Dynamic Black-Level Correction and Artifact Flagging for Kepler Pixel Time Series. J. J. Kolodziejczak[1], B. D. Clarke[2] and D. A. Caldwell[2], [1]Space Science Office, NASA Marshall Space Flight Center, Huntsville, AL 35812; kolodz@nasa.gov, [2]SETI Institute, NASA Ames Research Center; bruce.d.clarke@nasa.gov; Douglas.Caldwell@nasa.gov>.

Introduction: Methods applied to the calibration stage of Kepler pipeline data processing [1] (CAL) do not currently use all of the information available to identify and correct several instrument-induced artifacts. These include time-varying crosstalk from the fine guidance sensor (FGS) clock signals, and manifestations of drifting moiré pattern as locally correlated nonstationary noise, and rolling bands in the images which find their way into the time series [2], [3]. As the Kepler Mission continues to improve the fidelity of its science data products, we are evaluating the benefits of adding pipeline steps to more completely model and dynamically correct the FGS crosstalk, then use the residuals from these model fits to detect and flag spatial regions and time intervals of strong time-varying black-level which may complicate later processing or lead to misinterpretation of instrument behavior as stellar activity.

FGS Crosstalk: This artifact appears in the images as a pattern like that shown in figure 1. To mitigate prelaunch risk, we defined a set of long cadence artifact removal pixel (ARP) targets and continue to collect them throughout the mission. These pixels are read out at the same time as the offending periods of FGS readout and are fit cadence-by-cadence, along with the trailing black collateral data, to extract the time-dependent profile of the crosstalk. Examples of this variation over nearly 2 years are shown in figure 2.

Rolling Bands: The residuals of the FGS crosstalk spatial model fits reveal time-varying features in the black level caused by the drifting moiré patterns and scene dependent response to variable stars. These features are too complex to correct, but the presence of the largest variations, the rolling bands, can be flagged in the pixel time series and the flags can then be carried forward to the light curves to provide end users with knowledge of affected time intervals. Figure 3 shows an example of recurring strong rolling bands in the trailing black over a 2 year interval. The band repeats annually, but not at precisely the same time in the same region.

Summary: The FGS crosstalk pixels are present in 20-25% of targets but typically vary slowly enough to create a very small risk of reduced sensitivity or increased false positive rate in the transit search. They do have the potential to complicate or reduce the effectiveness of cotrending algorithms by introducing additional cotrending terms into the light curves which are not associated with prior relations. We will present results regarding the improvement in cotrending performance as a result of including FGS corrections in the calibration.

The rolling bands appear in only ~10% of channels and are present only in 3% of the total exposure, but we estimate that because of the rotation of stars through the affected sky groups, about 30% of light curves are ultimately affected. Thus the utility of this is expected to be high. We will discuss the effectiveness of the proposed flagging and illustrate with some affected light curves.

References: [1] J. M. Jenkins, et al. (2010) *ApJ, 713*, L87. [2] D. A. Caldwell et al. (2010) *ApJ, 713*, L92. [3] J. J. Kolodziejczak. (2010) *Proc. SPIE*, 7742, 38.

Figure 1. Pattern of FGS crosstalk in images.

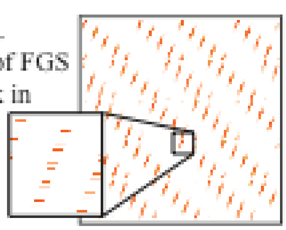
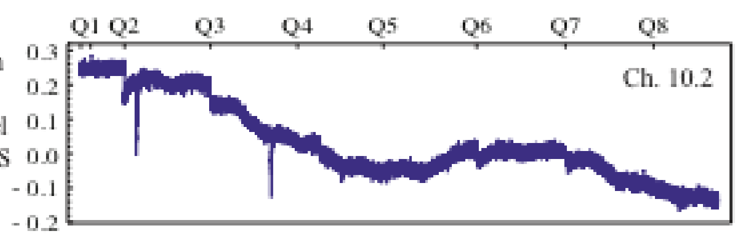


Figure 2. Long-term trend in black-level due to FGS crosstalk.



