**TESS Data for Asteroseismology: Timing Verification**

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Abstract

The Transiting Exoplanet Survey Satellite (TESS) is NASA’s latest space telescope dedicated to the discovery of transiting exoplanets around nearby stars. Besides the main goal of the mission, asteroseismology is an important secondary goal and very relevant for the high-quality time series that TESS will make during its two-year all-sky survey. Using TESS for asteroseismology introduces strong timing requirements, especially for coherent oscillators. Although the internal clock on board TESS is precise in its own time, it might have a constant drift. Thus, it will need calibration, or else offsets might inadvertently be introduced. Here, we present simultaneous ground- and space-based observations of primary eclipses of several binary systems in the Southern ecliptic hemisphere, used to verify the reliability of the TESS timestamps. From 12 contemporaneous TESS/guidestar observations, we determined a time offset equal to 5.8 ± 2.5 s, in the sense that the barycentric time measured by TESS is ahead of real time. This offset is consistent with zero at the 2.3σ level. In addition, we used 405 individually measured mid-eclipse times of 26 eclipsing binary stars observed solely by TESS in order to test the existence of a potential drift with a monotonic growth (or decay) affecting the observations of all stars. We find a drift corresponding to σ drift = 0.009 ± 0.015 s day−1. We find that the measured offset is of a size that will not become an issue for comparing ground-based and space data for coherent oscillations for most of the targets observed with TESS.

Unified Astronomy Thesaurus concepts: Asteroseismology (73); Observational astronomy (1145); Eclipsing binary minima timing method (443); Eclipsing binary stars (444)

1. Introduction

Owing to the high-precision and long-duration time series provided during the last decade by space missions such as Kepler (Borucki et al. 2010; Koch et al. 2010), K2 (Howell et al. 2014), and CoRoT (Auvergne et al. 2009), the field of asteroseismology has led a revolution in stellar astrophysics. The power of the method lies in accessing the stellar interiors through the study of the surface manifestation of internal resonant oscillations. In addition to its contribution to stellar physics (e.g., Chaplin et al. 2013; Bowman 2017; Hekker & Christensen-Dalsgaard 2017; Garcia & Ballot 2019), asteroseismology has also helped advance the study of exoplanets (van Eylen et al. 2014; Lundkvist et al. 2016).

In April, 2018, the Transiting Exoplanet Survey Satellite (TESS) joined the short list of space-based telescopes dedicated to finding planets by means of the transit method (Ricker et al. 2015). TESS hosts four charge-coupled device (CCD) cameras, aligned with the ecliptic poles, that stare at the same fraction of the sky for two of the TESS orbits (2 × 137 days, approximately). The observations collected by the four CCDs during two consecutive orbits are defined as a sector. Due to the large field of view of the CCDs (24 × 24 degrees each), the ecliptic hemispheres are divided in 13 sectors, specifically 13 in the southern hemisphere and 13 in the northern hemisphere during the primary mission. Different from Kepler, TESS is designed to detect transiting planets around very bright stars, which permits us to easily carry out ground-based radial velocity follow-ups to determine planetary masses (Rodríguez et al. 2019; Trifonov et al. 2019). However, using TESS for asteroseismology introduces strong timing requirements (Lund et al. 2017). Although the internal clock of TESS might be very accurate in its own time, it may have a constant drift, offset, or variation in the length of a second, caused by hardware limitations, software errors, lags in electronics after safe-modes/downlinks, missed leap seconds, and wrong reference frames, among others. In consequence, time stamps require verification and possibly calibration.

The TESS Asteroseismic Science Consortium (TASC) hosts the group “TESS Data for Asteroseismology” (T’DA), which is in charge of delivering light curves for all of TASC, hence encompassing many different types of stars, including all targets found in full-frame images. Requested by the TESS Science Processing Operations Center (SPOC), T’DA was also asked to carry out independent verification of TESS timestamps. This exercise is required to ensure the highest level of asteroseismic inference from TESS data, and works as a mechanism to prevent and diagnose any timing malfunction, as happened to Kepler timestamps.7 To carry out this work, TESS has been continuously observing a modest list of eclipsing

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* Based on observations made at the Argentinian Complejo Astronómico El Leoncito (CASLEO).

7 https://archive.stsci.edu/kepler/release_notes/release_notes19/DataRelease_19_20130204.pdf
binary systems (EBs) with relatively short periods, most of them between 0.7 and 4.5 days with the exception of TV Nor, which has an orbital period of 8.5 days. In order to achieve accurate timing measurements, the EBs are mostly of Algol type, presenting deep, V-shaped, and relatively short eclipses. They cover a range of latitudinal and longitudinal ecliptic coordinates, to ensure observability throughout TESS’s first year.

