Requirement Specifications for TESS: Timing requirements for Asteroseismology

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The present document describes the primary set of timing requirement specifications for the asteroseismic part of the TESS mission. The aim of the document is to provide input to the overall TESS requirement specifications document. The present document will only focus on timing requirements.

For asteroseismology we have the following requirements related to timing:

1. In order to fully reach the photometric quality of the shot cadence data and reach the photon noise limit for the brightest stars one will need to ensure that absolute photometry is accurate and stable. This will require that each exposure has the same length. Requirement no. RS-TASC-01 below defines this.

2. In order to be able to reach the theoretical accuracy of high amplitude coherent oscillations one will need the time at which each exposure is taken to be very accurate over one observing period (one month). Requirement no. RS-TASC-02 below defines this for coherent oscillators while requirement no. RS-TASC-05 is for solar-like oscillators. We also need to transform those times to Barycenter Julian Day (BJD) at the same accuracy. Requirement no. RS-TASC-03 below defines this. RS-TASC-03 concerns the possibility to correct for the time difference between observed times and the barycenter time. We need this time difference to reach same accuracy as RS-TASC-02.

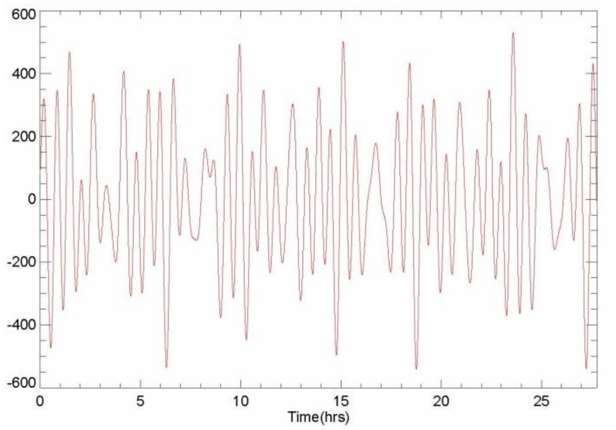
3. In order to compare stellar oscillations observed by TESS with ground-based observations we need to be able to estimate the absolute time of a given photometric data point and establish a stable reference (e.g. central time of a given observation). Requirement no. RS-TASC-04 below defines this. RS-TASC-04 is a requirement that concerns how well we know the absolute timing of BJD. This requirement is significantly less demanding than RS-TASC-03 since we will only need the absolute reference if we need to compare the TESS measurements to other less accurate (e.g. ground-based) data.

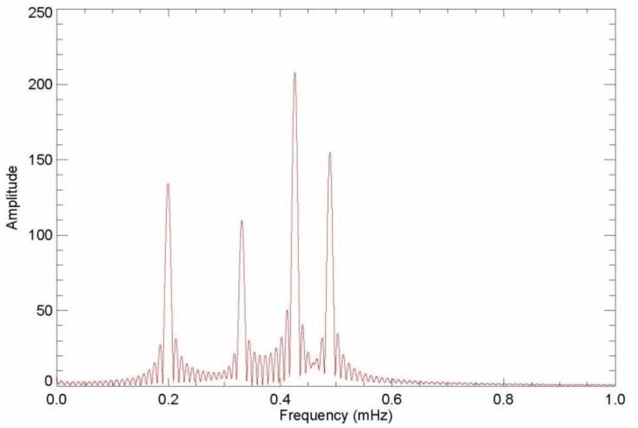
Specific estimates of requirements specifications

Individual stellar oscillation modes are characterized by amplitude, phase and period. Some modes are stable over long time scales (longer than the observing period) such that the oscillation can be described as a coherent pulsation while other modes are damped and re-excited at shorter time scales (shorter than length of the observing period). The requirements for those two types of oscillation phenomena are very different.

The strongest requirements are for high amplitude coherent oscillations like those one observe in classical pulsators (e.g. in delta Scuti stars and RR Lyrae stars).

