Removal of systematics in Kepler data and applicability for future space missions

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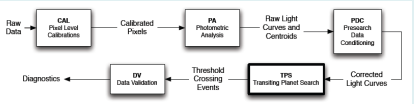
Abstract

We review the removal of systematic effects in the Kepler Project pipeline focusing in particular on the differences between the the RAW flux from the CAL part of the pipeline and the PDC flux. Furthermore we show how spacecraft features and events such as pointing error, focus drift, reaction wheel zero crossings, reaction wheel temperatures, safe modes, quarterly rolls, pointing tweaks and monthly data downlinks significantly affect photometry. We show ways how spacecraft induced systematics are removed in the pipeline and suggest improvements being currently studied and implemented. In particular:

- **Safe modes** introduce large flux discontinuities in the flux time series, that are hard to correct for and multiple safe modes in a quarter can severely degrade the scientific utility of data.
- **Pointing tweaks, monthly downlinks and quarterly rolls** or any other interruption in the time series also severely affects the data quality
- **Removal of systematics effects in the PDC part of the pipeline affect stellar variability** on long timescales by shifting power into high frequency domains. Solutions including constraining fitting coefficients by Bayesian methods are being investigated.
- **Intrinsic variability of stars** is likely higher than previously expected during design of the mission
- The science office is developing methods to include a **more complete set of basis functions including ensemble photometry** during Pre-Search Data Conditioning (PDC) to better removal systematics.
- **Bayesian constraints on the fitting coefficients** during systematics removal in PDC are being investigated

Overview of Kepler pipeline

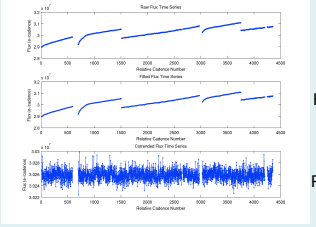


We concentrate on the CAL, PA and PDC parts of the pipeline in this poster since PA and PDC products are made publicly available. For a complete overview of the pipeline see Jenkins et al 2009. The CAL part of the pipeline performs pixel level calibrations, which are then used to perform aperture photometry in the PA module followed by the Pre-Search Data Conditioning (PDC) where most of the spacecraft induced systematics removal takes place. The Transit Planet Search (TPS) and Data Validation (DV) modules are dealt with elsewhere.

What is the difference between RAW and PDC flux and why is it so important?

Photometric Analysis (PA) produces flux, which is not detrended against spacecraft systematics and can be used for long term stellar variability. In this poster we aim to highlight some of the ongoing issues with removal of systematics that takes place in the PDC part of the pipeline, in particular how detrending in PDC can alter or destroy astrophysical variability.

Twicken et al. 2010



PA flux

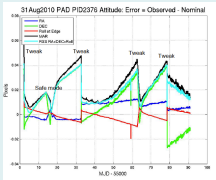
Fitted time series

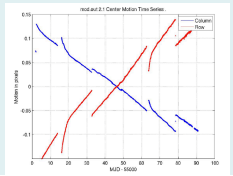
PDC flux

Sources:

- Van Cleve, J.E., Jenkins, J.M., Twicken, J.D., Smith, J.C., & Fanelli, M.N. 2011, American Astronomical Society Meeting Abstracts, 217, #140.08
- J. Van Cleve, J. Christiansen, P. Machalek, and the Kepler Data Analysis Working Group (DAWG), Data Characteristics Handbook and Data Release Notes at MAST, http://archive.stsci.edu/kepler/documents.html
- Jenkins, J et al. Kepler Instrument Handbook, 2009, KSCI-19033, http://archive.stsci.edu/kepler/manuals/KSCI-19033-001.pdf
- Twicken et al. - Presearch data conditioning in the Kepler Science Operations Center pipeline, 2010, http://archive.stsci.edu/kepler/papers/
- Twicken et al. - Photometric analysis in the Kepler Science Operations Center pipeline,2010, http://archive.stsci.edu/kepler/papers/
- Quintana et al. - Pixel-Level Calibration in the Kepler Science Operations Center Pipeline, 2010, , http://archive.stsci.edu/kepler/papers/

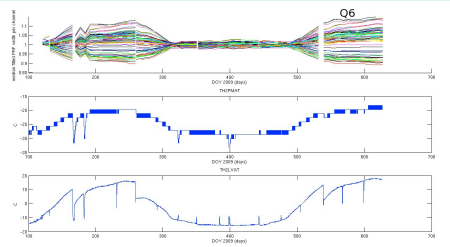
Systematics in the Kepler data





Pointing error

Pointing changes of the spacecraft introduce discontinuities in the photometry and stellar centroids. Above is an example of spacecraft pointing (left) for Quarter 2 (Summer 2009), which shows 1 safe mode and 3 spacecraft pointing tweaks. The right panel shows the focal plane pixel level shifts induced by the spacecraft pointing on the left. Discontinuities at days 30 and 60 are due to monthly Earth downlinks.



