<u>Report on the Calibration of EPOXI spacecraft timing and reduction to Barycentric Julian Date</u>

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Background

The primary application for the EPOXI/EPOCh high precision photometric imaging of stellar sources is to investigate the transit timing of their companion planets. The granularity in the timing accuracy limits the photometric precision and the base criteria require calibration of the spacecraft clock. The wavefronts from each extrasolar planetary system reaches the Sun, Earth, and spacecraft with time lags. A stellar target is observed for a period spanning weeks and the change in the position of the spacecraft, associated with the orbital motion, introduces significant variation to the time lags. We resolve this timing variations by reducing the time marks to a clock at the solar system barycenter. Commensurate with extrasolar planet transit science convention, the timing is required as a Barycentric Julian Date (BJD). During the SDC processing of raw frames a BJD time is calculated (based on the SPICE kernels) and inserted into the data products (e.g., raw products and calibrated radiance reversible products in the RADREV branch). This report is a summary of an independent calculation (using EPOXI spacecraft trajectory data recorded in HORIZONS as of June 2008) that validated these time stamps recorded in those data products.

Calibrating the temporal marks from the spacecraft clock

For the observing period of interest to the EPOCh science, JPL provided a series of spacecraft time marks with their corresponding ground clock times. These time tags are reduced to a time period relative to 2008 Jan 01 0 hrs UT. For each of the spacecraft time marks, we added the spacecraft to Earth light travel time, predicted by the HORIZONS facility, to transform the spacecraft time marks to a comparable terrestrial clock. The difference between the transformed spacecraft time marks and the standard UT based ground clock, shown in Fig.1a, is the correction for the spacecraft clock. The correction is applied to the relative time tags and finally converted to absolute Julian dates.

This process permitted the absolute calibration of the time marks of the spacecraft clock. The granularity in the clock correlation imposes a 0.3 s precision limit to the spacecraft clock calibration. As an example, let us consider the correction to a HAT-P-4 from DOY 2008/022. The RADREV branch file hv0254232898_9400000_001_rr.fit (hv08012200_9400000_001_rr.fit in the archive) records the spacecraft clock time (ADCTIME in FITS header) as 254232898.0. The pipeline processing prior to Apr. 02, 2008 had generated and recorded a midpoint Julian date time (OBSMIDJD in FITS header) of 2454487.516009 in this file. The calibration procedure indicates the time (for this particular pipeline processing) should be advanced by 16.0 s. The calibration procedure has since been adopted in the pipeline data processing, and we compared the revised time record in a RADREV file from DOY 2008/233. File hv0272461619_9200010_048_rr.fit (HAT-P-7, hv08082000_9200010_048_rr.fit in the archive), has a spacecraft clock time 272461619.1 and mid point JD of 2454698.500100 and is within 0.1 seconds of the above independent calculation.