In this work, we present the timing requirements to be able to carry out asteroseismology using TESS data in Section 2, and we show the photometric data collected from two ground-based telescopes located in Argentina and gathered by TESS in Section 3. We detail our strategy for determining the mid-eclipse times and the model functions used in Section 4, and we present the timing verification computed from contemporaneous ground and ground as well as ground and space-based data in Sections 5.1 and 5.2, along with the timing verification carried out solely using TESS data in Section 5.3. We close this work with our final remarks in Section 6.

2. Timing Requirements for Asteroseismology

The requirements for timing for asteroseismology are mainly of importance for high-amplitude coherent oscillators (such as δ Sc and RR-lyr stars), while the requirements for stochastic oscillators are less strict. The formal requirements are specified in the internal document SAC_TESS_0002_5.pdf, which discusses three main categories: (1) accurate values for the exposure length, required to reach the photon noise limit (requirement RS-TASC-01); (2) accurate knowledge of differential times within one month of observations, required to achieve the theoretical accuracy of oscillation-mode frequencies and amplitudes (especially important for coherent oscillators). Also important here is the conversion of spacecraft times to barycentric Julian date (BJD), which should be as accurate as possible for the determination of differential times (requirements RS-TASC-02 and RS-TASC-03); (3) to compare observations taken from TESS with ground-based facilities, time stamps have to be in BJD (requirement RS-TASC-04).

The requirements are strongest for bright, high-amplitude, coherent oscillators. Considering a \( m_V = 4 \) star with an amplitude of 10% relative variability and a period of a few hours, target values have been set to 5 msec over the course of an observing sector for periods (1) and (2), while the target value is 0.5 s for point (3). For a solar-like oscillator, the times should be accurate over a period of 10 days to better than 1 s (3 s for a red giant oscillator).

In this analysis, we consider points (2) and (3) of the above, and refer the interested reader to SAC_TESS_0002_5.pdf for more details (see also Montgomery & Odonoghue 1999).

3. Observations and Data Analysis

3.1. Ground-based Photometry

The ground-based observations presented in this work were collected using mainly the 2.15 meter telescope, Jorge Sahade (henceforth, CASLEO-2.15; programs JS-2018B-14, JS-2019A-02), and to a lesser extent, the 0.6 meter telescope Helen Sawyer Hogg (henceforth, CASLEO-0.60; Director’s Discretionary Time). Both telescopes are located at the Argentinian Complejo Astronómico El Leoncito (CASLEO). For CASLEO-2.15, we used a Roper Scientific model VersArray 2048B camera with a charge-coupled device (CCD) detector (manufactured by Princeton Instruments) to collect the photometry. The imaging area is 2048 × 2048 pixels, where each pixel is 13.5 × 13.5 μm. The CCD is sensitive to wavelengths between 300 and 1000 nm. To reduce dark current, the camera is cooled with liquid nitrogen and kept at approximately −120 degrees Celsius. With the mounted focal reducer, the circular, unvignetted field of view has a diameter of ~9 arcminutes. CASLEO-0.60 has an SBIG STL-1001E CCD, which is exclusively used for photometry. The imaging area is 1024 × 1024 pixels, with a pixel size of 24 × 24 μm. The CCD is sensitive to wavelengths between 400 and 1000 nm, and is cooled down with a Peltier system. The telescope does not suffer vignetting, so the total field of view is 9.26 × 9.26 arcmin. All our observations were performed using an R filter, with an effective central wavelength, \( \lambda_R \), of 635 nm and a full width at half maximum (FWHM) of 107 nm. The main reason for this choice was to use a filter with a transmission response as similar as possible to the transmission response of TESS (\( \lambda_T = 785 \) nm, FWHM = 400 nm), thus minimizing differences in the light curves associated with the wavelength-dependent stellar limb darkening. For a better overall photometric quality, this filter also circumvents the large telluric contamination around the I band. Contrary to TESS’s constant 120 s cadence, the exposure time of the ground-based light curves depends mainly on the brightness of the star of interest, the altitude of the star during observations, and the photometric quality of the night during observations. In consequence, we adjusted the exposure time during an observing run so that the peak of the target point-spread function was kept at around half the dynamic range of the CCD. This choice allows for an adequate compromise between linearity and good signal.

To achieve high-precision photometry from the ground, we observed with the telescopes slightly defocused (Kjeldsen & Frandsen 1992; Southworth et al. 2009). The achieved photometric precision per observing run is listed in column 4 of Table 1, along with other quantities derived from our observations.

