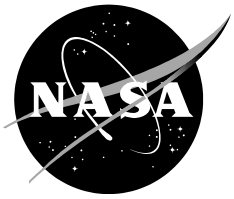
NASA/TM—2019—220500



TESS Data Release Notes:
Sector 20, DR27

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February 21, 2020

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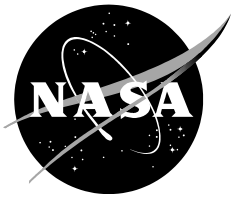

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Acknowledgements

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, 2017).[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.pdf
[2] https://archive.stsci.edu/kepler/manuals/KSCI-19081-002-KDPH.pdf

1 Observations

TESS Sector 20 observations include physical orbits 47 and 48 of the spacecraft around the Earth. Data collection was paused for 1.53 days between the orbits to download data. An instrument reset also occurred in orbit 48—no data were collected for two minutes between TJD 1865.49753 and 1865.50030. In total, there are 24.79 days of science data collected in Sector 20.

Table 1: Sector 20 Observation times

	UTC	TJD[a]	Cadence #
Orbit 47 start	2019-12-24 23:55:23	1842.49831	442831
Orbit 47 end	2020-01-06 08:31:23	1854.85664	451729
Orbit 48 start	2020-01-07 21:19:23	1856.38997	452833
Orbit 48 end	2020-01-20 07:41:22	1868.82191	461784

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

The spacecraft was pointing at RA (J2000): 129.3867°; Dec (J2000): +75.2520°; Roll: −25.4311°. Two-minute cadence data were collected for 20,000 targets, and full frame images were collected every 30 minutes. See the TESS project Sector 20 observation page[3] for the coordinates of the spacecraft pointing and center field-of-view of each camera, as well as the detailed target list. Fields-of-view for each camera and the Guest Investigator two-minute target list can be found at the TESS Guest Investigator Office observations status page[4].

A number of important changes were made in Sector 20, which are described in detail below. For ease of reference, here is a brief summary:

- The sizes of photometric apertures for bright targets were slightly increased (§4).
- "Scattered light" quality flags are now determined on a target-by target basis (§2).
- New flags related to the target-by-target "Scattered light" flags have been added (§2).

1.1 Notes on Individual Targets

Three bright stars (Tmag $\lesssim$ 1.8) with large pixel stamps were not processed in the photometric pipeline. Target pixel files with raw data are provided, but no light curves were produced. The affected TIC IDs are 423088367, 229540730, and 303256075.

Two target stars (341873045 and 471011933) 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 (802622517) is closely blended (within 0.5 arcseconds) with three other comparably bright stars (471012682, 341573000 and 802622516). In this case, the assigned aperture is disjoint and the resulting photometry is unreliable.

