TESS Data Release Notes:
Sector 5, DR7

Michael M. Fausnaugh, Christopher J. Burke
Kavli Institute for Astrophysics and Space Science, Massachusetts Institute of Technology,
Cambridge, Massachusetts

Douglas A. Caldwell
SETI Institute, Mountain View, California

Jon M. Jenkins
Ames Research Center, Moffett Field, California

Jeffrey C. Smith, Joseph D. Twicken
SETI Institute, Mountain View, California

Roland Vanderspek
Kavli Institute for Astrophysics and Space Science, Massachusetts Institute of Technology,
Cambridge, Massachusetts

John P. Doty
Noqsi Aerospace Ltd, Billerica, Massachusetts

Eric B. Ting
Ames Research Center, Moffett Field, California

Joel S. Villasenor
Kavli Institute for Astrophysics and Space Science, Massachusetts Institute of Technology,
Cambridge, Massachusetts

February 27, 2019
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.

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 Observations

TESS Sector 5 observations include physical orbits 17 and 18 of the spacecraft around the Earth. Data collection was paused for 1.35 days during perigee passage while downloading data. The use of Camera 1 in attitude control was disabled for the last $\sim 0.5$ days of orbit 18 due to strong scattered light signals (see §1.2), and data taken with Camera 1 during this period were excluded from the pipeline analysis (see §2). In total, there are 25.23 days of science data collected in Sector 5.

Table 1: Sector 5 Observation times

<table>
<thead>
<tr>
<th>UTC TJD</th>
<th>Cadence #</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit 17 start</td>
<td>2018-11-15 07:47:48</td>
</tr>
<tr>
<td>Orbit 17 end</td>
<td>2018-11-27 16:44:46</td>
</tr>
<tr>
<td>Orbit 18 start</td>
<td>2018-11-29 01:09:22</td>
</tr>
<tr>
<td>Camera 1 Guiding Disabled</td>
<td>2018-12-11 10:31:39</td>
</tr>
<tr>
<td>Orbit 18 end</td>
<td>2018-12-11 21:35:39</td>
</tr>
</tbody>
</table>

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

The spacecraft was pointing at RA (J2000): 73.5382°; Dec (J2000): −31.9349°; Roll: 191.05°. Two-minute cadence data were collected for 20,000 targets, and full frame images were collected every 30 minutes. See the TESS project Sector 5 observation page³ 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 page⁴.

1.1 Notes on Individual Targets

Four very bright stars ($\text{Tmag} \lesssim 2$) 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, 231308237, 38877693, and 325685265.

Two targets, 300015238 and 300015239, lie within one pixel of each other. The contaminating flux for these objects is very large, and the pipeline assigns them disjoint photometric apertures, which likely causes uncorrected systematic errors in the light curves.

One target (220393543) had a small aperture 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 3.0 days. FFIs taken during these times are marked with bit 6 (Reaction Wheel Desaturation Events) set. Only one or two FFIs are affected by each momentum dump.

³https://tess.mit.edu/observations/sector-5
⁴https://heasarc.gsfc.nasa.gov/docs/tess/status.html
At the end of orbit 18, the Earth was $< 35^\circ$ from the boresight of Camera 1. At these low angles, the level of scattered light is too high for meaningful guide star centroids to be measured. Guiding with Camera 1 was therefore disabled at this time, starting at TJD 1463.93945 until the end of the sector. When Camera 1 guiding was disabled, the spacecraft attitude shifted by a small amount, about 1 arc-second (0.05 pixels).

Figure 1 summarizes the pointing performance over the course of the sector based on Fine Pointing telemetry. Disabling Camera 1 guiding near the end of the Sector caused a brief impulse in pointing, which settled out within minutes. The other periods of increased dispersion are generally correlated with the momentum dumps. Several shorter impulse-like events are also evident, which are associated with quasi-instantaneous changes in the internal friction of the reaction wheels.

![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. The brief period of large dispersion at the end of the sector is caused by disabling Camera 1 for guiding (see §1).](image)

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 5, the main stray light features are caused by the Earth rising above the sunshade at the end of each orbit, and strong glints appear during these times. As noted in §1.2, the Earth moves quite close to the boresight of Camera 1 at the end of orbit 18.

![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 upturn at the end of each orbit is caused by the Earth rising above the sunshade.](image)

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 upturn at the end of each orbit is caused by the Earth rising above the sunshade.

## 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.

The following flags were not used in Sector 5: bits 2, 7, 9, and 11 (Safe Mode, Cosmic Ray in Aperture, Discontinuity, and Cosmic Ray in Collateral Pixel).

Cadences marked with bits 1, 3, 4, 6, and 12 (Attitude Tweak, 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 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 5, these cadences were identified using spacecraft telemetry from the fine pointing system. All cadences with pointing excursions >21 arc-seconds (©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.
Figure 3: Angle between the four camera boresights and the Earth/Moon as a function of time. When the Earth/Moon moves within $\sim 35^\circ$ of a camera’s boresight, scattered light patterns and complicated features such as glints may appear. At larger angles, low level patchy features may appear. 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.

FFIs were only marked with bit 6 and 12 (Reaction Wheel Desaturation Events and Straylight). Only one or two FFIs are affected by each momentum dump.