The ground-based data are reduced and the light curves are constructed by means of the Differential Photometry Pipelines for Optimum Lightcurves, DIPOL. A full description of DIPOL can be found in von Essen et al. (2018). In brief, the first component of the pipeline is based on IRAF’s command language (Tody 1993), and it does aperture photometry. First, normal calibration sequences take place, depending on the availability of bias, darks, and flatfield frames. The reduction continues with cosmic-ray rejection and posterior alignment of the science frames. Afterward, reference stars within the field are automatically chosen, usually of similar brightness to the target star to minimize the noise in the differential light curves (Howell 2006). Photometric fluxes and errors are measured for all stars with different apertures, usually dividing the range from 0.5 to 3 times the nightly averaged FWHM in ten, and we use three different background rings for each of these. In this work, we do not detrend the data, as the eclipses are deep (usually \( \Delta \text{Flux} \sim 50\%–80\% \)). Instead, we treat their noise as explained in Section 3.2. The second part of DIPOL is written in Python. The routine produces several light curves using different combinations of reference stars. The final differential light curve is the unweighted...
sum of the flux of the target star divided by the sum of the unweighted fluxes of the reference stars that produced the light curve with the smallest point-to-point scatter. The pipeline repeats this process per aperture and sky ring. The code outputs the time that the differential fluxes, the photometric error bars, and the detrending uncertainties by the so-called \( \beta \) factor in order to account for correlated noise (Pont et al. 2006; Carter \\& Winn 2009).

To compute the \( \beta \) factor, as described in von Essen et al. (2013), we first compute residuals by fitting a high-order, nonphysical, polynomial to the ground-based light curves. Next, we divide the residuals into \( M \) bins of \( N \) averaged data points. This average accounts for changes in exposure time that might be needed to compensate for changes in airmass or transparency during the observing runs. Due to the usual length of our ground-based data sets, we consider bins of four different lengths, namely 10, 15, 20, and 25 minutes.

In general, if the data have no correlated noise, then the noise in the residuals should follow the expectation of independent random numbers:

\[
\sigma_N = \sigma N^{-1/2} \sqrt{M/(M - 1)}, \tag{1}
\]

where \( \sigma \) is the standard deviation of the unbinned residual light curve, and \( \sigma_N \) corresponds to the standard deviation of the data binned with \( N \) averaged data points per bin:

\[
\sigma_N = \sqrt{\frac{1}{M} \sum_{i=1}^{M} (\bar{\mu_i} - \bar{\mu})^2}. \tag{2}
\]

In the equation above, \( \bar{\mu} \) corresponds to the mean value of the residuals per bin (\( \bar{\mu} \)) and \( \bar{\mu_i} \) is the mean value of the means. The value of \( \beta \) is calculated by averaging \( \beta_N = \sigma_N/\sigma_N \).
computed in the time bins mentioned before. When we found $\beta$ to be larger than unity, we enlarged the individual photometric errors of the ground-based light curves by this factor, and only then did we carry out the determination of the individual mid-eclipse times.

### 3.3. TESS Data

During the first 13 sectors, the eclipsing binary systems comprising our timing verification list were observed with a cadence of 120 s. For the 120 s cadence data, we adopted the PDCSAP light curves provided by the Science Processing Operations Center (SPOC; Jenkins et al. 2016) pipeline in the Target Pixel Files (TPFs), which were downloaded from the TASOC database. Only for BD Dor was it necessary for us to create custom light curves for Sectors 2–5, as BD Dor was incorrectly associated with the target TIC 220402290 during these sectors. Because this target lies only ~3 pixels away from the correct target, TIC 220402294, both stars were included in the photometric aperture. The eclipses of BD Dor were consequently observable, but were highly diluted by the contribution of TIC 220402290 to the total flux. This misidentification, which was also found in other catalogs, was reported by our group to the Centre de Données astronomiques de Strasbourg and corrected. As previously mentioned, given the proximity of the two stars, they are both contained in the TPFs for TIC 220402290, so we simply defined a new aperture around the correct target. In later Sectors, BD Dor is correctly associated with TIC 220402294.

### 4. Determination of the Mid-eclipse Times

Depending on the specific binary system observed, and thus the spectral type of the stars, their relative sizes and their mutual distances, the overall shape of the eclipses will significantly change from one system to the other. Using only one model to determine mid-eclipse timings would not accommodate a wide range of difference eclipse shapes. To overcome this, we have developed three different ways to extract the eclipse timings of ground- and space-based data. The first involves the use of a time-dependent second-order polynomial, the second an inverted Gaussian function, and the third is similar to a cross-correlation between two contemporaneous light curves. The first two techniques are specified in Section 4.1, while the cross-correlation method is detailed in Section 4.2. Regardless of the model used, timing offsets between TESS and ground-based data are computed in three ways. From the three results, we always report the one with the smallest difference.