[3] https://tess.mit.edu/observations/sector-20

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

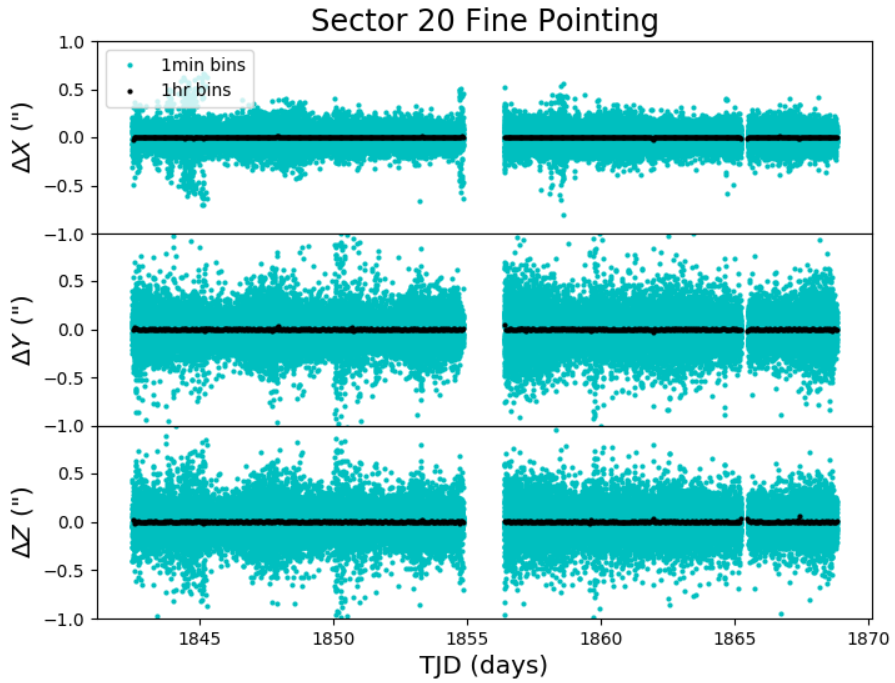

Figure 1: Guiding corrections based on spacecraft fine pointing telemetry. The delta-quaternions from each camera have been converted to spacecraft frame, binned to 1 minute and 1 hour, and averaged across cameras. Long-term trends (such as those caused by differential velocity aberration) have also been removed. The ΔX/ΔY directions represent offsets along the the detectors' rows/columns, while the ΔZ direction represents spacecraft roll.

1.2 Spacecraft Pointing and Momentum dumps

Camera 1 and Camera 4 were both used for guiding in orbit 47; Camera 4 alone was used for guiding in orbit 48. The reaction wheel speeds were reset with momentum dumps every 5.35 days (orbit 47) or 5.5 days (orbit 48). 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 20, the Moon passes through the field of view of Camera 1 at the start of orbit 48, saturating the detectors. In Sector 20, we have added new data anomaly flags to characterize the different ways that the scattered light can affect the data—see §2 for details.

