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Securing the Legacy of TESS through the Care and Maintenance of TESS Planet Ephemerides

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Abstract

Much of the science from the exoplanets detected by the Transiting Exoplanet Survey Satellite (TESS) mission relies on precisely predicted transit times that are needed for many follow-up characterization studies. We investigate ephemeris deterioration for simulated TESS planets and find that the ephemerides of 81% of those will have expired (i.e., 1σ mid-transit time uncertainties greater than 30 minutes) 1 yr after their TESS observations. We verify these results using a sample of TESS planet candidates as well. In particular, of the simulated planets that would be recommended as James Webb Space Telescope (JWST) targets by Kempton et al., ~80% will have mid-transit time uncertainties >30 minutes by the earliest time JWST would observe them. This rapid deterioration is driven primarily by the relatively short time baseline of TESS observations. We describe strategies for maintaining TESS ephemerides fresh through follow-up transit observations. We find that the longer the baseline between the TESS and the follow-up observations, the longer the ephemerides stay fresh, and that 51% of simulated primary mission TESS planets will require space-based observations. The recently approved extension to the TESS mission will rescue the ephemerides of most (though not all) primary mission planets, but the benefits of these new observations can only be reaped 2 yr after the primary mission observations. Moreover, the ephemerides of most primary mission TESS planets (as well as those newly discovered during the extended mission) will again have expired by the time future facilities such as the ELTs, Ariel, and the possible LUVOIR/Origins Space Telescope missions come online, unless maintenance follow-up observations are obtained.

Unified Astronomy Thesaurus concepts: Surveys (1671); Transits (1711); Ephemerides (464); Exoplanets (498)

1. Introduction

Of the nearly 4000 exoplanets known to date, 75% transit their host star despite the relatively low probability of this favorable alignment. This is largely due to the Kepler mission (Borucki et al. 2010), with help from the CoRoT mission (Barge et al. 2008) and long-term ground-based transit surveys such as the Optical Gravitational Lensing Experiment (OGLE; Konacki et al. 2003), SuperWASP (Pollacco et al. 2006), HATNet/HATSouth (Bakos et al. 2004, 2013), KELT (Pepper et al. 2007, 2012), MEarth (Nutzman & Charbonneau 2008), TrES (O'Donovan et al. 2006), and XO (McCullough et al. 2005), as well as the more recent surveys TRAPPIST (Jehin et al. 2011), NGTS (West et al. 2016), and MASCARA (Talens et al. 2017).

The Kepler sample in particular has greatly advanced our understanding of exoplanet occurrence and system architecture. Major discoveries include evidence that planets smaller than Neptune are more common than larger planets (Fressin et al. 2013; Petigura et al. 2013), the fact that small planets often form in compact multiplanet systems (Latham et al. 2011; Lissauer et al. 2011; Rowe et al. 2014), and the presence of circumbinary planets (Doyle et al. 2011; Welsh et al. 2012). While immensely significant, these discoveries also raise new questions. To further understand the origins of these planet populations, we need to determine the composition of the planets by measuring their masses, probing their atmospheres, and characterizing their host stars in detail. However, the vast majority of Kepler systems are too distant and faint for these studies.

The recently launched Transiting Exoplanet Survey Satellite (TESS) comes to the rescue with a promise to revolutionize the field of exoplanet research. TESS is expected to discover thousands of transiting planets, including several hundred orbiting stars within 100 pc of the solar system (Sullivan et al. 2015; Barclay et al. 2018; Huang et al. 2018). Thus, many TESS systems are bright and amenable to detailed characterization. In the next few years, we will make considerable strides toward a population-level grasp not just of small planets' sizes and period distributions, but also of their masses, atmospheres, and host stars' properties.

TESS is finding transiting planets with a variety of sizes and a relatively wide range of orbital periods, but longer-period transiting planets are rarer due to the reduced probability of transit farther from the host star and finite TESS observing baseline. This factor, combined with the desire to study exoplanets across a wide range of equilibrium temperatures, makes the discovery of long-period transiting planets quite valuable. At the same time, given the mission duration and observing strategy, many of the longer-period planets have few transits observed by TESS. All else being equal, long-period planets thus have a greater uncertainty in their periods, as determined from the TESS observations alone. This can lead to a larger uncertainty in the mid-transit time after a given stretch of time, relative to a shorter-period planet.

TESS planets will be the targets of a variety of follow-up observations beyond confirmation and mass measurements. Here we collectively refer to those that depend sensitively on a planet's ephemeris as "time-sensitive characterization observations" (TCOs). The science goals of TCOs include

1. atmospheric characterization (particularly through transmission or secondary eclipse spectroscopy),
2. orbital obliquity measurements (through Doppler tomography or the Rossiter–McLaughlin effect),
3. measurements of transit timing and duration (for orbital decay or transit timing variation (TTV) mass measurements or searches for exomoons or additional planets in a system),
4. transit parameter refinement (e.g., for improving the precision of the measured planet radius or orbital inclination), and
5. characterization of the host star through measurements of limb darkening and star-spot properties, as well as constraints on the stellar surface gravity.

In order to schedule TCOs, particularly those making use of expensive resources like the Hubble Space Telescope (HST) or the James Webb Space Telescope (JWST), the mid-transit time should ideally have an uncertainty of less than 30 minutes. In this paper, we consider a planet's ephemeris to be expired when the 1σ uncertainty on its mid-transit time becomes greater than 30 minutes. Such an uncertainty requires devoting an additional 2 hr to any TCOs in order to have 95% confidence that the full transit will be observed.

Previous work partly related to the subject of ephemeris deterioration was published by Deeg & Tingley (2017), who devoted a section of their paper to investigating the timing precision of 20 hypothetical 2 minute cadence TESS planets observed during one TESS pointing (27.4 days) and spanning a range of parameters. Our work differs in several ways. We use the latest planet yield simulations to obtain a bulk picture of the ephemeris deterioration for the entire set of expected TESS planets. In so doing, our analysis naturally incorporates the effect of time coverage by multiple 27.4 day sectors, which affects a disproportionate number of simulated TESS planets (a selection effect whereby the detectability of a transiting planet increases the longer it is observed). In addition to 2 minute cadence planets, we also examine 30 minute cadence planets, for which ephemeris deterioration is the most severe and the need for rescue is greatest. Finally, while the principal product of Deeg & Tingley (2017) is a transit and eclipse timing precision estimator, our aim is to analyze in detail the outcomes of TESS ephemeris precision, explore the problem of fast ephemeris deterioration, and propose follow-up strategies for correcting this problem. We also note a white paper by Bouma et al. (2017) that investigated the impact and yield of various TESS extended mission scenarios and noted that a repeat of the primary mission (PM) would be most beneficial for ephemeris refreshment of PM planets.

This paper is organized as follows. In Section 2 we briefly describe the TESS mission and the planet yield simulations we used in our analysis. In Section 3 we present the details of our analysis and results as a function of period, planet size, stellar magnitude, and stellar effective temperature for the simulated planet sample. We also examine the ephemeris deterioration of real TESS planet candidates in Section 4. We discuss the implications of those results and the impact of the extended TESS mission and make recommendations for maintaining accurate TESS ephemerides in Section 5. We summarize our findings and conclude in Section 6.

2. The TESS Mission and Yield Simulations

TESS (Ricker et al. 2015) is a NASA space telescope searching for transiting planets that launched in 2018 April with a 2 yr prime mission. TESS acquires observations in two modes. A selection of about 200,000 target stars (TSs) are observed at a 2 minute cadence, while images of the entire field of view (full-frame images (FFIs)) are observed at a 30 minute cadence. The short-cadence TSs are selected as prime targets for transit detection and are primarily bright and/or cool dwarf stars.

TESS observes the sky in a set of pointed observations in which the spacecraft nearly continuously observes a section of the sky stretching from 6° from the ecliptic to the ecliptic pole for 27 days, with each section referred to as a sector. The mission steps around in ecliptic longitude, has used 13 sectors to cover most of the southern ecliptic hemisphere over the course of a year, and has recently rotated so that it is now observing the northern hemisphere. Near the ecliptic poles, subsequent sectors overlap, so that stars in those regions can be observed for many months. The majority of the sky observed by TESS (74%) has an observational time baseline of only ~27 days. For transiting exoplanets with orbital periods longer than 13.5 days seen in only a single sector, TESS can only capture one or two transits, and for planets in those regions with periods longer than 27 days, TESS can only capture at most one transit. In these cases, the ephemerides of the planets are difficult to determine using TESS data alone.

