Pointing and Photometric Errors Induced by Variable Guide Star in C6

Addendum to K2 C6 Data Release Notes, http://keplerscience.arc.nasa.gov/k2-data-release-notes.html#k2-campaign-6

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Early in the *Kepler* mission variable guide stars were identified as a problem (see §4.5 of the *Kepler* Data Characteristics Handbook). Since the sky background is not removed before first-moment centroiding on-board the spacecraft, the centroids can vary with stellar magnitude unless the guide stars are exactly centered in their apertures and the background level is flat. Any such centroid variations get averaged with the centroids of the other guide stars. Because there are far fewer guide stars in *K2* (4) than in *Kepler* (40), the effect of a variable guide star on the overall pointing is magnified in *K2*. The spacecraft attitude control system attempts to null out this variable signal by moving the spacecraft to follow the centroid, causing a periodic error in the actual pointing. This pointing error in turn causes spurious photometric signals, as shown in KDCH §4.5 and K2 DRN Figure C6-BLS.

In campaign 6, the folded light curve (K2 DRN Figure C6-GuideStar) for the eclipsing binary (EB) on module 25 has two similar features in its 0.6046 d period, for an effective fundamental period of 0.3023 d = 14.79 LCs = 0.1377 cycles per hr. Figure 1 shows a sinusoidal fit with this period to the attitude solution derived from *K2* science data by the pipeline photometer attitude determination (PAD) module. The sinusoid clearly matches the attitude during the low-torque parts of the campaign where roll is not the dominant systematic, and is phase-coherent throughout the campaign. The amplitude of the attitude error is about 10 mas (20 mas peak-to-peak) in both RA and DEC. While this is only 1% of the amplitude of the *K2* roll, image motion of this magnitude was of photometric concern in *Kepler* and apparently also in K2.

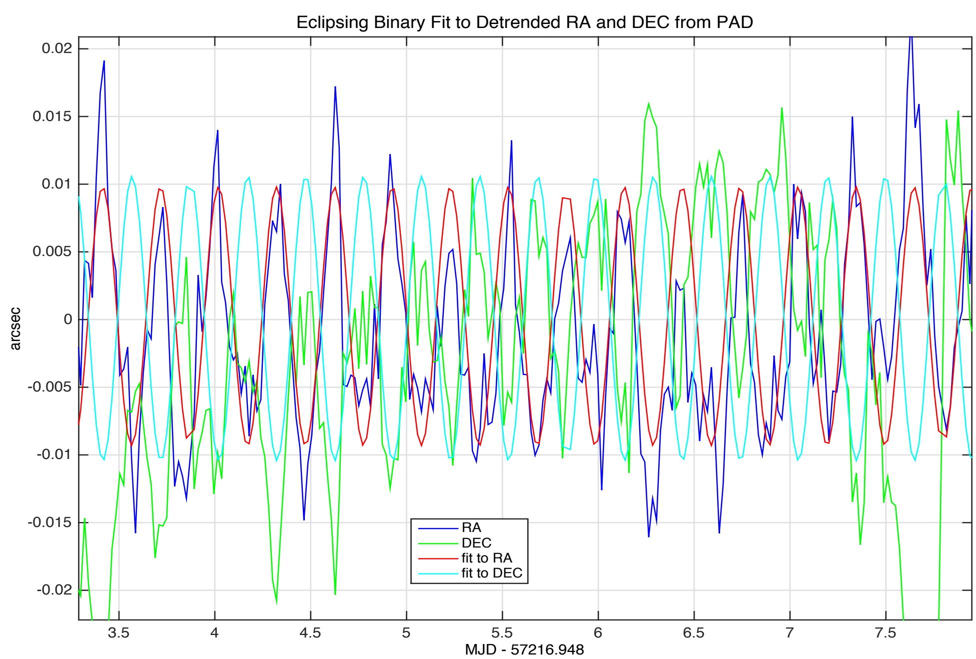

Figure 1: Fit of sinusoid with binary half-period to *Kepler* attitude solution during low-torque period early in campaign.