Due to the scattered light in Camera 1 at the end of orbit 18, the data from cadences 170313 to 170601 (the end of the sector) from Camera 1 were manually excluded from the pipeline analysis. These cadences for targets in Camera 1 are marked with bit 12 (Straylight) and set to NULL in the light curve files. Raw and flux-calibrated pixels for these cadences are provided in the target pixel files, but no photometry or centroid positions were calculated.

3 Anomalous Effects

3.1 Smear Correction Issues

1. Camera 4, CCD 4, Columns 431–437: There is a bright star in the upper buffer rows, which bleeds slightly into the upper serial register and affects the smear rows in this column.

We have identified some moderately bright stars in the upper buffer rows that affect the first
Figure 4: Median absolute deviation (MAD) for the 2-minute cadence data from Sector 5, 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.

row of the virtual smear region. However, the smear correction is robust against these cases.

3.2 Black Flutter

Flutter in the mean black level was observed in two cameras during Sector 5: camera 2, CCD 2, all outputs, cadences 152300–153000 and 162000–163000; and camera 4, CCD 2, output D, cadences 155450–156660.

Popcorn noise in the mean black level was observed in three cameras during Sector 5: camera 1, CCD 3, output C, cadences 155190–157700; camera 3, CCD 1, output B, throughout the sector; and camera 4, CCD 1, output A, throughout the sector. 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 5. 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 time. 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 5 used ranging data collected only through late August, 2018; as a result, the extrapolation to Sector 5 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 \( \sim 1.7 \) seconds at the end of orbit 18 (2018-12-11 UTC). This error also implies that the durations of the individual cadences are underestimated by about 20 microseconds and the FFIs are
Figure 6: 1-hour CDPP. The red points are the RMS CDPP measurements for the 19,996 light curves from Sector 5 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.

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 Change in 1-D Black Correction

Starting with Sector 5 processing, the SPOC pipeline 1-D Black correction has been changed to a two-component model from the polynomial fit that had been used prior (see the Sector-1 Data Release Notes, § 3.9, for a discussion of issues with the polynomial fit). The new black model consists of two components: a time-varying correction and a static row-by-row correction. The time-varying component is the robust mean of the selected overclock columns and rows for each cadence. After removing the time-varying mean black level, the row correction contains one value for each row and is the robust mean over columns and time. The 1-D black correction ignores the first column of each overclock region, which can be contaminated by flux from the imaging pixels. The time-varying component of the model

removes cadence-to-cadence black variations as well as the black flutter and popcorn noise seen on some CCDs. The static row-dependent component is designed to correct the “tired chain” effect (TESS Instrument Handbook §6.8.5) where bright illuminated pixels cause an increase in the black level of subsequent pixels. The updated model removes this small (∼10 ADU/cadence) residual bias.

### 4.2 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. This is the first data release in which the goodness metrics reported in the light curve files match the calibrated values shown in Figure 5.

Figure 6 shows the achieved Combined Differential Photometric Precision (CDPP) at 1-hour timescales for all targets. The measured CDPP values level out between 20 and 30 ppm at the bright end, and the residual error after accounting for known sources of uncertainty (photon noise in the target and background, read noise, etc.) is about the same down to Tmag = 10–11. The uncertainties at lower magnitudes are probably somewhat overestimated, perhaps due to crowding/blends and other sources of excess light in the photometric aperture.

### 4.3 Transit Search and Data Validation

In Sector 5, the light curves of 19,996 targets were subjected to the transit search in TPS. Of these, Threshold Crossing Events (TCEs) at the 7.1σ level were generated for 829 targets. Cadences at the end of orbit 18, from 170013 to 170519, were excluded from the transiting planet search due to the effects of rapidly changing scattered light and glints (see Figure 2). Cadences near the first and second-to-last momentum dump also caused an inordinate number of TCEs on an initial run of TPS. Approximately 16 hours around those times were also
excluded from the planet search, in order to reduce the number of false positives. These periods extended from cadence 153522 to 154022 and 167607 to 168107.

The top panel of Figure 7 shows the distribution of orbital periods for the TCEs found in Sector 5. There is an excess of TCEs at periods near 10.5 and 14 days. These periods are mainly caused by the spacing of momentum dumps between the first and second orbit, as shown by Figure 8—the isolated peak in the first orbit near the second momentum dump is separated from the peaks in the second orbit by \( \sim 10.5 \) and 14 days. The slight depressions in Figure 8 near the first momentum dump, the second-to-last momentum dump, and the very end of the sector mark the periods excluded for the planet search, described above.

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 1248 TCEs were ultimately identified in the SPOC pipeline on 829 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 5 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>505</td>
<td>505</td>
</tr>
<tr>
<td>2</td>
<td>246</td>
<td>492</td>
</tr>
<tr>
<td>3</td>
<td>66</td>
<td>198</td>
</tr>
<tr>
<td>4</td>
<td>9</td>
<td>36</td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>–</td>
<td>829</td>
<td>1248</td>
</tr>
</tbody>
</table>
Figure 7: Lower Left Panel: Transit depth as a function of orbital period for the 1248 TCEs identified for the Sector 5 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 epochs 1444.0 & 1457.5).
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