#### 4.1. Model Functions for the Mid-eclipse Times

A method for computing accurately the mid-eclipse times was first given by Kwee & van Woerden (1956). Following their approach, our first model corresponds to a time-dependent, second-order polynomial,

$$ f(t) = at^2 + bt + c, \quad (3) $$

where $a$, $b$, and $c$ are the fitting parameters. Here, the mid-eclipse time is computed as $T_e = -b/2a$, and its associated error is computed from standard error propagation.

The second model is an inverted Gaussian function,

$$ g(t) = \beta - \alpha e^{-\frac{(t-\mu)^2}{2\sigma^2}}, \quad (4) $$

where $\alpha$, $\beta$, $\mu$, and $\sigma$ are the fitting parameters, and the mid-eclipse time is computed as $T_e = \mu$.

#### 4.2. Optimum Window around Mid-eclipse to Derive Accurate Timings

While TESS data are largely continuous within a sector, ground-based observations face other challenges, mainly imposed by the diurnal rotation of the Earth and the cloud coverage. In consequence, the coverage from CASLEO does not resemble that from TESS. In some cases, the eclipse coverage is asymmetric: in some eclipses, the instant of minimum flux is missing; in some others, there are gaps without data. This inconsistent coverage will have an impact in the precision of the derived timings. To overcome this, before calculating the mid-eclipse times, we sort the data in order to find an optimum number of data points (and thus, eclipse coverage) that best match our models. The sorting function will gradually remove data points with a flux larger than a specified value. After each round of trimming, the remaining data points are fitted with our models (Section 4.1). The gradual chopping starts at the maximal observed flux, $f_{max}$, and ends at $f_{min} + 0.1$ ($f_{max} - f_{min}$), where $f_{min}$ corresponds to the minimum observed flux value, and 0.1 is user-specified. The reason why the sorting does not reach $f_{min}$ is to ensure that the amount of fitting parameters does not exceed the number of data points. An example of the use of this sorting strategy can be seen in Figure 1, where three different fits are shown for three different chopping values. As we are only determining the optimum window that best matches our models, the fits are carried out by means of a simple least-squares minimization. After performing each fit, we compute the reduced chi-squared, $\chi^2_{red}$, considering...
at each step the changing number of data points. The final
eclipse coverage of the ground-based light curves used to
determine mid-eclipse times is the one corresponding to a \( \chi^2_{\text{red}} \) value equal to (or close to) one. In the figure, the eclipse
coverage that best matches our model lies between the blue and
cyan lines.

4.3. Cross-correlation

Our third method resembles a cross-correlation between
TESS and CASLEO data. Here, the proper time lag between
data sets is determined by minimizing the sum of the squared
residuals. This sum should approach zero as the correlation
between the two data sets become larger. It is generally
straightforward to visualize the method in the following way.
As one data set is kept fixed through the entire process, the
other set is shifted along the abscissa with a given time lag and
and a scaling is applied to the ordinate values to scale one light
curve to the other. Due to the continuity of the TESS data, the
full eclipse is typically covered, unlike the ground-based light
curves (for the eclipse coverage, see column 9 of Table 1).
We therefore always considered the TESS data as the data being
shifted, because here one can better scale the light curve.
The scaling is applied because the light curves may appear different
due to limb darkening or due to errors while constructing them,
such as aperture losses or intrapixel variations. The first step in
the program is to center the eclipses around zero in the ordinate
so that the applied scale will squeeze or stretch the light curve
from TESS, rather than simply multiplying the flux by a given
factor. This is done by calculating and subtracting the mean of
each data set separately. With the data sets varying in size, the
mean value is computed considering data points where both
TESS and CASLEO observations are defined. A time lag is
then applied to the TESS data and the flux is linearly
interpolated and evaluated at the times of the ground-based
data. The mean is then recalculated and subtracted once more
from the TESS data, which is necessary to account for the
potential change after interpolating to CASLEO’s timings. We
then proceed in calculating the sum of the squared residuals.
Both time lags and scaling factors are obtained from grids with
sensible ranges: ±60 s with a step of 1 second for the time lag,
and ±10% variability with a step of 0.5% for the scaling. For
each combination of parameters, the sum of squared residuals
is computed. The final time lag is the one that minimizes the
sum of squared residuals.