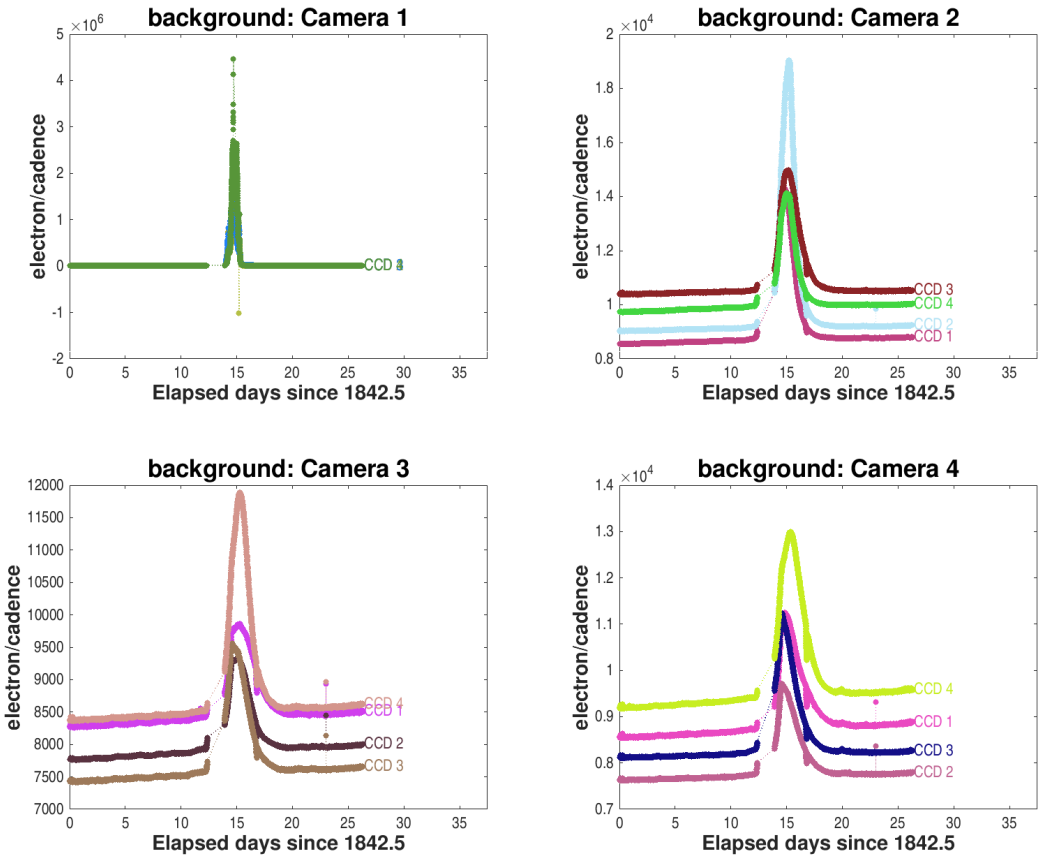

Figure 2: Median background flux across all targets on a given CCD in each camera. The changes are caused by variations in the orientation and distance of the Earth and Moon.

2 Data Anomaly Flags

There are two new data quality flags introduced in Sector 20, as well as a major change for the use of the "Scattered light flag" (bit 13, value 4096) introduced in Sector 14.

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 as a result, not every target on a CCD is affected at the same time. Starting in Sector 20, each individual target now can have a unique set of cadences marked with the "Scattered light flag." Cadences are flagged for periods of time where the measured background rises above the baseline background level by a factor of two and where the measured background exceeds a specified fraction of the target flux (0.25 in this sector).

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

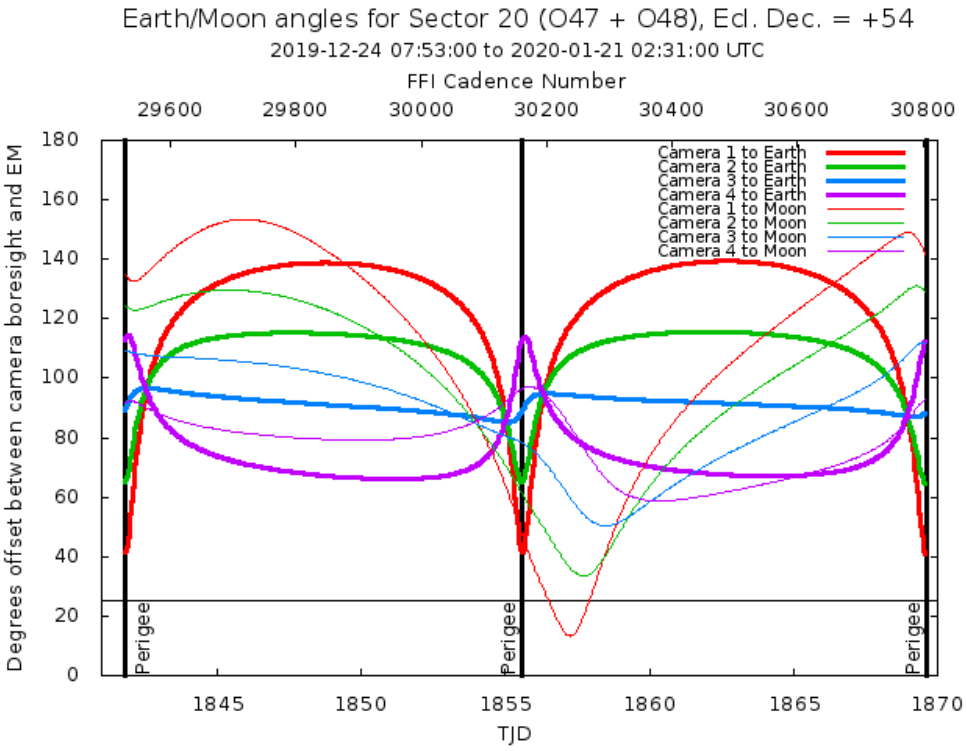

Figure 3: Angle between the four camera boresights and the Earth/Moon as a function of time. When the Earth is within $\sim 25°$ of a camera's boresight, transiting planet searches may be compromised by high levels of scattered light. At larger angles, up to $\sim 35°$, scattered light patterns and complicated 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.

error correction can be applied at these times. A new data quality flag has been assigned to mark this situation, bit 16 (value 32768, "Insufficient Targets for Error Correction Exclude").