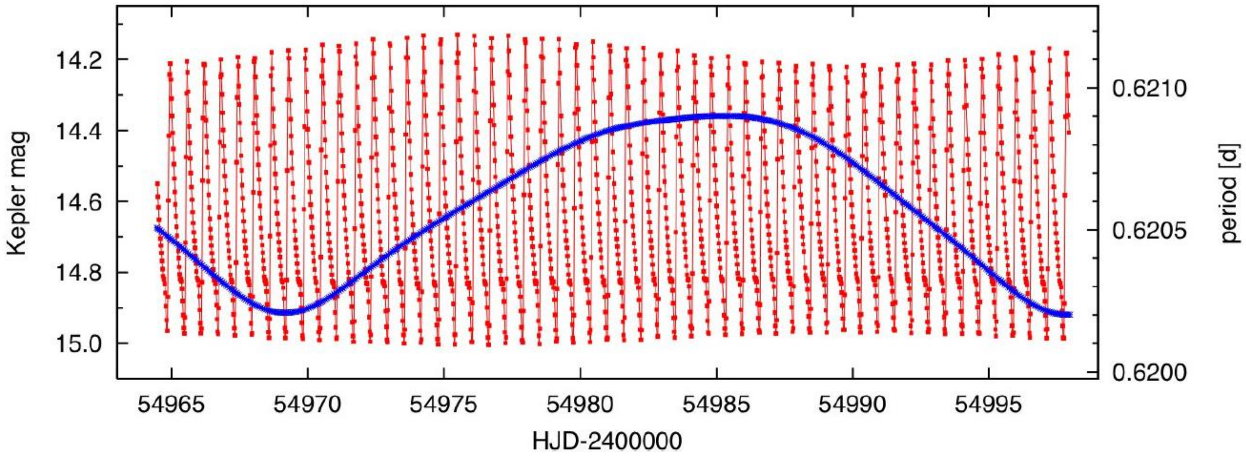
Below we show a simulated multi-mode pulsator (in the time domain and in the amplitude spectrum) with four coherent pulsations. The accuracy at which one can determine the frequency, amplitude and phase depends on the length of the time series (number of data points) and the noise per measurement.





Frequencies are determined in the amplitude (or power) spectrum. If we want to reach the theoretical accuracy for a given oscillation mode we need be able to know the phase of the oscillation accurately over the whole observing run.

Below we show as an example the relationship between the period change and amplitude modulation over the Blazhko cycle for the star KIC 5559631 observed by Kepler (figure provided by Kohlenberg). The red dots show the Kepler data and the blue line shows the period changes determined by following slow phase changes of the main period.



The key for the accuracy is to be able to measure a stable phase and for a coherent oscillator the accuracy of the phase of a pulsation can be determined via

$$\sigma(\phi) = \sqrt{\frac{2}{N}}\frac{\sigma(m)}{a},$$

where *σ(m)* is the relative scatter per measurement, *N* is the number of measurements and a is the amplitude of the oscillation. The accuracy at which we need to know the clock in order to ensure a stable phase is then