4.4. Errors on the Mid-eclipse Times

To compute reliable uncertainties for the mid-eclipse times
determined from TESS and CASLEO data using the three
approaches described in Section 4, we determine the timing
uncertainties by fitting the data and models using a Markov
Chain Monte Carlo (MCMC) approach, as implemented in
PyAstronomy,12 a collection of Python routines imple-
mented in the PyMC (Patil et al. 2010) and SciPy (Jones et al.
2001) packages. The best-fit mid-eclipse times and their
uncertainties are derived from the mean and standard deviation
(1\(\sigma\)) of the posterior distributions of the fitted parameters,
which are drawn from 10^5 iterations after carrying out a
conservative burn-in of 20% of the initial samples. This burn-in
was determined from prior visual inspection of the chains.

5. Results

5.1. Testing Timings between CASLEO-2.15 and
CASLEO-0.60

Verifying TESS timestamps from ground-based observations
means that the TESS timestamps will be limited by the
accuracy of the ground-based observations. In consequence, the
success of this technique relies on how accurately CASLEO’s
telescopes can report their own timestamps. Both telescopes
collect the universal time from two identical global positioning
systems (GPS). The sidereal time is based on a microcontroller
synchronized with the GPS that sends its timing to the
Programmable Logical Controllers, which in turn are in charge
of collecting the data. Despite the professional setup, we
carried out an independent check of their timing resemblance.
To do so, on the night of 2018 June 7, we observed the
eclipsing binary KX Aqr contemporaneously with CASLEO-
2.15 and CASLEO-0.60. The target was not observed by
TESS. Figure 2 shows CASLEO-2.15 data in red, and
CASLEO-0.60 data in blue. The timing difference between
the two data sets was obtained using the cross-correlation
method described in Section 4.3. Its value, 19 ± 85 s, is
consistent with zero at the 1\(\sigma\) level. The large uncertainty,
in this case, reflects the high noise in the CASLEO-0.60 light
curve. A detailed description of the observations can be found
in the first two lines of Table 1.

5.2. Testing for a Time Offset

Our work is based on the determination of mid-eclipse times
of selected binary systems observed from TESS and from
CASLEO’s telescopes. Thus, it is expected that the times of
minimum flux will occur simultaneously. This will not
necessarily be observed, if there is a time offset or a time
shift in the clock on board TESS. To determine a potential time
offset of the TESS timestamps, we observed eclipses from
several binary systems during TESS’s first 13 sectors. Several
aspects reduced the number of good contemporaneous data
sets. Some examples are outdated ephemerides, which
produced inaccurate windows at which to observe from the
ground, and poor weather conditions during observations,
which led to poor photometric quality in the derived light
curves. As a consequence, not all the eclipses listed in Table 1

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12 https://github.com/sczesla/PyAstronomy
have contemporaneous ground-space observations; only the twelve specified with a (C) next to their names do. For each one of these eclipse observations, we computed the mid-eclipse times as detailed in Sections 4.1 and 4.3, as well as the timing differences between TESS and ground (Table 1). Figure 3 shows the corresponding light curves. The errors in the Observed-minus-Calculated (O–C) points are computed from simple error propagation, taking into account the individual timing uncertainties. Averaging the timing differences computed from the 12 contemporaneous eclipses, the derived mean timing offset is $5.8 \pm 2.5$ s. As some of our points in the O–C diagram have a larger offset and a corresponding large uncertainty, in order to properly take them into account, our reported offset was obtained computing the weighted mean, and its uncertainty was derived from the standard error of the weighted mean. The timing differences are shown as black squares in Figure 4. If no time offset exists, the O–C points should be normally distributed with zero mean. Only recently, the TESS team discovered a time offset of 2 s.13 By taking this offset into consideration, our results improve to $3.8 \pm 2.5$ s, only $1.5 \sigma$ away from zero. It is worth mentioning that, as of sector 20, the data products on the Mikulski Archive for Space Telescopes (MAST) are corrected by the 2 second offset.

13 https://archive.stsci.edu/missions/tess/doc/tess_drn/tess_sector_22_drn31_v01.pdf
If our derived mid-eclipse times are properly computed and do not show any systematic effect that arises purely from our procedures, they should follow a normal distribution. To assess this, we performed a Kolmogorov–Smirnov test (Karson 1968) in which we compared our TESS ground timing differences against a normal distribution. The derived $p$-value of $p = 0.913$ does not allow us to reject the null hypothesis that both distributions are the same. In addition, we used the best-fit orbital periods and mid-eclipse times of reference listed in Table A1 to determine the timing differences between the observed mid-eclipse times corresponding to the four (NC) data sets and the corresponding ones computed from the ephemeris. Two of the O–C points are shown in Figure 4 in blue triangles, as the other two are off-range to allow for proper visual inspection. The derived timing offset is $2 \pm 11$ s, consistent with zero at the $1\sigma$ level.