In Sector 20, the predicted stray light flag (bit 12, value 2048) is disabled for the 2-minute 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.

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 20: bits 1, 2, 7, 9, and 11 (Attitude Tweak, Safe Mode, Cosmic Ray in Aperture, Discontinuity, Cosmic Ray in Collateral Pixel).

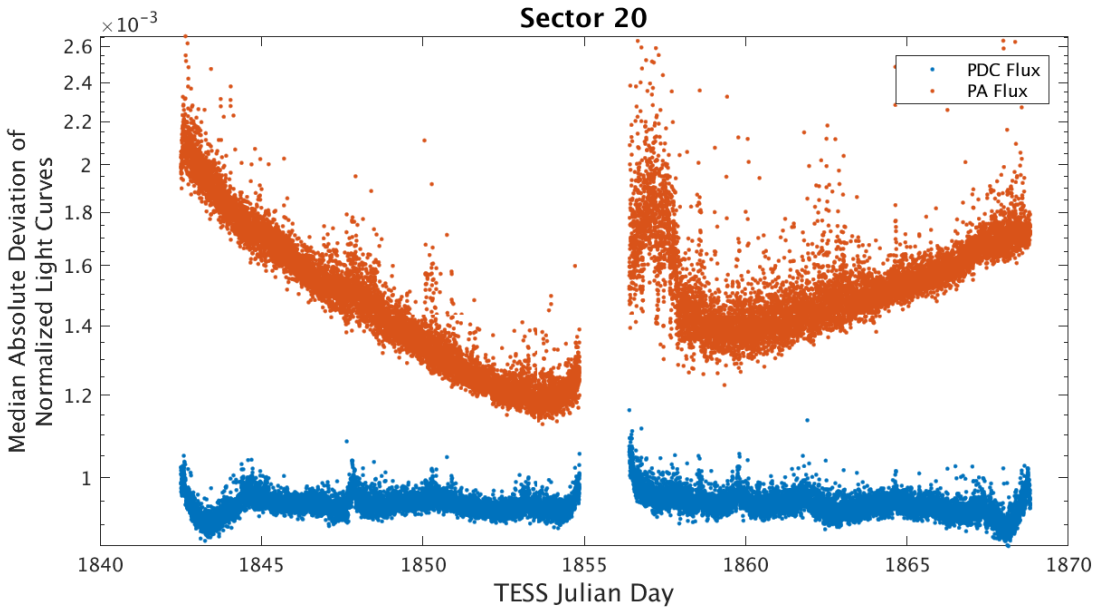

Figure 4: Median absolute deviation (MAD) for the 2-minute cadence data from Sector 20, showing the performance of the cotrending after identifying Manual Exclude data quality flags. The MAD is calculated in each cadence across stars with flux variations less than 1% for both the PA (red) and PDC (blue) 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 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.

Cadences marked with bit 8 (Manual Exclude) are ignored by PDC, TPS, and DV for cotrending and transit searches. In Sector 20, these cadences were identified using spacecraft telemetry from the fine pointing system. All cadences with pointing excursions >7 arcseconds (∼0.3 pixel) were flagged for manual exclude. See Figure 4 for an assessment of the performance of the cotrending based on the final set of manual excludes.

FFIs were only marked with bits 3, 6 and 12 (Course Point, Reaction Wheel Desaturation Events and Straylight). 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 4, CCD 2, Column 2002, Star Eta Draconis