$$\sigma(time) = \sqrt{\frac{2}{N}}\frac{\sigma(m)}{a}\cdot\frac{P}{2\pi}.$$

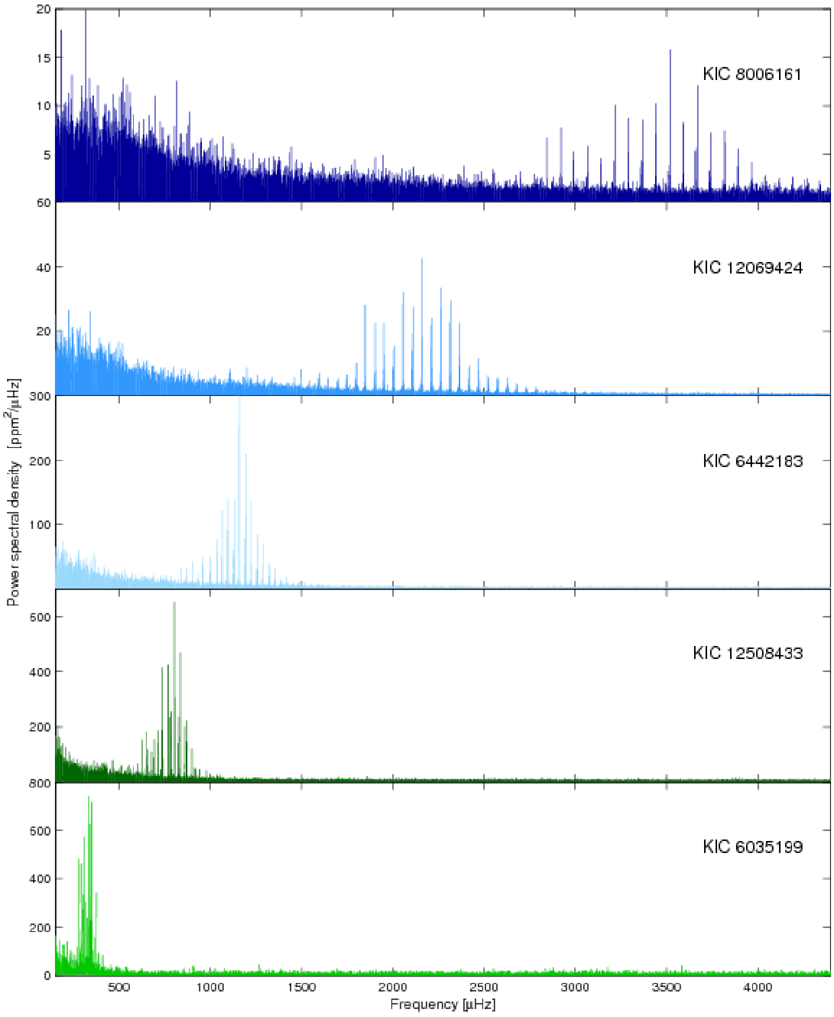
where *P* is the period of the oscillation. If we use a bright high-amplitude short periodic pulsating star as our reference one can estimate the accuracy at which we should know the time (differentially) in any part of the time series. The photon noise per minute for a star with magnitude v=7 is about 300 ppm. A v=4 star will have a photon noise of 75 ppm. The amplitude of a high-amplitude star is around 10% and the period for such a star could be a few hours (similar numbers follow if we use an amplitude of 1000 ppm and a period of a few minutes). 1 month of observing will give about 40,000 data points. Using the equation above we then find (for a v=4 star) that the clock should be accurate to 5 msec. If we consider stars observed over longer periods one will need a higher accuracy.

For v=4 stars the photon noise will be 75 ppm and one will require that the exposure times are accurate and stable (at least over time scales of hours) to $75/10^6 \cdot 60$sec ≈ 5 msec.

We will also need to correct for the acceleration of the spacecraft relative to the centre of gravity in the solar system. We therefor need to be able to calculate the light travel time between the accurate local on-board clock and the centre of gravity for the Solar system (correction to BJD with high internal accuracy). This correction should be done to the same accuracy as we require for the clock itself.

The above discussed accuracies are for the internal clock. If we want to compare the pulsations observed by TESS with ground-based pulsations one will have to transform the TESS time to absolute time (e.g. to absolute BJD). This will not need the done to higher accuracy than the accuracy of the ground-based observations which in general are less accurate than those expected from TESS.

If one therefore compares TESS measurements with ground-based observations one will need during an observing period to be able to estimate local phase differences (between a long-term TESS time series and a shorter ground-based time series). This will require one to synchronize the two clocks (ground-based and TESS) to better than 75 ppm / 2π / 10% · 4000 sec = 0.5 sec, corresponding to requirements for a v=4 star with a period of 4000 sec and an amplitude of 10%.



For solar-like oscillations like those measured by SoHO, BiSON and GONG for the Sun and by Kepler for a large number of F- and G-stars one will not need the same clock stability.

The figure at left (figure provided by Chaplin) shows an example of oscillations for a number of solar-type stars.