5.3. Testing for a Time Drift

The time drift method relies solely on space-based data, exploiting the power of the continuous observations of all the short-period binary systems followed by TESS for the time verification. The advantage of this method is that it can be run without having ground-based data. The disadvantage is that care must be taken when trying to interpret the derived O–C diagrams. Even though a trend may occur, this does not necessarily stem from TESS timing drifts; it could instead be a result of the physics in the system itself. Thereby, the same trend must occur in the O–C diagram for several binary systems. It will also not be possible to infer anything about the absolute timing with this method, as the TESS time is not compared to an outside source, so the only possible result from this method is an assessment of a potential drift in the times.

To determine the potential time drift in TESS timings, we proceed as follows. For each system, we determine the individual mid-eclipse times by carrying out the mid-eclipse timing strategy presented in Section 4. From the individual mid-eclipse times, we determine the orbital period and mid-eclipse time of reference per system. To compute the timing deviation compared to a constant period, we fit the observed mid-eclipse times, $T_{o,i}$, to the expression:

$$T_{o,i} = P \times E_i + T_0$$  \hspace{1cm} (5)

Here, the orbital period, $P$, and the mid-eclipse time of reference, $T_0$, are the previously mentioned fitting parameters, and $E_i$ denotes the epochs with respect to the mid-eclipse time of reference. Both orbital period and mid-eclipse time of reference determined in this work are listed in Table A1 for the 26 eclipsing binary systems that were followed by TESS during the first year of observations to fulfill its timing verification. For the fitted parameters, errors are obtained from the 68.27% confidence level of the marginalized posterior distribution. While the individual mid-eclipse times and their uncertainties are computed from the posterior distributions obtained from $10^5$ MCMC steps, the ephemeride refinements are created by $10^6$ MCMC steps. In both cases, we apply a conservative 25% burn-in of the initial chains. For each of the binary systems, we visually inspect the posterior distributions for normality. We check for convergence of the chains by subdividing the remaining 75% in three, computing the usual statistics in each case, and checking for $1\sigma$ consistency in the periods and mid-eclipse times of reference. We carried out this procedure to reject the stars showing either a large spread in their O–C diagrams or intrinsic timing variability. Figure 4 shows, in red points, the O–C values of the binary systems that did not show a large spread. The O–C points were constructed subtracting to each observed mid-eclipse time (O) the mid-eclipse time computed assuming a constant period (C). As a timing requirement, we considered a standard deviation of the O–C points smaller than 30 s. This limit rejected a few binary systems whose O–C points were clearly showing intrinsic variability. The figure includes 405 O–C points, and has been made from primary eclipses only, as the secondary eclipses in most cases were shallow ($\Delta$Flux $\sim 0.1\%$) and thus not providing timings as precise as their primary counterparts.

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**Figure 4.** O–C diagram of the 120 s TESS data in red; timing differences between the contemporaneous TESS and CASLEO data in black squares, and the noncontemporaneous in blue triangles. Uncertainties are given at the 1σ level in all cases. The large uncertainty and offset of the last black square correspond to RR Nor, and are the products of a partial observation.
If a time drift is taking place in TESS photometry, this should be manifested equally in all the O–C points. In consequence, rather than fitting to the individual mid-eclipse times (Equation (5)), we considered the following expression, which was fitted to the 405 eclipse times jointly:

$$T_{\text{obs},i,j} = P_i E_{i,j} + T_{0,i} + \sigma_{\text{drift}} \times (t - t_{\text{ref}}),$$  

where $j$ runs over the different eclipsing binary systems, and $i$ over the number of eclipses for a given system. The shared constant drift among all systems is given by $\sigma_{\text{drift}}$ in seconds per day, and $t_{\text{ref}}$ is a common reference time for the drift. For a given system, $P_i$, $T_{0,i}$, and $E_{i,j}$ correspond to the orbital period, time of reference, and eclipse ephemeris. In this work, for simplicity, we have always considered the drift to vary linearly with time, and we tested $\sigma_{\text{drift}}$ against both a monotonic growth and decay. As a simple example to stress the power of the method, if we consider a time drift of $\sigma_{\text{drift}} = +1$ s day$^{-1}$, after a year of observations, the last eclipse of a star located in the continuous viewing zone would be shifted about 6 minutes with respect to its nonshifted counterpart. This difference can easily be detected by eye when comparing contemporaneous observations from space and from the ground. However, a shift like this could pass unnoticed if only a single space-based data set is analyzed. To reliably carry out asteroseismology studies from TESS data, potential drifts and the absolute time for TESS observations must be known to high accuracy. Even though the internal clock on board TESS is very accurate in its own time, drifts and offsets could take place, as happened to the Kepler space telescope. In consequence, we have carried out a photometric follow-up of several eclipsing binary systems from TESS and from the ground, using two telescopes located at the Complejo Astronómico El Leoncito, in Argentina. Comparing the timings of 12 primary eclipses of binary systems of Algol type from the ground to those observed by TESS, we find a time offset of $5.8 \pm 2.5$ s (in the sense that the barycentric time measured by TESS is ahead of real time), indicative of a small offset but still consistent with zero at the 2.3$\sigma$ level. It is worth mentioning that the TESS team has recently discovered a time offset of 2 s that accounts for some portion of our detected time drift.