A number of simulations of the TESS planet yield have been carried out: Sullivan et al. (2015), Bouma et al. (2017), Barclay et al. (2018), Huang et al. (2018), Muirhead et al. (2018), Ballard (2019), and Villanueva et al. (2019). The simulations from Ballard (2019) and Muirhead et al. (2018) focused on the planet yield for M dwarfs, while Villanueva et al. (2019) focused on the yield of planets for which only one transit would be observed by TESS, so none of those three yield simulations that are sufficiently general for the scope of this paper. Of the remaining four studies, Sullivan et al. (2015) and Bouma et al. (2017) drew stars from a Galactic model, while the other two used real stars as listed in the TESS Input Catalog (TIC; Stassun et al. 2018) for their simulations.

Compared to Barclay et al. (2018), the simulations of Huang et al. (2018) use an updated 2 minute target list, Gaia-updated stellar parameters, more realistic noise parameters and multiplanet system occurrence rates, and stars with TESS magnitudes as faint as $T = 15$. However, the two works find similar planet yields for bright stars (Barclay et al. 2018 only used stars with TESS magnitudes brighter than about $T = 13$, depending on the stellar temperature). Since we aim to examine statistically how our knowledge of TESS planet ephemerides depends on the parameters of the planetary systems, we do not expect our overall results to depend on the number of planets found, only on planetary and stellar parameters. Since the simulation results of Huang et al. (2018) are not currently publicly available, while those of Barclay et al. (2018) are, we select the latter as the basis for our analysis.

3. Ephemeris Expiration Analysis and Results Using Planet Yield Simulations

The simulations of Barclay et al. (2018) predict that TESS will detect 1296 TS planets and 3080 FFI planets (with at least two transits observed by TESS).

3.1. Analysis

For each planet, we determined the signal-to-noise ratio (S/N) for one transit, using the combined S/N (S/NF) and number of TESS transits ($N_{\rm transits}$) included in the simulated planet catalog. Next, we calculated ingress duration (τ) using the following formula:

$$\tau = \frac{Rp}{a}\frac{P}{\pi}, \tag{1}$$

which assumes a circular orbit and an inclination of 90° for every planet. Then, we used the equations of Price & Rogers (2014) to compute the uncertainty on the mid-transit time (δT_c) for an individual transit c:

$$\delta T_c = \frac{1}{\rm S/N}\sqrt{\frac{\tau T_{\rm dur}}{2}}\frac{1}{\sqrt{1 - \frac{I}{3\tau}}},\ \tau \geqslant I, \tag{2}$$

$$\delta T_c = \frac{1}{\rm S/N}\sqrt{\frac{I T_{\rm dur}}{2}}\frac{1}{\sqrt{1 - \frac{\tau}{3I}}},\ I \geqslant \tau, \tag{3}$$

where $T_{\rm dur}$ is the transit duration and I is the integration time. We note that Equation (2) indicates that for I shorter than τ, δT_c decreases with increasing τ. In other words, the better the ingress and egress are sampled, the better the precision on the mid-transit time measurement.

For each planet, at the end of the TESS observations, there is an ephemeris, represented by the mid-transit time $T_0 \pm \delta T_0$ (corresponding to the epoch of the last TESS transit) and associated period $P \pm \delta P$. This ephemeris is determined from the individual measured times of transit from the TESS observations ($T_c \pm \delta T_c$), as follows. All uncertainties (δT_0, δP, σ_{t_c}) correspond to one standard deviation (1σ) from the mean.

For each planet, we generated 1000 sets of $N_{\rm transits}$ mid-transit times as would be observed by TESS. For each simulated transit, we represent the observed mid-transit time as a value drawn from a Gaussian distribution centered on the "true" mid-transit time and with a standard deviation equal to the calculated δT_c. We also assign an uncertainty of δT_c to each transit. For a given planet, we then fit a linear regression to all transits using least-squares minimization. We take the mean of the 1000 best-fit slope values as the best-fit period. We compute the uncertainty on the period (δP) by taking the standard deviation of the distribution of best-fit period values across all 1000 simulations of that planet.

We then determine the uncertainty on a future mid-transit time, $\delta T_{0,m}$, where m represents the time elapsed from the end of the TESS observations of a particular target. We calculate $\delta T_{0,m}$ for every simulated TESS planet as follows[13]:

$$\delta T_{0,m} = n_m \delta P + \delta T_{0,\rm TESS}, \tag{4}$$

where $\delta T_{0,\rm TESS}$ is the uncertainty on the midpoint of the last TESS transit, $\delta P_{\rm TESS}$ is the uncertainty on the period determined from the TESS observations, and n_m is the number of planet orbital cycles between $T_{0,\rm TESS}$ and $T_{0,m}$ (see also Zellem et al. 2020).

Our analysis does not take into account TTVs that may occur in multiplanet systems. The amplitude of any TTV is affected by the masses, periods, and orbital eccentricities of planets in the system. However, TTVs are predicted to be uncommon in TESS data (Hadden et al. 2019) and were not incorporated in the TESS planet simulations we used here.

3.2. Results

We performed the analysis described above separately for simulated TS and FFI planets. We show $\delta T_{0,m}$ evaluated 1 yr after the end of a planet's TESS observations ($\delta T_{0,1y}$) as a function of orbital period and planet size (represented by the color gradient) in Figure 1, with TS planets on the left and FFI planets on the right.

A few features stand out in Figure 1. The higher cadence of the TS observations leads to slower ephemeris deterioration for these planets than for the FFI planets because δT_c is smaller, thus reducing δP as well. We also note that in general, larger planets have smaller $\delta T_{0,1y}$.

The upper range of $\delta T_{0,1y}$ increases with increasing period until just after $P \sim 10$ days. For longer periods, $\delta T_{0,1y}$ begins to decrease with period. To explore this further, we examined the fraction of planets with $\delta T_{0,m} < 30$ minutes (i.e., the threshold we use to determine whether the ephemeris has deteriorated, as described in Section 1) as a function of period for three different values of m for TS and FFI planets (Figure 2). The fraction of planets with $\delta T_{0,m} < 30$ minutes decreases as the period increases, but only until $P \sim 10$ days; beyond this threshold, the fraction of planets with $\delta T_{0,m} < 30$ minutes increases with period. This trend mirrors the features seen in Figure 1 and holds for different values of m (though it weakens with increasing m). For planets with short periods, a large proportion of candidates have $\delta T_{0,m} < 30$ minutes due to TESS observing many transits of these planets, resulting in a smaller initial uncertainty in the period. A large proportion of long-period planets have $\delta T_{0,m} < 30$ minutes because, while δP may be larger due to TESS observing fewer transits of these planets, these planets also experience fewer orbital cycles during the

[13] Here P and $T_{0,\rm TESS}$ are not independent variables. However, in our analysis, it is not trivial to accurately determine the amount of covariance between them (since we are not analyzing simulated light curves but rather simulated mid-transit times with simulated uncertainties). Therefore, to be conservative and avoid underestimating the uncertainty on future mid-transit times, we assume that P and T_0 are fully correlated. We note that the choice of adding linearly versus in quadrature only changes the future mid-transit time uncertainty by a negligible amount.

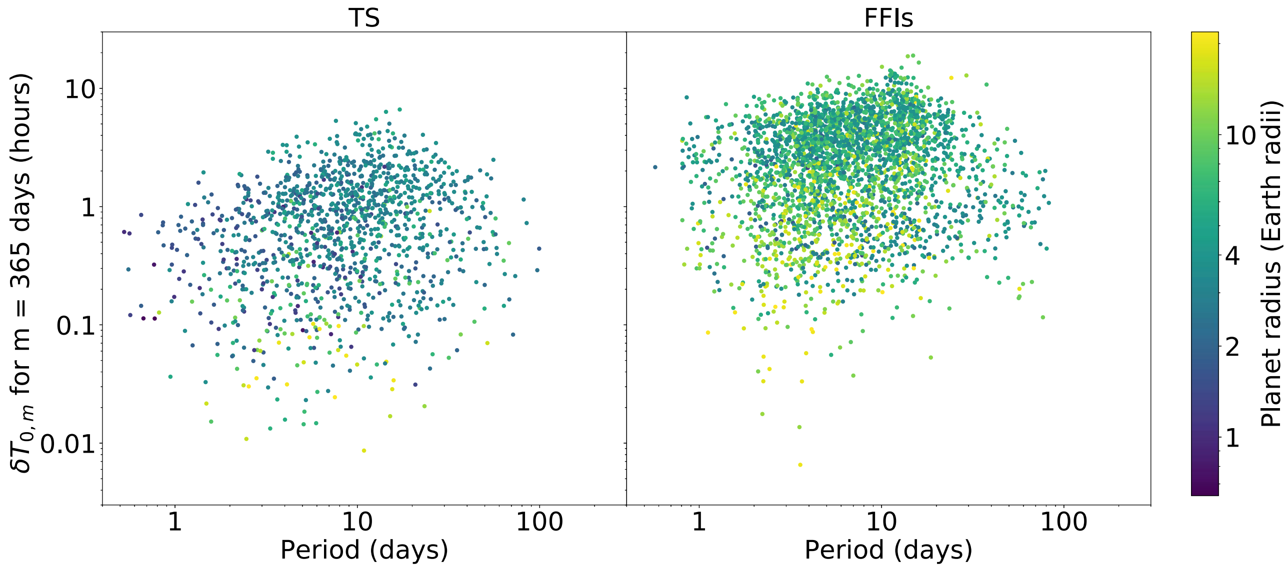

Figure 1. Uncertainty in mid-transit time for simulated planets 1 yr after TESS observes them as a function of orbital period. The colors represent planet radius. Left: TS planets. Right: FFI planets. The ephemerides of 61% of TS and 89% of FFI planets will have expired 1 yr after their TESS observations.