The main differences between the oscillation modes discussed above and those for solar-like pulsators are the low amplitude and the relatively short mode life time. If we use the same requirement for phase stability as discussed above for coherent oscillators one will for a bright solar-type star (v=4) with an amplitude 10 ppm, a mode life-time of 10 days and a period of a few minutes find that the clock need to be accurate to a few seconds.

Calibration of the absolute time

As specified above the timing requirement for asteroseismology will require *knowledge* of absolute time (HJD) for a given data point. Calibration of the on-board clock requires cross reference to an absolute time and a specific procedure should be setup to ensure that the requirement will be meet.

In order to ensure a direct cross reference to an absolute clock we intend to use simultaneous observations of a number of eclipsing binary stars observed for a period of 4-6 hours a few times during a month. All targets will brighter than V=10.

The procedure will be the following:

1. 3-5 bright (V<10) short periodic eclipsing binaries – in each TESS FOV - will be included on the TESS target list with the purpose of using them for calibration of the absolute time. The observations will be done using the short cadence mode on TESS. Targets near the ecliptic poles will be prioritized highest.

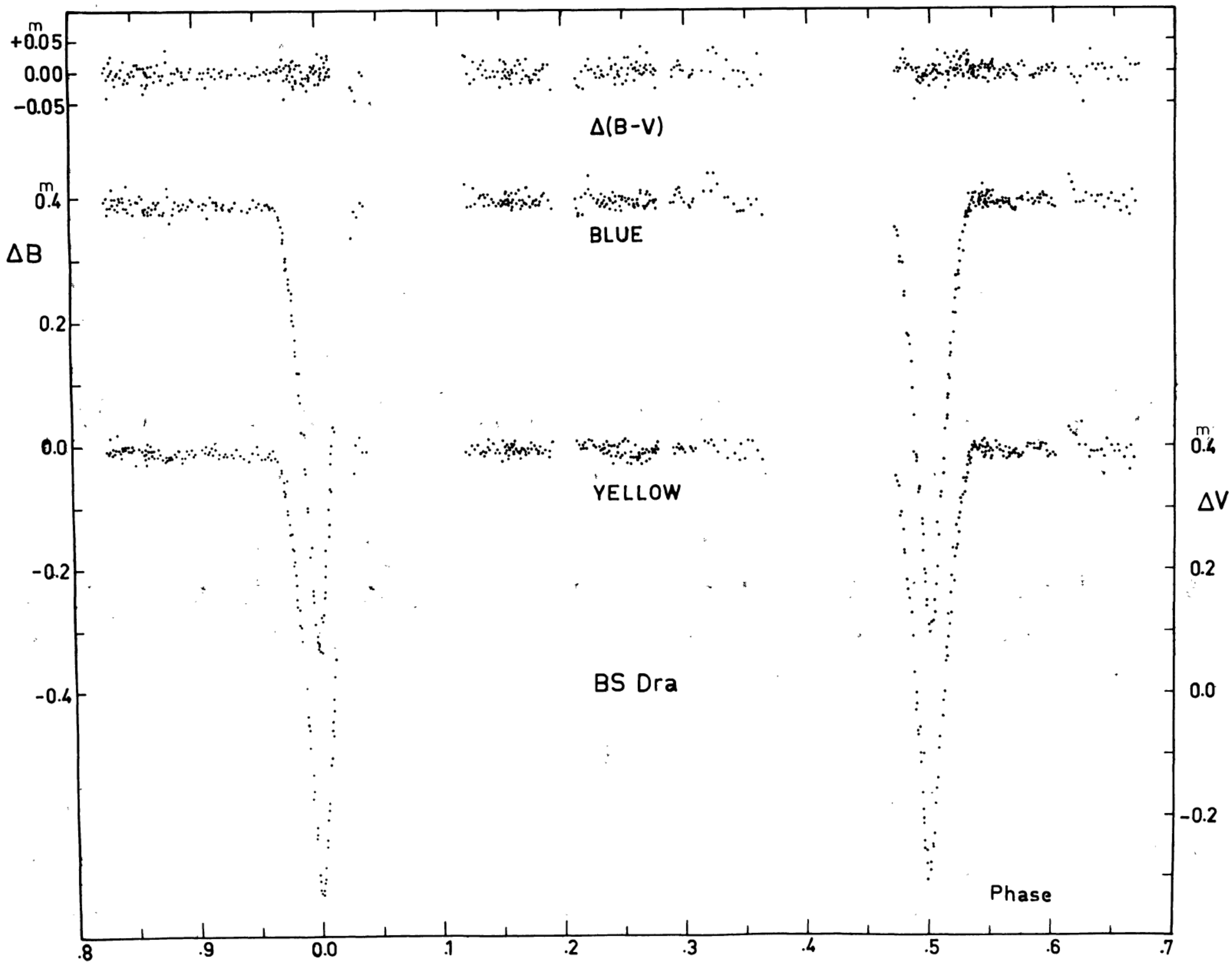
2. Every 10-15 days one of those eclipsing binary stars will be observed on ground for 4-6 hours during eclipse. Those observations will be done by the SONG telescope (http://song.au.dk/). The data sampling will be 10 seconds. Observations will be done in white light.