### Figure 5

Resulting Markov chain for $\sigma_{\text{drift}}$. Left: posterior distribution. Right: evolution of the traces.

### Figure 6

Injected vs. recovered time drift. Figure shows the difference between the recovered and the injected drift, as a function of the injected drift. Uncertainties are given at the 1$\sigma$ level.

### 6. Conclusion

To reliably carry out asteroseismology studies from TESS data, potential drifts and the absolute time for TESS observations must be known to high accuracy. Even though the internal clock on board TESS is very accurate in its own time, drifts and offsets could take place, as happened to the Kepler space telescope. In consequence, we have carried out a photometric follow-up of several eclipsing binary systems from TESS and from the ground, using two telescopes located at the Complejo Astronómico El Leoncito, in Argentina. Comparing the timings of 12 primary eclipses of binary systems of Algol type from the ground to those observed by TESS, we find a time offset of $5.8 \pm 2.5$ s (in the sense that the barycentric time measured by TESS is ahead of real time), indicative of a small offset but still consistent with zero at the 2.3$\sigma$ level. It is worth mentioning that the TESS team has recently discovered a time offset of 2 s that accounts for some portion of our detected time drift.
offset. As of sector 20, the data products on MAST are corrected. Taking this offset into consideration improves our results to a total time offset of 3.8 ± 2.5 s, consistent with zero at the 1.5σ level. Carrying out a joint analysis of 405 individual mid-eclipse times collected from 26 eclipsing binary systems, we find TESS to have a time drift consistent with zero, equal to \( \sigma_{\text{drift}} = 0.009 \pm 0.015 \text{s/day} \). For this, we assumed a monotonic, linearly growing (and decaying) time-dependent drift. To the precision that our joined data can achieve, we can confirm that the TESS clock presents neither a clear time offset nor a time drift.

It is clear that we cannot reach a precision on the estimation of the time drift or offset satisfying the requirements given in Section 2. It is, however, worth remembering that these were defined based on the very brightest, highest-amplitude, and shortest-period pulsators. So, while our current analysis cannot guarantee TESS observations with timing specifications that ensure an optimum asteroseismic analysis for these, there will still be many fainter, lower-amplitude, longer-period pulsators whose requirements are fulfilled. In Figure 7, we show the amplitudes that can be reached for a given pulsation period and TESS magnitude, given the estimated drift and absolute offset. Given the relatively large uncertainties on our estimates, the amplitude values were obtained from a Monte Carlo sampling rather than using standard error propagation. To compute the noise per measurement that enters in the calculations, we used the prescription by Sullivan et al. (2015), even though we are aware that the mission will do better than the estimates here.

We combined this with measured values from the TASOC pipeline for mean flux and number of pixels in an aperture as a function of TESS magnitude (Handberg & Lund 2019). We adopt a systematic noise of 5 ppm hr\(^{-1}\), which mainly affects the noise at the very bright end (\( T_{\text{mag}} \lesssim 4 \)).

As shown in Figure 7, it will be possible to compare stellar oscillations observed by TESS with ground-based observations for several of the stars listed in SAC_TESS_0002_5 based on the measured absolute time offset. We find that the measured offset is of a size that will not become an issue for comparing ground-based and space data for coherent oscillations for most of the targets observed with TESS. Specifically, we find that for all TESS stars fainter than \( T_{\text{mag}} = 4 \), oscillations with periods longer than one hour and amplitudes below \( \sim 5 \text{ mmag} \) (0.5%) are unaffected. For stars fainter than \( T_{\text{mag}} = 9 \), oscillations with periods longer than one hour and amplitudes below \( \sim 50 \text{ mmag} \) (5%) are unaffected.

Only for one of the stars in SAC_TESS_0002_5 does the measured time drift allow for the theoretical accuracy to be reached. In the case of solar-like oscillators, with amplitudes of a few ppm and periods of the order of a few minutes on the main sequence, to a few hundred ppm and periods on the order of a day on the red-giant branch, the current timing measurements are sufficient to reach the theoretical accuracy on the determination of frequencies and comparison with ground-based facilities.