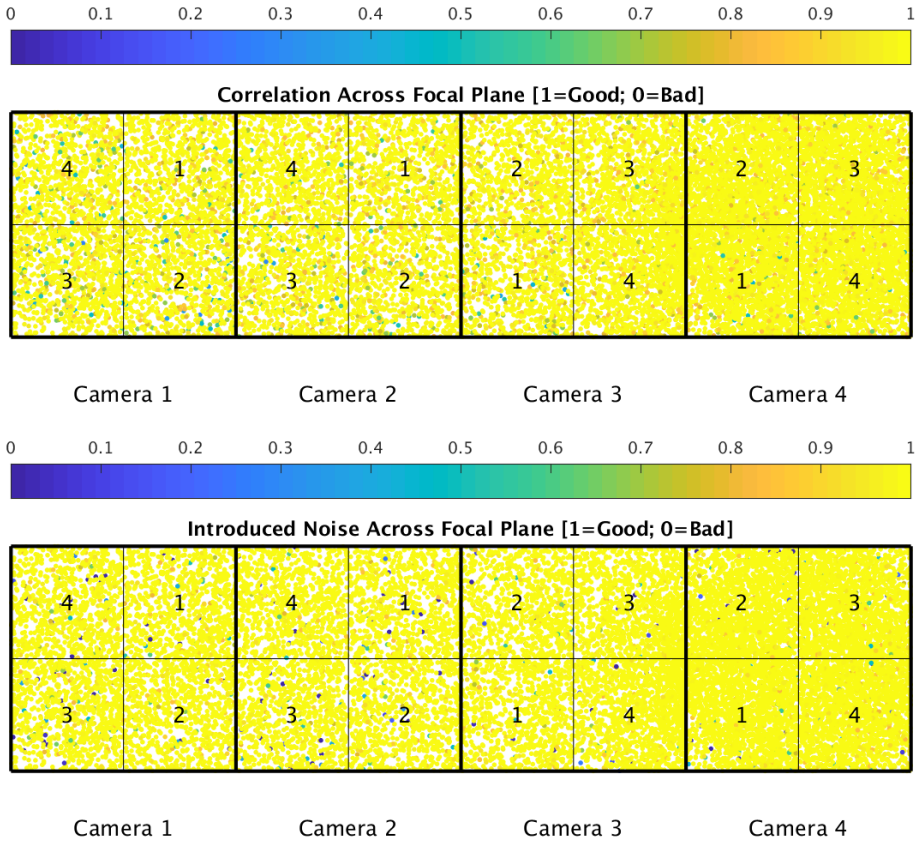

Figure 5: PDC residual correlation goodness metric (top panel) and PDC introduced noise goodness metric (bottom panel). The metric values are shown on a focal plane map indicating the camera and CCD location of each target. The correlation goodness metric is calibrated such that a value greater than 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 20. These phenomena are small, spatially extended, comet-like features in the images—created by sunlit particles in the