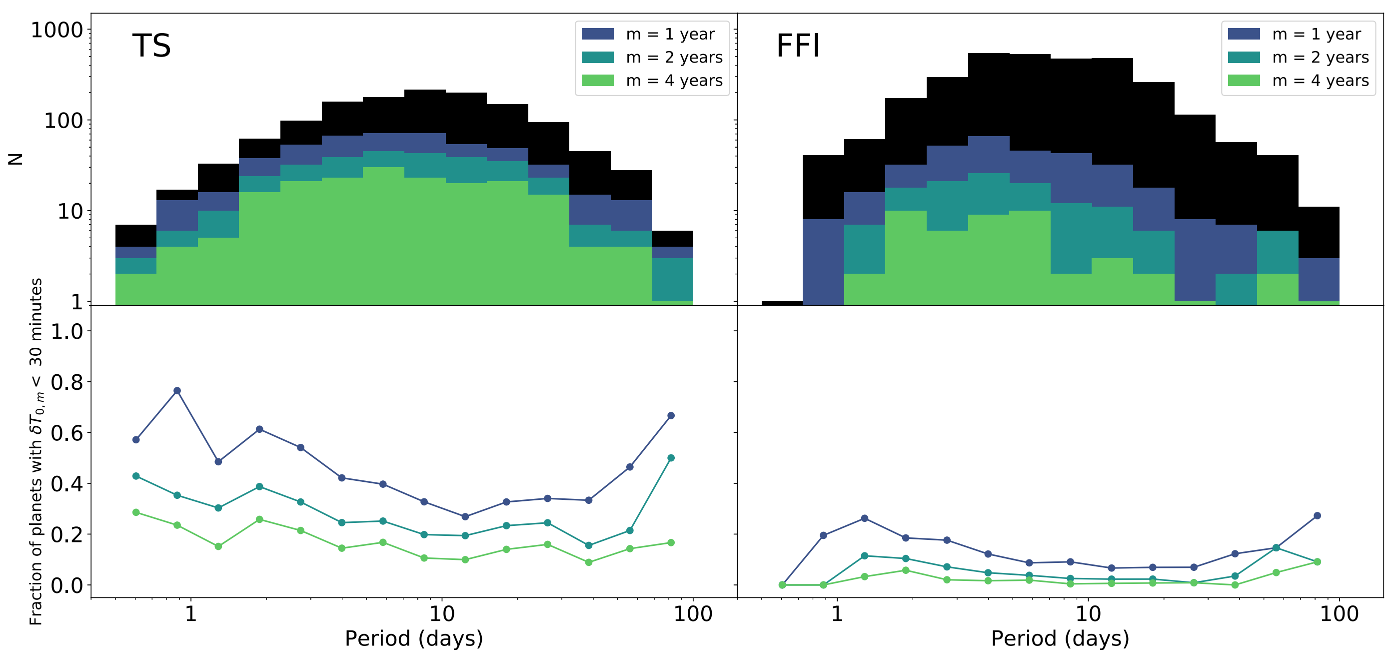

Figure 2. In the top panels, black corresponds to the distribution of the full sample of simulated planets used in our analysis (1296 TS and 3080 FFI planets) as a function of period. Navy, turquoise, and green represent the distributions of planets with $\delta T_{0,m} < 30$ minutes for $m = 1$, 2, and 4 yr (from the end of the TESS observations of each planet) as a function of period. The bottom panels show the fraction of planets (with $\delta T_{0,m} < 30$ minutes for $m = 1$, 2, and 4 yr) relative to the full sample as a function of period. The figures on the left and right correspond to TS and FFI planets, respectively.

subsequent time span. We find that the latter effect overcompensates for the former, such that the uncertainty on the future mid-transit time for the longer-period planets does not increase as quickly as it does for planets with intermediate periods.

We also looked at the effects of planet radius (Figure 3), host star brightness (Figure 4), and stellar effective temperature (Figure 5) on ephemeris deterioration. The rate of ephemeris deterioration seems to depend on the planet radius. This is easily explained for the larger planets: S/N generally increases with planet size, and $\delta T_{0,\mathrm{TESS}}$ (and thus δP) is inversely proportional to the S/N. However, this trend changes direction around $5\,R_{\mathrm{Earth}}$, and the rate of ephemeris deterioration decreases with size below this R_p value. We believe this effect is due to a correlation between the radii and periods of the simulated planets. Indeed, we find that below this R_p threshold, the fraction of simulated planets with $P < 10$ days versus $P > 10$ days increases with decreasing R_p. However, the fact that smaller planets are harder to detect with TESS at longer periods likely contributes to this effect as well.

The fraction of planets with $\delta T_{0,m} < 30$ minutes does not significantly depend on either the TESS magnitude or the effective temperature of the host stars. Some large changes in this ratio are apparent for some values of these two parameters, but these fluctuations correspond to bins with very small number statistics and are thus unlikely to be significant.

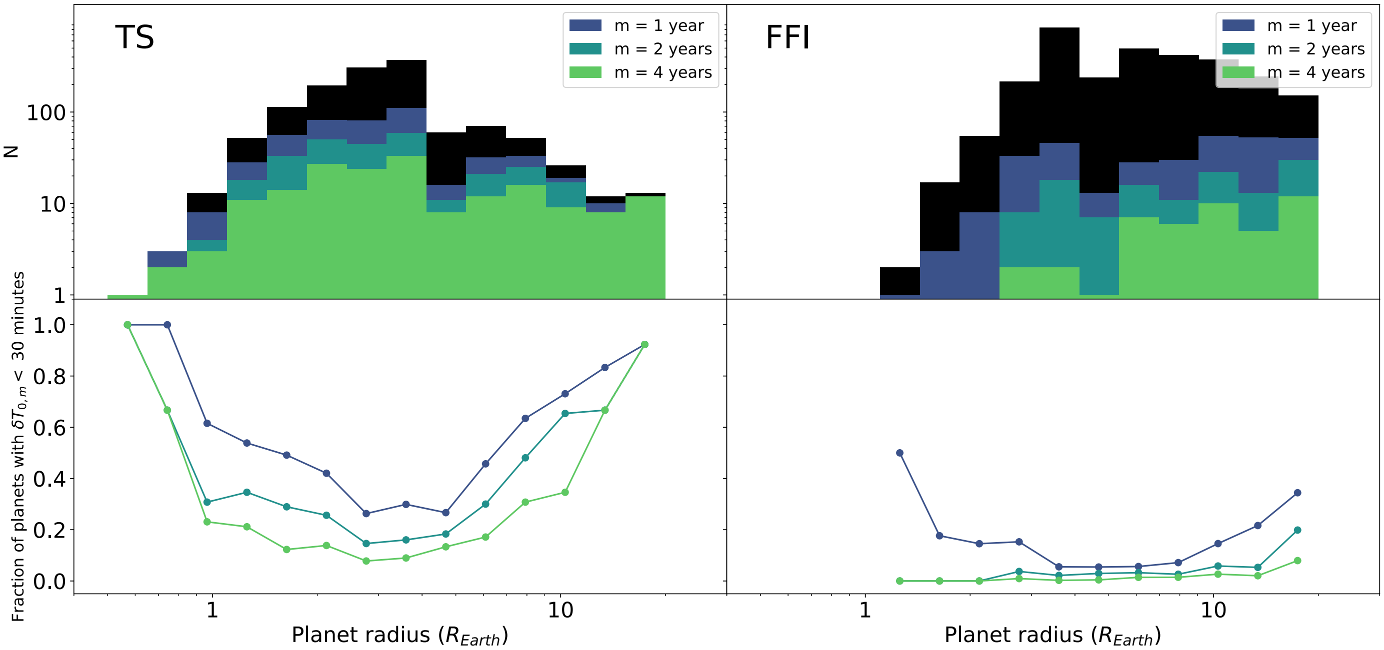

Figure 3. Distribution (top) and fraction (bottom) of planets with $\delta T_{0,m} < 30$ minutes as a function of planet radius for different values of m, with TS planets on the left and FFI planets on the right. Colors are the same as in Figure 2.

