PRECOVERY OF TESS SINGLE TRANSITS WITH KELT

XINYU YAO,1 JOSHUA PEPPER,1 B. SCOTT GAUDI,2 THOMAS G. BEATTY,3,4
NICOLE D. COLÓN,5 DAVID J. JAMES,6 RUDOLF B. KUHN,7,8
JONATHAN LABADIE-BARTZ,1,9 MICHAEL B. LUND,10 JOSEPH E. RODRIGUEZ,6
ROBERT J. SIVERD,11 KEIVAN G. STASSUN,10,12 DANIEL J. STEVENS,2
STEVEN VILLANUEVA, JR.,2 AND DANIEL BAYLISS13

1Department of Physics, Lehigh University, 16 Memorial Drive East, Bethlehem, PA 18015, USA
2Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA
3Department of Astronomy & Astrophysics, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA
4Center for Exoplanets and Habitable Worlds, The Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA
5NASA Goddard Space Flight Center, Exoplanets and Stellar Astrophysics Laboratory (Code 667), Greenbelt, MD 20771, USA
6Harvard-Smithsonian Center for Astrophysics, 60 Garden St, Cambridge, MA 02138, USA
7South African Astronomical Observatory, P.O. Box 9, Observatory 7935, South Africa
8South African Large Telescope, P.O. Box 9, Observatory 7935, South Africa
9Department of Physics and Astronomy, University of Delaware, Newark, DE 19716, USA
10Department of Physics and Astronomy, Vanderbilt University, 6301 Stevenson Center, Nashville, TN 37235, USA
11Las Cumbres Observatory Global Telescope Network, 6740 Cortona Dr., Suite 102, Santa Barbara, CA 93117, USA
12Department of Physics, Fisk University, 1000 17th Avenue North, Nashville, TN 37208, USA
13Department of Physics, University of Warwick, Gibbet Hill Road, Coventry CV4 7AL, UK

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ABSTRACT

The NASA Transiting Exoplanet Survey Satellite (TESS) mission will discover thousands of candidate transiting exoplanets. Due to the mission configuration, 74% of the area to be observed by TESS will only have an observational baseline of 27 days. For those planets with orbital periods longer than 13.5 days, TESS can only capture one or two transits, which means the true ephemerides will be difficult to determine from TESS data alone. Follow-up observations of the transits of these candidates to efficiently confirm and characterize them will require precise ephemerides. We explore the value of using existing ground-based wide-field photometric surveys to constrain
the ephemerides of the TESS single-transit candidates. The Kilodegree Extremely
Little Transit (KELT) survey has a long observation baseline (up to eight years) and
monitors fields that largely overlap with the TESS footprint, and also observes stars
of similar brightness. We insert simulated TESS-detected single transits into KELT
light curves, and evaluate how well their orbital periods can be recovered. We find
that KELT photometry can be used to confirm ephemerides with high accuracy for
planets of Saturn size or larger with orbital periods as long as a year, and therefore
span a wide range of planet equilibrium temperatures. In a large fraction of the sky
we recover 30% to 50% of the warm Jupiter systems (planet radius of 0.9 to 1.1 $R_J$
and $13.5 < P < 50$ days), 50% to 80% of the warm inflated Jupiters (planet radius of
1.1 to 2 $R_J$), 5% to 18% of the temperate Jupiters ($50 < P < 300$ days), 10% to 50%
of the temperate inflated Jupiters and 10% to 30% of the warm Saturns (planet radius
of 0.5 to 0.9 $R_J$ and $13.5 < P < 50$ days). The resulting periods and ephemerides of
the signals can then be used by follow-up teams, whether part of the TESS mission or
community-organized TESS follow-up, to plan and coordinate follow-up observations
to confirm candidates as planets, eclipsing binaries, or other false positives, as well
as to conduct detailed transit observations with facilities like JWST or HST.

Keywords: planets and satellites: detection — planets and satellites:
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1. INTRODUCTION

Of the $\sim$3,700 exoplanets discovered to date, $\sim$2,900 of them are known to transit their host star. The vast majority of known transiting planets have come from two types of surveys. The space-based missions CoRoT (Auvergne et al. 2009), Kepler (Borucki et al. 2010; Koch et al. 2010), and the reborn K2 mission (Howell et al. 2014), have discovered nearly 2,600 transiting planets, representing 90% of all known such planets. The other main source of known transiting planets are the ground-based transit surveys that use relatively wide field telescopes such as SuperWASP (Street et al. 2003), HATNet (Bakos et al. 2004), HATSouth (Bakos et al. 2013), KELT (Pepper et al. 2007, 2012), XO (McCullough et al. 2005), TrES (Alonso et al. 2004), and QES (Alsubai et al. 2013).

Discovering large numbers of exoplanets can reveal the underlying demographics and frequencies of various types of planets (Mayor et al. 2011; Howard et al. 2012), and for more recent analysis see Fulton et al. (2017); Johnson et al. (2017); Petigura et al. (2017a,b); Weiss et al. (2017). Transiting planets are especially valuable because the transit itself constrains the planet radius and orbital inclination, and together with radial velocity observations, it provides the mass and density of the planet. Furthermore, for transiting planets it is possible to study the atmosphere of the planet via transmission or emission spectroscopy (Charbonneau et al. 2002, 2005; Deming et al. 2005) and constrain the planet’s eccentricity with secondary eclipses. However, those atmospheric observations generally require bright host stars to provide the needed signal-to-noise ratio for spectroscopic observations and thus radial velocity confirmation and mass measurements.

The bulk of known transiting planets come from Kepler and K2, and most of those orbit faint host stars. Of the 1776 transiting planet host stars with a known optical magnitude discovered by the space missions Kepler, K2, or CoRoT, only 85 have an optical magnitude brighter than $V < 12$, and only 9 are brighter than $V < 10^1$. The ground-based surveys are generally sensitive to brighter host stars; 125 of the 224 host stars of planets discovered by those surveys are brighter than $V \sim 12$, and 23 are brighter than $V \sim 10$. However, most of the planets discovered by the ground-based surveys are in very short-period orbits, with none of the ground-based discoveries having orbital periods longer than 20 days. Figure 1 shows that only 12 known transiting planets have host stars brighter than $V \sim 10$ and also have orbital period longer than 20 days. This is due to a well-known selection effect against longer period planets in transit surveys (e.g. Pepper et al. 2003; Gaudi et al. 2005). Since atmospheric studies of planets benefit from being able to probe a range of planetary equilibrium temperatures, this region of parameter space (planets on long periods orbiting bright host stars) must be populated with new discoveries before a more comprehensive study of exoplanet atmospheres can be undertaken.