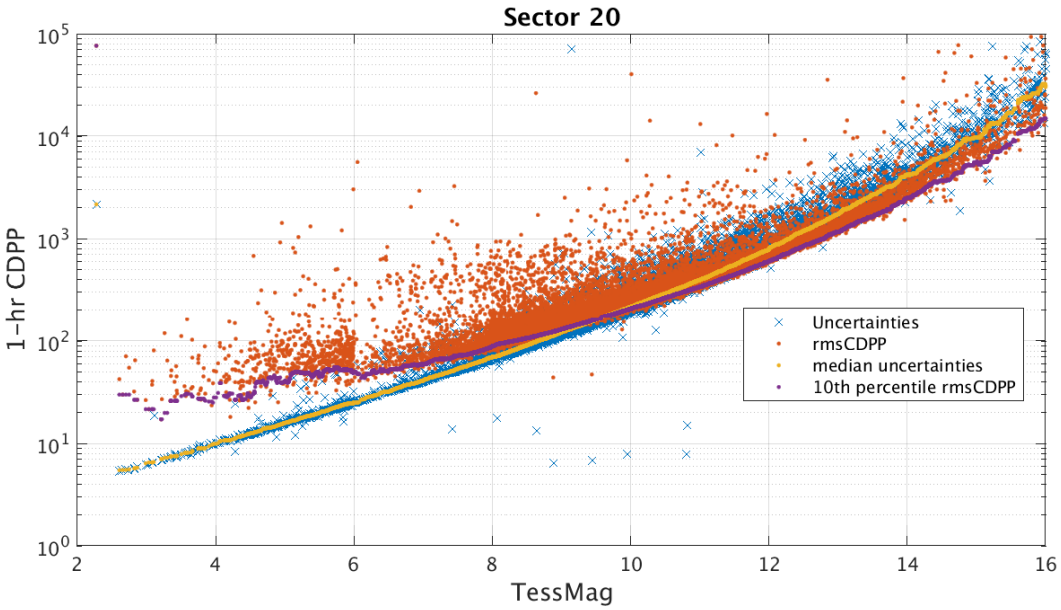

Figure 6: 1-hour CDPP. The red points are the RMS CDPP measurements for the 19997 light curves from Sector 20 plotted as a function of TESS magnitude. The blue x's are the uncertainties, scaled to 1-hour timescale. The purple curve is a moving 10th percentile of the RMS CDPP measurements, and the gold curve is a moving median of the 1-hr uncertainties.

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.

Table 2: Sector Fireflies and Fireworks

FFI Start	FFI End	Cameras	Description
2020002185923	2020002192923	1	Fireflies
2020005165923	2020005172923	3	Firefly

3.3 Corrections to Data Product Timestamps

In Sector 20, the the FFI timestamps have been adjusted for the 0.5 second staggered readouts of the four cameras and the 0.02 second staggered readouts for individual CCDs within a camera. As a reminder, TSTART and TSTOP in the FFIs of previous sectors need to be adjusted for the readout offsets of each camera—see DRN 25 for additional details.

An issue was also discovered with the assigned timestamps of the previously released data products. The reported times are too large by 2 seconds. The issue was caused by an off-by-one error in ground system software that identifies the timestamps of individual two second exposures.

The Sector 20 data products have updated and accurate timestamps. Future data releases will include reprocessed data from Sectors 1 to 19 with corrected timestamps. Until

these reprocessed products are available, timestamps from Sectors 1–19 can be corrected by subtracting 2 seconds.

Two other small adjustments were made to the timestamps. The start times of integrations for every 2 minute and 30 minute cadence were shifted forward by 31 milliseconds, and the end times were shifted forward by 11 milliseconds. These offsets correct for effects in the focal plane electronics that were not accounted for in previous data releases.

Until reprocessed data products for Sectors 1–19 are available, the timestamps of FFIs from previous data releases can be corrected by adding these values to the appropriate start and stop times in the image headers. Two-minute data products report the TJD at midexposure, and so should be corrected by adding 21 milliseconds to the timestamps. Note that the correction only applies to the timestamps themselves; the reported exposure times in data product headers and flux values (electrons per second) are correct, as they already account for the 20 millisecond relative offset between start and stop times discussed here.

4 Pipeline Performance and Results

4.1 Light Curves and Photometric Precision

Figure 5 gives the PDC goodness metrics for residual correlation and introduced noise 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 targets.

In Sector 20, the photometric apertures for targets with Tmag < 11 were slightly increased. This change most noticeably affects the light curves of saturated stars, which had higher flux losses during periods of increased pointing jitter using the smaller apertures.

4.2 Transit Search and Data Validation

In Sector 20, the light curves of 19997 targets were subjected to the transit search in TPS. Of these, Threshold Crossing Events (TCEs) at the $7.1\,\sigma$ level were generated for 675 targets.

We employed an iterative method when conducting the Sector 20 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 deemphasis 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 deemphasis 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 20. 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 972 TCEs were ultimately identified in the SPOC pipeline

on 675 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.

