Asteroid Observations from the Transiting Exoplanet Survey Satellite: Detection Processing Pipeline and Results from Primary Mission Data

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Abstract

The Transiting Exoplanet Survey Satellite (TESS) is a NASA Explorer-class mission designed for finding exoplanets around nearby stars. TESS image data can also serve as a valuable resource for asteroid and comet detection, including near-Earth objects (NEOs). In order to exploit the TESS image data for moving object detection and potential object discovery, our team has developed an image processing pipeline as part of the Lincoln Near-Earth Asteroid Research (LINEAR) program, sponsored by the NASA NEO Observations Program. The LINEAR-TESS pipeline is currently in operation and reporting asteroid observations to the Minor Planet Center. In this paper we discuss the algorithms and methodology utilized to push the limits of the astrometric accuracy and photometric sensitivity of the TESS instrument for asteroid detection without a priori information on the ephemerides of the objects, and report on observation statistics from the first two years of TESS mission data.

Key words: Solar system astronomy – Astronomy data analysis – Asteroids – Near-Earth objects – Astrometry – Astronomy software

1. Introduction

The Transiting Exoplanet Survey Satellite (TESS) is a NASA Explorer-class mission led by the MIT Kavli Institute for Astrophysics and Space Research (MKI) in partnership with MIT Lincoln Laboratory, NASA’s Goddard Spaceflight Center, Orbital ATK, NASA’s Ames Research Center, the Harvard-Smithsonian Center for Astrophysics, the Aerospace Corporation, and the Space Telescope Science Institute. Since launching in 2018 April, TESS has proven extremely successful in its mission to find exoplanets orbiting nearby stars (e.g., Huang et al. 2018; Dragomir et al. 2019; Ricker 2019; Vanderspek et al. 2019; Wang et al. 2019). TESS data has also proven valuable for a range of science applications including supernova detection (Valley et al. 2019), solar flare observations (Günther et al. 2019), and astroseismology (Handler et al. 2019).

Although the TESS instrument was not designed for an asteroid search mission, TESS observes many asteroids in its field of view, particularly near the ecliptic plane, and has been identified as a resource for solar system science. Research by Pál et al. (2018) explores the utility of TESS data for solar system science and asteroid light curve measurements. Wong (2019) analyzes light curves of solar system objects in the TESS image data and demonstrates the value of TESS data for asteroid light curve characterization. TESS observations of comet 46P/Wirtanen provide detailed temporal characterization of a comet outburst in a study by Farnham et al. (2019). Holman et al. (2019) and Payne et al. (2019) discuss “shift-and-stack” techniques to apply to slower moving targets for the detection of faint outer solar system objects. Pál et al. (2020) create a catalog of lightcurves of solar system objects in TESS data, providing fundamental rotation characteristics for 9912 objects.

TESS image data can also serve as a valuable resource for the discovery of new asteroids and comets, and for near-Earth objects (NEOs) moving at angular rates up to a few deg day−1. Asteroid discovery requires a completely different approach than analyzing known objects whose locations within the TESS images can be predicted from their ephemerides. In order to exploit the TESS image data for moving object detection and potential object discovery, our team has developed an image processing pipeline as part of the Lincoln Near-Earth Asteroid Research (LINEAR) program, sponsored by the...
NASA Near-Earth Object Observations (NEOO) Program. The software is substantially adapted from the existing LINEAR processing pipeline, which was developed to detect asteroids in data from the 3.5 m Space Surveillance Telescope (Viggh et al. 2015; Ruprecht et al. 2018). The LINEAR-TESS pipeline is currently in operation and reporting asteroid observations derived from TESS images to the Minor Planet Center (MPC7). The MPC is supported by the NASA Planetary Defense Coordination Office and serves under the auspices of the International Astronomical Union (IAU) as the central body responsible for maintaining orbits on all minor planets, including main-belt asteroids and near-Earth objects (NEOs).

In this paper we discuss the algorithms and methodology utilized to push the limits of the astrometric accuracy and photometric sensitivity of the TESS instrument for new object discovery and measurements of known objects without reference to their ephemerides. Generating the most accurate and complete set of single-frame detections in the TESS full frame images requires overcoming a number of challenges inherent in a wide field-of-view, space-based system. These challenges include effects from differential velocity aberration (DVA) that result from spacecraft motion relative to the optical axis, significant field distortion due to the wide field-of-view optics, and an undersampled point-spread function (PSF) designed for precision photometry. In the sections that follow we discuss these challenges and methodologies for working with the available data to maximize the return on moving object detection. Section 2 provides background and context for the TESS asteroid search program, and Section 3 gives an overview of the TESS observatory. We describe details of the detection processing pipeline in Section 4, including the astrometric calibration in Section 4.3 and the image conditioning in Section 4.4. Section 5 contains the results of the data processing, and Section 6 provides a brief summary.

2. TESS Asteroid Search Role in Context

The motivation to utilize TESS data for asteroid detection derives from the global concern for the potential threat of an asteroid impact on Earth. In 1998, NASA committed before Congress to detect and catalog 90% of Near-Earth Objects (NEOs) larger than 1 km, with the recognition that an impact from an object of that size would likely have worldwide effects, including the possibility of extinction of the human race. A 2005 Congressional mandate extended the search target to catalog 90% of objects of diameter 140 m or greater. The 2017 Science Definition Team (SDT; Stokes et al. 2017) report quantifies the financial risks of an asteroid impact and finds that the benefits of funding nearly all asteroid search systems significantly outweigh the associated costs. The SDT report assessed the expected number of objects larger than 1 km to be 934 NEOs and the number of objects larger in diameter than 140 m to be ~25,000. Using those estimates and the latest statistics on the number of known objects from JPL’s Center for Near-Earth Object Studies (CNEOS8) this suggests that as of 2020 February, survey completeness is ~96% for objects 1 km or larger and ~36% for objects >140 m in size. Hence, the number of undiscovered large NEOs is substantial and the effort to catalog them would benefit from the processing of suitable data for object detection wherever possible.