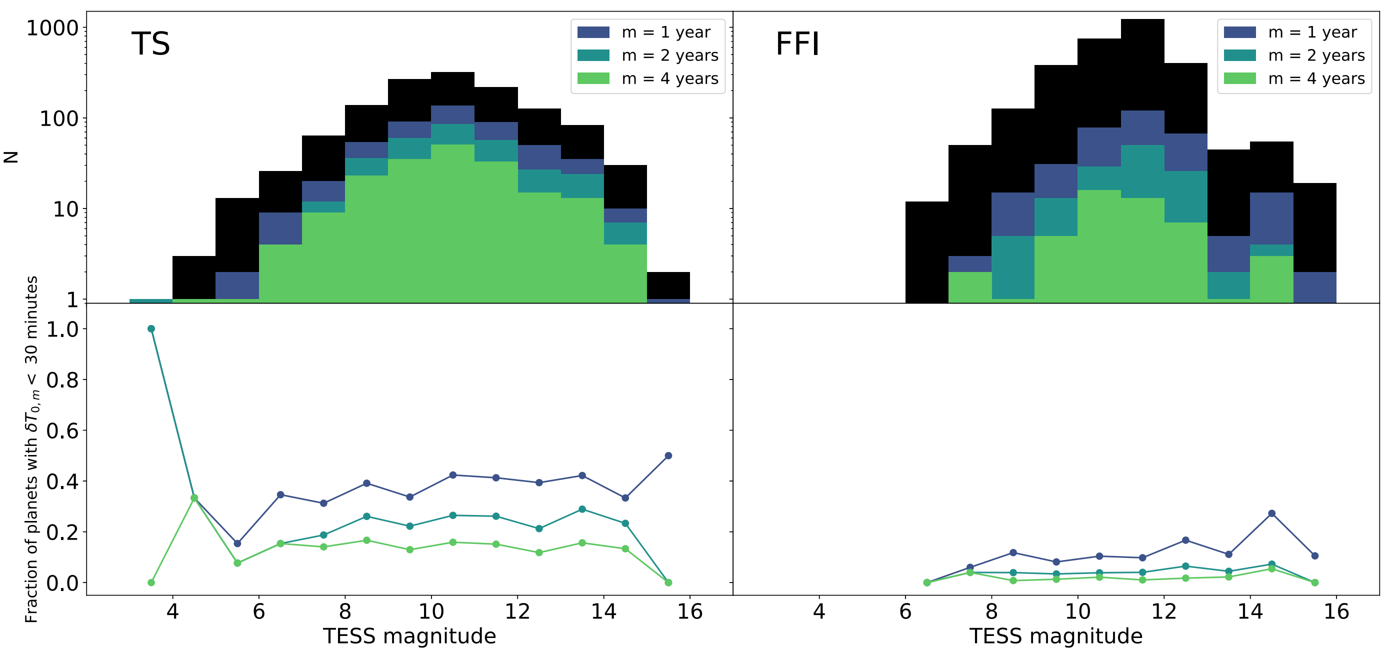

Figure 4. Distribution (top) and fraction (bottom) of planets with $\delta T_{0,m} < 30$ minutes as a function of TESS magnitude for different values of m, with TS planets on the left and FFI planets on the right. Colors are the same as in Figure 2. We remind the reader that our analysis uses the TESS planet yield simulations of Barclay et al. (2018), who used real stars as listed in the TIC (rather than drawing stars from a Galactic model as other works have done) for their simulations (see Section 2 for details).

4. Ephemeris Expiration Analysis and Results Using Real TESS Planets and Planet Candidates

Since over 1000 real planet candidates (known as TESS objects of interest (TOIs)) have already been released, we use Equation (4) to also determine $\delta T_{0,1y}$ for TOIs in order to cross-check our results based on the simulated planets. We use the δP and $\delta T_{0,\mathrm{TESS}}$ values provided by the TESS Science Office (TSO) for each TOI (available on ExoFOP-TESS[14]).

Figure 6 shows the 1 yr ephemeris deterioration for the 1604 TOIs available on 2020 January 15 and can be compared to Figure 1. We caution that the TOI sample contains an unknown number of false positives (FPs; primarily eclipsing binaries) and is biased toward larger and shorter-period planet candidates (which are easier to detect). Despite these biases, we find similar features between the simulated planet sample and the TOI sample: the ephemerides of the TS TOIs deteriorate slower than those of the FFI TOIs, larger planets generally have smaller $\delta T_{0,1y}$, and there is a peak in the distribution just past

[14] https://exofop.ipac.caltech.edu/

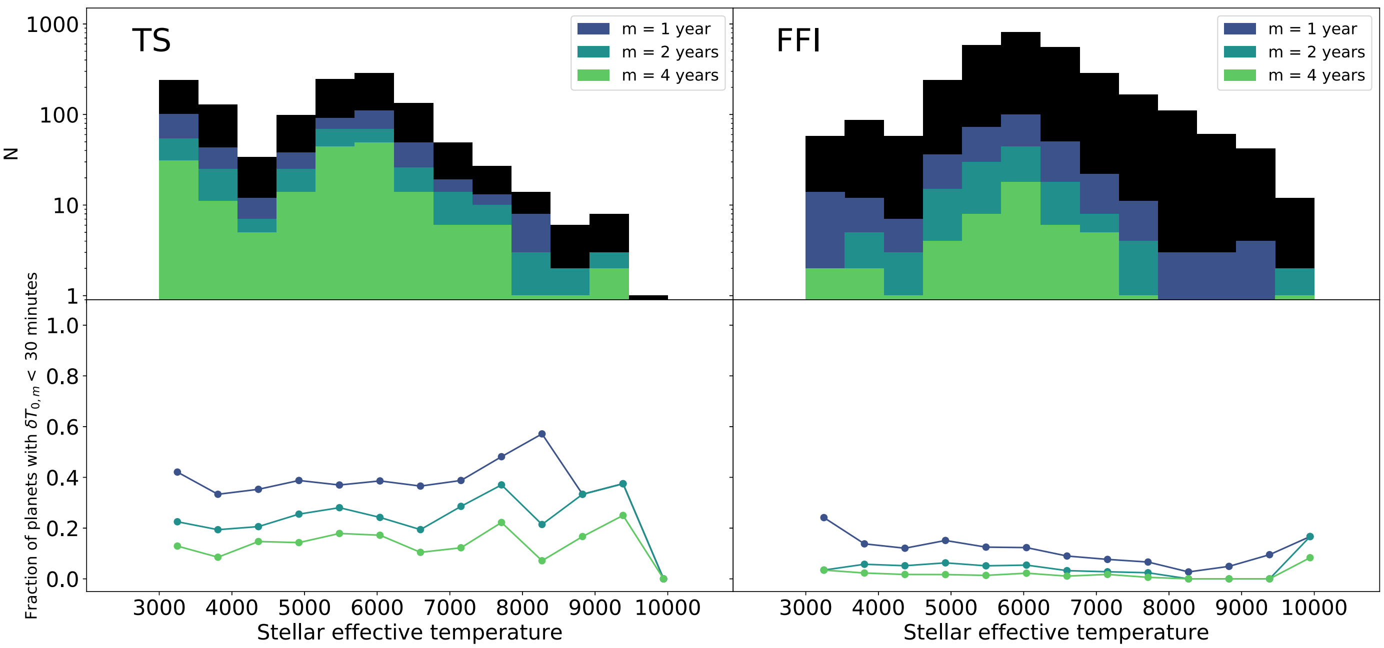

Figure 5. Distribution (top) and fraction (bottom) of planets with $\delta T_{0,m} < 30$ minutes as a function of stellar effective temperature for different values of m, with TS planets on the left and FFI planets on the right. Colors are the same as in Figure 2.

