everest

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abstract

Because of the reduced pointing accuracy of the *K2* telescope, its raw photometry is significantly noisier than that of the original mission. Several methods[1,2,3] have been proposed to correct for instrumental systematics based on centroid fitting, yielding light curves that approach the *Kepler* precision. Here we present **EVEREST**, an open-source pipeline that recovers the original precision of the *Kepler* spacecraft for stars brighter than K_p = 13 and achieves a precision within a factor of two of the original precision for fainter targets. **EVEREST** employs a variant of pixel level decorrelation[4] (PLD) to remove systematics introduced by the spacecraft's pointing error and a Gaussian process[5] (GP) to capture astrophysical variability. We perform cross-validation and transit injection and recovery tests to validate the pipeline, and compare our light curves to the other de-trended light curves available for download at the MAST High Level Science Products archive. We find that **EVEREST** achieves the highest average precision of any of these pipelines for unsaturated *K2* stars. The improved precision of these light curves will aid in exoplanet detection and characterization, investigations of stellar variability, asteroseismology, and other photometric studies. The **EVEREST** pipeline can also easily be applied to future surveys, such as the *TESS* mission, to correct for instrumental systematics and enable the detection of low signal-to-noise transiting exoplanets. The **EVEREST** light curves and the source code used to generate them are freely available online.

1 Vanderburg, A. and Johnson, J. A. 2014, PASP, 126, 948
2 Armstrong et al. 2015, A&A, 579, A19
3 Aigrain et al. 2016, MNRAS, 459, 2408
4 Deming, D. et al. 2015, ApJ, 805, 132
5 Ambikasaran, S. et al. 2016, TPAMI, 38, 252

performance

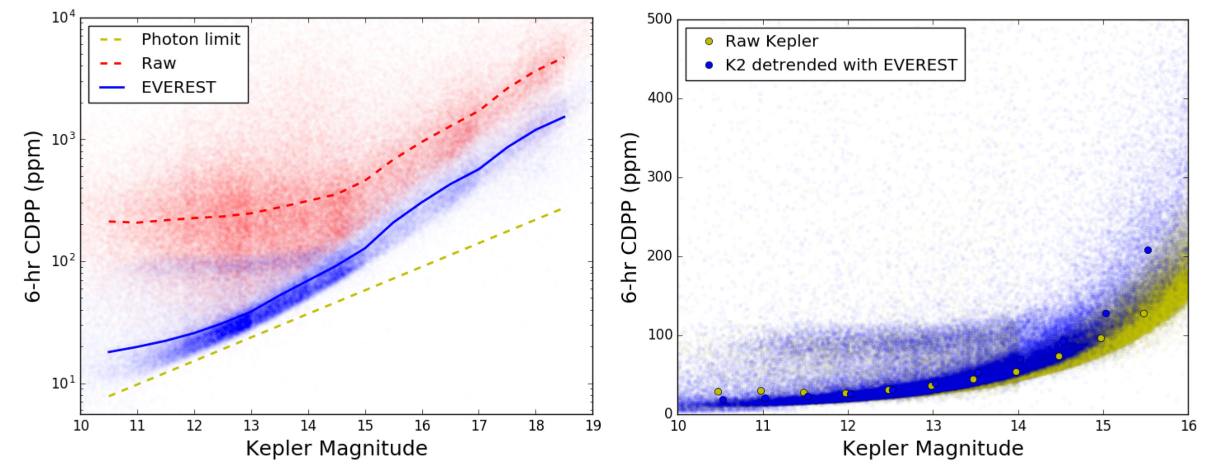
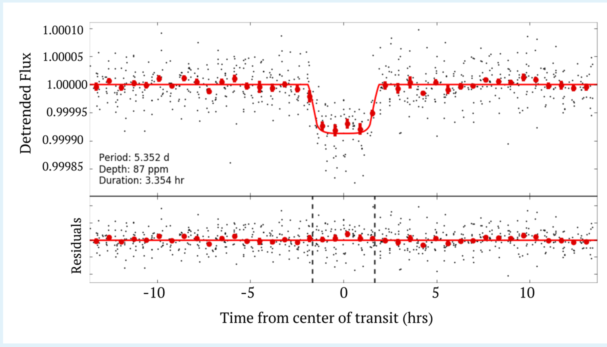