NASA’s NEOO Program within the Planetary Defense Coordination Office supports a range of asteroid search programs. These programs include large ground-based optical telescopes for efficient search in deep, wide area surveys such as the Catalina Sky Survey (Drake et al. 2009) and Pan-STARRS (Chambers et al. 2016), as well as smaller ground-based optical telescopes for short forecast alerts such as the Asteroid Terrestrial-impact Last Alert System (ATLAS; Tonry et al. 2018). The NEOO Program also funds space-based asteroid detection at IR wavelengths under the NEOWISE mission (Mainzer et al. 2014). The most productive NEO discovery systems in the last three years have been Pan-STARRS, Catalina, ATLAS, and NEOWISE (Figure 1). Of these systems, only NEOWISE presently has access to the full southern hemisphere and although future ground-based systems in the southern hemisphere are planned, none of those systems are currently operational.9

Although TESS does not reach the limiting magnitude or survey efficiency of large ground-based systems like Pan-STARRS or Catalina, the TESS mission provides a source of publicly available data that can help to fill the gap in coverage in the southern hemisphere that cannot be observed by more sensitive ground-based surveys. The TESS mission is a nearly all-sky survey, covering the southern hemisphere in year 1 and the northern hemisphere in year 2. The extended mission will observe the southern hemisphere in year 3, and is expected to include some coverage in the ecliptic plane in year 4 as well as partial coverage of the northern hemisphere. The wide area coverage and persistent monitoring of the TESS observing campaign are well matched with the needs of an asteroid survey. Furthermore, TESS maintains anti-solar pointing to reduce solar contamination and maintain stable viewing conditions during science data collection in its High Altitude Science Operations (HASO) mode, which results in optimal viewing conditions for observing near-Earth objects at opposition.

3. Application of the TESS Observatory for Asteroid Detection

Utilizing the TESS data for asteroid detection requires careful consideration of the unique features inherent in a space-based optical system. The TESS asteroid detection pipeline

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7 https://www.minorplanetcenter.net/
8 https://cneos.jpl.nasa.gov/
9 https://www.nature.com/articles/d41586-018-05969-2
Section 4 applies a moving object detection strategy which relies on the “difference image” method. The difference image in its basic form is the subtraction of a static sky image from each individual image, which in the ideal case removes all non-moving and non-varying sources such as most stars and galaxies, while leaving the moving objects in the images. Any effects that lead to non-static conditions create artifacts in the subtracted image and negatively impact the sensitivity of the moving object detection. Fortunately, the TESS mission was designed to maintain observing conditions that are as stable as possible to support the mission goals of sensitivity to planetary transits. An overview of the observing strategy and the TESS camera are discussed in Sections 3.1 and 3.2. We explore the limits of image stability in a space-based optical system and their impact on the asteroid pipeline in Sections 3.3 and 4.

3.1. Observing Strategy

The observing strategy takes advantage of the sensor’s efficient sky coverage made possible by the optical design. The system covers 24 × 24 square degrees in each of four cameras for an impressively large, 96 × 24 square degree instrument field of view. The instrument pointing is maintained continuously for 27 days, which correspond to two Earth-orbits of the satellite. In year 1 of the TESS mission, the TESS sky coverage for each sector spans 96 deg in ecliptic latitude, ranging from −6 deg ecliptic latitude to wrap over the pole by 12 deg. The ecliptic longitude coverage for each sector spans 24 deg, centered on solar opposition for the middle date of each sector. During year 2 the coverage is in the northern hemisphere with some sectors offset away from the ecliptic to mitigate stray light performance. Figure 2 illustrates the sky coverage in ecliptic latitude and longitude during years 1 and 2. The four cameras are arranged along a line with camera 1 pointing closest to the ecliptic, then cameras 2, 3, and 4, such that camera 4 covers the pole.

TESS full-frame images are made available to the public via the Mikulski Archive for Space Telescopes (MAST\textsuperscript{10}) at the Space Telescope Science Institute (STScI) one sector at a time, along with data release notes, supplemental engineering data, and other science data products. Full-frame images are collected continuously during each 27 days observing period; this continuous stream of image data represents an advantageous feature that was not available from the Kepler mission.

3.2. The TESS Camera

The TESS optical design simultaneously maintains wide field-of-view (FOV, 24 × 24 square degrees) and color-corrected images over a large bandpass (600–1000 nm). The optics, and therefore the PSF, are tuned for optimal sensitivity to exoplanets transiting F5 through M5 spectral type stars. The TESS camera, by design, favors exoplanet detection around cooler M-type stars. Sensitivity to longer wavelengths is supported by the TESS devices, which are 100 μm thick, fully depleted back-illuminated CCDs developed by MIT Lincoln Laboratory (Suntharalingam et al. 2015). The camera focus balances spatial variations across the wide field-of-view and chromatic effects across the broad wavelength coverage to mitigate variation in the realized PSF across the full field.

\textsuperscript{10} https://archive.stsci.edu/
The photometric precision required for the detection of exoplanet transits, as well as the desire for wide area coverage, led to an optical design that favors a PSF that is compact compared to the pixel size and a plate scale that fits a considerable amount of sky onto a single pixel. The $21''$ pixel$^{-1}$ plate scale is advantageous for exoplanet science, where photometric noise is reduced by concentrating a substantial fraction of the total flux in the brightest pixel (Gilliland et al. 2011). However, the compact PSF is not ideal for asteroid detection, which has more stringent requirements for astrometric precision than for photometric precision. The fraction of ensquared energy in the brightest pixel varies from 0.40 at the center to 0.25 at the corners. The four CCDs in each camera are arranged in a $2 \times 2$ layout centered on the optical axis.