\footnote{https://exoplanetarchive.ipac.caltech.edu/}
The Transiting Exoplanet Survey Satellite (TESS) is designed to detect transiting planets of bright stars across the whole sky. However, most of the TESS transit detections will have short orbital periods, due to the short TESS observing time for most of the sky (\(~ 27\) days). In this paper, we explore the potential of combining data from an existing ground-based survey (specifically, the Kilodegree Extremely Little Transit [KELT] survey) with TESS observations. The goal is to refine the orbital properties of the long-period transiting exoplanets orbiting bright hosts discovered by TESS, which will be extremely valuable for the ability to probe transiting planets at a range of equilibrium temperatures. We test the feasibility of this endeavor by simulating single transit events as detected by TESS, and then inserting them as periodic signals into real KELT light curves. We then use standard techniques to recover those signals from the KELT data, and characterize how the recovery rate depends on the properties of the simulated planets and stars. The approach is effectively “precovery” of TESS-detected signals from existing data, in which we leverage the information provided by the TESS single transit detections as constraints on the automated search for transits in the existing ground-based survey data.

**Figure 1.** Optical magnitude versus orbital period of host stars of known transiting exoplanets. The region inside the red dashed lines shows the 12 exoplanets with bright hosts and orbital periods longer than 20 days. The data displayed here comes from the NASA Exoplanet Archive, accessed on May 15, 2018.
One of the key goals of TESS is to discover transiting planets orbiting bright stars to provide a rich set of targets for detailed atmospheric measurements by HST and JWST. Spectroscopic observations can reveal a planet's atmospheric composition, structure, and dynamics, and is a key objective of JWST (Beichman et al. 2014). Atmospheric observations using transmission or emission spectroscopy, verification of planet eccentricity and albedo through secondary eclipse observations, spin-orbit alignment measurements, and transit timing observations all require the ability to schedule observations at future transit times. Given the high demand for space telescope time, transit observations must be known to a precision of roughly 30 minutes, otherwise precious observing time on high-demand telescopes will potentially be wasted.

It is already known that the ephemerides of even multiple-observed transits degrade over time, and any improvement offered by archival data can save such systems for future space-based transit observation. Benneke et al. (2017) demonstrated that this kind of ephemeris improvement was necessary for a 33-day period candidate (K2-18b) observed in the 80-day K2 observing window (see also Stefansson et al. (2018) for more examples).

In this paper, we explicitly do not attempt to model or predict the number of single-transit detections that TESS will make (see Villanueva et al. (2018) for such predictions), nor the number of those that the KELT data will be able to precover. Rather, what we investigate here is the overall efficiency of the precovery procedure to establish the ephemerides of single-transit systems across a range of empirical properties, regardless of the abundance of such systems that are actually seen by TESS.

We discuss the nature of the data used to conduct this analysis in Section 2, including a description of why the KELT survey is specifically useful for this project. Section 3 describes the methodology for inserting transits and recovering the signals. Section 4 presents the results of the recovery tests, describing the types of transiting planets for which this method can be successfully applied. In Section 5 we discuss the significance of our findings and ways to build upon these initial results.

2. DATA

2.1. The TESS mission

TESS (Ricker et al. 2015) is a NASA mission that will monitor bright and nearby stars for transiting planets, with a prime mission lasting two years. The combined field of view is $24^\circ \times 96^\circ$ with four $4096 \times 4096$ pixel CCDs, at $\sim 21''$ per pixel, and a bandpass between 600 nm and 1000 nm, referred to as $T$-band. It will acquire observations in two modes. A selection of about 200,000 stars will be observed at a 2-minute cadence, while all stars in the field of view will be observed at a 30-minute cadence, including about 30 million stars brighter than $T = 15$. The short-cadence
observations are commonly referred to as the postage-stamp targets, while the longer
cadence observations are referred to as Full Frame Image (FFI) targets.

The 2-min TESS targets are selected based on the suitability for detection of small
transiting planets. That requirement leads generally to a selection of bright, cool,
dwarf stars. The target selection process must account for a number of factors, and
can lead to a range of expected planet yields. Papers that have looked at the expected
yields include Sullivan et al. (2015), Bouma et al. (2017), and Barclay et al. (2018).
Each of these papers simulates the TESS survey, and the resulting physical and
observational properties of the detected planets. They find that while the key goals
of TESS generally center on small planet discovery, TESS will also discover hundreds
of planets larger than $4R_\oplus$ from the 2-minute observations, and of order thousands
such planets from the FFIs, with rough agreement between those two predictions
about the numbers of planets that will be detected of different sizes.

TESS will observe the sky in a set of pointed observations in which the spacecraft
will nearly continuously observe a section of the sky stretching from the ecliptic to
the ecliptic pole for 27 days, with each section referred to as a sector. The mission
will step around ecliptic longitude over the course of 13 sectors to cover most of an
ecliptic hemisphere over the course of a year, and then rotate and observe the other
hemisphere. Near the ecliptic poles, subsequent sectors will overlap, so that stars in
those regions can be observed for many months. However, the majority of the sky
observed by TESS (74%) will have an observational baseline of only $\sim 27$ days. For
those transiting exoplanets that have orbital periods longer than 13.5 days, TESS
can only capture one or two transits, and for periods longer than 27 days, TESS can
only capture one transit. In these cases, the true ephemerides of the planets will be
difficult to determine from TESS data alone.

