# TESS Data Release Notes:
## Sector 31, DR47

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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
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[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 31 observations include physical orbits 69 and 70 of the spacecraft around the Earth. Data collection was paused for 1.40 days between the orbits to download data. A star tracker anomaly occurred at UTC 2020-11-16 10:37, which led to the instrument being turned off. As a result, the data collection period in orbit 70 ended 2.08 days earlier than scheduled; there is no other effect on the data. The cameras were turned on and returned to normal operations on 2020-11-20, at the beginning of Sector 32. In total, there are 24.03 days of science data collected in Sector 31.

Table 1: Sector 31 Observation times

|  | UTC | TJD[a] | Cadence # |
|---|---|---|---|
| Orbit 69 start | 2020-10-22 00:11:12 | 2144.50927 | 660279 |
| Orbit 69 end | 2020-11-03 22:51:11 | 2157.45371 | 669599 |
| Orbit 70 start | 2020-11-05 08:31:11 | 2158.85648 | 670609 |
| Orbit 70 end | 2020-11-16 10:37:11 | 2169.94398 | 678592 |

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

The spacecraft was pointing at RA (J2000): 57.6357°; Dec (J2000): −35.7835°; Roll: 201.2334°. See the TESS project Sector 31 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 31 observation page and the observations status page.

## 1.1 Notes on Individual Targets

There are no issues with missing light curves or clipped apertures in the 20-second data products.

For the 2-minute cadence data, four bright stars (Tmag $\lesssim$ 1.8) with large pixel stamps were not processed in the photometric pipeline. 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 328228602, 38877693, 325685265, and 92252969.

Twelve target stars (766092864, 766018849, 651559663, 651236341, 651236339, 649766486, 630222973, 44678216, 321087975, 321055375, 311092847, 167602316) are blended with comparably bright stars—the contaminating flux for these objects is very large, and the resulting photometry for such targets is expected to be unreliable.

One target star (651379982, Tmag = 6.07) lies within the same pixel of a very bright star (88523071, Tmag = 3.45). In this case, no optimal aperture was assigned. A target pixel file with original and calibrated pixel data is provided, but no light curve was produced.

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[3] https://tess.mit.edu/observations/sector-31
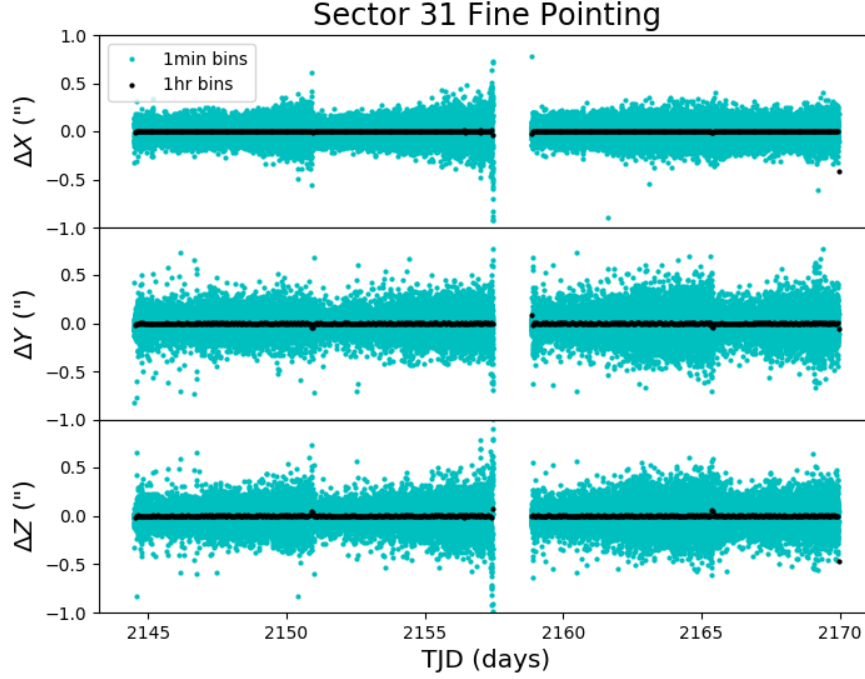[4] https://heasarc.gsfc.nasa.gov/docs/tess/status.html

Figure 1: The delta-quaternions from each camera have been converted to spacecraft frame, binned to 1 minute and 1 hour, and averaged across cameras. Long-term trends (such as those caused by differential velocity aberration) have also been removed. The $\Delta X/\Delta Y$ directions represent offsets along the the detectors' rows/columns, while the $\Delta Z$ direction represents spacecraft roll.