Figure 3 illustrates the TESS PSF for the example case of camera 3, CCD 3 in both linear and log10 scaling to bring out faint features. The field angles are 0.5, 4.5, 8.5, 12.5, and 16.5 deg on the diagonal from near-center to corner. The PSF varies minimally from camera to camera, and is similar for each CCD with appropriate rotation about the optical axis. Differences in the PSF between cameras or CCDs may exist as a result of slight variations in the optical alignment, but are not significant compared to the variation across the field.

### 3.3. Pointing Stability and Jitter

Pointing stability and jitter performance play an important role in the asteroid detection pipeline performance because they...
values reveal the pointing stability in the directions corresponding to the x-axis and y-axis of the cameras, respectively, and the z-offset is the perpendicular direction. The blue points are the measured average value in the bin; the red line is the fit which is later subtracted to remove long term trends. The x-offset and y-offset values reveal the pointing stability in the directions corresponding to the x-axis and y-axis of the cameras, respectively, and the z-offset is the perpendicular direction.

In this analysis we assess the time history of the jitter performance on a frame-to-frame basis, which is relevant for the image subtraction step of our pipeline. Our approach is to evaluate the average camera delta-quaternions, which are camera orientation parameters, provided in the MAST Archive in bins of 30 minutes to understand the time history of the pointing jitter. The observed pointing offset is evaluated as the average of the delta-quaternions within each time bin. We take the mean of all four cameras to reduce the measurement noise and partially cancel the effects of DVA (see Section 3.4). Figure 4 shows the average delta-quaternions during the first orbit of sector 10. The time, given in TESS Julian Days (TJD) is shown relative to the start of the exposure of the first full frame image in the sector. The mean in each bin is shown with blue points; the red lines are fits to the data indicating long term trends, mainly due to residual DVA.

3.4. Differential Velocity Aberration

DVA is a consequence of the finite travel time of photons and the relative motion of the spacecraft against an inertial reference frame. DVA produces a slight shift in the apparent angle of a photon’s arrival by an amount that depends on the angle between the line of sight and the velocity vector of the spacecraft. The relative effect varies as the spacecraft velocity changes, reaching a maximum when the spacecraft is at periapse. Although the fine pointing system partially accounts for the velocity aberration, the magnitude and direction of velocity aberration varies across the cameras, and there is unavoidable residual, uncorrected apparent motion of the stars in the centered frame. Nguyen et al. (2018) describe the effects of velocity aberration on the spacecraft pointing via the apparent drift of guide stars across the field.
For the purpose of image subtraction, what matters is the change in DVA at a given focal plane position as a function of time. Following the prescription in Lockwood (2013), we compute the time derivative of the DVA from the change in the velocity vector of the spacecraft in the heliocentric J2000 ecliptic reference frame and the Cartesian representation of the position angle of a star in the J2000 ecliptic frame. The technical details of these calculations are provided in a forthcoming paper. In summary, from the mid-point of the first image to the mid-point of the last image, in which the time difference within 17 frames spans 8.0 hr, for the case of camera 1, CCD 3, the star centroids will shift by a few milli-pixel/hour during data collection in HASO, resulting in >20 milli-pixels of total shift during the 8.0 hr in a frameset. Creating a difference image from frames with a timespan of 8 hr results in residual flux from stars left behind as a result of the change in DVA over time, which are clearly visible in the difference images, with a magnitude that can be predicted from the spacecraft position and pointing geometry. While the magnitude and direction of DVA across the focal plane can be predicted with high precision, the resulting shift in flux from one pixel to the next is more challenging to compute due to the undersampled PSF whose realization is dependent on the subpixel registration. As a result of the excellent image stability, we find it is more accurate not to re-register and re-sample the PSF when differentiating images, and instead keep the median combined frames to a timespan of 8.0 hr. Our findings are consistent with the work of Pál et al. (2020), who report that the magnitude of DVA can reach 0.1 pixel throughout a sector, and that DVA is most prominent farther away from the spacecraft boresite. Their processing handles the variations in PSF and effects of DVA by applying an image convolution step to the median differential background reference image (derived for an entire sector) and the background subtracted images, while our pipeline selects shorter timespans over which we apply image subtraction to avoid the necessity of the image convolution.

The implications for residual uncorrected flux for stars whose apparent shift on the focal plane result in artifacts during image subtraction for time periods of larger change in DVA as the spacecraft approaches perigee, as seen in the cutouts of full frame images shown in the upper panels of Figure 6. The lower panels show the same region of sky in the subtracted images collected while the spacecraft is closer to apogee when the change in DVA is smaller.

4. The Detection Processing Pipeline

Successfully detecting asteroids in the TESS image data requires the development of image processing algorithms optimized for the detection of dim, moving objects. The TESS asteroid detection pipeline begins with photometric and astrometric calibration, and then proceeds to image conditioning and moving object detection. The pipeline is outlined in Figure 7, which reveals the overall data flow. Section 4.1 gives an overview of the image data at the starting point, Section 4.2 describes the photometric zero-point calculation, Section 4.3 gives details of the astrometric calibration, Section 4.4 contains an overview of the image conditioning, Section 4.5 describes the tracker, and Section 4.8 describes the strategy and timelines for processing with the Lincoln Laboratory Supercomputing Center.

4.1. Calibrated Full Frame Images

The pipeline utilizes the calibrated full frame images (FFIs) from the MAST archive. The observing cadence of the full frame images is 30 minutes. The native integration time for the TESS image frame is 2 s. When combining images to make the postage stamp data and the full frame image data, the on-board processing incorporates a cosmic ray mitigation algorithm which discards the highest and lowest per pixel values in a set of 10 frames and sums the values from the middle 8 frames. This results in an effective exposure time of 24 minutes for the full frame image data (reduced from 30 minutes). The calibrated FFIs have been corrected for bias, flat-fielding, pixel response non-uniformity, nonlinearity, overshoot and undershoot, and gain correction (Jenkins et al. 2016). An initial astrometric solution is provided in the FITS images in the World Coordinate System (WCS) framework. Cosmic rays are removed in onboard processing prior to the generation of the calibrated FFIs. Cosmic ray mitigation will remove anything that looks like a single-point outlier in the 2 s readout of image frames; objects moving faster than 21″ in 2 s will be affected.
Even fast-moving NEOs will not be removed by the cosmic ray algorithm.