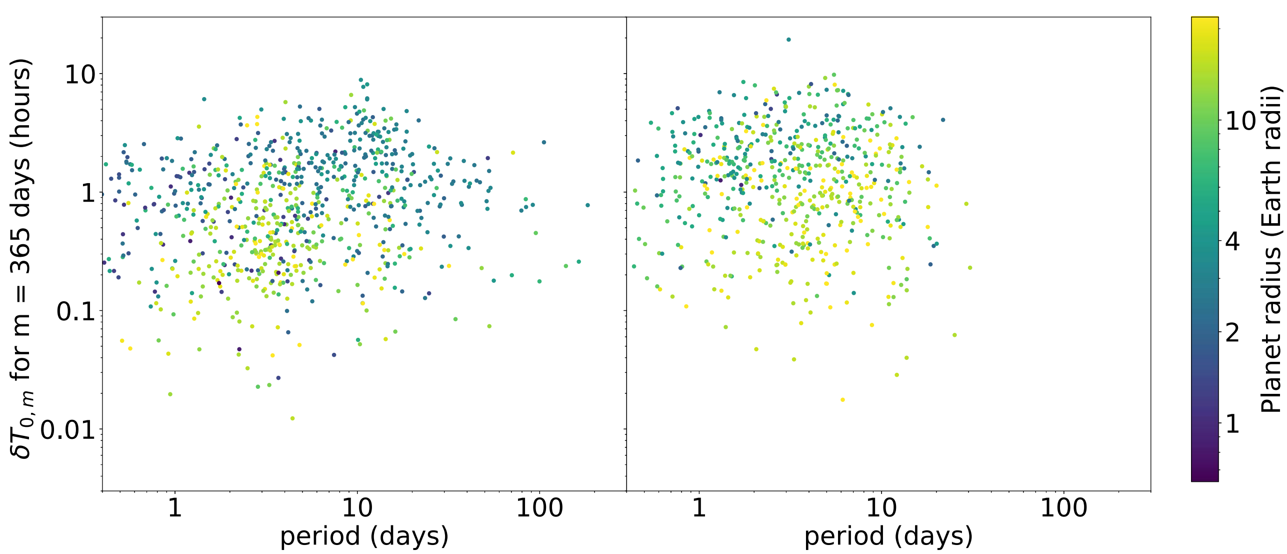

Figure 6. Uncertainty in mid-transit time for real TOIs 1 yr after TESS observes them as a function of orbital period. The colors represent the planet radius. Left: TS planets. Right: FFI planets.

$P \sim 10$ days (this feature is not as obvious in the FFI TOI sample, likely because the period space has not been sufficiently populated at longer periods). We thus feel confident in the accuracy of the predictions, interpretation, and recommendations for ephemeris maintenance that we present in this paper based on the simulated planet sample.

5. Discussion

5.1. Considerations for JWST Observations

Transmission spectroscopy with JWST represents the most widely anticipated type of TCO, and we do not expect or recommend that JWST will observe transits with transit midpoint uncertainties greater than 30 minutes, particularly if this uncertainty can be reduced by additional ground-based observations. In this section, we examine the ephemeris deterioration of TESS planets as a function of their suitability for JWST observations.

We use $m = 2$ yr as a representative value for the average time span between the $T_{0,\mathrm{TESS}}$ of a typical PM planet (i.e., observed in 2019 July) and the time when JWST should begin science operations (i.e., 6 months after its currently planned launch date of early 2021). In Figure 7, we show $\delta T_{0,m}$ evaluated 2 yr after the end of a planet's TESS observations as a function of the transmission spectroscopy metric (TSM) described in Kempton et al. (2018). Briefly, the TSM corresponds approximately to the S/N for 10 hr (with 5 hr occurring during transit) of observations with the NIRISS instrument on JWST under the assumptions made in Kempton et al. (2018). Table 1 of Kempton et al. (2018) lists cutoff TSM values corresponding to the top TESS planets for atmospheric

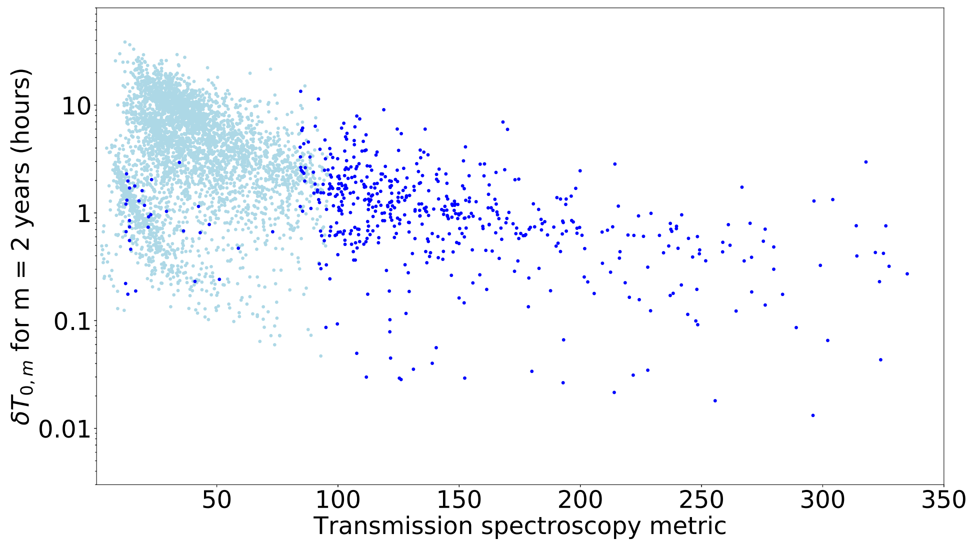

Figure 7. Uncertainty in mid-transit time for simulated planets 2 yr after TESS observes them as a function of the TSM. Planets above the TSM thresholds listed in Table 1 of Kempton et al. (2018) are highlighted in dark blue.

characterization. In Figure 7, we highlight in dark blue the 395 planets that are above those cutoff values.

The TSM correlates with the TESS S/N, so in general, the planets having the highest TSM experience less ephemeris deterioration than those with lower TSM values. However, under our assumptions, the majority of the planets (313 out of 395, or 79%) recommended by Kempton et al. (2018) would still have $\delta T_{0,m} > 30$ minutes by the time they would be observed with JWST (if no follow-up transits are observed). In particular, for small ($R_p < 4\ R_{\mathrm{Earth}}$) planets with a TSM above the Kempton et al. (2018) thresholds, the ephemerides of 64 out of 81 transiting M dwarfs and 56 out of 60 transiting F/G/K dwarfs will have expired by the time JWST begins science observations. Most JWST targets will thus require ephemeris "refreshment" (i.e., reducing $\delta T_{0,m}$ to less than 30 minutes) prior to scheduling them for observations (unless they have been reobserved as part of the extended TESS mission before the JWST scheduling takes place).

5.2. Resources for Keeping Ephemerides Fresh

Transits deeper than ~1000 ppm (e.g., Günther et al. 2019) and with durations shorter than ~7 hr can generally be recovered with ground-based meter-class telescopes. The TESS Follow-Up Observing Program (TFOP) subgroup 1b (SG1b) focuses on ground-based photometric follow-up. It marshals tens of telescopes for follow-up photometry to verify TOIs to either confirm them as planets or identify FPs. In so doing, these efforts also refresh the ephemerides for those planets whose transits they observe.

To keep fresh ($\delta T_{0,m} < 30$ minutes) the ephemerides of planets with long or shallow transits, which make up 69% of all simulated planets, it will be necessary to use space-based observatories. The TFOP SG5 coordinates a number of space-based follow-up efforts toward this goal. There are three recent or current space-based observatories that can realistically be used for this purpose: the CHaracterising ExOPlanets Satellite (CHEOPS), Spitzer, and HST. We also consider the impact of the extended TESS mission in Section 5.3.

5.2.1. Spitzer

The now-defunct Spitzer space telescope has an 85 cm aperture. In its warm phase, it could observe in two channels, 3.6 and 4.5 μm. Thanks to its Earth-trailing orbit, Spitzer could observe any target for at least ~80 days yr^{-1}. Spitzer has already rescued the ephemerides of several K2 planets (e.g., Benneke et al. 2017; Kosiarek et al. 2019; Livingston et al. 2019). A recent large program to achieve the same goal for the TESS planets most amenable to atmospheric characterization improved the ephemerides of 34 TOIs (I. Crossfield 2020, private communication) before the Spitzer mission was terminated in 2020 January. While valiant, this effort only scratches the surface of the more than 2000 TESS planets that are expected to require space-based follow-up in order to refresh their ephemerides (see Section 5.4).