## 1.2  Spacecraft Pointing and Momentum dumps

Camera 1 suffered from strong scattered light signals at the end of orbit 69 and orbit 70, and so Camera 4 alone was used for guiding during this sector. A single momentum dump was performed halfway through each orbit. 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.

In Sector 31, the Moon introduces a strong glint in Camera 1 at the end of orbit 69, followed by scattered light signals in all cameras caused by the Earth. Due to the star tracker anomaly, no data was not taken during periods of high scattered light in orbit 70.
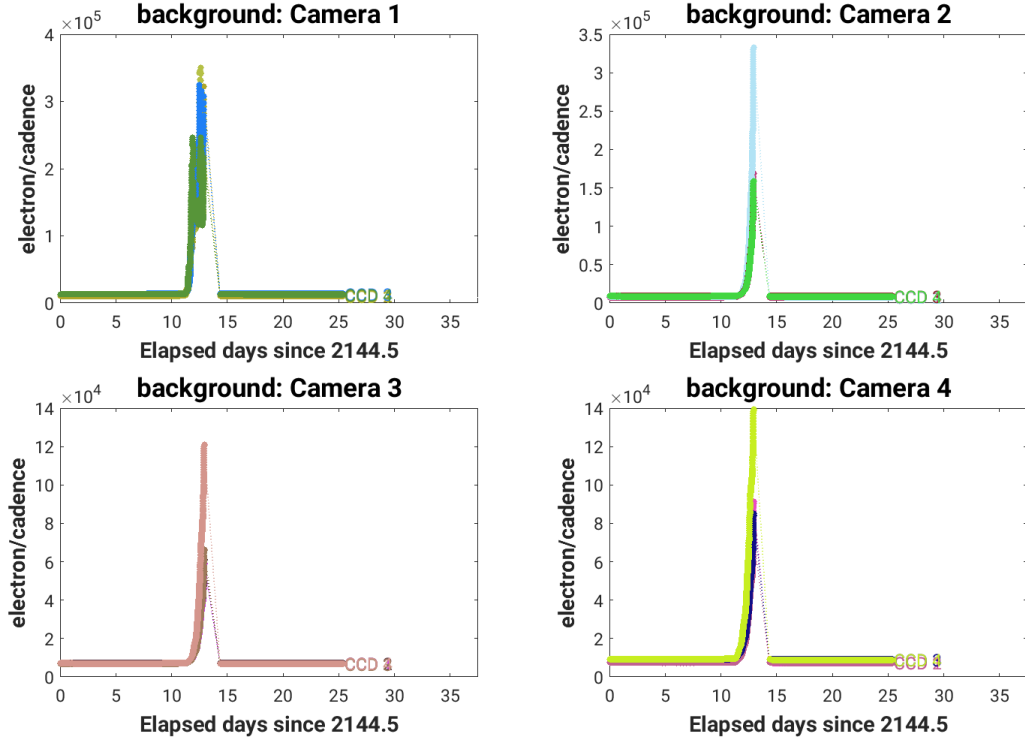
2

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.

# 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 31: bits 1, 2, and 9 (Attitude Tweak, Safe Mode, and Discontinuity).

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.