4.2. Photometric Zero-point

The photometric calibration of the detected objects in the TESS field is straightforward thanks to having the calibrated FFIs as the starting point, leaving only the calculation of the photometric zero-point. To compute the zero-point, we start with the detection of bright, unsaturated, uncrowded stars detected in the FFIs. We compute the zero-point for each CCD of each frame independently. The open source software Source Extractor (Bertin & Arnouts 1996) is used for object detection and produces a local-background subtracted instrument magnitude (MAG_AUTO). We use the python astropy interpretation of the WCS solution from the image header to convert from the measured pixel position (XWIN_IMAGE, YWIN_IMAGE) of the stars to right ascension and declination (RA, Dec), which is sufficiently accurate for matching to catalog stars.

Our photometric reference stars are derived from a subset of the Gaia DR2 catalog (GAIA Collaboration 2018), which have been selected for calibration by removing known extended and variable sources. The photometric zero-point is then computed for the matched reference stars in the Gaia G-band. The conversion from instrument magnitude to G-band photometry yields a typical value of the zero-point of ∼21.0 mag. For comparison of TESS observations translated to magnitudes in other photometric systems, we estimate the approximate color conversion between G-band and other systems by computing colors for a set of 25,243 solar-type stars from the Candidate Target List (CTL)-8 (CTL: Stassun et al. 2019 11). The average color terms for this set of solar-type stars yields the approximate conversions from TESS (T): T = G − 0.486, T = V − 0.671, V = G + 0.185. Given the typical T-band zero-point 12 reported as 20.6 mag, this translates to (20.6 + 0.486) = 21.09 in G, consistent with our typical G-band zero-point of ∼21.0 mag.

4.3. Astrometric Calibration

High-quality astrometric calibration is important for the asteroid detection pipeline in order to provide accurate orbit determination. The astrometric calibration depends on the measurement of the pixel centroid of the detected object and on the conversion from pixels to (RA, Dec). The MPC requires astrometric residuals less than 2.5′′ for acceptance in their database. Dedicated asteroid search systems such as the Catalina Sky Survey and Pan-STARRS employ cameras with smaller pixel sizes than the TESS cameras and routinely produce superior astrometric performance with residuals well below 1″ (Veres et al. 2017). Achieving <2.5″ using the TESS camera with a pixel size of 21″ and substantial optical distortion is feasible with the appropriate calculations.

In order to accurately characterize the optical distortions of the TESS cameras, the pipeline employs a three-step model to generate the astrometric plate solutions for the individual full-frame images. The plate model relies on transforming a set of Gaia DR2 catalog stars in the field of view from their catalog coordinates to their approximate pixel locations for matching with observed standard stars from the images. Once the catalog stars and observed standard stars are matched, the transformation is fully specified in the direction of sky to pixel coordinates. Applying the reverse transformation to the star

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11 Accessed at https://filtergraph.com/4701718.

12 Reported in the software tool tasoc.dk/code.
or asteroid detections provides the resultant sky coordinates. The steps of the astrometric plate solution are as follows:

1. Gnomonic (tangential) projection, centered at the nominal pointings of the optical axes of each of the four TESS cameras.
2. Optical distortion correction using a Brown–Conrady model.
3. Fifth order polynomial fit to the remaining uncorrected distortion.

This methodology for the astrometric model has also been successfully implemented in the analysis of Pál et al. (2020) in order to extract precise flux values for known asteroids in the TESS image data.

4.3.1. Gnomonic Projections

In the first step, we apply gnomonic (tangential) projections to a set of Gaia DR2 catalog stars in the camera field of view. The projections are centered at the nominal pointings of the optical axes of each of the four TESS cameras. These attitude numbers are based on the appropriate FITS header keywords for the spacecraft pointing (see RA_NOM, DEC_NOM and ROLL_NOM) while for the individual cameras these are computed by applying the appropriate spatial rotations by ±12° and ±36° with respect to the spacecraft frame.

4.3.2. Optical Distortion Model

The optical distortion at each field corner is as large as 47 pixels in displacement, which must be compensated for in order to achieve an accurate plate model. In this next step, we apply a third-order radial Brown–Conrady model with the constants of \( K_i \) (i = 1, 2, 3) to describe the optical distortion:

\[
\begin{pmatrix}
\hat{x}_d \\
\hat{y}_d
\end{pmatrix} = \begin{pmatrix}
x_u \\
y_u
\end{pmatrix} + \left[ \begin{pmatrix}
x_0 \\
y_0
\end{pmatrix} - \begin{pmatrix}
x_0 \\
y_0
\end{pmatrix} \right] \left[ \sum_{i=1}^{3} K_i r^{2i} \right]
\]

where \((x_u, y_u)\), \((x_0, y_0)\) and \((x_0, y_0)\) are the distorted, undistorted and optical axis coordinates, respectively, and \( r^2 = (x_u - x_0)^2 + (y_u - y_0)^2 \). We derived the radial components experimentally for the TESS cameras using data from the post-launch period and have kept the resulting coefficients constant throughout all subsequent analysis of TESS astrometry. The values we compute for the TESS camera are: \( K_1 = 0.2855 \), \( K_2 = -0.5389 \) and \( K_3 = 8.4151 \). The coefficients do not need to be perfect because small variations in the apparent optical distortion which vary frame to frame are derived for each frame individually in the final step, as described in the next section. The more significant consideration in choosing our approach is that the optical axis of the TESS camera is off the corner of the CCD. This means that the pixel coordinates corresponding to the \((x_0, y_0)\) position of the optical axis are out of the effective full frame image areas. Traditional WCS formalism is optimized for solutions where the optical axis is at the center of the images (and of course, much smaller field-of-views) which means that the WCS keywords in the astrometric solution provided with the full-frame images are not ideally suited to capturing the astrometric solution of the image. Large-scale accuracy is more likely to be guaranteed if we account for the optical distortions with reference to the axis of symmetry, and we find that this astrometric procedure yields more accurate results on the whole image due to the application of the Brown–Conrady model.