3. Cross correlation analysis between the TESS short cadence time series data and the ground-based observations will provide an absolute time signature which is better than 2 sec per observing run (4-6 hours) and better than 0.35 sec (RMS) after two years TESS observing (50-70 individual observing runs with SONG). The accurate calibration of the absolute time will be established throughout the mission. Close monitoring of the accuracy will be done routinely during operational phase of TESS.

The detailed observing program will be defined in the coming years. However if one search for bright (V<10) eclipsing binaries in within 13 degrees from ecliptic north pole we find at least 8 objects (RR Dra, RZ Dra, SX Dra, UZ Dra, BS Dra, BH Dra, WW Dra and RX Dra) as well as one bright RR Lyrae star (XZ Dra).

Below we discuss BS Draconis as an example of how accurate we can perform the calibration of the absolute time.

BS Draconis is an eclipsing binary (Algol type) with a period of 3.36401 d (Güdür et al., 1979, *Astron. Astrophys Suppl.,* **36**, 65-72). The ecliptic coordinates of BS Dra is (e.long: 48.5704, e.latt: 78.0272). The out of eclipse magnitude is V=9.14. The eclipse depth of both the primary and secondary eclipse is about 50% and the eclipse time for both eclipses are about 5 hours. The phase curve for BS Dra (Güdür et al. 1979) is shown below (next page).


m
+0.05
0.00
−0.05
Δ(B-V)
m
0.4
ΔB
0.2
BLUE
0.0
YELLOW
−0.2
−0.4
BS Dra
m
0.4
ΔV
0.2
0.0
−0.2
Phase
.8
.9
0.0
.1
.2
.3
.4
.5
.6
.7

Timing requirements specification for Asteroseismology

We specify the timing requirements as follows:

RS-TASC-01: The exposure times are accurate and stable (over time scales of at least a few hours) to better than **5 msec.** This corresponds to a clock stability of 0.5 ppm.

RS-TASC-02: For *coherent pulsation modes* the time given for each exposure (e.g. as the central time of a given exposure) should be accurate over a period of one month to better than **5 msec.** This corresponds to an internal clock accuracy of 0.002 ppm.

RS-TASC-03: For *coherent pulsation modes* the transformation from the local on-board time to HJD needs to be done with an accuracy better than what is given by RS-TASC-02 i.e. **5 msec**. This will require knowledge of the spacecraft 3D-position to better than **1500 km** relative to the Sun at any given time (the light travel time corresponding to 5 msec). It should be noted that this requirement concerns internal accuracy and not absolute precision (see RS-TASC-04). A stable systematic offset of a fraction of a second (as specified by RS-TASC-04) will be acceptable.

RS-TASC-04: For *coherent pulsation modes* the absolute time (in HJD) should be known to better than **0.5 sec** and one need to have fully defined reference for this time (e.g. we need to be able to estimate both central time, beginning of exposure and end of exposure to this accuracy).

RS-TASC-05: For *solar-like oscillation modes* the time given for each exposure (e.g. as the central time of a given exposure) should be accurate over a period of 10 days to better than **1 sec.** This corresponds to an internal clock accuracy of 1 ppm.