Sullivan et al. (2015) predict that long period planets ($P > 20$ days) will account for
approximately 20% of the TESS transit detections, while Bouma et al. (2017) find
similar expectations. Since follow-up confirmation observations are expensive in time
and resources, the ability to determine the precise ephemerides for these systems is
extremely valuable. Even though the orbital period can be roughly estimated from
a single transit (Seager & Mallén-Ornelas 2003; Yee & Gaudi 2008; Osborn et al.
2016), additional information is still needed to precisely determine these ephemerides
and reduce the associated uncertainty in the transit time. These estimates require
an assumption or constraint on the orbital eccentricity, as well as a precise estimate
of the density of the host star, and are often fairly imprecise, thereby necessitating
either extensive photometric follow-up, or radial velocity observations (Yee & Gaudi
2008).

Villanueva et al. (2018) have done a comprehensive simulation and investigation
into the likely TESS single-transit population. They predict about 1200 single-transit
events in TESS. Those numbers are higher than that of the other simulation efforts by
factors of 20% to 50%, but possibly because the other simulations are not as complete
at the long-period end. The actual number of single-transit detection will depend on many observational factors unknown at the present, but all indications are that there will a minimum of several hundred such cases.

2.2. The KELT survey

The Kilodegree Extremely Little Telescope (KELT) transit survey (Pepper et al. 2007, 2012) is a photometric survey using two small-aperture (42 mm), wide field ($26^\circ \times 26^\circ$) telescopes located at Winer Observatory in Arizona, US, (KELT-North) and the SAAO observing station in Sutherland, South Africa, (KELT-South). Each camera contains a CCD with $4096 \times 4096$ pixels and provide a pixel scale of roughly $23''$ pixel$^{-1}$. The effective passband that KELT uses is roughly equivalent to a broad $R$-band filter. The KELT fields cover about 70% of the sky including a very large fraction of the TESS footprint in both year 1 and year 2 of the TESS mission. Figure 2 shows a map of KELT fields, along with Kepler and K2 fields, and a sample set of TESS fields. Table 2 lists the names of KELT fields with the sky coordinates of the field centers. Fields are observed every season since their first observation, with observations starting between 2005 and 2013. Although some fields have been observed for over twelve years, the reduced data available for the analysis in this paper only contained observations for the first eight years of the survey, which sets the maximum time baseline used in the analysis here. The observing procedure leads to an average cadence of about 20 minutes, with $\sim$1500 observations every year. All KELT fields overlap at least partially with TESS fields. The photometric precision of KELT ranges from several mmag RMS at the bright end of its magnitude range, around $V = 7.5$, where stars begin to saturate in normal KELT observations, to $\sim$5% RMS around $V = 13$. The KELT survey is optimized for the discovery of transiting planets in the range $8 < V < 10$, and to date has discovered 23 exoplanets (see Pepper et al. (2018) for references).

KELT has several features which make it especially useful for combination with TESS. The magnitude range of greatest photometric sensitivity overlaps with that of TESS. The wide field of KELT ($26^\circ \times 26^\circ$) allows it to cover a large fraction of the entire sky, and the relatively stable and regular observing strategy provides light curves with consistent noise and sampling properties over long time baselines.

3. METHODS

3.1. General Approach

Although the KELT survey has a lower photometric precision and duty cycle than TESS, the KELT fields cover a large fraction of the TESS footprint in both the first year of TESS observations of the southern ecliptic hemisphere and the second year of TESS observations of the ecliptic north (Figure 2), and the KELT light curves have long time baselines. Furthermore, KELT data are essentially uncorrelated on timescales of longer than a few hours. When phased and binned on 20-hour timescales (the duration of a long-period transiting planet, the RMS of the detrended KELT
Figure 2. Equatorial map of the sky, with the galactic plane displayed in pink. Colors indicate the locations of the KELT fields (green), the Kepler and K2 fields (cyan), and a sample location layout for the TESS fields (blue).

lightcurves is typically 0.5 mmag. Thus, for single-transit TESS detections with deep enough transits, KELT can detect the signals in phase-folded data, and determine the ephemerides of the TESS single-transit candidates. Our overall approach is therefore to simulate TESS single-transit detections, insert the transits into a selection of KELT light curves, and attempt to recover the inserted signals using standard techniques.

3.2. Selection of KELT Light Curves

In the analysis for this paper, we made use of KELT light curves already obtained for the survey transit search (see Siverd et al. (2012) and (Kuhn et al. 2016) for details). Since the reduction and extraction of KELT light curves is a time-intensive process, we did not make use of the entire set of KELT data, but we will use the full KELT data set by the time TESS light curves are publicly released.

KELT uses a German equatorial mount, which requires a flip as it tracks stars past the meridian. Thus, the optics and detector are rotated 180 deg with respect to the stars between observations in the Eastern and Western sides of the meridian. As a result of that meridian flip, a given star experiences different detector defects, optical distortions, PSF shape, flat-fielding errors, etc., in each orientation. Those conditions require us to treat observations in the east and west essentially as two separate data sets (Siverd et al. 2012). We also use the Trend Filtering Algorithm (TFA) (Kovács et al. 2005) to correct various types of systematic noise. This results in 4 separate light curves for each KELT star: an uncorrected east version, and uncorrected west version, and a TFA-processed version of each.

We first select high quality KELT light curves, meaning those with relatively low RMS. In each KELT field, we create a plot of the RMS of each KELT light curve
Table 1. KELT field locations (J2000.0)