4.3.3. Polynomial Fit to the Astrometric Solution

We generate the astrometric solutions using the implementation provided by the FITSH package (Pál 2012). For the final step we employ a cross-match of up to 2500 stars in the Gaia DR2 catalog with Gaia G-band between 8.0 and 12.0 mag covering the footprint of the CCD. The Gaia DR2 catalog stars have had the gnomonic projection applied and the optical distortion map applied, as described in the previous two sections. The catalog star selection is filtered to avoid reference stars that are saturated or blended in the large TESS pixels. This automatic process yields a success rate of 98%–99%, with a so-called convex hull ratio around 99.8% This latter quantity, defined as the fraction of the areas for the convex hulls of the matched and extracted star positions, therefore confirms that the cross-match succeeds even at the very corners of the images where the optical distortions are largest. We allow up to a fifth order polynomial for the plate model fit, which takes care of any uncorrected optical distortion, uncorrected differential velocity aberration, and pointing offsets.

The appropriate (R.A., decl.) values in the J2000 system for any \((x, y)\) pixel coordinate is then computed by applying the three steps of the transformation in reverse order. This kind of astrometry was previously applied during the simulations and extractions of light curves of known asteroids on TESS images (see Pál et al. 2018, 2020).

4.3.4. Characterizing the Astrometric Residuals

The method for the measurement of the PSF centroid can significantly affect the astrometric errors in TESS images due to the undersampled PSF, which is asymmetric at large field angles. Our analysis shows that a 2D Gaussian fit yields the most precise and consistent measurement of the object positions, compared to flux weighted centroids (Source Extractor: X_IMAGE, Y_IMAGE) or windowed centroids (Source Extractor: XWIN_IMAGE, YWIN_IMAGE). The centroiding method was selected based on comparison of the measured residuals resulting from generating the astrometric solution for a given set of reference stars using the same FITSH implementation (using stars detected with each of the different centroiding methods). We then evaluated the accuracy of the different centroid methods by applying the computed astrometric solution to a larger set of stars and comparing their measured (R.A., decl.) position with
the Gaia DR2 catalog positions. Figure 8 shows the cumulative distribution of astrometric errors using each of the three centroiding methods. It is necessary to solve for the astrometric solution separately for each set of centroids to avoid introducing a bias that would otherwise arise if the centroiding method used to determine the object position is not identical to the method used to generate the astrometric solution. The bias increases at large field angles where the PSF is more asymmetric. Therefore, we advise caution when applying an astrometric solution provided in an image header, as optimal accuracy can only be achieved when using the same centroiding method that was implemented for generating the astrometric solution.

For comparison, recent work by Bouma et al. (2019) includes the application of the astrometric solution to observed stars compared to Gaia DR2 catalog stars using the WCS and SIP polynomial provided in the TESS image headers, and using a Gaussian centroid fit to their detections. They report a mean residual of 0.118 pixel (248) and a 90th percentile of 0.213 pixel (447). Using the Gaussian fit method for measured catalog stars shown in Figure 8, we measure the 90th percentile of the astrometric residuals at about 125. The stars in our comparison set are selected to be bright and unsaturated to understand the limitations of the expected performance. Asteroids that are streaking or are detected closer to the sensitivity limit will necessarily have worse performance than the stars due to the lower signal to noise ratio of the detection.

We assess astrometric residuals of submitted asteroid observations, which includes both errors in centroiding and errors in the astrometric solution. Figure 9 shows the astrometric residuals for a set of 857,535 asteroid observations for which the Minor Planet Center provided evaluation of the quality of the astrometry compared to the expected positions from their propagation of the catalog of known objects. The astrometric residuals are plotted as a function of distance from the optical axis (field angle) in the top panel, and as a function of TESS magnitude in the bottom panel. The absence of a strong trend as a function of distance from the optical axis suggests that the astrometric solution performs well across the full field, while the trend with magnitude suggests that at low signal levels, noisy centroid measurements dominate the astrometric residual. Therefore, we conclude that errors in astrometry are dominated by centroiding errors of faint objects and that the astrometric solution is valid across the full field.

4.4. Image Conditioning and Moving Object Detection

The pipeline generates a clean set of difference images in which to detect moving objects by first applying a series of checks to remove frames with high jitter (see Section 3.3), and removing frames with significant stray light variation or DVA variation (see Section 3.4) that would otherwise lead to artifacts in the subtracted image. Generating difference images with minimal artifacts is critical to pushing the sensitivity limit of the moving object detection, at the expense of losing data in the excluded frames. Each difference image is created by subtracting a per-pixel median frame and dividing by a per-pixel clipped standard deviation. Dividing by the per-pixel
The algorithm to reduce low-frequency features due to stray light
and median count level using iterative sigma-clipping. Once we
are: DETECT_MINAREA = 1, DETECT_THRESH = 1.75,
ANALYSIS_THRESH = 1.75, DEBLEND_NTHRESH = 32,
DEBLEND_MINCONT = 0.005, CLEAN = Y, CLEAN_PARAM = 1.0, FILTER = Y. The filter is a 3 × 3 convolution
mask of a Gaussian PSF with FWHM = 1.5 pixels.