5.2.2. HST

The HST has a 2.4 m aperture and can observe TESS transits with much higher S/N than TESS. It has an equatorial orbit, part of which it spends between the Earth and the Sun, so most of the sky cannot be observed continuously, and many transit observations will not sample the full transit. The transit time precision of HST should still be sufficient for ephemeris refreshment.[15] We expect that a number of TESS planets will be proposed for atmospheric characterization, particularly in the years prior to JWST. TESS planets with very shallow transits may even be proposed solely for ephemeris refinement, especially since Spitzer is no longer available. Assuming the corresponding HST observations themselves are scheduled before $\delta T_{0,m}$ becomes too large, a lucky few TESS planets will have their ephemerides refreshed during transmission spectroscopy observations.

[15] Even for the 1000 ppm transit of HD 97658b, the uncertainty on T_0 is only 8 minutes (Knutson et al. 2014), which is sufficient for long-term ephemeris refreshment as long as the time elapsed between the end of the TESS observations and the HST transit observation is long enough (see Section 5.4).

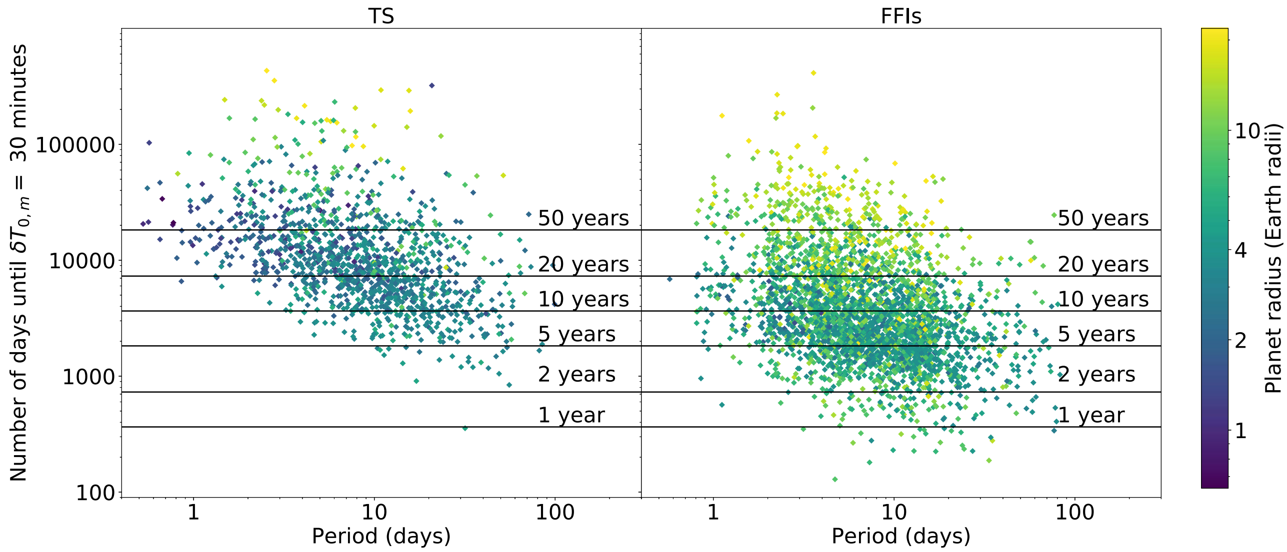

Figure 8. Number of days ephemerides stay fresh ($N_{\delta T_{0,m}<30\ \mathrm{minutes}}$), starting from 2 minute cadence extended mission TESS observations assumed to take place 2 yr after the PM observations.

5.2.3. CHEOPS

The European Space Agency (ESA) successfully launched CHEOPS (Broeg et al. 2013) on 2019 December 18, and the satellite is currently in its commissioning phase. CHEOPS has a 30 cm aperture, and its passband spans the 0.4–1 μm range. Only 20% of CHEOPS's observing time is open and allocated through an ESA Guest Observer program, but the CHEOPS consortium may observe transits of TESS planets as part of the Guaranteed Time Observing program (which manages the remaining 80% of CHEOPS's time). It is anticipated to achieve significantly better photometric precision than TESS thanks to its larger aperture. There are two downsides of CHEOPS that are important to recognize for its role in ephemeris refreshment. The first is that large portions of the TESS footprint surrounding the ecliptic poles (where TESS is expected to discover a disproportionate number of planets) will not be observable by CHEOPS due to the operational and pointing constraints of its orbit. The second is that it is in low Earth orbit, and for most stars, observations will be periodically interrupted by the Earth. However, as for HST observations, the transit time precision should still be amply sufficient for ephemeris refreshment.

5.3. Extended TESS Mission

Perhaps the most compelling resource for preventing deteriorated ephemerides is the extended TESS mission. This 2.5 yr extension (including a repeat of year 1 in year 3 and a partial repeat of year 2 in year 4) to the TESS PM was approved in the summer of 2019. Thus, a large fraction of planets will be reobserved by TESS approximately 2 yr after their PM observations. However, as shown in Figure 1, the ephemerides of most TESS planets will have expired just 1 yr after their TESS observations, making it difficult to schedule TCOs such as transit spectroscopy with the HST or ground-based facilities or Rossiter–McLaughlin observations in the 1–2 yr until TESS reobserves these targets. Moreover, the extended mission will not have refreshed the ephemerides of many TESS planets (particularly those from the northern ecliptic hemisphere) in time for Cycle 1 of JWST, making it challenging or even impossible to schedule observations unless follow-up transits are observed with other facilities.

Even for TCOs that will take place during or after the extended mission, there are a few important caveats. Approximately 5%–10% of PM TESS planets and candidates will fall into the gaps between sectors during the extended mission and will not be reobserved. In addition, as currently planned, TESS's year 4 will only include ∼65% of the PM northern ecliptic hemisphere, leaving many northern TOIs unobserved. Lastly, the extended mission will find hundreds to thousands of new planets (Bouma et al. 2017; Huang et al. 2018) whose ephemerides will eventually need to be rescued as well. Therefore, we recommend establishing an ephemeris refreshment procedure for TESS planets and planet candidates to address these caveats and complement the extended mission.

Nevertheless, since the majority of PM planets and candidates will be reobserved during the extended mission, we investigate how long their ephemerides will remain fresh after their second round of observations. During the extended mission, TESS will again observe ∼200,000 targets yr^{-1} at 2 minutes cadence, while FFIs will be taken every 10 minutes (instead of 30 minutes, as was done during the PM). Since at least 80% of the short-cadence targets will be selected through the Guest Investigator program from among targets proposed by the community, we do not yet know the properties of those targets. Therefore, we perform our investigation using our simulated yield planets for both cadences. Figure 8 shows the length of time for which the PM TESS planet ephemerides remain fresh ($N_{\delta T_{0,m}<30\ \mathrm{minutes}}$) from the time of the hypothetical 2 minute cadence extended mission observations (assumed to take place 2 yr after the PM observations). Figure 9 is identical, except that we assume 10 minutes cadence during the extended mission.

These figures primarily show that even with the extended mission, the ephemerides of most PM TESS planets will expire in as little as 10 yr unless they are refreshed again (through either another TESS extension or transit observations with other telescopes). This 10 yr timescale is comparable to time lines for major post-JWST facilities like ARIEL, GMT, E-ELT,

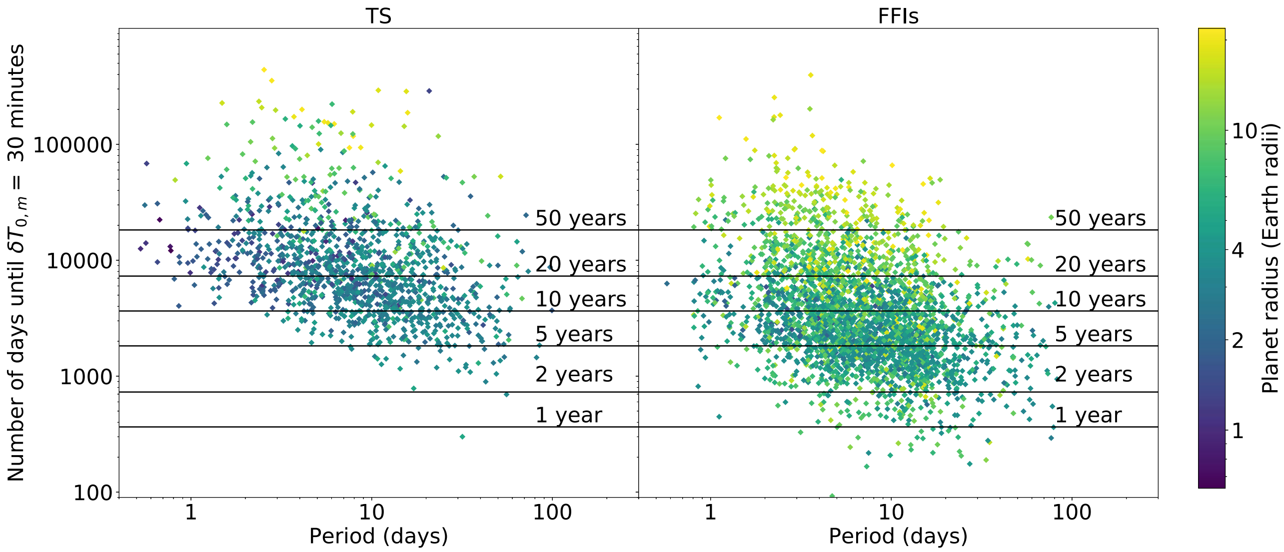

Figure 9. Same as Figure 8 but assuming a 10 minute cadence for the extended mission observations.

and TMT, as well as more distant, prospective observatories (e.g., LUVOIR, Origins Space Telescope, etc.).