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.
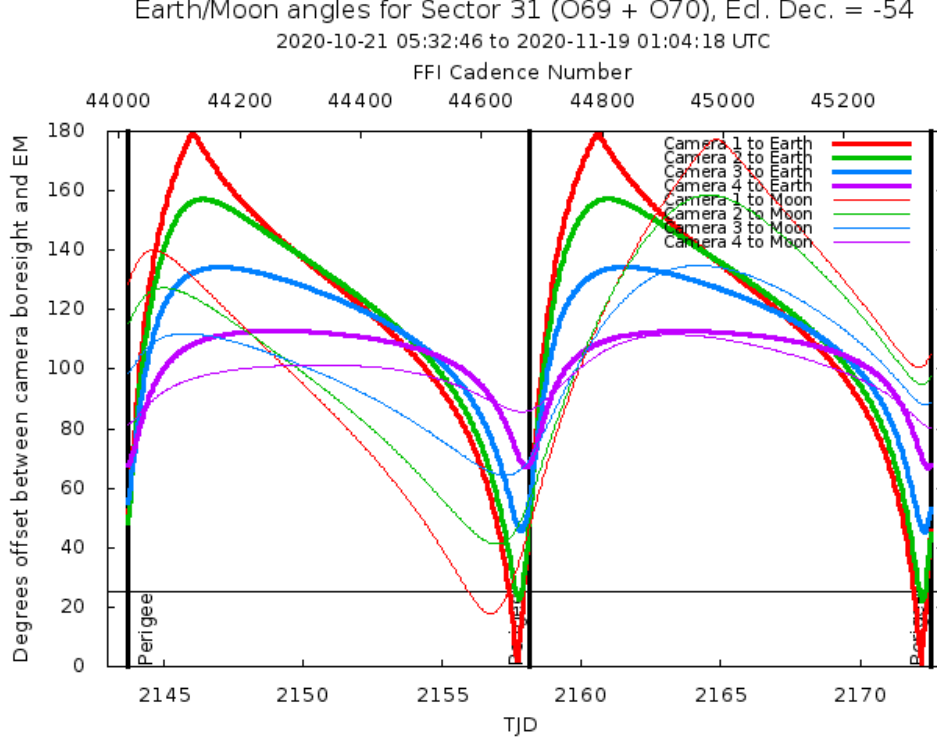
Figure 3: Angle between the four camera boresights and the Earth/Moon as a function of time. When the Earth is within $\sim 25°$ of a camera's boresight, transiting planet searches may be compromised by high levels of scattered light. At larger angles, up to $\sim 35°$, scattered light patterns and complicated 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 $\sim 35°$. 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 bit 8 (Manual Exclude) are ignored by PDC, TPS, and DV for cotrending and transit searches. In Sector 31, 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.

In Sector 31, the predicted stray light flag (bit 12, value 2048) is disabled for the 2-minute and 20-second data products. Instead, the scattered light exclude flag (bit 13, value 4096) identifies cadences at which individual targets are affected by scattered light. The predicted stray light flag (bit 12) continues to be 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.

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
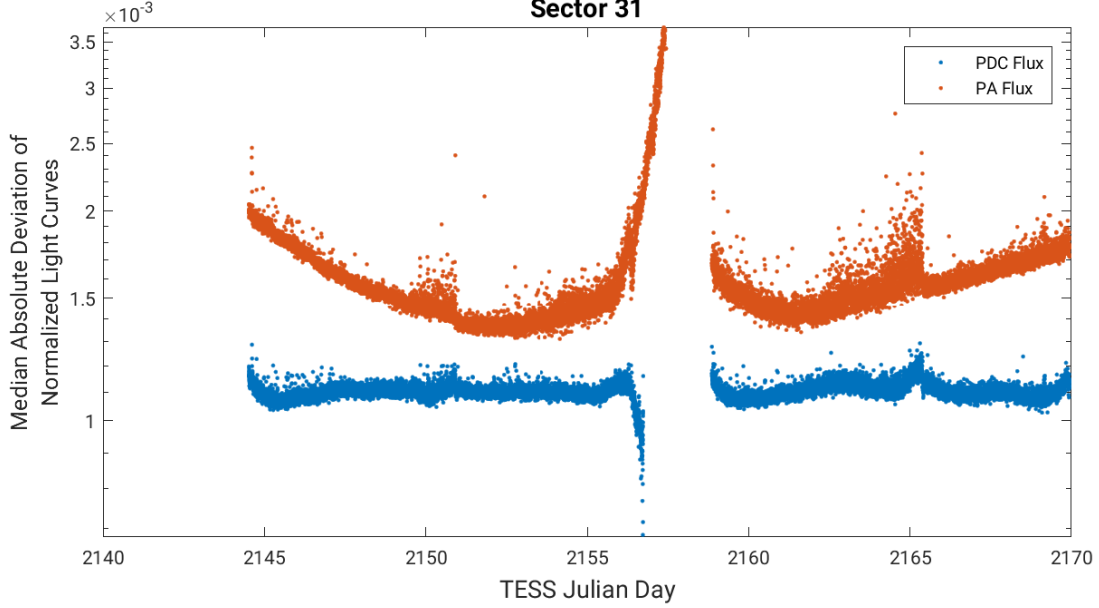
Figure 4: Median absolute deviation (MAD) for the two-minute cadence data from Sector 31, showing the performance of the cotrending after identifying Manual Exclude data quality flags. The MAD is calculated in each cadence across stars with flux variations less than 1% for both the PA (red) and PDC (blue) 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.