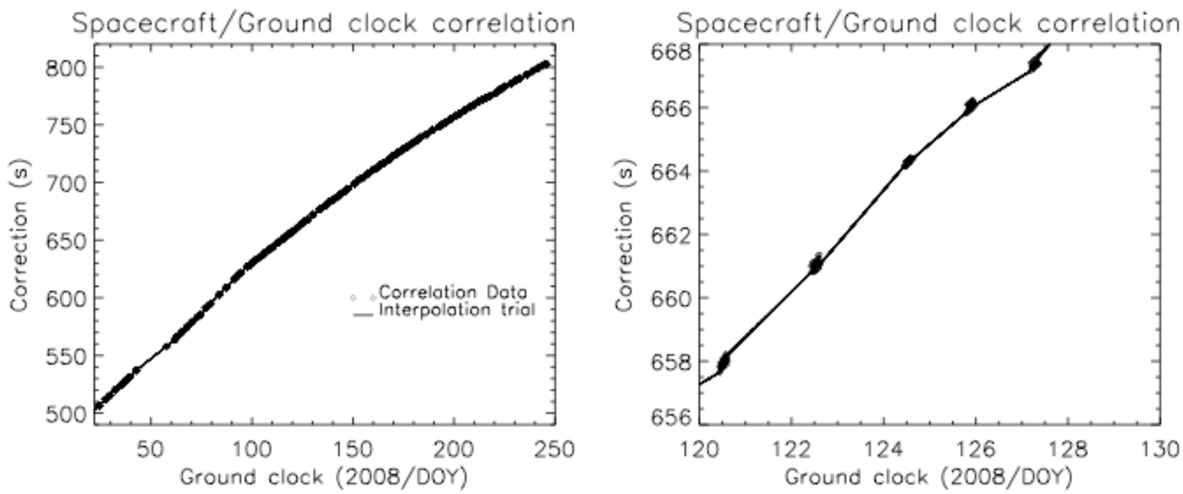

Figure 1a: Left panel shows the spacecraft ground clock correlation for the period spanning the EPOCh observations. Also shown is an interpolation to a finer time grid to investigate the precision of calibrating an arbitrary instance in time. A ten day time period is shown on an expanded scale on the right. The calibration data form a single notch for each day.

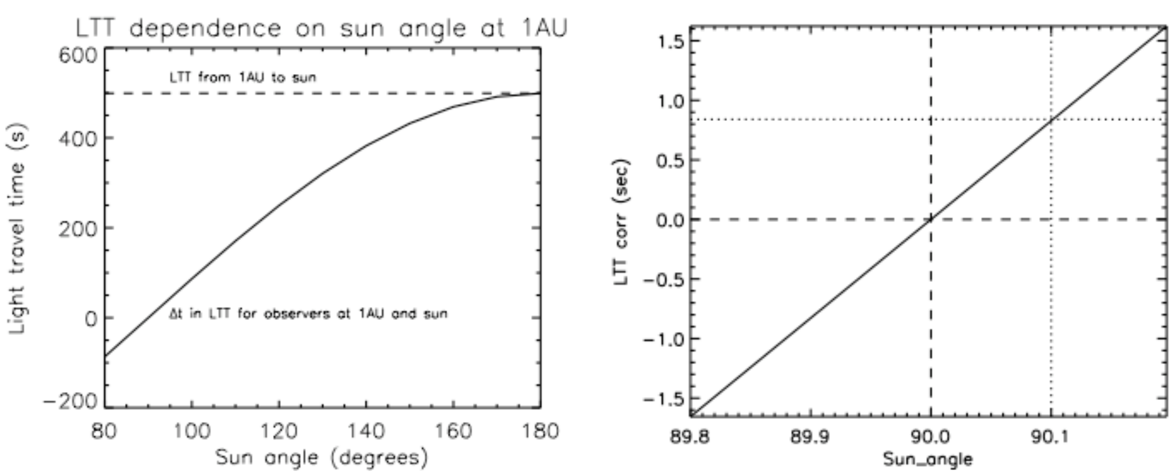

Figure 1b: left panel shows light travel time difference, as a function of angle between star and sun angle, and the right panel is an expanded portion for the sun angle close to 90°.

Reduction of calibrated spacecraft clock to a Barycentric Julian Date

For stars of interest to the EPOCh science investigation, it is sufficient to assume optical wavefronts are in the plane parallel approximation (see Appendix A for details). The optical path difference ($d - s$) for wavefronts arriving at the Solar System Barycenter (SSBC) and the spacecraft is given by

$$d - s = r\cos\beta \qquad (1)$$

where r and β are the radius vector to EPOXI from SSBC and angle between the directions to target star and SSBC, respectively. The problem thus reduces to calculating this angle and spacecraft-SSBC distance. For example, the correction at 1 AU as a function of the angle is shown if Fig.1b.

We used the HORIZONS ephemeredes server to calculate the position of SSBC on the celestial sphere as seen by an observer on the EPOXI spacecraft. Since HORIZONS does not support observer quantities (RA,DEC) as position information for solar system dynamical points (such as SSBC), we extracted the state vectors with respect to a Cartesian coordinate system. The HORIZONS server was queried for these quantities and the spacecraft distance (r) to be generated on a 4-minute interval for the time span 01-Jan-2008 through 15-Sep-2008. The vector positions were then converted to RA (α_1) and DEC (δ_1) and recorded in a local file with the spacecraft-SSBC distance. For each stellar observation, we used an interpolation within this table to determine the SSBC position corresponding to the absolute time tag of the observation midpoint. The celestial coordinates (α_2, δ_2) of the EPOCh target starts are given in table 1. The angle between the vectors from EPOXI to SSBC and the target star is calculated using the spherical law of cosines:

$$\beta = \cos^{-1}\left(\sin\delta_1 \sin\delta_2 + \cos\delta_1 \cos\delta_2 \cos(\alpha_1 - \alpha_2)\right) \qquad (2)$$

We verified that double precision computations produce well condition solutions using equation (2) to sub-arc second level.