4.5. Tracker: Moving Object Detection

The purpose of the tracker is to take a set of detections and
determine which belong to objects moving with piece-wise
linear motion through the field of view. The approach used in
the TESS pipeline is similar to that presented by Kubica et al.
(2007) for the intra-night linking of detections. The algorithm
starts by creating a three-dimensional kd-tree of detections. Then, for each detection, the kd-tree is searched for a second
detection that could correspond to the same object. This search
is limited by a user-specified maximum velocity and the time
difference between the frames.

Given two detections which could belong to a moving
object, the linear trajectory of such an object is projected to the
times of the other images. The kd-tree is again queried for
detections along the projected trajectory. If a sufficient number
of supporting detections are found in the data then the track is
saved. While the tracker assumes linear motion to within a 1.2
pixel limit, asteroids in the FOV do not generally maintain
linear motion for the entire period they are observable by
TESS. For this reason, the tracker is run on short blocks of 54
frames of data for which the linear assumption is valid, which

standard deviation reduces the shot noise from the brighter
sources, which would otherwise cause false alarms after
the median of the star is subtracted. This enables us to operate with
lower thresholds for detection to improve probability of
detection of fainter objects for a given false alarm rate. The
median frame is built from a moving window of 17 frames,
which corresponds to 8 hr from the mid-points of the first and
last frames in the set. We select the number of frames
combined in the median as a balance between a longer
timespan for better statistics and accommodation of slow-
moving objects with minimal per-pixel motion, and a shorter
timespan to reduce variations from DVA and stray light. To
calculate the per-pixel standard deviation in a computationally
efficient manner, we bin all of the frames in the sector into sets
of 100 frames per frameset. We compute the per-pixel standard
deviation within each frameset, and apply it to all of the frames
in the frameset.

Each of the difference images is run through a field flattening
algorithm to reduce low-frequency features due to stray light
variation on the timescale of the 100-frame frameset. The effects
of the image conditioning steps are illustrated in Figure 10. The
field flattening algorithm bins the image into regions of size
64 × 64 pixels. For each region, the algorithm estimates a mean
and median count level using iterative sigma-clipping. Once we
have estimated the background level in each bin, we apply a
median filter across the image. This helps to reduce the effect of
bright star artifacts or moving objects present in the difference
image, which can significantly bias the local statistics in a single
64 × 64 pixel region. The default median filter size is 3 × 3,
meaning the background level for a given bin is the median of it
and its immediate neighbors in all directions, including
diagonally. The algorithm then interpolates between those values
to the position of every pixel in order to generate a smooth
estimate of the background level across the frame.

Figure 10. Left panel: original image; Middle panel: (original—median) image, Right panel: (original—median)/ clipped standard deviation. Careful selection of the
median window and the clipped standard deviation window bring out faint features and suppresses star artifacts. The residual flux from imperfectly subtracted stars is
visible in the middle panel. In the right panel, residual flux is reduced when dividing by the standard deviation resulting in a cleaner difference image for object
detection. The bright spot in the center of the right panel is an asteroid, which is not removed by the subtraction of a static image.
4.6. False Alarm Filtering

The pipeline includes a strong false alarm filtering algorithm for the tracker to reject artifacts and other false positives. The algorithm implements the following checks to remove false tracks: (1) reject linked points that remain nearly stationary from frame to frame; (2) reject linked points that deviate from a piecewise 2nd order polynomial curve fit to R.A. versus MJD, or from decl. versus MJD, where a 2nd order polynomial is necessary because the tracks can appear curved on the timescale of 24 hr; (3) reject tracks along CCD columns; (4) reject points with magnitudes outside of a moving window median. The moving window is necessary to accommodate asteroids experiencing a magnitude trend as the solar phase angle changes over time, as well as to accommodate sources that may have a rotational light curve.

In each of these tests, tuning the values of the parameters for each check is important because stricter criteria will reduce the number of false positives at the cost of filtering out more true detections. Our false alarm rejection algorithms favor tracks with larger numbers of detections and those belonging to faster moving objects. The maximum distance for a point from the fit to MJD versus R.A., or MJD versus decl. varies with the track length and velocity, ranging from 6.5 for slow moving detections with velocity $<0.9$ deg day$^{-1}$ to 19.5 for objects with velocity $>4.0$ deg day$^{-1}$. We remove potentially stationary objects moving slower than 0.055 deg day$^{-1}$. Our analysis of the resulting tracks shows that $\sim0.2\%$ of the tracks that pass false alarm filtering are likely false alarms due to artifacts (Section 5).

4.7. Submission to the Minor Planet Center

The tracks that pass the false alarm filtering step are assigned a unique track ID and output to conform with the MPC’s Astrometry Data Exchange Standard (ADES 2018). The geocentric Cartesian position ($x$, $y$, $z$) of the TESS satellite must be reported to the MPC along with the asteroid observations at each point in time. We generate the spacecraft position based on the JPL Horizons ephemeris service with the Geocenter as the reference point. Note that the JPL Horizons ephemeris service requires Terrestrial Time (TT), while the TESS image headers provide a timestamp in UTC which includes a barycentric correction term, and the MPC format requires UTC time without a barycentric correction. Therefore, we apply a series of time system conversions to pull the correct TESS ephemeris from the JPL Horizons service and report

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Figure 11. Number of observations per track (left panel), and timespan of tracks from the first to last detection (right panel).
observations to the MPC. The observations are reported to the MPC in UTC time at the midpoint of the integration.

4.8. Processing Time using the Lincoln Laboratory Supercomputing Center

The LINEAR-TESS pipeline is designed for parallel processing using the Lincoln Laboratory Supercomputing Center (LLSC), a shared-use supercomputing facility that is available to Lincoln Laboratory research staff for program development and execution (Reuther et al. 2018). Once the frames are uploaded to the LLSC servers, the time to process all of the ~1200 frames in one sector belonging to one CCD through all the steps of the pipeline is 1.5–2 hr. We typically process two CCDs at once in separate threads, resulting in a total processing time of 12–16 hr to generate formatted asteroid tracks for an entire sector of data. In recent trials, downloading the images from the MAST to the LLSC typically takes 1.5–2 hr for all full frame images of one CCD in one sector. By coordinating the data download and the pipeline processing, asteroid tracks from the first CCD can be submitted to the MPC as soon as 4 hr from data release, and asteroid tracks from the last CCD can be submitted about 36 hr after the initial data release.