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, 12, and 15 (Course Point, Reaction Wheel Desaturation Events, 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

## 3.1 Smear Correction Issues

The following column was impacted by a bright star in the science frame, and/or upper buffer rows, which bleeds into the upper serial register resulting in an overestimated smear correction.
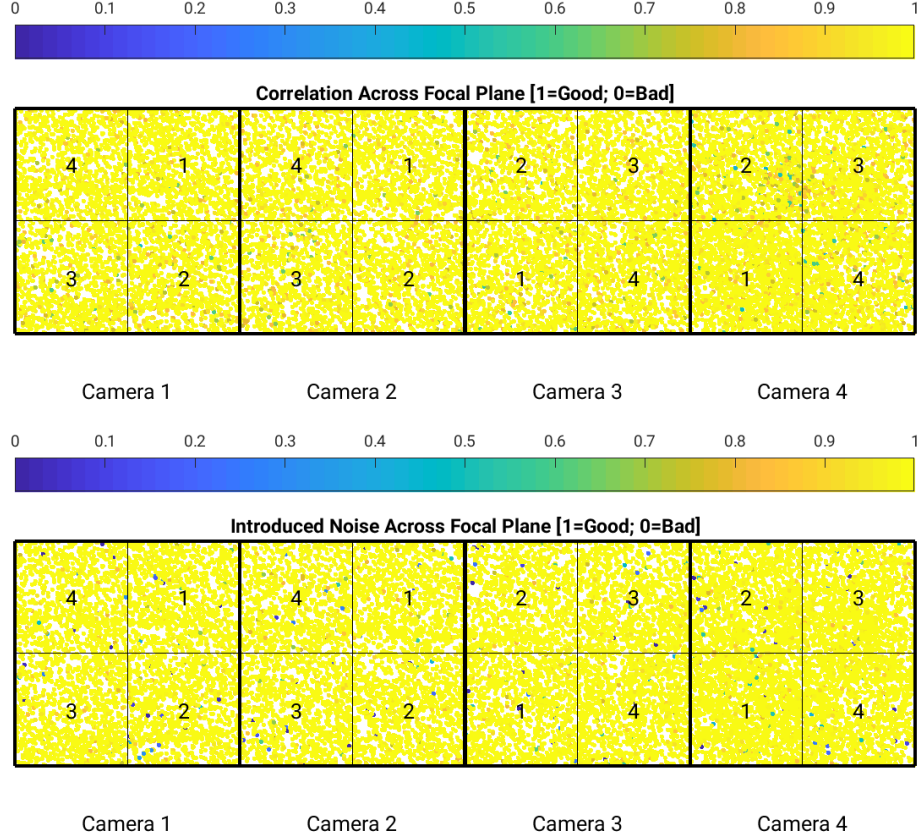
- Camera 3, CCD 1, Column 536, Star HD 32400

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.

## 3.2 Fireflies and Fireworks

Table 2 lists all firefly and fireworks events for Sector 31. These phenomena are small, spatially extended, comet-like features in the images—created by sunlit particles in the camera FOV—that may appear one or two at a time (fireflies) or in large groups (fireworks). See the TESS Instrument Handbook for a more complete description.

