 1024 TCEs were ultimately identified in the SPOC pipeline on 732 unique target stars. Table 2 provides a breakdown of the number of TCEs by target. Note that targets with large numbers of TCEs are likely to include false positives.

Table 2: Sector 50 TCE Numbers

Number of TCEs	Number of Targets	Total TCEs
1	494	494
2	193	386
3	37	111
4	7	28
5	1	5
–	732	1024

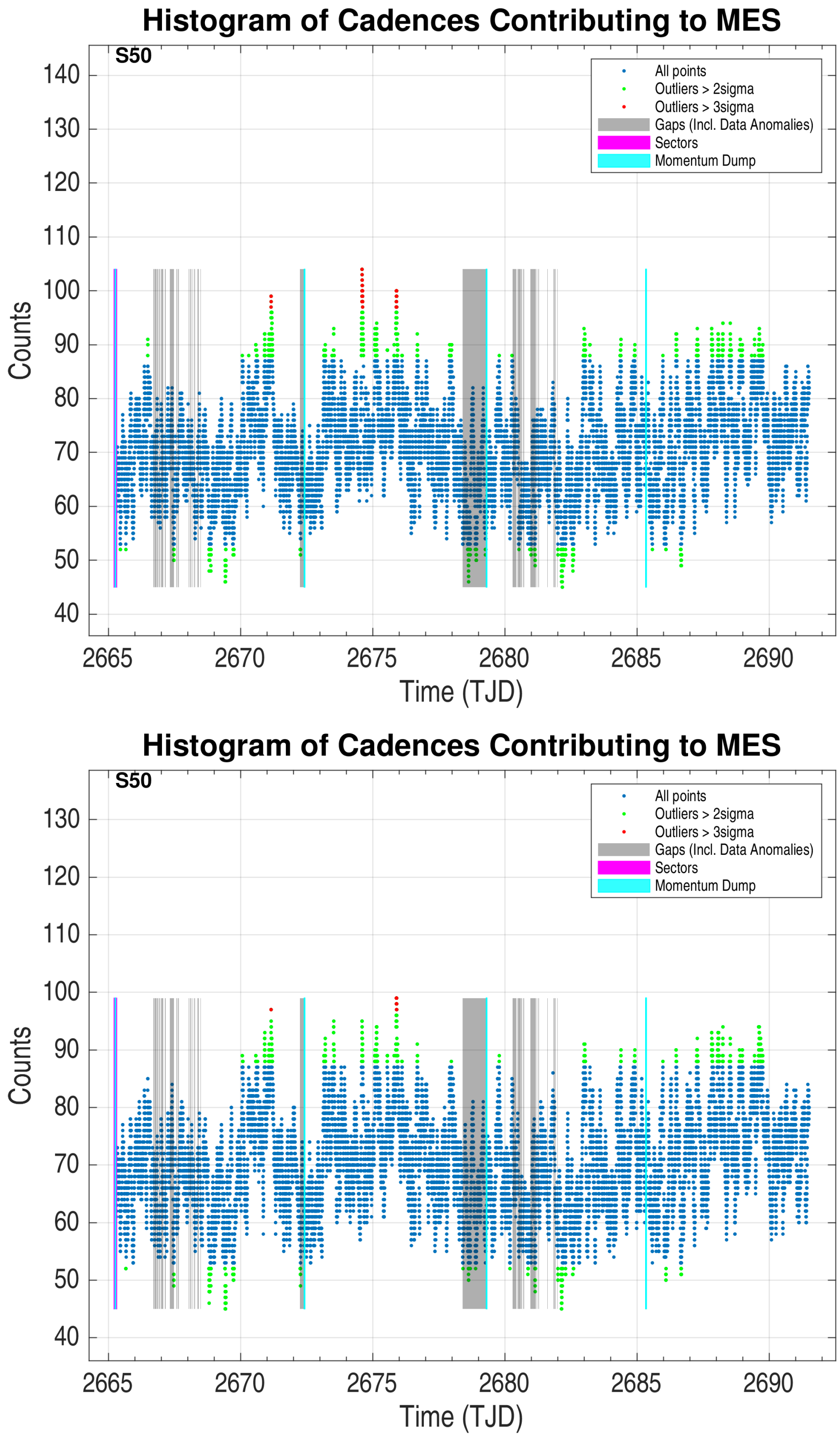

Figure 7: Top panel: Number of TCEs at a given cadence exhibiting a transit signal, based on an initial run of TPS. Any isolated peaks are caused by single events that result in spurious TCEs. These peaks were used to define de-emphasis weights that suppress problematic epochs for the transit detection statistics in a second iteration of TPS. Bottom panel: Results from the second run of TPS.