Figure 3 — *Left:* The 6-hr CDPP (Combined Differential Photometric Precision) for stars in campaigns 0-7 de-trended with **EVEREST**. The CDPP is a measure of the noise level on timescales comparable to a planet transit. Red and blue dots correspond to the raw and de-trended CDPP of individual stars; the curves show the median CDPP as a function of the K_p magnitude. For the brightest targets, **EVEREST** improves the CDPP by an order of magnitude and approaches the photon noise floor. *Right:* A comparison of the de-trended **EVEREST** CDPP to the raw CDPP of the original *Kepler* mission. For stars brighter than about K_p = 13, **EVEREST** light curves have CDPP similar to or lower than that of *Kepler*. Currently, **EVEREST** performs poorly on highly saturated stars and stars with highly contaminated apertures, since the assumptions of PLD break down in those cases.

Note

Check out the poster by **Ethan Kruse** on the detection of low signal-to-noise planets in *K2* using **EVEREST**.



The lower CDPP of **EVEREST** light curves allows for the detection of previously unknown small planets in *K2*, like the one shown above.

github.com/rodluger/everest

archive.stsci.edu/prepds/everest

pixel level decorrelation

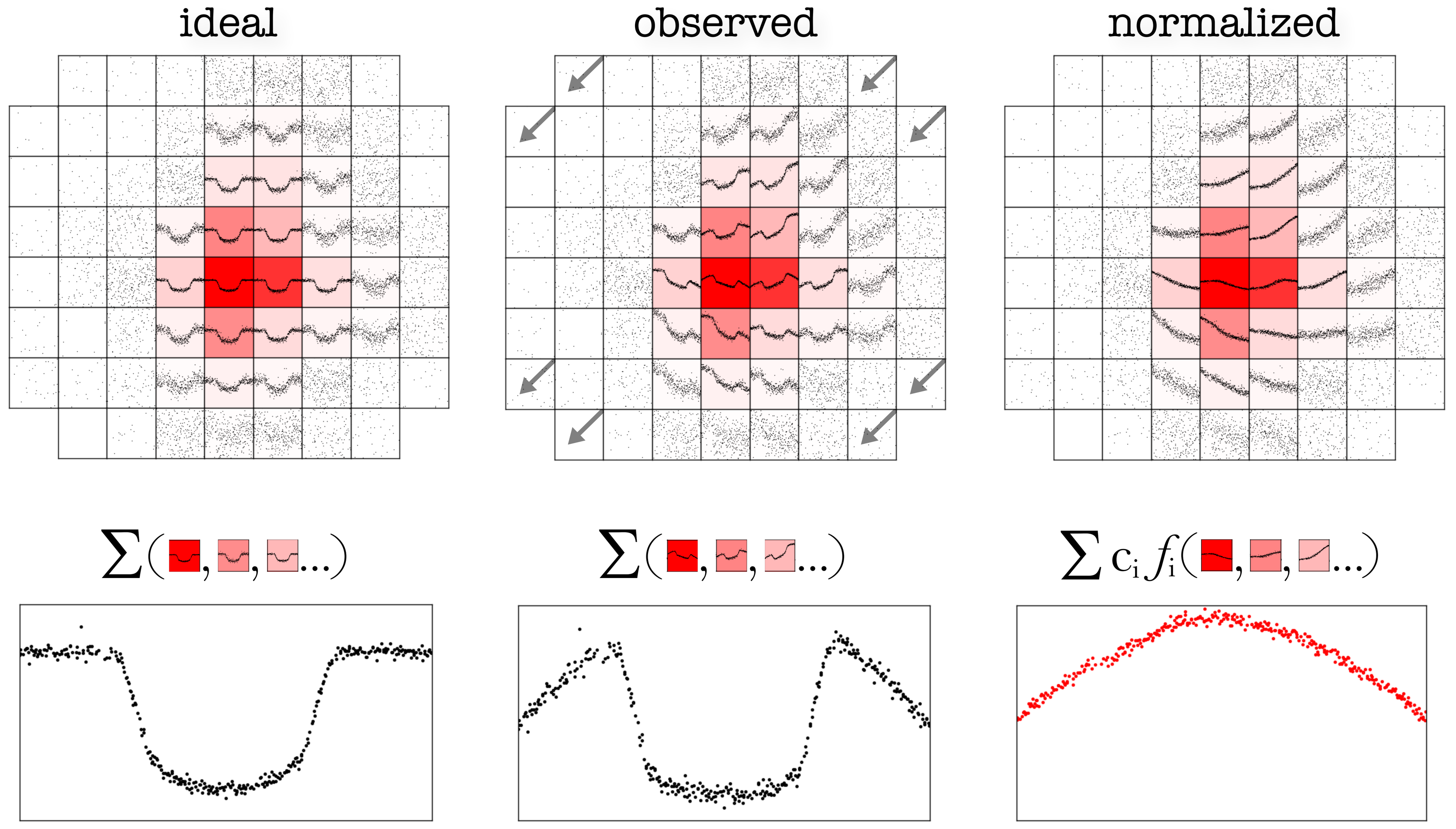