The guide star variability also shows up photometrically in the cotrending basis vectors (CBVs) generated in PDC, which represent the systematic errors in the ensemble of stellar light curves. The root-sum-square forward sum (RSSFS) of a time series *s* with Fourier transform *F* and power spectral density (PSD) $|F|^2$ is:

$$R(\nu) = \sqrt{2\int_0^{\nu} |F(\nu')|^2 d\nu'}.$$

The RSSFSs of the CBVs show steps where there are particularly strong, narrowband periodic contributions to the systematic error. Figure 2 shows steps in the CBV RSSFSs at the EB half period of 0.1377 hr^{-1} in vectors 4 and 7, and a step at the roll period of 0.1699 h^{-1}.

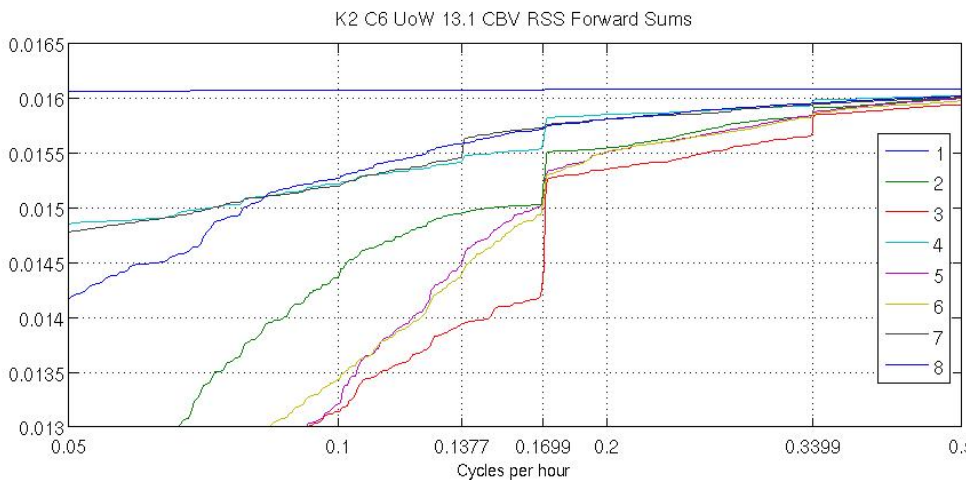

Figure 2: RSS Forward Sum of basis vectors from K2 C6 PDC, showing a distinct separation between the step at the EB half period at 0.1377 hr^{-1} in vectors 4 and 7, and the step at the roll period at 0.1699 h^{-1}.

The strength of the uncorrected EB signature in the time domain may be estimated by taking the dot product of a CBV with a normalized sinusoid and multiplying by the eigenvalues of the CBV normalized by the largest eigenvalue. This is a measure of the sinusoid's photometric strength in the ensemble of uncorrected light curves. By this metric, the EB strength before PDC correction is a few parts per thousand. The same metric for sinusoids at the roll period (exactly 12 LCs) is an order of magnitude greater, especially in CBV number 3.

While the EB signal is captured in the CBVs, PDC has not been entirely effective at removing it. In the time domain, the EB signal shows up in the folded time series (K2 DRN Figure C6-GuideStar). In an effort to estimate the strength of the EB signal remaining after PDC's corrections, we integrated the PSD in the frequency domain over a narrow (Q = 50) band centered on 0.1377 hr^{-1}, divided by the integrated baseline PSD in the absence of the EB signal, and subtracted 1 to get the net relative power of the EB signal. Roughly speaking, the SNR of the EB signal is the square root of the net relative power. This estimated net relative power can be <0 in the presence of noise in real data, so we set the EB SNR to zero in these cases. We estimated the baseline PSD from the average PSD just outside the narrow band. As shown in Figure 3, the amplitude and scatter of EB SNR increases with K_p up to a magnitude bin median value of 1.7 at K_p = 15, but does not significantly increase at greater magnitudes. For many targets, the estimated net relative power is < 0 (for which we show SNR = 0 in Figure 3) and the EB is undetectable. EB SNR > 1 may be troublesome for signals with a period close to the EB half-period. For reference, EPIC 212592841 in K2 DRN Figure C6-GuideStar has an EB SNR of 5.0, which is at the 95th percentile of the EB SNR distribution, and is easily seen in the folded light curve.