5. Asteroid Detection Performance Results

The LINEAR-TESS pipeline has processed all publicly available full frame images to date. Here we report on the performance of the pipeline using the data from the first 13 sectors, i.e., the full set of observations from mission year 1, and a more limited set of statistics from the year 2 data. The LINEAR-TESS team recorded over 10 million observations of approximately 42,000 unique objects passing through TESS images in years 1 and 2. A plot of all moving object detections derived from the LINEAR-TESS pipeline in the years 1 and 2 data can be seen in Figure 12. The variation in asteroid search productivity from sector to sector which can been seen in Figure 12 is a result of changing stray light conditions. In sectors where the Earth spends significant time within about 40° of the TESS camera boresight, detection sensitivity is reduced and asteroid detection productivity decreases as a result. Sensitivity is also reduced if the Moon is in or near the FOV of any of the TESS imagers. Asteroid detection is particularly reduced when scattered light from the Earth or Moon is significant in camera 1, as this is the camera closest to the ecliptic where the density of asteroids on the sky is highest. Examples and data related to stray light in the TESS images are documented on the TESS website. 14 Detailed information about the stray light conditions in each camera as a function of time can be found in the data release notes for each sector. 15

We developed a software toolset for matching the moving objects detected by the LINEAR-TESS pipeline to the propagated positions of all asteroids in the MPC catalog in order to understand the characterize the pipeline performance. This analysis involved matching all numbered objects from the MPC catalog that were in the FOV of each sector to the TESS detections and measuring the fraction of catalog objects in a given magnitude or angular rate bin that were detected by the processing pipeline. The results of this analysis on the year 1

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14 https://tess.mit.edu/observations/scattered-light/
15 https://archive.stsci.edu/tess/tess_drn.html
The data are shown in Figure 13 (left panel) and demonstrate that the TESS asteroid search is approximately 90% complete at V-band magnitudes brighter than 19.0 under dark sky conditions, with the completeness rapidly falling off at magnitudes fainter than 19.25 mag in V-band. In previous work, the sensitivity of the TESS full-frame images for observing solar system bodies with good photometry was estimated by Pál et al. (2018) to be 19th magnitude in V-band and more recent work using TESS FFIs to extract lightcurve data on known asteroids has demonstrated sensitivity to magnitude \( \sim 18.6 \) in the TESS \( I_c \) band, corresponding to about magnitude 19.3 in V-band (Pál et al. 2020).

In order to separate the sensitivity due to object angular rate from the detection sensitivity of the pipeline, the set of objects used for comparison in understanding the sensitivity of the pipeline to angular rate was further limited to objects brighter than 18.5 mag in V-band, where the TESS pipeline performance is not dominated by the object brightness. The right panel of Figure 13 shows that the TESS pipeline can reliably detect objects moving 1–1.5 deg day\(^{-1}\) and is able to detect some objects moving as fast as 4.5 deg day\(^{-1}\). Unfortunately, the number of catalog objects predicted to be moving quickly through the TESS FOV in each sector is small, which makes the data on the fast end sparse.

The injection of synthetic detections into the TESS image data prior to point source detection and moving object linkage could provide a more complete estimate of the TESS pipeline sensitivity to moving objects as a function of brightness and velocity, particularly for fast moving objects where there are relatively few objects in the catalog to compare against. We have opted not to pursue this option for assessing the completeness of the LINEAR-TESS pipeline because of the technical difficulty of reliably injecting accurate targets into the TESS imagery. The TESS PSF is highly irregular and varies significantly as a function of field angle. Therefore, the problem of accurately inserting synthetic detections is non-trivial and to do so carefully would be a significant development effort that would yield only modest improvements in our understanding of pipeline performance. In estimating the limiting magnitude of the TESS survey, the known asteroid catalog provides a high-quality source of truth detections well beyond the limiting magnitude of the TESS system and allows us to make reasonable estimates of the true detection performance of the system.

In Figure 14 we inspect the velocity distribution of detections from all tracks generated by the pipeline, including those that do not correlate to the known catalog. The number of objects observed peaks at apparent velocities between 0.2 and 0.3 deg day\(^{-1}\), consistent with the main belt population. The fastest objects from our pipeline reach up to 5 deg day\(^{-1}\), which corresponds to a streak length of 18 pixels in the 30 minutes frame. Our validation of the fast-moving objects through visual inspection of track frames and stacked images indicates that most of the fast-moving tracks represent real detections.

A summary of the LINEAR-TESS pipeline detection statistics from year 1 data is provided in Table 1. The table shows the number of calibrated image frames available from the MAST, as well as the number of frames included in track processing after removing frames affected by pointing jitter, significant DVA, or stray light. The number of frames removed...
Figure 14. The number of detected objects peaks between 0.2 and 0.3 deg day$^{-1}$, for the year 1 data consistent with observations of the main belt population. A few tracks are generated with motions of up to 5 deg day$^{-1}$. The left and right panels show the same data set with different range of velocities for visibility of the faster moving population.