| Field | RA (deg) | DEC (deg) | Field | RA (deg) | DEC (deg) | Field | RA (deg) | DEC (deg) |
|-------|---------|-----------|-------|---------|-----------|-------|---------|-----------|
| N01   | 001.50  | 31.67     | N21   | 200.80  | 57.00     | S19   | 046.00  | -53.00    |
| N02   | 030.52  | 31.67     | N22   | 240.80  | 57.00     | S20   | 069.00  | -53.00    |
| N03   | 059.54  | 31.67     | N23   | 280.80  | 57.00     | S21   | 091.80  | -53.00    |
| N04   | 088.56  | 31.67     | N24   | 320.80  | 57.00     | S22   | 138.00  | -20.00    |
| N05   | 117.58  | 31.67     | N25   | 054.09  | 79.00     | S23   | 161.00  | -20.00    |
| N06   | 146.60  | 31.67     | N26   | 126.46  | 79.00     | S24   | 184.00  | -30.00    |
| N07   | 175.62  | 31.67     | N27   | 197.61  | 79.00     | S25   | 207.00  | -30.00    |
| N08   | 204.64  | 31.67     | N28   | 269.76  | 79.00     | S26   | 230.00  | -20.00    |
| N09   | 233.66  | 31.67     | N29   | 342.12  | 79.00     | S27   | 299.00  | -53.00    |
| N10   | 262.68  | 31.67     | S05   | 091.80  | 03.00     | S28   | 322.00  | -53.00    |
| N11   | 291.70  | 31.67     | S06/N14 | 114.90 | 03.00    | S29   | 345.00  | -53.00    |
| N12   | 320.72  | 31.67     | S12/N15 | 253.00 | 03.00    | S30   | 045.00  | -36.00    |
| N13   | 349.74  | 31.67     | S13   | 276.00  | 03.00     | S35   | 115.05  | -20.00    |
| N16   | 000.80  | 57.00     | S14   | 299.00  | 03.00     | S36   | 261.00  | -53.00    |
| N17   | 040.80  | 57.00     | S15   | 322.00  | 03.00     | S37   | 226.80  | -53.00    |
| N18   | 080.80  | 57.00     | S16   | 345.00  | 03.00     | S38   | 192.60  | -53.00    |
| N19   | 120.80  | 57.00     | S17   | 000.00  | -53.00    | S39   | 158.40  | -53.00    |
| N20   | 160.80  | 57.00     | S18   | 023.00  | -53.00    |

(before and after TFA-processing) versus approximate V-band magnitude, bin the data in magnitude space between $V = 9$ and $V = 11$, and fit a curve to the 70th percentile of RMS in each bin. We define the set of light curves below that fitted curve and also below a fixed limit of 30 mmag RMS as the “high-quality” KELT light curves for that field. We also require that each light curve must have at least 3000 observations. This process is carried out separately for all the KELT light curves in each field orientation.

An example of the selection method in one field is shown in Figure 3. The orange line represents the 30 mmag limit of RMS, while the blue line is fitted to the 70th percentile of the RMS range in each bin. Stars whose light curves (in both raw and detrended version) fall below both the orange and blue lines are selected for analysis.

If both the east and west light curve of a star pass these cuts, then the light curves are combined into a single light curve and used for later steps. However, if the star only passes in east (west) field, then the light curve in only east (west) field is used. In all, $\sim 360,000$ stars are selected from the 4.5 million KELT stars with light curves. The selected stars are then cross-matched with the TESS Candidate Target
List (CTL; Stassun et al. 2017). The CTL contains stellar information such as TESS mag (T-mag), $T_{\text{eff}}$, stellar mass, and radius.

We end up with $\sim$133,000 combined KELT light curves matched to the TESS CTL ($\sim$70,000 light curves in northern KELT fields and $\sim$63,000 light curves in southern KELT fields). In addition, $\sim$52,000 KELT light curves in solely east or west orientations are selected. The fact that less than half the high-quality KELT light curves match to the CTL is not surprising. The CTL contains only stars that are especially useful for transit detection, meaning that giant stars and very hot stars (OBA spectral types) are generally excluded, while no such restriction was applied to the KELT light curves.

We display distributions of the number of observations and observational time baseline for all KELT light curves that pass these cuts in Figure 4. Because KELT-North has been observing for longer than KELT-South, and generally has more observations and a longer time baseline, we split the two sets of light curves. For the selected KELT-North light curves, the number of observations is irregularly distributed be-

Figure 3. RMS vs. approximate V magnitude for raw data in one example field (west field of N05) with selection criteria. The orange dashed line represents the 30 mmag cut; blue dots correspond to the 70th percentile RMS in each 0.25 magnitude bin between $V=9$ and $V=10.25$, and the blue solid line represents the fit to the dots. Stars brighter than $V \sim 7.5$ experience saturation and nonlinearity effects, and so have large scatter.
between 3,000 and 11,000, while the baselines range from 2.5 years up to \( \sim 8 \) years. For the selected KELT-South light curves, the number of observations is irregularly distributed between 3,000 and 8,000, while the baselines range from 2.5 years up to \( \sim 6 \) years. The KELT survey is ongoing, and the number of observations and length of the observing baseline will continue to grow as new observations are made, and as more existing data are reduced.

KELT is a magnitude-limited survey. As such, it is affected by selection biases including Malmquist bias (Bieryla et al. 2015). As a result of that, plus the selection of the brighter, low-RMS light curves, the stars that make it past the cuts tend to be solar mass or greater. Figure 5 illustrates the stellar properties for the matched KELT-North combined light curves. Most stars are generally F-type, with radii between 1 and 2.5 \( R_\odot \), masses between 1 and 2 \( M_\odot \), and effective temperatures between 5500 and 7500 K. The TESS magnitudes range mostly from 9 < \( T < 11 \).

3.3. Inserting Simulated Transits

We assume that the transit depth \( \delta \), transit duration \( T \), and mid-transit times \( (T_C) \) will be easily measurable in TESS data for the events relevant to this work. Since the smallest RMS for the brightest stars in KELT data is a few mmag, we are only considering events detected in TESS with depths of this order and larger. This corresponds very roughly to planetary radii larger than 4\( R_\oplus \) for planets transiting mid-type main sequence stars.

The following parameters were used to insert box-shaped transits into each selected KELT light curve: The \( T_C \) was generated randomly between July 1st, 2018 and July 1st, 2020 corresponding to the expected start and end of the primary TESS mission; the orbital period was assigned randomly from 13.5 days to 300 days in log space; 
Figure 5. Histograms of stellar properties (radius, mass, TESS magnitude and effective temperature) for the matched KELT-North combined light curves.

The transit depth was assigned randomly from 3 mmag to 20 mmag in log space; the transit duration was estimated based on Equation (18) and (19) of Winn (2010) by assuming equatorial transits in a circular orbit ($b = 0$):

$$T = 13 \text{ hr} \left( \frac{P}{365 \text{ days}} \right)^{1/3} \left( \frac{\rho_*}{\rho_{\odot}} \right)^{-1/3}.$$  

(1)

The stellar density $\rho_*$ in equation (2.1) was calculated from stellar mass and radius obtained from CTL-6.