If RS-TASC-01 can't be achieved one will not be able to reach the photon noise limit for the brightest stars. If the final stability is ten times worse (50 msec) one will only be able to reach the photon noise limit for stars fainter than magnitude v=9.

If RS-TASC-02 and RS-TASC-03 can't be achieved one will not be able to reach the theoretical limit for the determination of the oscillation frequencies and phases. If the final stability is ten times worse than specified (50 msec) one will only be able to reach the theoretical limit for fainter stars, stars with longer periods and/or lower amplitudes. The calculation behind those requirements assumed a v=4 stars with a 10% coherent oscillation and a period of a few hours. If we only consider a 1% amplitude one will indeed get a 50 msec requirement. It should be noted that amplitudes of 10% or larger is only relevant for classical pulsators like RR Lyrae stars. For most objects the amplitude will be significantly lower. The table below provide examples of bright pulsating stars. In all cases we calculate the required accuracy in relation to RS-TASC-02.

For solar-like oscillations we will only need a clock stability of 1 ppm.

Examples of bright variable stars relevant for TESS. The timing requirements for a one month observation should be seen in relation to the 5 msec defined in RS-TASC-02 and RS-TASC-03. Note that the list is not complete. However very few additional stars will have a timing requirement below 30 msec.

Name	Type	Magnitude	Amplitude (%)	Period	Timing requirement (TESS)
TESS timing requirement RS-TASC-02 and RS-TASC-03:					*5 msec*
SX Phe	HADS	7.2	29	0.05496 d	6 msec
α Cir	roAp	3.2	0.3	6.8 min	8 msec
HD 24712	roAp	6.2	0.6	6.2 min	14 msec
ν Eri	β Cep	3.9	7.1	0.1735 d	17 msec
β Cru	β Cep	1.3	2.0	0.1912 d	20 msec
δ Sct	δ Sct	4.7	9.1	4.65 hrs	21 msec
λ Sco	β Cep	1.6	2.1	0.2137 d	25 msec
β Cep	β Cep	3.2	3.5	0.1905 d	27 msec
VC Cnc	δ Sct	7.7	26	4.28 hrs	27 msec
G 29-38	ZZ Ceti WD	13.0	14	13 min	30 msec
Baloon09010001	sdB	12.1	4.1	356 sec	31 msec
GD 165	ZZ Ceti WD	14.3	5	160 sec	31 msec
DX Cet	δ Sct	7.0	9.6	2.5 hrs	31 msec
BE Lyn	δ Sct	8.8	20	2.30 hrs	32 msec
RR Lyr	RR Lyr	7.6	63	0.56687 d	34 msec
DD Lac	β Cep	5.3	7.3	0.1931 d	35 msec
β CMa	β Cep	2.0	2.0	0.2513 d	36 msec
W Uma	W Uma	7.9	40	0.3336 d	37 msec
EH Lib	δ Sct	9.9	26	2.12 hrs	37 msec
γ Peg	β Cep	2.8	1.6	0.1518 d	40 msec
GP And	HADS	10.7	29	0.0787 d	43 msec
XZ Cyg	RR Lyr	9.5	79	0.46670 d	54 msec
BPM31594	ZZ Ceti WD	15.0	14	10 min	57 msec
BW Vul	β Cep	6.5	8.1	0.201 d	57 msec
KP Per	β Cep	6.4	6.9	0.2018 d	64 msec
DH Peg	RR Lyr	9.5	35	0.25551 d	67 msec
GD 99	ZZ Ceti WD	14.6	3.5	210 sec	67 msec
V1719 Cyg	RR Lyr	8.1	19	0.26730 d	68 msec
AD CMi	δ Sct	9.4	15	2.95 hrs	72 msec
MT Tel	RR Lyr	9.0	32	0.31690 d	72 msec
CC And	δ Sct	9.3	12	3.0 hrs	87 msec
Solar twin	solar-like	0.0	0.0004	5 min	1 sec
RGB star	RGB	4.0	0.03	3 hrs	3 sec