TESS Data Release Notes: Sector 6, DR8

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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 Product 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.

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This report is available in electronic form at

https://archive.stsci.edu/tess/

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1 Observations

TESS Sector 6 observations include physical orbits 19 and 20 of the spacecraft around the Earth. The first $\sim$3 days of orbit 19 were used to collect calibration data for measuring the pixel-response function of the cameras under the improved pointing system (introduced in Sector 4). Data collection was paused for 1.09 days during perigee passage while downloading data. In total, there are 20.68 days of science data collected in Sector 6.

Table 1: Sector 6 Observation times

<table>
<thead>
<tr>
<th>UTC</th>
<th>TJD$^a$</th>
<th>Cadence #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit 19</td>
<td>2018-12-12 17:05:01</td>
<td>1465.21262</td>
</tr>
<tr>
<td>Data Collection Start</td>
<td>2018-12-15 18:27:38</td>
<td>1468.26998</td>
</tr>
<tr>
<td>Orbit 19 end</td>
<td>2018-12-24 12:27:37</td>
<td>1477.01998</td>
</tr>
<tr>
<td>Orbit 20 start</td>
<td>2018-12-25 14:41:37</td>
<td>1478.11304</td>
</tr>
<tr>
<td>Orbit 20 end</td>
<td>2019-01-06 13:01:37</td>
<td>1490.04359</td>
</tr>
</tbody>
</table>

$^a$ TJD = TESS JD = JD - 2,457,000.0

The spacecraft was pointing at RA (J2000): $92.0096^\circ$; Dec (J2000): $-30.5839^\circ$; Roll: $178.6367^\circ$. Two-minute cadence data were collected for 20,000 targets, and full frame images were collected every 30 minutes. See the TESS project Sector 6 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 with all two-minute targets can be found at the TESS Guest Investigator Office observations status page$^4$.

1.1 Notes on Individual Targets

Five very bright stars ($T_{\text{mag}} \lesssim 2$) 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 255559489, 238196512, 38877693, 134501440, and 322899250.

Three stars (93279196, 50743458, and 300015238) had very bright stars nearby (93280676, 50743469, and 300015239, respectively). The contaminating flux for these objects is very large, and the pipeline assigns them disjoint photometric apertures that likely causes uncorrected systematic errors in the light curves.

Seven targets (436103278, 269273552, 220393543, 124918771, 124751941, 156934909, and 150110391) had apertures selected (25x25 pixels) that did not fully capture the bleed trails.

1.2 Spacecraft Pointing and Momentum dumps

The reaction wheel speeds were reset with momentum dumps every 3.125 days. FFIs taken during these times are marked with bit 6 (Reaction Wheel Desaturation Events) set. Only

$^3$https://tess.mit.edu/observations/sector-6
$^4$https://heasarc.gsfc.nasa.gov/docs/tess/status.html
one or two FFIs are affected by each momentum dump. Figure 1 summarizes the pointing performance over the course of the sector based on Fine Pointing telemetry.

![Sector 6 Fine Pointing](image)

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 $\Delta X/\Delta Y$ directions represent offsets along the detectors' rows/columns, while the $\Delta Z$ direction represents spacecraft roll.

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 6, the main stray light features are caused by the Earth rising above the sunshade at the end of orbit 19, which continues through the start of orbit 20.

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 Instrument Handbook for a more detailed description of each flag.
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. The peak between orbits was caused by the Earth rising above the sunshade.

The following flags were not used in Sector 6: bits 1, 2, 7, 9, 11, and 12 (Attitude Tweak, Safe Mode, Cosmic Ray in Aperture, Discontinuity, Cosmic Ray in Collateral Pixel, and Straylight).

Cadences marked with bits 3, 4, and 6 (Coarse Point, Earth Point, and Reaction Wheel Desaturation Event) were marked based on spacecraft telemetry.

Cadences marked with bit 5 and 10 (Argabrightening Events and Impulsive Outlier) were identified by SPOC pipeline results. 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 6, these cadences were identified using spacecraft telemetry from the fine pointing system. All cadences with pointing excursions >21 arcseconds (~1 pixel) were flagged for manual exclude. See Figure 4 for an assessment of the performance of the detrending based on the final set of manual excludes.

FFIs were only marked with bit 6 (Reaction Wheel Desaturation Events). Only one or two FFIs are affected by each momentum dump.