The particular ranges of transit depth and orbital period we probe here are based on a rough accounting of where the KELT data will be most useful. The single-transit events seen by TESS will generally have minimum orbital periods of half the 27-day observing baseline for a sector, or 13.5 days. We use 300 days as a convenient
Precovery of TESS Single Transits

13

outer range for periods to probe, although see the discussion at the end of the paper for comments on that limit. We selected a minimum depth of 3 mmag since that is about the shallowest transit for which a transit can be detected in KELT data, and a maximum depth of 20 mmag since that is approximately the greatest transit depth observed to date, although there are a handful of known transiting planets with larger transit depths. We also reject those inserted light curves (∼15% of the total sample) whose transit signals correspond to transit planets with radius larger than twice Jupiter’s radius.

Since transit signals are inserted randomly into the light curves, the properties of the host stars are uniform across the range of transit depths and orbital periods. However, we can use equation 1 to relate the inserted orbital periods, along with the stellar densities, to plot the distribution of stellar properties across transit duration in Figure 6. We see that the distribution of stellar parameters is clearly not uniform across transit duration. Specifically, smaller, higher density, cooler stars exhibit shorter transit durations. Since the transit duration for a given orbital period depends on the mass and radius of the star, signals that were inserted with a given period will have shorter duration for smaller stars. Long duration transits generally correspond to those with long orbital periods, as in equation 1. But they also scale with the low stellar densities and hence large stellar radii, and are therefore preferentially hotter stars or sub-giants. These features have important implications for the use of this analysis for TESS users, as explained in the discussion below.

3.4. Recovery of Inserted Transits

We use the box-fitting least-squares algorithm (BLS) (Kovács et al. 2002), as implemented in the VARTOOLS (Hartman & Bakos 2016) software package, to search for transits in the KELT data with a fixed transit duration at a given $T_C$, using the values from the inserted signals. The concept behind this approach is that since the parameters $T_C$ and $T$ for a given transit signal will be known with high fidelity from the TESS observations, we can then search the KELT light curves for repeating transit signals with the same duration and transit time as seen in the TESS data. While we could also require that the search algorithm require the transit depth to be the same as seen in the TESS data, we believe that such a restriction would not be advisable. Although KELT and TESS have roughly similar pixel scales, the different bandpasses, field angles, and other properties of the telescopes yield different blending properties for the same stars, and thus different measured transit depths are expected. We searched for signals with periods ranging from 10 days to 310 days, with a frequency resolution of 300,000. This period range is similar but not identical to the inserted period range.

4. RESULTS

For the bulk of the analysis we present here, we investigate only the collective results using KELT-North lightcurves. Compared to KELT-South, the KELT-North data
Figure 6. Distributions of stellar properties (radius, mass, density and effective temperature) in transit duration parameter space for the matched KELT-North combined light curves, with stellar properties taken from the TIC. The light gray region corresponds to the median absolute deviation in one hour bins. Note that since the TIC determines stellar mass based on $T_{\text{eff}}$ (see section 3.3.2 of Stassun et al. (2017)), the plot of stellar mass looks almost identical to that of temperature.

Cover longer time baselines and have more total observations, and will generally yield larger rates of precovery. We do that partly to provide an optimistic perspective on the value of this effort for TESS. Also, since the data available at the time of this analysis does not include the last one to four years of KELT data (still being reduced), the larger current KELT-North data set is a better reflection of the KELT data available for precover in the next year. For completeness sake, we include summary plots of the KELT-South precovery rates at the end of the paper.

For a successful recovery of an inserted transit signal, we require that the percent error between the output period and the inserted period be within 0.01%. That
limit was selected because we find it to naturally divide the populations of recovered versus failed cases, as shown in Figure 7. The exact value of the cut is somewhat arbitrary, but can be shifted with little overall effect on the overall results. However, for the frequency spacing used in this analysis (300,000), the cut cannot be much smaller than that, without running into the resolution of the retrieved period at the long-period end.

This criterion cannot be used to determine actual recovery of signals with real data, since it is not an observable, but we can use it to gauge the accuracy of the precovery process for different star, planet, and light curve properties. To examine the practical use of the precovery approach, we investigate the use of the SNR of the recovered transit below in section 4.2.

As is common in searches for periodic variability, we find that a small number of the searches identify a period that is a small fractional multiple of the true period, at a rate much higher than random chance, but not as high as the true period recovery rate. Overall, we find that between 1% and 7% of the inserted signals are found within 0.01% of either 1/2, 3/2, or twice the inserted period. In the analysis below, we do not include those cases as successful recoveries, but we discuss how they might be used in the discussion section.

We can examine how well our results match theoretical expectations. The SNR of a transit (Pepper et al. 2003; Gaudi et al. 2005) is:

$$SNR = \sqrt{N f_tr \frac{\delta}{\sigma}}$$  

where $N$ is the total number of data points in light curve, $f_tr$ is the fraction of time the planet is in transit ($T/P$), $\delta$ is the transit depth and $\sigma$ is the fractional photometric uncertainty. We can express SNR in terms of the stellar density and orbital period:

$$SNR = \sqrt{N \frac{\delta}{\sigma} \left( \frac{3}{G \pi^2} \right)^{1/6} P^{-1/3} \rho_*^{-1/6}}$$  

We can also express SNR in terms of transit duration:

$$SNR = \sqrt{N \frac{\delta}{\sigma} \left( \frac{3}{G \pi^2} \right)^{1/2} T^{-1} \rho_*^{-1/2}}$$

From these equations, we can see that the SNR is proportional to the transit depth, while it has negative correlation with stellar density, orbital period, and transit duration.