Table 3: Sector 20 TCE Numbers

Number of TCEs	Number of Targets	Total TCEs
1	436	436
2	192	384
3	36	108
4	11	44
–	675	972

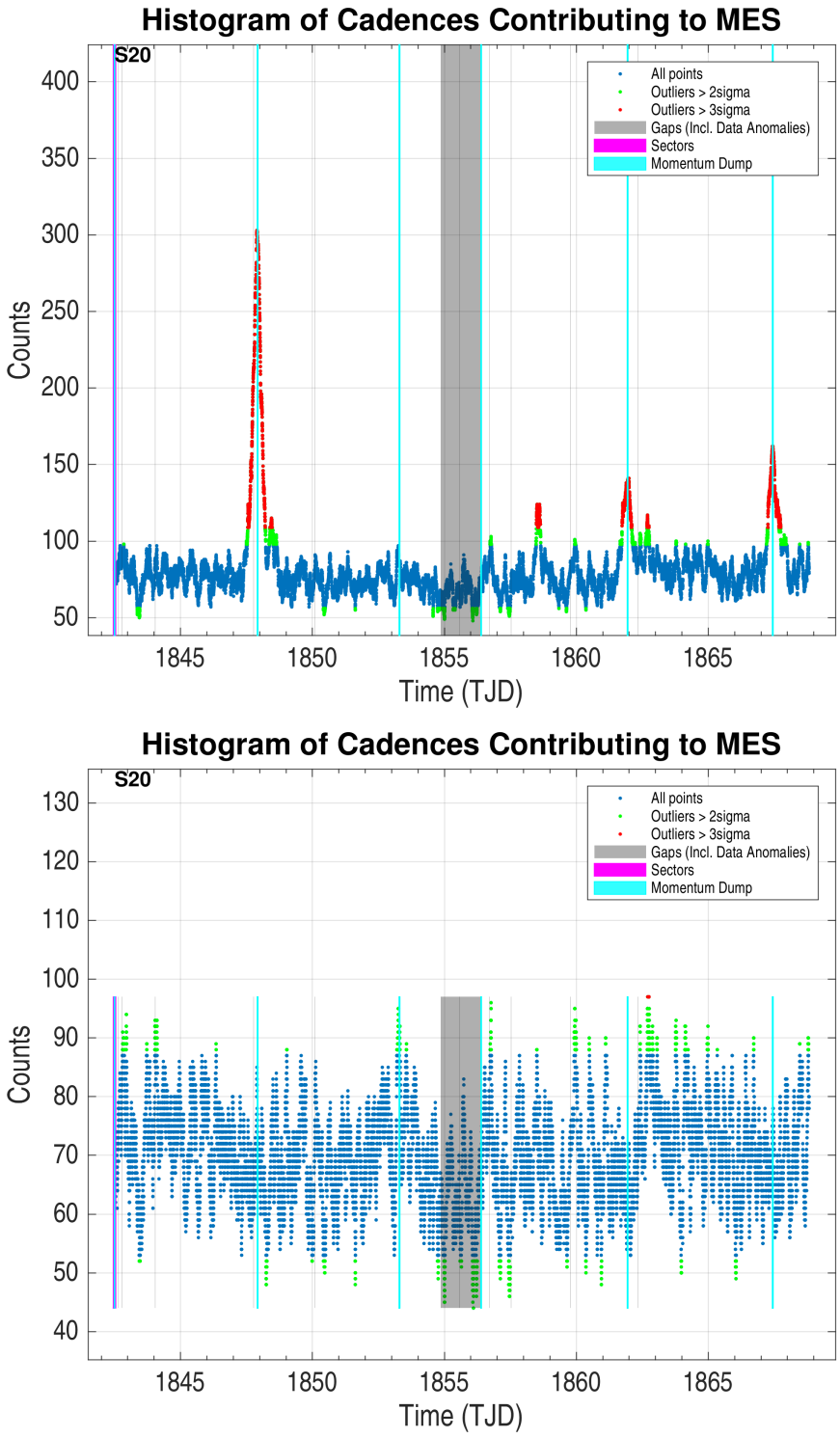

Figure 7: Top panel: Number of TCEs at a given cadence exhibiting a transit signal, based on an initial run of TPS. Any isolated peaks are caused by single events that result in spurious TCEs. These peaks were used to define deemphasis weights that suppress problematic epochs for the transit detection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