# 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
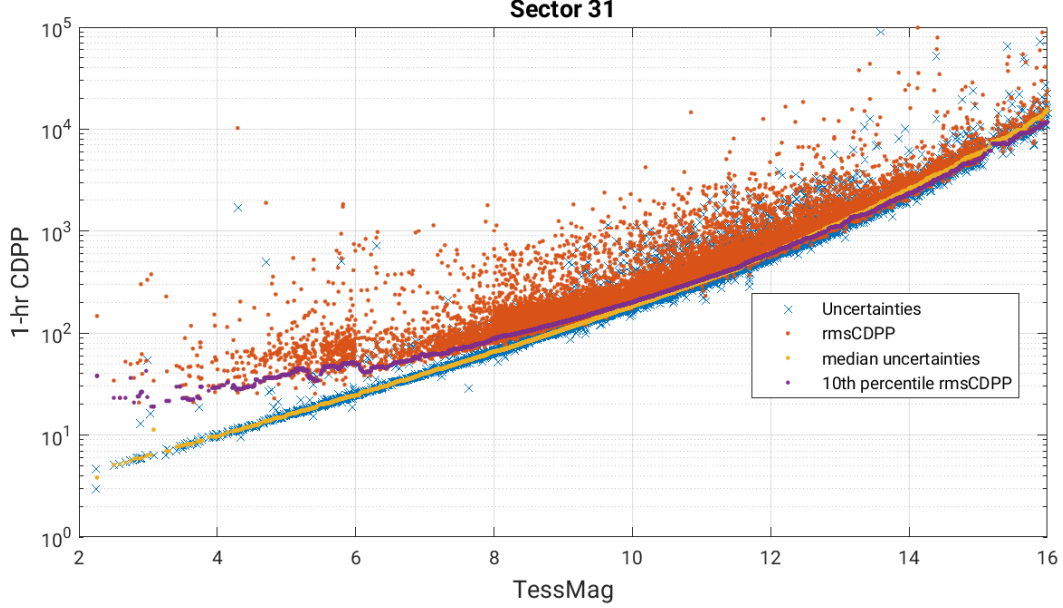
Figure 6: 1-hour CDPP. The red points are the RMS CDPP measurements for the 19,995 light curves from Sector 31 plotted as a function of TESS magnitude. The blue x's are the uncertainties, scaled to 1-hour timescale. The purple curve is a moving 10th percentile of the RMS CDPP measurements, and the gold curve is a moving median of the 1-hr uncertainties.

Table 2: Sector Fireflies and Fireworks

| FFI Start | FFI End | Cameras | Description |
|---|---|---|---|
| 2020296053912 | 2020296054912 | 1 | Firefly |
| 2020296183912 | 2020296184912 | 2,3,4 | Fireflies |
| 2020297205912 | 2020297210912 | 2,3 | Firefly |
| 2020298201912 | 2020298203912 | 1,2,3 | Fireworks |

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 31, the two-minute light curves of 19,995 targets were subjected to the transit search in TPS. Of these, Threshold Crossing Events (TCEs) at the $7.1\,\sigma$ level were generated for 773 targets.

We employed an iterative method when conducting the Sector 31 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-$\sigma$ 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 31. 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 1064 TCEs were ultimately identified in the SPOC pipeline on 773 unique target stars. Table 3 provides a breakdown of the number of TCEs by target. Note that targets with large numbers of TCEs are likely to include false positives.

Note that for those targets observed in both Year 1 and Year 3, Year 3 processing was done using TIC 8.1 while TIC 7 was used for Year 1 processing; this may result in differences in results for certain targets. Differences for some crowded and/or dim targets may also result from the background correction algorithm update introduced in Sector 27 (see DRN38).