4.1. Recovery results

We display the results of these tests in several ways. The simulated recovery rate distributions across transit depth vs. orbital period and transit depth vs. transit duration for the KELT-North combined light curves are shown in Figure 8 and Figure 9, respectively.
In Figure 8, the recovery rates decrease with smaller depths and longer periods monotonically. The inserted transit depths and orbital periods are distributed uniformly across the full set of light curves, and so the number of data points in the light curves, stellar density, and photometric uncertainty, are distributed uniformly across Figure 8. Therefore from Equation 3, the only parameters that affect the recovery rate difference in this plot are transit depth and orbital period.

In Figure 9, the recovery rates no longer vary monotonically from upper left to lower right. This is because stellar densities are no longer uniformly distributed across transit duration (see Figure 6), and the stellar density has negative correlation with transit duration (Equation 1). That is because from Equation 4, the relation between SNR and transit duration becomes more complex. To examine this effect across transit duration, we divided transit duration into 20 bins. In each bin, we calculated the recovery rate and average SNR, and plot them in the same figure to compare their trend (Figure 10). We see that the overall trends are similar in structure. We can see the reasons for this behavior in Figure 6, which shows that at short transit durations the stars are significantly more dense. That explains the decrease in recovery at very short transit durations. Conversely, Equation 4 shows

Figure 7. The histogram and scatter distributions of the fractional period recovery with inserted orbital period for KELT North light curves. The red dashed lines represent 0.01%.
that SNR is a stronger function of transit duration than stellar density. Therefore at long durations, we see an increase in recovery rates.

The plots convey the operational efficiency of the existing KELT light curves in terms of the key parameters of the inserted signals: transit depth and orbital period or transit duration. It is also possible to display the vertical axis not in terms of transit depth, but rather in terms of planet radius $r$, which is shown in Figure 11. The planet radius is calculated based on the inserted transit depth and the host star’s radius from the CTL, assuming perfect deblending of the host star from any nearby neighbors. The listed radius is therefore a “true” depth rather than an “observed” depth. Since the simulated transits were drawn from a logarithmic distribution of depths, rather than radii, a small number of light curves are excluded from the plot, in which the inserted signals represent planets smaller than $0.5 \, R_J$. We have also continued to exclude the small number of initially inserted signals that would represent planets larger than $2 \, R_J$.

For the KELT-North light curves, for warm Jupiter systems (planet radius of 0.9 to 1.1 $R_J$ and $13.5 < P < 50$ days) we recover 30% to 50% of the transits. For warm inflated Jupiter systems (planet radius of 1.1 to 2 $R_J$), we recover 50% to 80% of the transits. For temperate Jupiters ($50 < P < 300$ days), we recover 5% to 18% of the transits, and for temperate inflated Jupiters, we recover 10% to 50%. For warm

\[ \text{Figure 8. Recovery rates of simulated transits for orbital period-transit depth bins of the KELT-North light curves. The grayscale bar indicates the fraction of the transits that are correctly recovered, which is also represented by the percent value in each bin.} \]
Figure 9. Recovery rates of simulated transits for transit duration-transit depth bins
KELT-North light curves. The grayscale bar indicates the fraction of the transits that are
correctly recovered, which is also represented by the percent value in each bin.

Saturns (planet radius $0.5 \text{ to } 0.9 \, R_J$ and $13.5 < P < 50 \, \text{days}$) we recover 10% to 30% of the transits.

4.2. Precovery in Practice

We can display the results of this analysis in a way that would be more useful for
investigators pursuing TESS candidate follow-up. Importantly, the previous plots
considered a successful recovery as one in which the strongest peak in the BLS search
corresponded to an orbital period within 0.01% of the true period. However, no
signal strength criterion was applied. We adopt an approach whereby for each bin
in transit depth-transit duration space, we determine the value of the signal-to-pink-
noise (SPN) ratio such that at least a given fraction of all the light curves in that bin
with that SPN value demonstrate a successfully recovered period.

That information can be seen for the full set of light curves in Figure 12, showing
the distribution of SPN values, along with the fraction of light curves for a given SPN
for which the signal was successfully recovered. At SPN~ 6, half the signals were
recovered, and at SPN~ 7, about three fourths were recovered.

While those fractions provide overall guidance to the SPN threshold to use to de-
termine a likely successful signal detection, it would be more useful to break that
number down across the range of observable parameters from the TESS signals. We
Figure 10. Recovery rate (red line) and calculated SNR (blue line) versus transit duration. The effects of populating planets evenly in period space, but then converting to transit duration, created a more complex trend in transit duration when accounting for the underlying stellar population.

Therefore compute the distributions from Figure 12 across transit depth and transit duration space, and calculate the SPN values for which more than 10%, 50% and 90% of the signals are successfully recovered.

We display the results of that analysis in Figure 13. The plot displays the confidence that a user can have regarding the ability of the KELT data to detect the signal. For each bin, we display the fraction of KELT light curves in the bin such that 90%, 50%, and 10% of the light curves above the corresponding SPN limits are recovered at the correct period. Those numbers provide guidance for how useful the KELT light curves can be for obtaining ephemerides of single-transit signals, depending on the value of individual planet candidates and the availability of observing resources.

For instance, consider the bin for signals with durations of 8.2 to 11.7 hours and depths of 9 to 14 mmag. We find that in 29% of KELT light curves with signals with those properties, the SPN value of the transit search is large enough for a better than 90% confidence that the BLS search recovers the true period. In 43% of light curves, the SPN value is large enough for better than 50% confidence in the recovery reliability, and in 50% of light curves, the SPN value is large enough for better than
Figure 11. Recovery rate distributions displayed across period vs. planetary radius space (left) and transit duration vs. planetary radius space (right) for the KELT-North combined light curves. The color bar indicates the fraction of the transits that are correctly recovered, which is also represented by the percent value in each bin.

10% confidence in the recovery reliability. The corresponding SPN values for each cut are displayed next to the percentage values.

Someone analyzing a single-transit event in TESS with these characteristics can refer to this figure. If the target has a high-quality KELT light curve, and the SPN result of a BLS search is greater than the 90% threshold for that signal, or SPN = 7.8, they can schedule observations to confirm the ephemeris with a 90% confidence of a successful detection. If observational resources are plentiful, the observer may be willing to accept a 10% success rate, and can choose to pursue a large number of targets.