By eye, there are no large differences between Figures 8 and 9. Indeed, $N_{\delta T_{0,m}<30\ \mathrm{minutes}}$ varies by less than 50%, comparable to the likely uncertainty in the first-light time for the facilities listed above.

5.4. Recommendations for Keeping TESS Ephemerides Fresh

We investigated the impact of the follow-up baseline (i.e., the time elapsed between the end of the TESS observations and the follow-up transit observation), as well as the S/N and the cadence of the follow-up observations. For a fixed S/N and baseline, the choice of cadence of the follow-up observations only changes the length of time that the ephemeris stays fresh by at most a few percent, if ingress and egress are well sampled. However, if the cadence is such that fewer than one observation is taken during ingress or egress (see Equation (3)), then the amount of time the ephemeris stays fresh (i.e., $\delta T_{0,m} < 30$ minutes) can change by tens of percent, compared to a transit with several observations during ingress and/or egress. We note that the planets most at risk (periods longer than of order 10 days) are also those with longer ingress and egress durations, for which the cadence of follow-up observations matters least, as long as the sampling rate is not longer than a few minutes. The S/N of the follow-up observations is more important, since it is inversely proportional to the uncertainty on the mid-transit time of the follow-up transit ($\delta T_{c,m}$).

The following equation shows how δP depends on $\delta T_{0,\mathrm{TESS}}$, $\delta T_{c,m}$, and the number of orbital cycles elapsed between the two (n_m):

$$\delta P = \sqrt{\frac{\delta T_{0,\mathrm{TESS}}^2 + \delta T_{c,m}^2}{n_m}}. \tag{5}$$

We see from Equation (5) that while δP decreases with decreasing $\delta T_{c,m}$, it decreases faster with increasing n_m. Therefore, the most important variable to consider when planning follow-up transit observations is the baseline. In essence, a follow-up transit should be obtained as long as possible after the TESS observations (but while $\delta T_{0,m}$ is still small enough to allow for scheduling the follow-up observations).

Based on these considerations, we present an ephemeris refreshment plan that can reliably refresh the ephemerides of the vast majority of TESS planets for at least 2 yr from their corresponding $T_{0,\mathrm{TESS}}$, with just one transit per planet. We conservatively assume that transits deeper than 1000 ppm and with durations shorter than 7 hr (610 TS and 1542 FFI planets) can routinely be followed up from the ground, so for every simulated planet with a transit depth above this threshold, we calculated the S/N achievable with a 1.0 m telescope in the I band. We added in quadrature shot noise, scintillation noise (using Equation (1) of Mann et al. 2011), and atmospheric noise (estimated at 400 ppm, following Mann et al. 2011) to estimate the total photometric noise. We assumed an average airmass (1.3), as well as an exposure time and overhead of 30 s each (typical of ground-based observations with meter-class telescopes), for an overall sampling rate of 60 s. For each planet with transits shallower than 1000 ppm or longer than 7 hr (686 TS and 1538 FFI planets), we estimated the S/N that would be reached with Spitzer at 4.5 μm, assuming an exposure time of 2 s and negligible overhead, which is typical of the majority of Spitzer exoplanet observations.[16]

We used Equation (5) to estimate δP after the addition of a follow-up transit observation and Equation (4) (replacing $\delta T_{0,\mathrm{TESS}}$ with $\delta T_{c,m}$) with $\delta T_{0,m}$ set to 30 minutes to determine the improvement in the ephemerides after these follow-up observations. We examined how long it would take until the renewed ephemerides deteriorate again. Figure 10 shows the length of time for which the TESS planet ephemerides remain fresh ($N_{\delta T_{0,m}<30\ \mathrm{minutes}}$) with just one follow-up transit observed 3 (top) and 9 (bottom) months after the end of the TESS observations of each planet.

We find that the ephemerides of 89% of the TS planets and only 38% of the FFI planets can be refreshed for at least 2 yr from the follow-up transit observed at 3 months. In the context of JWST observations, this strategy should be sufficient for scheduling almost any of the northern ecliptic hemisphere TS

[16] As described above, the cadence of the observations has minimal impact on the effectiveness of a follow-up transit for ephemeris refreshment.

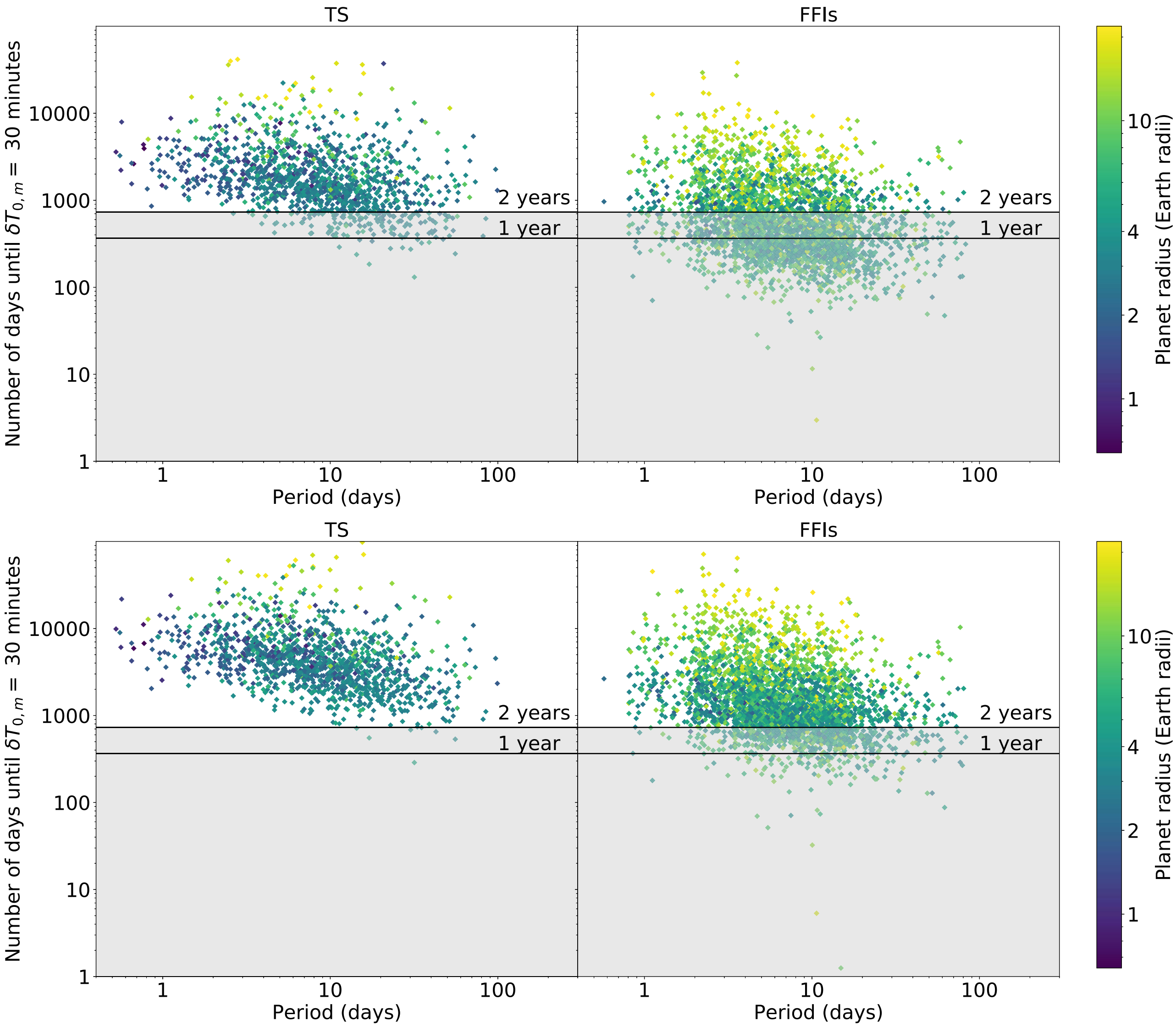

Figure 10. Top: number of days ephemerides stay fresh ($N_{\delta T_{0,m}<30\text{ minutes}}$) starting from a follow-up transit observed 3 months after the end of each planet's TESS observations. The shaded area represents $N_{\delta T_{0,m}<30\text{ minutes}} < 2$ yr. Bottom: same as top panel but after a follow-up transit observed 9 months after the end of each planet's TESS observations.