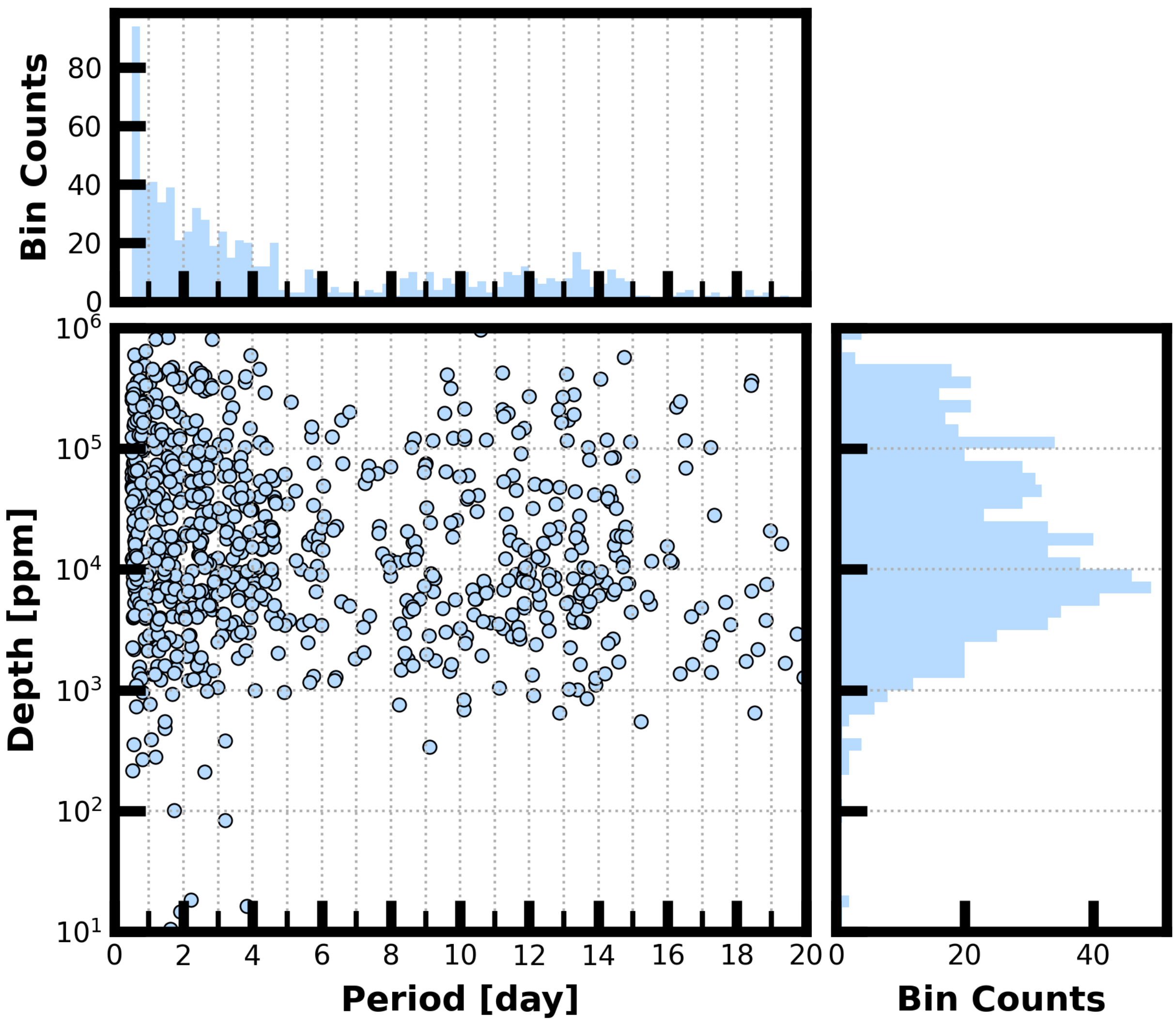

Figure 8: Lower Left Panel: Transit depth as a function of orbital period for the 1024 TCEs identified for the Sector 50 search. For enhanced visibility of long period detections, TCEs with orbital period <0.5 days are not shown. Reported depth comes from the DV limb-darkened transit fit depth when available, and the DV trapezoid model fit depth when 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.

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Acronyms and Abbreviation List

BTJD Barycentric-corrected TESS Julian Date

CAL Calibration Pipeline Module

CBV Cotrending Basis Vector

CCD Charge Coupled Device

CDPP Combined Differential Photometric Precision

COA Compute Optimal Aperture Pipeline Module

CSCI Computer Software Configuration Item

CTE Charge Transfer Efficiency

Dec Declination

DR Data Release

DV Data Validation Pipeline Module

DVA Differential Velocity Aberration

FFI Full Frame Image

FIN FFI Index Number

FITS Flexible Image Transport System

FOV Field of View

FPG Focal Plane Geometry model

KDPH Kepler Data Processing Handbook

KIH Kepler Instrument Handbook

KOI Kepler Object of Interest

MAD Median Absolute Deviation

MAP Maximum A Posteriori

MAST Mikulski Archive for Space Telescopes

MES Multiple Event Statistic

NAS NASA Advanced Supercomputing Division

PA Photometric Analysis Pipeline Module

PDC Pre-Search Data Conditioning Pipeline Module

PDC-MAP Pre-Search Data Conditioning Maximum A Posteriori algorithm

PDC-msMAP Pre-Search Data Conditioning Multiscale Maximum A Posteriori algorithm

PDF Portable Document Format

POC Payload Operations Center

POU Propagation of Uncertainties

PPA Photometer Performance Assessment

ppm Parts-per-million

PRF Pixel Response Function

RA Right Ascension

RMS Root Mean Square

SAP Simple Aperture Photometry

SDPDD Science Data Products Description Document

SNR Signal-to-Noise Ratio

SPOC Science Processing Operations Center

SVD Singular Value Decomposition

TCE Threshold Crossing Event

TESS Transiting Exoplanet Survey Satellite

TIC TESS Input Catalog

TIH TESS Instrument Handbook

TJD TESS Julian Date

TOI TESS Object of Interest

TPS Transiting Planet Search Pipeline Module

UTC Coordinated Universal Time

WCS World Coordinate System

XML Extensible Markup Language