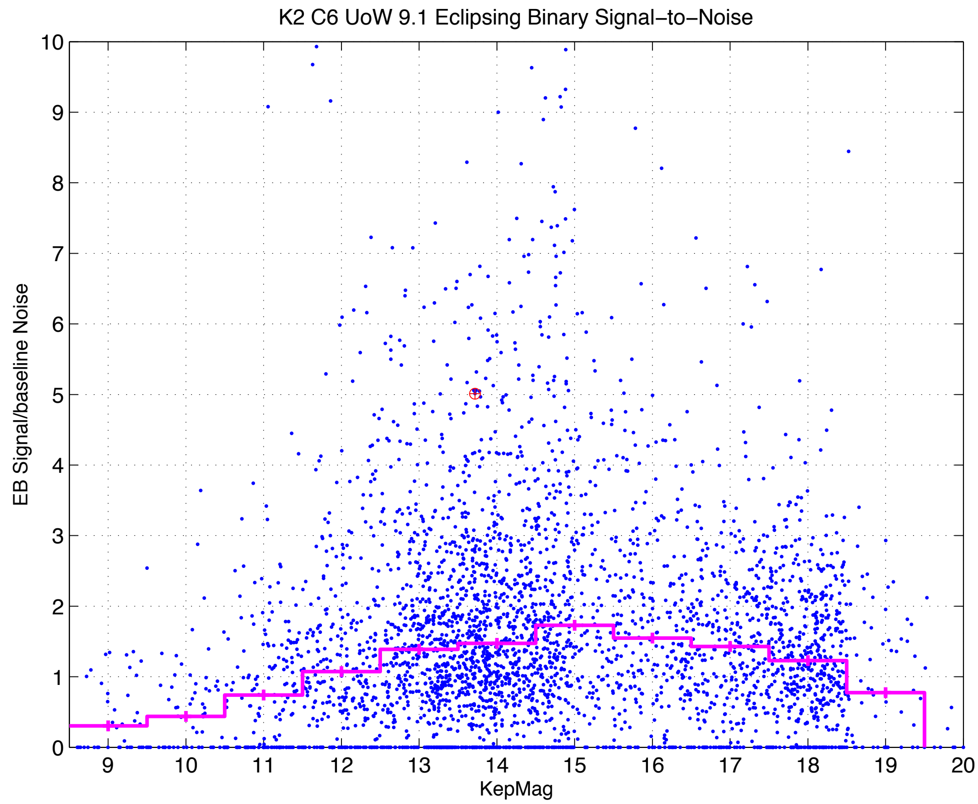

Figure 3: Narrowband SNR of EB signal in PDC-corrected light curves for 9 channels of K2 C6 data. The magenta line shows the median in each Kepler magnitude bin. Example target EPIC 212592841 is shown as a red dot.

The leakage of the EB signal through PDC may be due to the fact that the systematic error in the photometry due to the EB:

1. Lies close in period to the thruster firings,
2. Has an independent temporal envelope (i.e., the EB has a constant amplitude instead of varying by ~10x over a campaign like roll), and
3. Is small compared to roll, so under/overcorrection is difficult to detect in PDC metrics.

Though the EB and roll amplitudes are not correlated, projection of late-campaign roll error onto CBV number 4 introduces a correlation.

Users should consider regressing their PDC results against the EB waveform or its orthogonal decomposition, while being aware of the signal fidelity hazard posed by unrestricted linear regression.