planets TESS finds, since the JWST Cycle 1 observations are expected to happen approximately 2 yr from the second half of the TESS PM survey. For the remaining northern hemisphere planets (including most of the FFI planets), and for many of those in the southern ecliptic hemisphere, a longer baseline between the TESS observations and the follow-up transit (e.g., 9 months) will be necessary to sufficiently refresh their ephemerides, if those planets are to be observed during Cycle 1 of JWST.

We also examine the improvement in ephemeris refreshment with a transit observation 9 months after the end of TESS observations. Figure 10 shows that the longer baseline refreshes the ephemerides of 99% of all TS planets and the vast majority (80%) of FFI planets. While the longer 9 month baseline is more effective, in many cases, the initial TESS ephemeris would have already expired by $m = 9$ months. For those planets, transit follow-up observations should ideally be done both 3 and 9 months from $T_{0,\mathrm{TESS}}$.

Since our analysis does not account for TTVs, we recommend that for any system suspected of harboring more than one planet, observers should obtain an estimate of the amplitude of possible TTVs and consider it when scheduling follow-up transit observations. However, we note that only ∼20 systems that TESS will find are expected to show measurable TTVs (Hadden et al. 2019), so we do not expect this to be a consideration for preserving the ephemerides of the majority of TESS planets.

Finally, while we expect that observers interested in individual TESS systems will take the initiative to ensure that their ephemerides are refreshed prior to scheduling JWST (via TFOP SG1, SG5, or otherwise) or other expensive observations, we also summarize here the categories of planets most at risk of ephemeris deterioration for observers wishing to refresh TESS ephemerides in bulk:

1. planets that will not be reobserved during the extended mission,
2. FFI planets in general (whose ephemerides will deteriorate faster than those of TS planets),

3. TS planets with 4 days $\lessapprox P \lessapprox$ 40 days (whose ephemerides become uncertain faster than for planets with shorter or longer periods), and
4. TS planets with $R_p \lessapprox 5R_{\rm Earth}$.

5.5. FP Rate Considerations

Ideally, observations for ephemeris refreshment (particularly those that require space-based or larger ground-based telescopes) would only be carried out for confirmed TESS planets. Sullivan et al. (2015) and Barclay et al. (2018) estimated TESS FP rates for TSs (∼50%) and FFIs ($\gtrsim$85%), respectively. While it is still too early in the mission to know the true rates, the FP rate will be higher for FFI candidates (with the planets coming from this sample also being in the most dire need of ephemeris refreshment). However, standard vetting of TOIs (odd/even eclipse tests, centroid analyses, visual inspection, etc.) is already identifying a large number of FPs. The TFOP efforts are separating FPs from planets efficiently, within a few weeks for the most interesting TOIs.

By the time the TOIs go through basic TFOP observations (to be confirmed as planets or ruled out as FPs), assuming this will happen 2 months from $\delta T_{0,\rm TESS}$,[17] we expect that 209 (141 from FFIs and 68 from TSs) of the current (i.e., 1604) TOIs will have $\delta T_{0,2\ \rm months} > 30$ minutes. Approximately 92 of those should be detectable from the ground, and their ephemerides will be (temporarily) refreshed as part of the seeing-limited photometry step (under the umbrella of TFOP SG1b), if it can happen within 2 months of their TESS observations. For the remaining 117, space-based photometry will be urgently required before their ephemerides deteriorate further.

Note that Figure 6 may be of interest for TFOP photometric follow-up efforts of TOIs that will turn out to be FPs as well, since the figure (particularly the larger planet candidates, which are more likely to be eclipsing binaries) very likely contains a number of FPs.

6. Conclusion

Ephemeris deterioration constitutes a major problem that can impede exoplanet follow-up observations that need to be acquired at a specific time of the planet's orbit (most frequently during transit). While the efforts of programs such as the Transit Ephemeris Refinement and Monitoring Survey (Kane et al. 2009) have successfully refreshed the ephemerides of nearly a dozen transiting exoplanets (e.g., Dragomir et al. 2011), the ephemerides of many known transiting exoplanets have been thoroughly lost. These include the ephemerides of most CoRoT planets and planet candidates (H. Deeg 2020, private communication; Deeg et al. 2015), as only a handful have been reobserved since their CoRoT observations were taken over 5 yr ago (Raetz et al. 2019). A similar fate likely awaits Kepler planets (with a few exceptions, such as Kepler-167e; Dalba & Tamburo 2019) and even many K2 planets if measures are not taken to keep their ephemerides fresh.

In this work, we investigated the extent and progress of ephemeris deterioration for a simulated yield of TESS planets and cross-checked our results using the current sample of real TESS planets and planet candidates (i.e., TOIs). We studied the ephemeris expiration timescale as a function of several planetary and stellar parameters for both 2 and 30 minute cadence planets. We found that the ephemerides of 81% of simulated TESS planets will be expired 1 yr after their TESS observations. We found that the ephemerides of the planets observed with the longer cadence become uncertain faster due to the lower precision of the transit times, which in turn leads to a lower δP measured from the TESS light curves. We also found that the ephemerides of planets with short or long periods deteriorate slower than those of planets with 4 days $\lessapprox P \lessapprox$ 40 days.

The approval of a 2.5 yr extension for TESS has significantly improved the ephemeris refreshment prospects for PM planets. We find that the ephemerides of most PM planets will be refreshed for at least 10 yr past their extended mission observations. We also find that whether these new observations are taken at a 2 minute versus a 10 minute cadence does not impact this timescale nearly as much as the fact that they are taken 2 yr after the original observations, in line with our Section 5.4 finding that the cadence has a relatively low impact on the effectiveness of a new transit for ephemeris refreshment compared to the baseline.

However, due to the time line and observing strategy of the extended mission, follow-up transit observations will still be necessary for TCOs intended to take place over the next 1–2 yr in order to prevent ephemeris deterioration. Moreover, a number of PM planets will not be reobserved during the extended mission, so those planets should be prioritized for follow-up ephemeris refreshment observations. For sufficiently deep and short transits, this can be achieved with the multitude of ground-based telescopes that participate in TFOP SG1 activities. Critically, for shallower or longer transits (which make up half of the simulated planets), space-based telescopes such as HST or CHEOPS are needed. The longer the baseline between the TESS and follow-up observations, the longer the ephemerides will stay fresh. We find that for 98% of expected TESS planets, one or two follow-up transits observed 3 and/or 9 months after the end of a planet's TESS observations will refresh its ephemeris for 2 yr past the follow-up observations.

The ephemeris refreshment strategy we describe in this paper and the TESS extended mission should be sufficient for scheduling TCOs for TESS planets for the next few to several years. However, more distant TCOs (even for planets reobserved by TESS, but also for new planets discovered during the extended mission) with the future Extremely Large Telescopes and missions such as Ariel (Eccleston et al. 2016) (and beyond) will still eventually require additional transit follow-up to maintain fresh ephemerides. Alternatively, additional extensions to the TESS mission will solve much of this problem and preserve the ephemerides of TESS planets ready for characterization for decades to come.

This paper includes data collected by the TESS mission that are publicly available from the Mikulski Archive for Space Telescopes (MAST). Funding for the TESS mission is provided by NASA's Science Mission directorate. We acknowledge the use of public TESS Alert data from pipelines at the TESS Science Office and TESS Science Processing Operations Center. Resources supporting this work were provided by the NASA High-End Computing (HEC) Program through the NASA Advanced Supercomputing (NAS) Division at Ames Research Center for the production of the SPOC data products.

[17] Even though this has been the case for numerous TOIs (given that data releases are happening within a few weeks of the end of a sector), we note that the sheer number of TOIs is such that TFOP resources may not be sufficient to follow up all of them before they set for the season.

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