Table 3: Sector 31 TCE Numbers

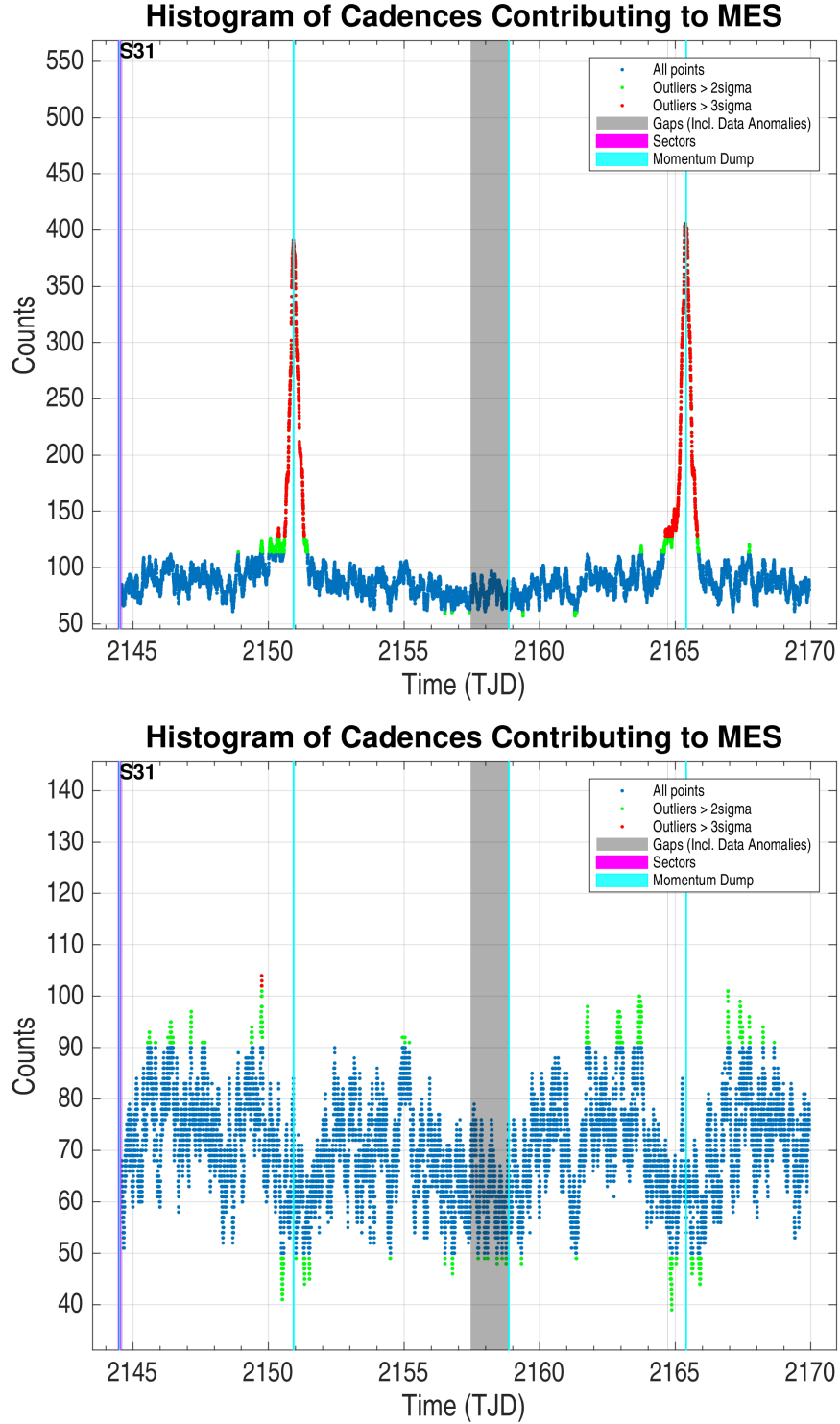| Number of TCEs | Number of Targets | Total TCEs |
|:---:|:---:|:---:|
| 1 | 535 | 535 |
| 2 | 191 | 382 |
| 3 | 42 | 126 |
| 4 | 4 | 16 |
| 5 | 1 | 5 |
| – | 773 | 1064 |