Using the interpolated values for β and d, we compute the light travel time corrections for calibrated time tags from each file (i.e., image frame). For example, the HAT-P-4 observation recorded in 022/hv0254232898_9400000_001_rr.fit has a spacecraft midpoint observation time of JD 2454487.516190. For this case, we calculated a star-SSBC angle of 90.714°. Since the spacecraft-SSBC distance $r = 0.955743AU$, our method predicts a light travel time correction of 5.9 s and a calibrated BJD of 2454487.516263 (UTC, coordinated universal time).

The pipeline processing also inserts a FITS header field (KPKSSBJT) for the BJD but in the form of TDB (barycentric dynamical time). All of the EPOCh transit observations were confined to 2008, and the difference between UTC and TDB is 65.184 s in that epoch. The specific file noted above had a BJD/TDB value of 2454487.51701271 recorded in the FITS header (field name: KPKSSBJT). This value differs from our estimate (paragraph above) by 64.77 s. Taking into account the difference in UTC and TDB for 2008, our estimate differs from the BJD encoded in the pipeline by 0.41 s. Fig. 2 summarizes the differences in time tags for **all** of the transit target imaging frames from the EPOCh mission. Our independent calculations validated the KPKSSBJT field values for the BJD (expressed as TDB). As seen in the figure, when converted to UTC the pipeline BJD time stamp differences, compared to our calculated values, are within 1.11 s (for the maximum deviation) and having a standard deviation of 0.3 s and are well within science requirements for the transit timing studies. This analysis demonstrates that the KPKSSBJT FITS header field values are appropriate for use in transit timing studies. It is likely that the differences noted result from cumulative rounding limits in our method. The total number of frames examined for the 8 targets was 193353, and the distribution of frames between these targets is shown in table 1.

Note that the aberration, due to the orbital motion of EPOXI, is a maximum for stars that are normal to the instantaneous velocity vector of the spacecraft. Even for this case, given the nominal velocity of EPOXI (~30 km s^{-1}), the correction due to aberration is ~20″ and the perturbation to the light travel time difference is negligible (<<1 s). This correction is ignored.