We note that the pulsators listed in SAC_TESS_0002_5 represent some of the stars with the very strongest timing requirements within their respective variability class, and the requirements for most stars observed by TESS will therefore be less strict. Also, the model used for the photometric noise represents the lower envelope. Thus, for many stars, the photometry will be noisier, and as a consequence, the timing requirement will be reduced.
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Software: This work made use of PyAstronomy (See footnote 12), PyMC (Patil et al. 2010), SciPy (Jones et al. 2001), matplotlib (Hunter 2007), numpy, IRAF (Tody 1993), DIP2OL (von Essen et al. 2018).

Appendix

This appendix contains the posterior probability distributions for some randomly selected orbital periods (Figure A1) and mid-eclipse times (Figure A2), along with their best-fit values for the whole sample (Table A1).

Figure A1. Triangle plot for 12 randomly selected orbital periods of eclipsing binaries observed by TESS. Red points correspond to the best-fit parameters, and shaded gray to white areas correspond to 1, 2, and 3σ uncertainty regions.
Figure A2. Same as Figure A1, but for the corresponding mid-eclipse times of reference.
Table A1
Orbital Period (P) and Mid-eclipse Time (T0) of Reference for the 25 Binary Systems Analyzed in This Work

| Name       | P (days)                 | T0 (BJD TDB)        |
|------------|--------------------------|---------------------|
| DW Aps     | 2.32969 ± 3.3 × 10⁻⁶     | 1626.66503 ± 0.00004|
| V379 Cen   | 1.874688 ± 1.5 × 10⁻⁵    | 1599.68944 ± 0.00009|
| WY Cet     | 1.938902 ± 1.8 × 10⁻⁵    | 1387.98849 ± 0.00010|
| TZ Eri     | 2.606213 ± 1.9 × 10⁻⁵    | 1439.30912 ± 0.000125|
| SU For     | 2.434594 ± 3.5 × 10⁻⁵    | 1386.75724 ± 0.00013|
| RX Hya     | 2.821730 ± 2.7 × 10⁻⁵    | 1518.10474 ± 0.00011|
| RR Nor     | 1.5137439 ± 2.1 × 10⁻⁶   | 1625.17032 ± 0.00003|
| GT Vel     | 4.6700996 ± 9.2 × 10⁻₆   | 1520.12020 ± 0.00004|
| UW Vir     | 1.810798 ± 5.6 × 10⁻⁵    | 1572.62214 ± 0.00036|
| UY Vir     | 1.9943626 ± 5.1 × 10⁻⁶   | 1571.16659 ± 0.00003|
| V636 Cen   | 4.283994 ± 7.0 × 10⁻⁵    | 1598.95471 ± 0.00016|
| V646 Cen   | 2.246539 ± 3.6 × 10⁻⁵    | 1572.84139 ± 0.00027|
| AF Cru     | 1.895661 ± 1.2 × 10⁻⁵    | 1599.39790 ± 0.00008|
| OU Lup     | 4.610498 ± 6.9 × 10⁻⁵    | 1601.87579 ± 0.00011|
| BH Pup     | 1.915908 ± 7.5 × 10⁻⁵    | 1519.08404 ± 0.00041|
| TV Nor     | 8.525456 ± 0.00014      | 1625.60512 ± 0.00017|
| YZ Ant     | 2.152446 ± 2.7 × 10⁻⁵    | 1546.45178 ± 0.00014|
| BV Ant     | 3.594289 ± 1.8 × 10⁻⁵    | 1546.43852 ± 0.00012|
| BD Nor     | 0.78524198 ± 3.8 × 10⁻⁷  | 1545.56357 ± 0.00003|
| AT Men     | 2.3446214 ± 1.0 × 10⁻⁶   | 1411.55316 ± 0.00006|
| DE Phe     | 1.4029532 ± 2.2 × 10⁻⁶   | 1354.37999 ± 0.00001|
| X Pic      | 0.86189657 ± 1.2 × 10⁻⁷  | 1386.63236 ± 0.00002|
| AO Pic     | 2.23418239 ± 3.9 × 10⁻⁷  | 1327.56424 ± 0.00003|
| FU Vel     | 2.446837 ± 1.8 × 10⁻⁵    | 1545.43215 ± 0.00019|
| EQ Vel     | 1.0802739 ± 2.1 × 10⁻⁵   | 1517.76048 ± 0.00005|
| NV Tel     | 3.545012 ± 8.9 × 10⁻⁵    | 1659.73105 ± 0.00026|

Note. Uncertainties are given at the 1σ level.

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