**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.
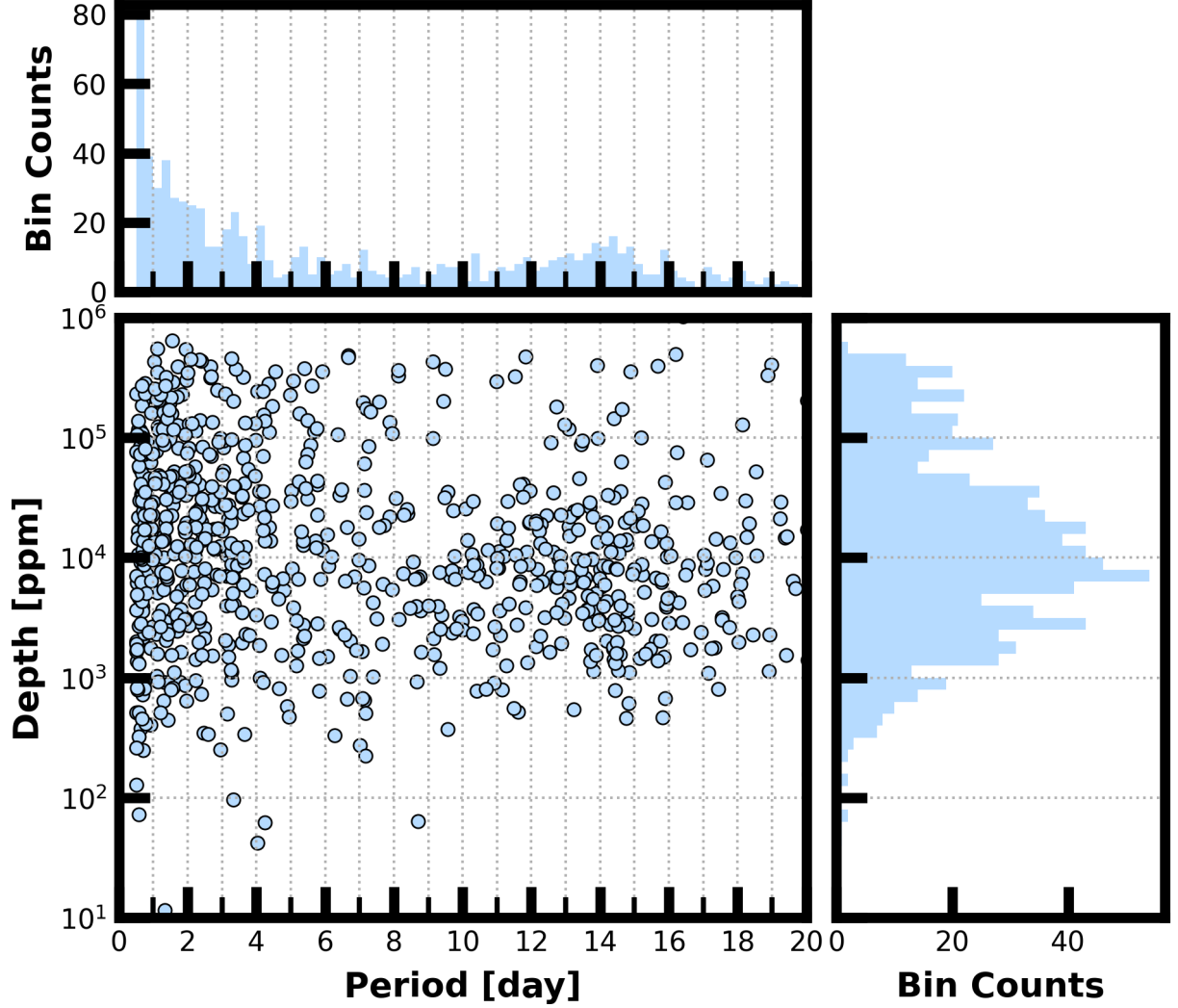
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Figure 8: Lower Left Panel: Transit depth as a function of orbital period for the 1064 TCEs identified for the Sector 31 search. For enhanced visibility of long period detections, TCEs with orbital period <0.5 days are not shown. Reported depth comes 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.

# References

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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

**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