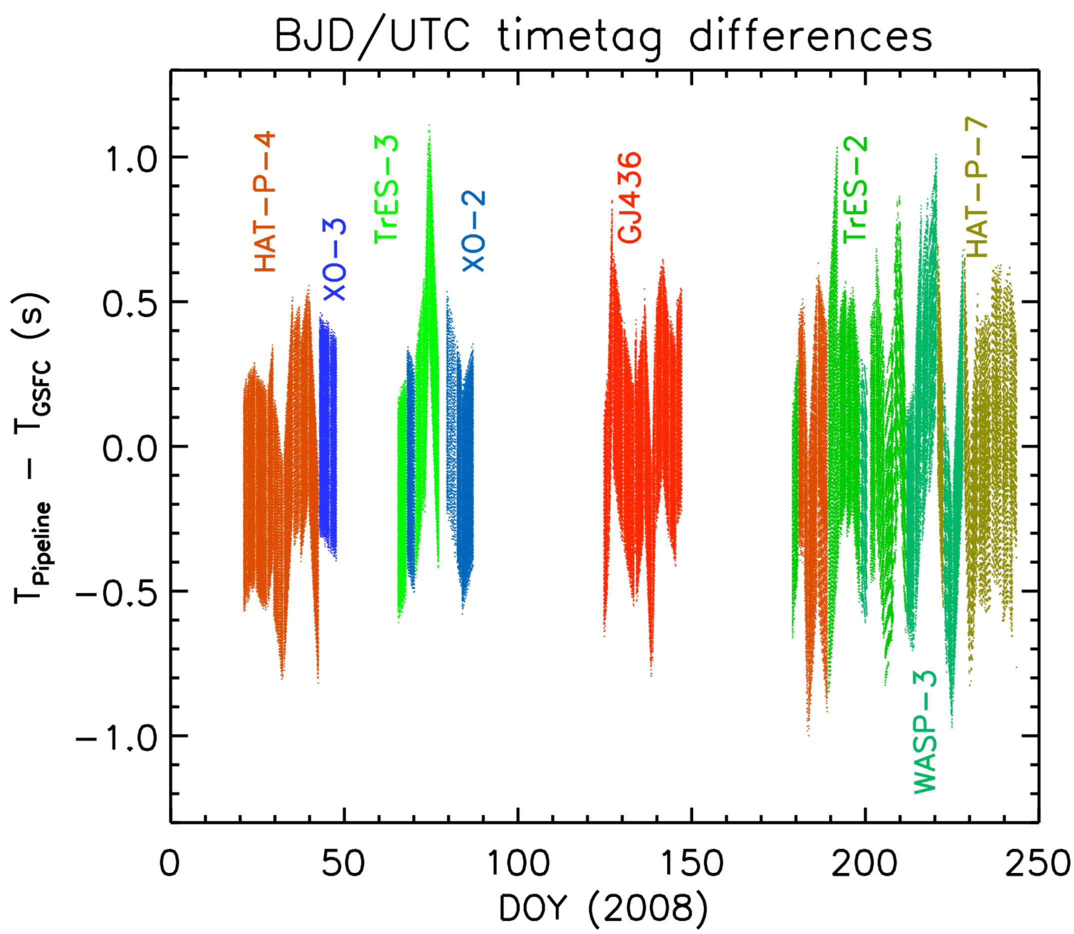

Figure 2: shows the differences in time tags encoded in the FITS headers (KPKSSBJT) by the EPOXI SDC processing and the GSFC calculations from the ADC time tag. The BJD time tags from the FITS headers were reduced to UTC (i.e., subtracted 65.184 s from the TDB values). The gaps correspond to periods where the spacecraft was in safe mode without acquiring science data.

TABLE 1

Object	RA	DEC	Frames
HAT-P-4	229.99167	36.229722	45318
XO-2	117.02917	50.225833	12353
TrES-3	268.02917	37.546111	14195
TrES-2	286.80833	49.316539	31210
GJ436	175.54583	26.706389	32689
XO-3	65.47083	57.816944	7679
WASP-3	278.63333	35.661667	24317
HAT-P-7	292.24583	47.969444	25592

Appendix A: Calculating the Barycentric Julian Date

In general, the distance to a star from EPOXI (s) is given by

$$s^2 = r^2 + d^2 + 2dr\cos(\theta + \gamma) \quad \text{(A1)}$$

where r is the SSBC to spacecraft distance, SSBC to star distance is d, EPOXI-SSBC-star angle is θ , and EPOXI-star-SSBC angle is γ. We show below that this expression reduces to the familiar expression given by equation (1) for stars at an infinite distance. Although our algorithms implement equation (A1), we confirmed that differences between equations (1) and (A1) are within fractions of a second for the closest stars.

For θ~90°, we can expand and retain first order terms

$$s^2 = d^2 + r^2 + 2dr(\cos\theta - \gamma\sin\theta) \quad \text{(A2)}$$

noting that γ^2<<1. Rearranging terms, using the approximation $s \approx d$, and dropping the second order term $(r/d)^2$ we find that (A2) reduces to

$$d - s = -r(\cos\theta - \gamma\sin\theta) \quad \text{(A3)}$$

For remote stars that subtend a small angle, equation (A3) further simplifies as

$$d - s = -r\cos\theta \quad \text{(A4)}$$

Equation (A4) is equivalent to finding the path difference by the projection of the spacecraft-SSBC separation (r) to the perpendicular to the two parallel rays from the star to the spacecraft and SSBC (i.e., (A4) refers to the limit of the being at an infinite distance from SSBC and EPOXI). For stars near the ecliptic pole (or located along the great circle described by a 90° sun angle), the path difference is commensurate with a small (order of seconds) light travel time correction. Clearly, the maximum light travel time correction is for stars in the antipodal direction given by r/c (~500 s), where c is the velocity of light.