The results described in this section so far make use only of KELT-North data, to demonstrate the potential of this project. For completeness, we display the plots of recovery rates in Figures 19 and 20 below. We see that the overall patterns are similar to those for KELT-North, only with lower recovery rates to the smaller number of data points and shorter time baselines. With the addition of yet-unreduced data for both KELT-North and KELT-South, the recovery rates for both sets should improve significantly. As more data is acquired over the next few years, both the time baseline and number of data points will grow, further improving the recovery rates.

Figures 15 through 18 show example light curves where the inserted signal was successfully or unsuccessfully recovered. A transit with a relatively short period of 35 days and shallow depth of 3 mmag was successfully recovered in Figure 15. A transit with a long period of 250 days and deeper depth of 7 mmag was successfully recovered in Figure 16. An example of a failure to recover is shown in Figure 17. In that case, the transit depth of 5 mmag is too shallow compared to the scatter in the
Figure 12. Distribution of SPN values for all light curves, colored by whether the transit signal was recovered with the correct period. The green color indicates that the recovered period was a low-integer multiple or fraction of the inserted period. The lower panel indicates the fraction of the light curves at a given SPN value in which the signal was successfully recovered. At SPN~6, half the signals were recovered.

KELT data. Figure 18 shows a case where the KELT observations happen to miss the inserted transit completely.

4.3. Considerations for 2-min Targets vs. FFIs

The tests described so far do not depend on whether the TESS planet candidates are extracted from the 2-min postage stamps or the 30-min FFIs. The main difference between the two types of data that we consider here are the longer cadence of the FFIs, which could lead to greater errors in the measured transit duration of the resulting single transits. We examine that effect by taking a subsample of the successfully
Figure 13. Fractions of KELT-North light curves that pass SPN criteria in transit duration-transit depth bins, and the corresponding SPN values. The percentages reflect the fraction of KELT light curves in that bin such that if the SPN value is greater than the indicated value, there is a 10%, 50%, or 90% confidence that the recovered period is correct, from upper left to lower right in each bin. The color bar indicates the fraction of KELT light curves that pass the 50% confidence threshold.

recovered light curves and add a random error to the transit duration ranging from -90 to +90 minutes. Figures 14 shows the impact of the duration error on the recovery rates for different period and depth regimes in the KELT-North combined data. We find that any uncertainty in the transit time and duration caused by the lower cadence of the 30-minute FFIs causes at most a ∼15% reduction in recovery rates.

5. DISCUSSION

Since this work demonstrates that KELT and similar ground-based surveys have the ability to detect significant numbers of long period exoplanets, it is natural to ask why the surveys have not already detected them. That is, the simulations described in this paper do not use actual TESS light curves, rather just signals inserted into archival KELT lightcurves, so if such signals are already in there, why are they not already found? In fact, none of the three most productive ground-based transit surveys (WASP, HAT, and KELT) have detected a transiting planet with an orbital period longer than 20 days.

The reason such signals have not been discovered so far is that long-period planets have smaller SNR, especially for transit surveys that search in phase-folded data,
Figure 14. Recovery rate distribution exploring the effect of an error in the identified inserted transit duration. The plot shows recovery rate for a range of duration error versus orbital period and transit depth for the $\sim$28,000 KELT-North light curves with simulated transits for which the transits were successfully recovered in the previous step.

along with the fact that at longer periods the transit probability is intrinsically smaller. Therefore ground-based surveys would have to intensively look for rare, low-SNR signals, which usually means lowering a SNR threshold on an automated search algorithm. That will result in a large number of spurious false positive candidates, which themselves are more difficult to follow up and confirm for long-period and long-duration signals. Existing surveys like KELT simply do not have the resources to chase that many candidates.

However, the availability of the TESS signal short-circuits that problem. Because TESS sees a transit at a particular time, for a particular star, with a particular transit duration, the parameter space that must be searched by an algorithm like BLS shrinks dramatically. For a given light curve, it is no longer necessary to search through a range of transit phases and transit durations. Rather, the $T_C$ is known, along with the duration, and the only unknown parameter is the period. Therefore the SNR threshold is effectively lowered, and smaller signals can be detected since the spurious signal rate is lowered. Mostly, though, the availability of the TESS signals means that the particular stars with signals are known, shrinking the number of light curves to be searched from hundreds of thousands to hundreds, since only those stars whose light curves that show a signal in TESS need to be searched. That means that the total number of candidates that emerges from the automated cuts is reduced by several orders of magnitude, and can be followed up with a reasonable set of observing resources.

5.1. Potential for Improvement

The procedures outlined here represent a first attempt to quantify the value of ground-based transit surveys for detecting single-transit events in TESS. There are a
number of steps in which we have simplified the analysis, and which can be improved in future work. Some of those steps involve a more realistic set of planet-star system properties. Although we are using real KELT light curves and the actual stellar properties for those stars in from the TIC, we have assumed circular and equatorial transits. A realistic distribution of those parameters would allow for a more accurate set of likely recovery rates. It would also be useful to redo the analysis using realistic transit models that account for limb-darkening, rather then using box-shaped inserted transits. In general, we would not expect that difference to have a large effect (Gould et al. 2006), but it should be investigated especially for stars observed with the 30-minutes cadence by TESS.

Furthermore, the analysis in this paper has addressed the overall sensitivity of the process - we have not attempted to perform an actual simulation of the total numbers of single-transit event TESS will detect, and the resulting total numbers that can be precovered using the KELT data. We intend to conduct such an exercise, using the Villanueva et al. (2018) simulations.

A key issue we have not addressed here is the combination of existing ground-based photometry and radial velocity (RV) measurements. A small fraction (about 5%) of the cases included in this analysis are systems where the inserted transit signal was found at a fractional multiple of the true period. Without additional information, those cases do not represent strong opportunities for follow-up, since it would be necessary to conduct several additional observations to investigate each separate multiple of the precovered period. However, if RV observations were available that ruled out one or more of the common multiples, the probability of catching the transit would significantly increase. In fact, RV observations could enhance the value of photometric precovery overall by constraining the possible orbital periods. The observational needs for such an effort is described in Villanueva et al. (2018) and also in Dragomir et al. (in preparation). The availability of photometric precovery should be a component to such a project, allowing observers to conserve resources by maximizing the probability of ephemeris conformation.