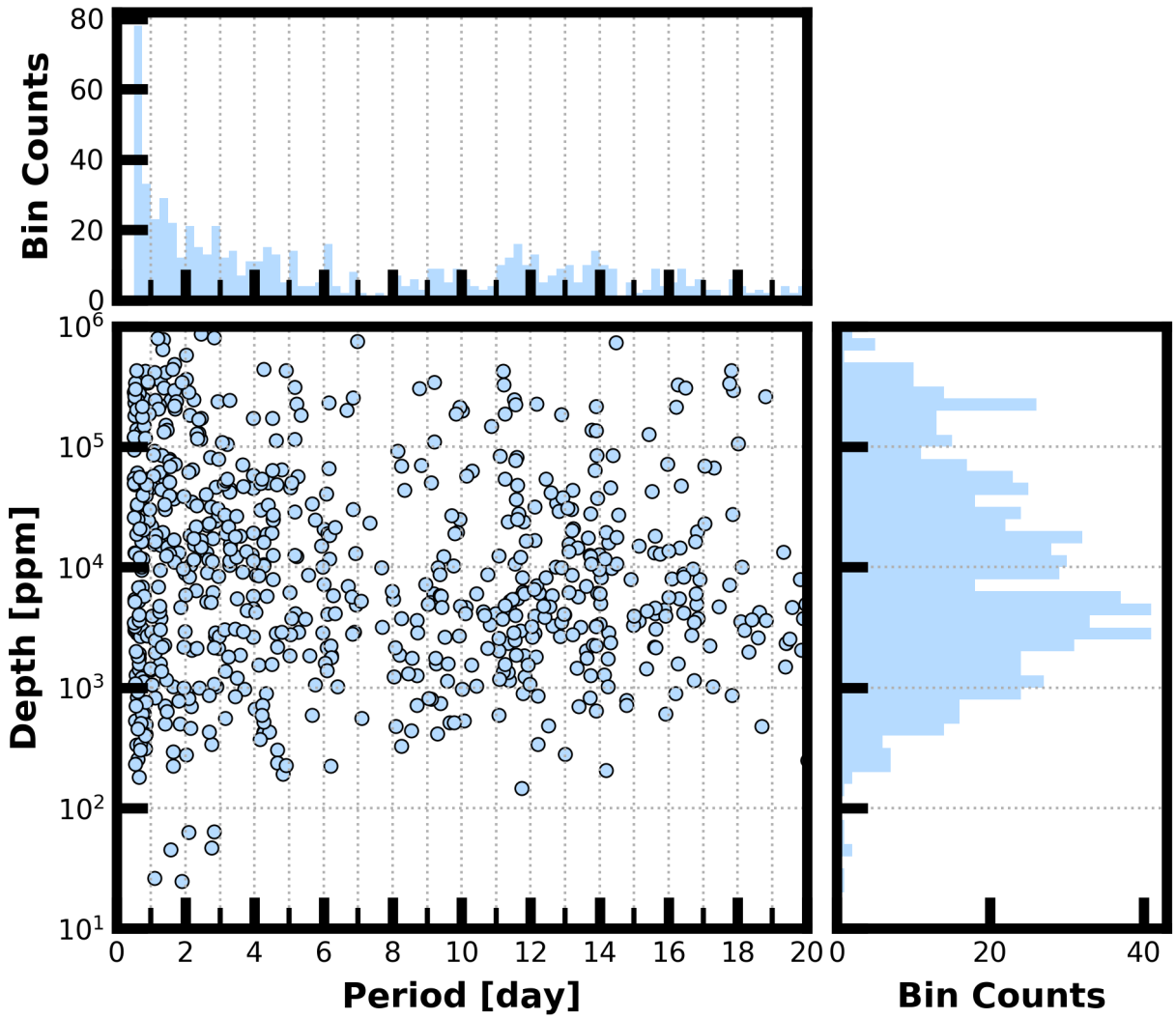

Figure 8: Lower Left Panel: Transit depth as a function of orbital period for the 972 TCEs identified for the Sector 20 search. For enhanced visibility of long period detections, TCEs with orbital period <0.5 days are not shown. Reported depth comes from the DV limb darkened transit fit depth when available, 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

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