Figure 1 — *Left:* A synthetic light curve during a planetary transit in the absence of instrumental noise. The figure at top shows the pixel-level light curve superimposed on the detector. Pixel intensities are represented by a color scale of white (dimmest) to red (brightest), and black dots correspond to the (normalized) flux measurements. Summing the fluxes in all pixels results in the SAP light curve shown at the bottom. *Center:* The same light curve in the presence of instrumental noise. A linear drift is introduced at the pixel level, adding low-order trends to the individual pixel fluxes. Although the total flux intercepted by the detector is unchanged, small variations in the sensitivity within and across pixels result in the skewed SAP light curve shown at the bottom. *Right:* By dividing each pixel by the SAP flux, one obtains a set of signals that do not contain any transit information. PLD uses functions of these signals as basis vectors to build a fit to the instrumental component of the noise (bottom, red).

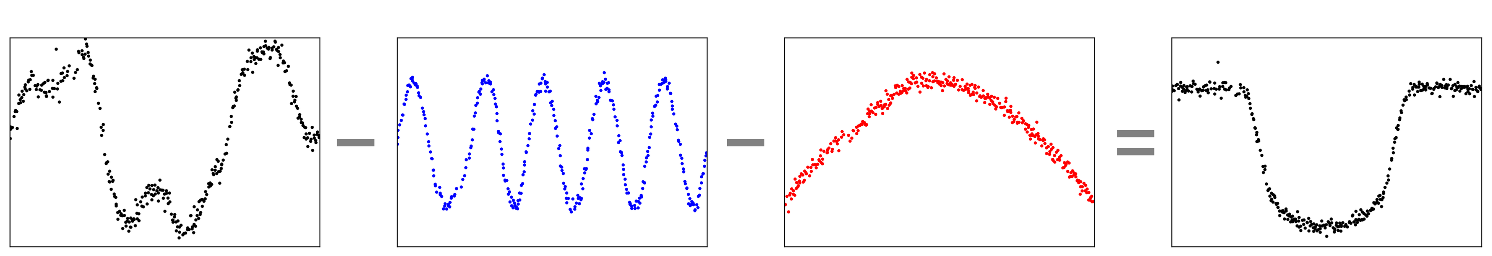
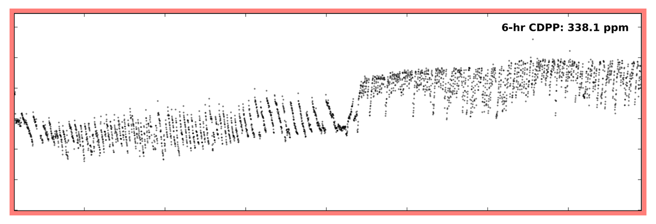
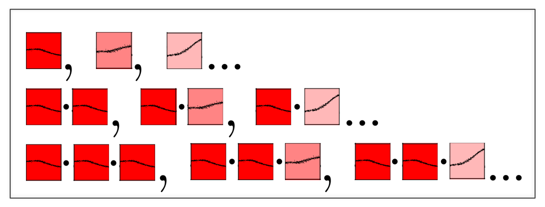


Figure 2 — The PLD process in a nutshell. The transit signal can be reconstructed by fitting the PLD basis vectors (Figure 1) to the SAP flux to obtain a model for the instrumental systematics. Stellar variability is simultaneously fit using a GP.