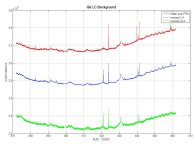
Focus drift

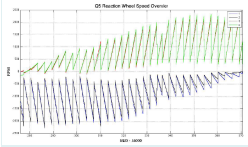
The graph above shows the median PRF width in pixel for each of the 84 Kepler channels throughout the 6 quarters of data analyzed so far. The top plot shows seasonal variations of focus, which closely correlate with the primary mirror temperature (middle) and launch vehicle adapter and bottom deck temperatures (bottom).

Background and argabrightenings

Background time series (right) shows the average background flux for all channels (blue) and for the channel closest (red) and furthest (green) to the Galactic plane.

The narrow spikes common to all 3 curves are Argabrightenings, which are presently unexplained diffuse illumination of the focal plane, lasting on the order of a few minutes. The physical cause for these is still being investigated.



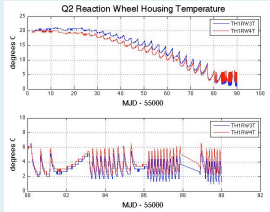


Reaction Wheel Zero Crossings

During normal spacecraft operations reaction wheels go through zero momentum points (left) which causes the wheel to rumble and the the pointing of the spacecraft is temporarily degraded, which then causes nonlinearities in Short Cadence photometry.

Reaction wheel temperatures

Reaction wheel temperatures change in unpredictable ways during a quarter (right, Quarter 2 shown [Summer 2009]). Changes in reaction wheel temperatures do affect photometry both on long (~months) and short (~3 day period of wheel desaturations) timescales. The physical principle of how reaction wheel temperatures affect detector pixel photometry is currently being investigated.



Ongoing improvements and unexpected features

Stellar variability higher than expected based on SOHO observations of the Sun

Stars were estimated to be uniformly variable at the 10ppm level for all spectral types (Jenkins et al 2009) based on SOHO observations of the Sun. There are indications that stars are intrinsically more variable than at the 10ppm level and this affects the photometric precision estimates for fainter objects.

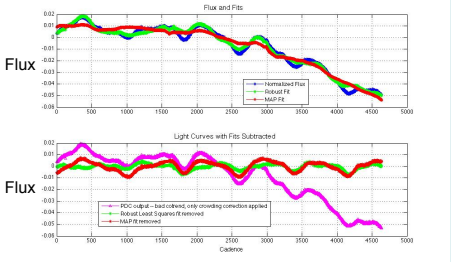
Need to develop a complete set of basis functions for systematic error removal

Currently the PDC part of the pipeline uses ancillary data such as vehicle adapter temperatures as a set of basis functions to remove systematics in the light curves produced by PA. Residuals systematics are still evident in the PDC light curves so more complete set of basis functions are now being investigated e.g. reaction wheel temperatures and ensemble photometry, given that there are thousands of stars on each modout.

Need to constrain fitting coefficients in order to constrain astrophysical signatures in variable stars

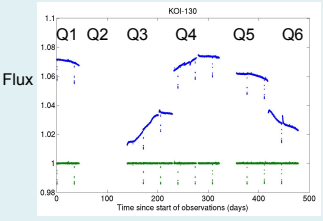
Kepler's Pre-Search Data Conditioning (PDC) part of the pipeline is designed for correct instrumental artifacts in order to identify very shallow transits (~100ppm) on short timescales (~3-12 hours). This works well for the ~70% of stars which are not intrinsically variable but PDC distorts intrinsic variability of stars with long term (t>>hours) and high amplitude (>>100 ppm) variability and shift the power from real astrophysical signals into high-frequency noise.

The Kepler Project is thus investigating ways how to remove long term systematics without removing astrophysical signal by constraining the magnitudes and signs of the fitted coefficients to prevent overfitting.



Impact on photometry from flight system attitude and thermal excursions

Monthly data downlinks, pointing tweaks, safe-modes and quarterly spacecraft rolls all introduce significant flux discontinuities and non linearities. Especially if there is more than one safe mode per quarter (as happened in Q2) the discontinuities in the flux can severely degrade the scientific use of that quarter even after attempts at removing the systematics. Mitigation strategies are being investigated.



Discovery Mission 10 - Launched 2009 - http://Kepler.NASA.gov

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