Table 1
LINEAR-TESS Year 1 Observing Statistics

| Sector | # Frames in Initial Set | # Frames Used in Track Detection | # Observations Submitted to MPC | # Tracks Submitted to the MPC | # Estimated Unique Catalog Objects | # Unmatched Tracks |
|--------|-------------------------|---------------------------------|--------------------------------|-------------------------------|----------------------------------|-------------------|
| 1      | 1267                    | 1248                            | 565,317                        | 4914                          | 1527                             | 88                |
| 2      | 1228                    | 1219                            | 840,782                        | 6369                          | 1865                             | 173               |
| 3      | 1204                    | 1178                            | 795,407                        | 6391                          | 2175                             | 200               |
| 4      | 1045                    | 1025                            | 825,838                        | 8449                          | 3022                             | 45                |
| 5      | 1188                    | 1149                            | 773,033                        | 7423                          | 2466                             | 162               |
| 6      | 975                     | 925                             | 374,588                        | 5159                          | 1877                             | 82                |
| 7      | 1086                    | 1072                            | 388,645                        | 4950                          | 1896                             | 114               |
| 8      | 963                     | 931                             | 356,488                        | 4180                          | 1921                             | 32                |
| 9      | 1141                    | 1123                            | 458,455                        | 4448                          | 1927                             | 32                |
| 10     | 1177                    | 1150                            | 380,925                        | 4102                          | 1916                             | 43                |
| 11     | 1279                    | 1249                            | 383,932                        | 4184                          | 1796                             | 73                |
| 12     | 1241                    | 1195                            | 211,261                        | 3027                          | 1180                             | 29                |
| 13     | 1308                    | 1281                            | 306,402                        | 4054                          | 1363                             | 45                |
| ALL    | 15,102                  | 14,745                          | 6,661,073                      | 67,650                        | 24,836                           | 1118              |

Notes.

a On average for all of the CCDs.

b Not necessarily unique objects. In some cases, multi-day linking misses the connection, and multiple tracks observed on different days will correlate to the same object. On average we report 2.7 sections of tracks for each unique object.

c Objects reported in each sector are unique to the sector. Total number of objects for all sectors is unique across all sectors, and only once counts the 95 objects seen in multiple sectors.

d This number includes tracks that pass our visual verification step and are not matched to the catalog of known objects.
Table 2

| Sector | # Frames Used in Track Detection | # Observations Submitted to MPC | # Tracks Submitted to the MPCb |
|--------|---------------------------------|---------------------------------|--------------------------------|
| 14     | 1237                            | 1204                            | 6013                           | 136                            |
| 15     | 1190                            | 1124                            | 8958                           | 180                            |
| 16     | 1118                            | 1098                            | 14,827                         | 373                            |
| 17     | 1126                            | 1060                            | 445,221                        | 5581                           |
| 18     | 1103                            | 1004                            | 486,820                        | 6167                           |
| 19     | 1150                            | 1132                            | 468,210                        | 6929                           |
| 20     | 1183                            | 1155                            | 629,004                        | 8706                           |
| 21     | 1262                            | 1215                            | 758,250                        | 8109                           |
| 22     | 1246                            | 1213                            | 640,981                        | 6175                           |
| 23     | 1235                            | 946                             | 490,888                        | 5212                           |
| 24     | 1224                            | 1209                            | 15,543                         | 234                            |
| 25     | 1167                            | 1146                            | 18,097                         | 208                            |
| 26     | 1146                            | 1054                            | 13,323                         | 170                            |
| ALL    | 15,387                          | 14,562                          | 3,996,135                      | 48,180                         |

Notes.

a On average for all of the CCDs.
b Not necessarily unique objects. In some cases, multi-day linking misses the connection, and multiple tracks observed on different days will correlate to the same object. On average we report 2.7 sections of tracks for each unique object.

varying by CCD; the average over all of the CCDs for the given sector is reported in the table. The number of observations submitted to the MPC counts each position measurement, i.e., each asteroid at each point in time. We estimate the number of unique catalog objects using our match to the propagated catalog. Designations are in the process of being formally assigned by the MPC, and the MPC will provide the official results once that process is complete. Our analysis shows we detect 24,836 unique objects out of the 67,650 tracks reported to the MPC in the year 1 data. Multiple sections of tracks from different days will correlate to the same object at a rate of approximately 2.7 tracks per unique object. Of the 67,650 total tracks, 1260 do not match to known objects. Visual review of the imagery associated with each unmatched track by multiple members of our team suggests that approximately 1118 of the unmatched tracks are true detections, and the remaining 142 are caused by artifacts and the rest are likely true detections. The fraction of spurious tracks compared to all tracks submitted to the MPC in the year 1 data is therefore ~0.2% (142/67,650).

We present a more limited set of statistics from the year 2 data in Table 2, in which we submitted 4.0 million observations in 48,180 tracks to the Minor Planet Center. Based on the scaling from the year 1 data of approximately 2.7 tracks per unique object, we estimate that these tracks represent 17,844 unique objects. Note that the relatively small numbers of tracks in sectors 14–16 and 24–26 is a result of the TESS sky coverage shifting far from the ecliptic plane (see Figure 2).

6. Summary

We have developed the software capability, based on the LINEAR pipeline built by our team for asteroid detection with the 3.5 m Space Surveillance Telescope, for the detection of asteroids in the TESS mission data. The TESS mission observed in the Southern hemisphere during the first year and in the Northern hemisphere during the second year of operations. Asteroid observations generated from the TESS data include more than 10 million observations of an estimated 42,000 unique objects. The completeness for the single frame detection of asteroids from the year 1 data is >90% complete at V-band magnitude brighter than 19.0 under dark sky conditions, with the completeness rapidly falling off at magnitudes fainter than 19.25 mag in V-band. Asteroids are detected out to an apparent velocity of 5 deg day$^{-1}$, corresponding to a streak length of 18 pixels in a 30 minutes frame.

The observations have been submitted to the Minor Planet Center for inclusion in their catalog. We will continue to run the LINEAR-TESS pipeline on all TESS data as it becomes available, and will make the asteroid observations available through the Minor Planet Center. Future improvements to the pipeline include new methods for multi-frame processing for faint streak detection and improved treatment of stray light in the images. As additional modes of observation are generated during the extended mission, we will adapt the pipeline to take advantage of new opportunities for detections on different timescales.

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