3 Anomalous Effects

3.1 Smear Correction Issues

The following columns were impacted by bright stars in the science frame and/or the upper buffer rows, which bleeds into the upper serial register resulting in an overestimated smear correction.
3.2 Black Flutter and Popcorn Noise

Flutter in the mean black level was observed in three cameras during Sector 6: camera 2, CCD 2, all outputs, cadences 173550 to 173870 and cadences 181750 to 183250; camera 3, CCD 2, outputs B, C and D, cadences 183000 to 183900; and camera 4, CCD 2, output D, cadences 176340 to 177120.

Popcorn noise in the mean black level was observed in three cameras during Sector 6: camera 1, CCD 3, output C, throughout the first orbit and output A, cadences 176450 to 179687 and cadences 185700 to 186150; camera 3, CCD 1, output B, intermittently...
Figure 4: Median absolute deviation (MAD) for the 2-minute cadence data from Sector 6, 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. Note that the first and last cadences in each orbit are treated as gaps by PDC.

through both orbits; and camera 4, CCD 3, output D, intermittently through both orbits. The time-varying component of the 1-D black model correction removes cadence-to-cadence black variations as well as the black flutter and popcorn noise so the impact to end users is minimal. See the Instrument Handbook §6.3.4 & 6.3.5 for more details about overclock popcorn noise and flutter.

### 3.3 Fireflies and Fireworks

Table 2 lists all firefly and fireworks events for Sector 6. These phenomena are small, spatially extended, comet-like features in the images that may appear one or two at a time (fireflies) or in large groups (fireworks). See the Instrument Handbook for a complete description.

### 3.4 TJD Calculation

The spacecraft clock drifts slowly relative to UTC time at a rate of \( \sim 35 \) milliseconds per day. This drift is captured in a clock kernel that is used to calculate TJD from spacecraft
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 of 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 of 0.8 means the power in broad-band introduced noise is only slightly above the level of uncertainties in the flux values.

The calculated clock kernel correcting this difference is based on the measured drift rate from periodic S-band and Ka-band ranging contacts.

The clock kernel used to calculate TJD in Sector 6 used ranging data collected only through late August, 2018; as a result, the extrapolation to Sector 6 times is slightly off. The error between true and calculated times grew linearly with time since August 2018, so that the calculated TJD values in all data products are offset from the correct values by $\sim2.0$ seconds at the end of orbit 20 (2019-01-06 UTC). This error also implies that the durations of the individual cadences are underestimated by about 20 microseconds and the FFIs are low by about 280 microseconds, as calculated by the difference between the TSTOP and TSTART times. This issue will be corrected if the data are reprocessed in a future data release.
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. The performance is a close match to Sector 5, with a systematic error floor between 20–30 ppm (down to Tmag = 10–11).

4.2 Transit Search and Data Validation

In Sector 6, the light curves of 19,995 targets were subjected to the transit search in TPS. Of these, Threshold Crossing Events (TCEs) at the 71σ level were generated for 812 targets. The top panel of Figure 7 shows the distribution of orbital periods for the TPS TCEs found in Sector 6. There is a small excess of TCEs with periods between ~7 and 15 days, with a tendency to pile up near integer multiples of the 3-day spacing between momentum dumps. The bottom panel of Figure 8 shows the number of TCEs at a given cadence that exhibit a transit signal. The isolated peak at the second momentum dump drives most of
these spurious TCEs. The distribution of TCE transits over cadences is otherwise quite uniform.

The vertical histogram in the right panel of Figure 7 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 1112 TCEs were ultimately identified in the SPOC pipeline on 812 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. Due to proximity to the galactic plane, the targets observed in Sector 6 tend to be more crowded than those observed in prior sectors. As a result, there are a larger number of false positive TCEs due to background sources in Sector 6 than were observed in earlier sectors.

### Table 3: Sector 6 TCE Numbers

<table>
<thead>
<tr>
<th>Number of TCEs</th>
<th>Number of Targets</th>
<th>Total TCEs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>570</td>
<td>570</td>
</tr>
<tr>
<td>2</td>
<td>198</td>
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<td>3</td>
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<td>5</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>–</td>
<td>812</td>
<td>1112</td>
</tr>
</tbody>
</table>
Figure 7: Lower Left Panel: Transit depth as a function of orbital period for the 1112 TCEs identified for the Sector 6 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 when not available, the DV trapezoid model fit depth. 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.
Figure 8: Number of TCEs at a given cadence exhibiting a transit signal. Isolated peaks are caused by a single event and result in spurious TCEs. The peaks typically align with pointing instabilities and strong background variations. The main features to be aware of are cadences impacted by momentum dumps (e.g., TJD epoch 1471.5).
References


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 Product 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
XML  Extensible Markup Language