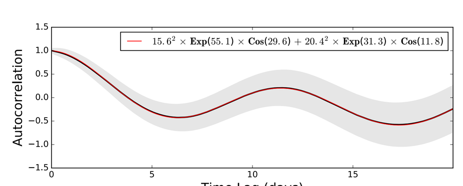
tl;dr



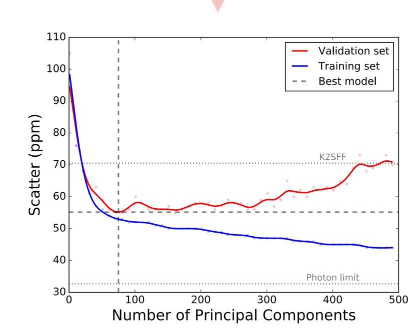
raw K2 light curve



compute basis set



train the GP



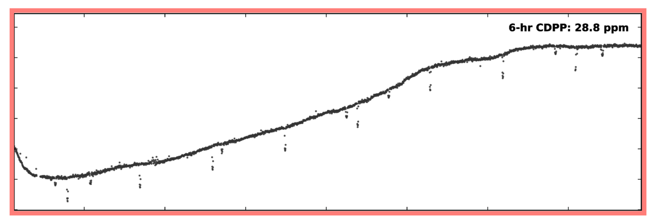
cross-validate

design matrix

model — $\mathbf{m} = \mathbf{X} \cdot \mathbf{c}$ — weights

$$\mathbf{c} = \left(\mathbf{X}^\top \cdot \mathbf{K}^{-1} \cdot \mathbf{X}\right)^{-1} \cdot \left(\mathbf{X}^\top \cdot \mathbf{K}^{-1} \cdot \mathbf{y}\right)$$