In a similar way, the assumption of a circular or near-circular orbit can be used to estimate the orbital period as outlined by Yee & Gaudi (2008). That information can be used to constrain the precovery results to improve the reliability of the precovery-derived periods at a given SNR, or to increase the number of candidates that can be investigated by selecting a lower SNR cutoff at the same confidence of correct transit recovery.

One final point is that while KELT might be the best-positioned of the current ground-based transit surveys for TESS single-transit precovery, other survey data should also be explored. The SuperWASP and HatNet surveys should have the ability to conduct a similar sort of precovery, especially for the lower-mass stars to which KELT is less sensitive. That is especially the case for the recently started Next Generation Transit Survey (Wheatley et al. 2018, NGTS), and the Multi-site All-Sky
CAMERA (MASCARA) survey (Talens et al. 2017) should be especially sensitive to transits of very bright ($V < 8$) stars. Combining data for the same star from multiple surveys with complementary time baselines and observing seasons offers an especially rich possibility for transit detection, as noted by Fleming et al. (2008).

5.2. Planet Confirmation

Precise ephemerides are important for determining the planetary nature of TESS transit candidates, whether via dynamical confirmation or statistical validation (Morton 2012; Torres et al. 2011). That is because the TESS pixels are very large on the sky, about 20 arcsec across. Because of that large pixel scale, a large fraction of TESS transit candidates will be blended with nearby stars in the TESS photometry. That will create uncertainty about which star is experiencing the transit, diluting the depth of the transit signal itself, and thus affecting the derived planet radius. Depending on the degree of blending and the depth of the transit, the TESS data, along with high-resolution images of the region around the target, can be used to determine the target star and true transit depth. But that will not be the case in all circumstances, primarily for crowded regions and shallow transits. It will therefore be necessary to conduct additional time-series photometry with higher spatial resolution to determine whether the signal is coming from the expected target star or a nearby blended eclipsing binary. In such circumstances, having a precise ephemeris will allow the efficient planning of observations and conserve observing resources. Additionally, reliable ephemerides can allow radial-velocity observers to schedule observations at quadrature for efficient dynamical confirmation of planets.

The TESS mission is planning follow-up observations to confirm planet discoveries through the TESS Follow-On Program (TFOP). TFOP will be focused on confirming the primary targets of the TESS mission, which are small planets with radii smaller than $4 \, R_E$. There is also a project being developed at the NASA Exoplanet Science Institute (NExScI) called ExoFOP-TESS to organize follow-up observations for all other TESS transit candidates, including giant planets and candidates detected in the FFIs. Given the sensitivity of the KELT photometry, this kind of precovery will be particularly useful for the ExoFOP-TESS project.

6. CONCLUSION

Between the targeted postage stamps and the FFIs, the TESS data will contain tens of thousands of detected transiting exoplanets, amidst hundreds of thousands of false positive signals, most of which will be eclipsing binary stars (Sullivan et al. 2015). Having precise and reliable ephemerides for the TESS transit candidates will be crucial for two reasons: planning confirmation observations, and conducting follow-up characterization studies. The recent announcement of the launch delay for JWST until 2021 means that even more time will pass between the TESS observations and JWST atmospheric observations, exacerbating the effects of imprecision of ephemerides as seen by Benneke et al. (2017).
This work demonstrates that the use of ground-based photometric data can be used to recover the ephemerides of TESS single transit events. Specifically, we find that when given information about a single transit from TESS data ($T_C$ and transit duration), the signal of the phase-folded transit can be detected in KELT data, and thus determine the ephemerides, of 30% to 50% of warm Jupiters, of 5% to 18% of temperate Jupiters, and 10% to 30% of warm Saturns and Neptunes. This technique can likewise be applied to data from other ground-based transit surveys in conjunction with TESS, further increasing the number of single-transit events from TESS with precisely determined ephemerides.

The work described here represents a proof of concept for the approach. In future papers, we intend to explore how the efficacy of precovery methods like this depends on other system parameters, such as the host star properties. We will also explore the particular value of this approach in cases where TESS sees two or three transits. In such cases, the initial ephemerides will be much more constrained by the TESS data directly, and we will examine the marginal increase in precision provided by data from ground-based data, rather than the overall recoverability question we probe in this paper.

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Figure 15. An example of a successfully recovered transit. The top panel shows the unphased light curve with the transit inserted; the middle panel shows the light curve phased at the true period, and the bottom panel shows the zoom-in on the inserted transit. The period of the transit is 35.33 days, with a duration of 19.8 hrs and a depth of 3 mmag. The light curve has an RMS when binned at the duration of the transit of 0.6 mmag.
Figure 16. Another example of a successfully recovered transit, similar to figure 15. The BLS output period is 250.2 days, with a duration of 17.9 hrs and a depth of 7 mmag. The light curve has an RMS when binned at the duration of the transit of 1.3 mmag.
Figure 17. An example of a failed transit recovery. In this case, the attempted recovery period from the BLS analysis is 144.5 days, while the inserted period is 25.4 days. The inserted transit duration is 8.2 hrs, and the depth is 5 mmag. The light curve has an RMS when binned at the duration of the transit of 1.1 mmag.
Figure 18. Another example of a failed transit recovery. In this case the KELT data missed the event. The attempted recovery period from the BLS analysis is 231.9 days, while the inserted period is 37.9 days, with a duration of 7.8 hrs and a depth of 18 mmag. The light curve has an RMS when binned at the duration of the transit of 2.7 mmag.
Figure 19. Recovery rates for orbital period-transit depth bins of the simulated KELT-South combined light curves.
Figure 20. Fractions of KELT-South light curves that pass SPN criteria in transit duration-transit depth bins, and the corresponding SPN values. The percentages reflect the fraction of KELT light curves in that bin such that if the SPN value is greater than the indicated value, there is a 10%, 50%, or 90% confidence that the recovered period is correct, from upper left to lower right in each bin. The color bar indicates the fraction of KELT light curves that pass the 50% confidence threshold.