compute model



de-trended light curve

comparison to other pipelines

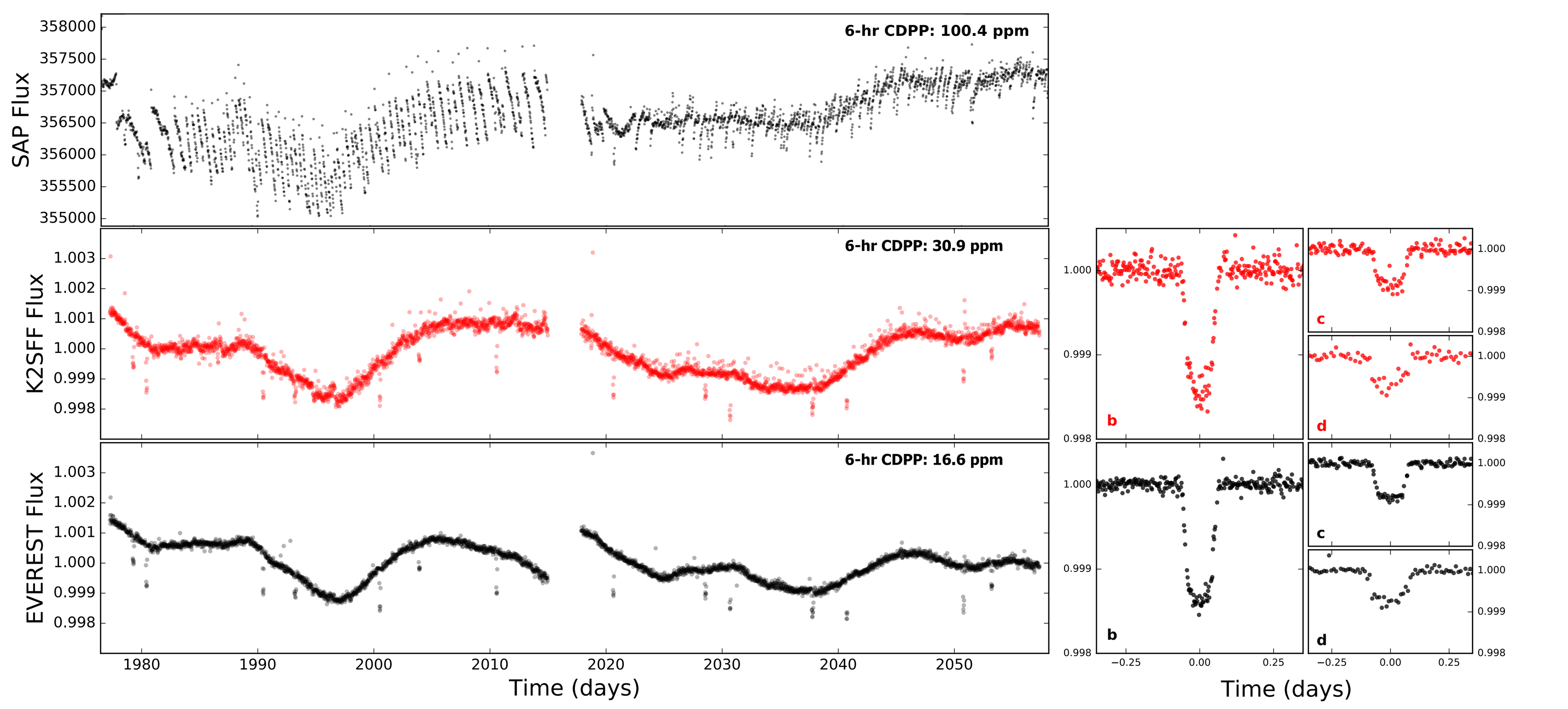


Figure 4 — *Top:* The raw light curve for EPIC 201367065, a *K2* Campaign 1 star with three known transiting planets. The raw CDPP is 100.4 ppm. *Center:* The normalized, de-trended light curve obtained by the **K2SFF** pipeline (left) and the light curve folded on the period of each of the three planets (right). The CDPP is 30.9 ppm, corresponding to a 3.2x improvement. All transits are visible to the eye. *Bottom:* The normalized, de-trended **EVEREST** light curve with a CDPP of 16.6 ppm, a 6x improvement over the raw data and a 1.9x improvement over the **K2SFF** light curve. The **EVEREST** light curves have significantly less scatter and far fewer outliers. The folded transits are also noticeably cleaner, enabling higher precision in the characterization of these planets.

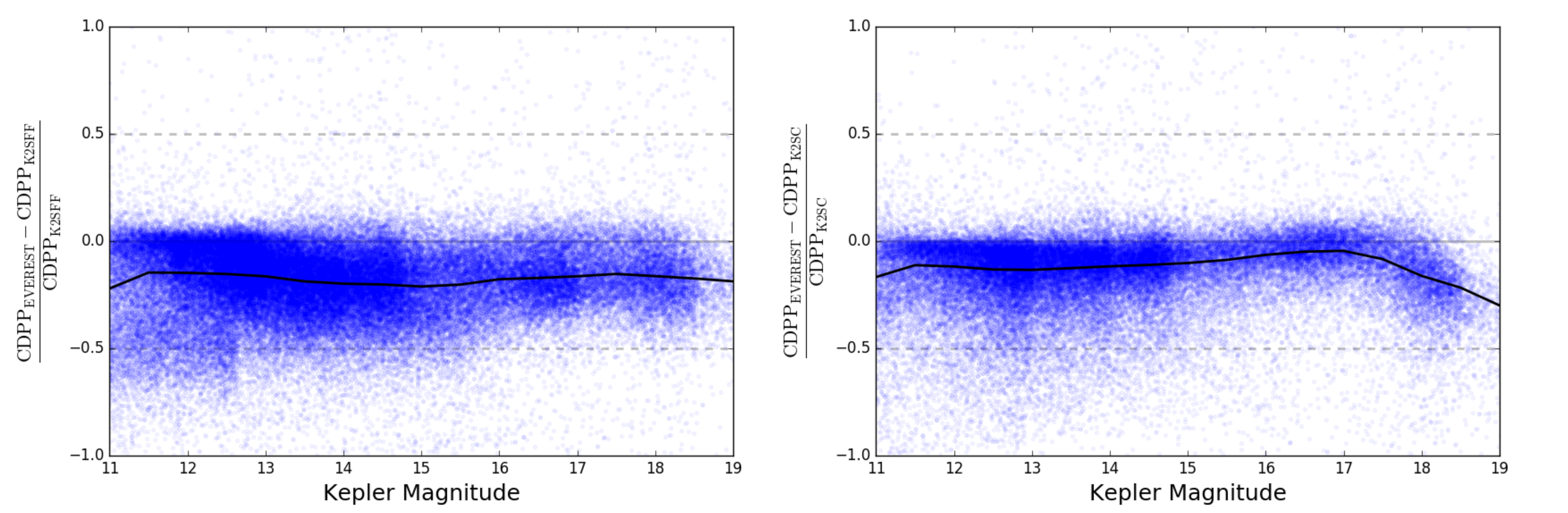


Figure 5 — *Left:* Relative 6-hr CDPP difference between **EVEREST** and **K2SFF** (left) and **K2SC** (right). Blue dots show differences for individual stars; the median is indicated in black. Negative values indicate a higher precision in the **EVEREST** light curves. On average, **EVEREST** light curves have 10-20% higher precision than both **K2SFF** and **K2SC**.