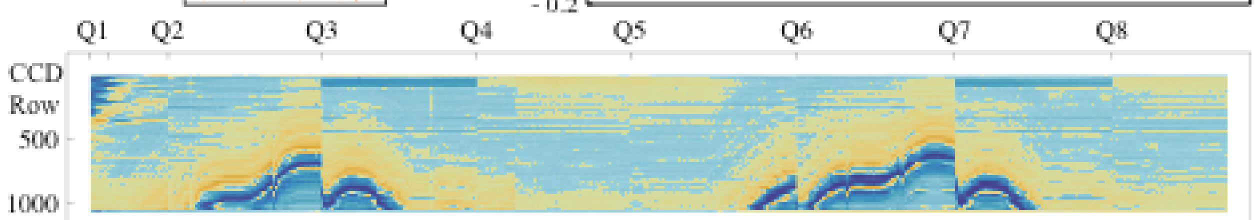


Figure 3. Channel 9.2 color map of trailing black residuals, indicating annually recurring rolling bands.

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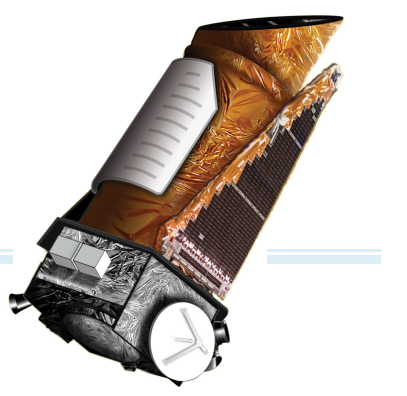

Abstract

Methods applied to the calibration stage of Kepler pipeline data processing [1] (CAL) do not currently use all of the information available to identify and correct several instrument-induced artifacts. These include time-varying crosstalk from the fine guidance sensor (FGS) clock signals, and manifestations of drifting moiré pattern as locally correlated nonstationary noise, and rolling bands in the images which find their way into the time series [2], [3]. As the Kepler Mission continues to improve the fidelity of its science data products, we are evaluating the benefits of adding pipeline steps to more completely model and dynamically correct the FGS crosstalk, then use the residuals from the model fits to detect and flag spatial regions and time intervals of strong time-varying black-level which may complicate later processing or lead to misinterpretation of instrument behavior as stellar activity.

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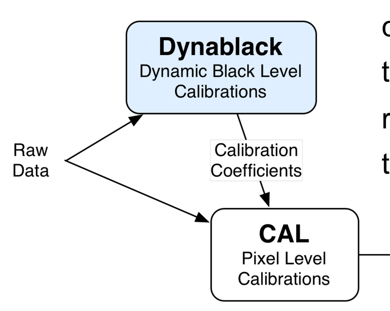
Proposed Dynamic Black-Level Correction Implementation in SOC Science Processing Pipeline

Pipeline Data Flow



A new component called *Dynablack* performs black level calibrations in a two-step process: first cadence-by-cadence, then across cadences. CAL is modified to use Dynablack results to calibrate science pixels (collateral, background and target) for each long or short cadence.

Dynamic Black Level Model Components

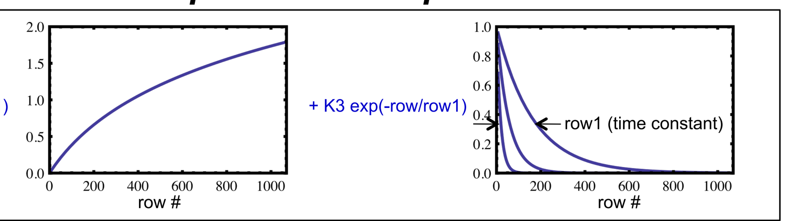
Time interval	Component	Current V.8.0	Proposed
Cadence-by-Cadence	Row Dependence	x	x
	Column Dependence		x
	Parallel FGS cross-talk		x
	Frame FGS cross-talk		x
	Moire Pattern – Rolling Bands		Monitored
	Undershoot		Monitored
Across Cadences	Time Dependence		x
	Temperature Dependence		x

Currently, all terms in the black-level model are static, except for the row dependence. Dynablack enables more complete modeling and accounts for cross-cadence time and temperature trends, as well as monitoring of moire pattern and undershoot.

Black-Level Model Component Descriptions

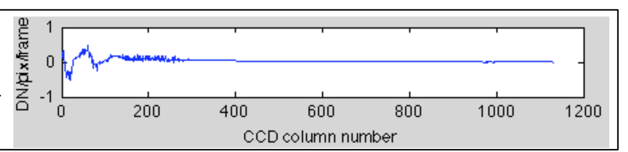
Row Dependence = K1 + K2 ln(row/214+1) + K3 exp(-row/row1)

Constant term accounts for large (~0.15DN/frame) jitter in mean black level for image, enabling smoothing or cotrending of other coefficients

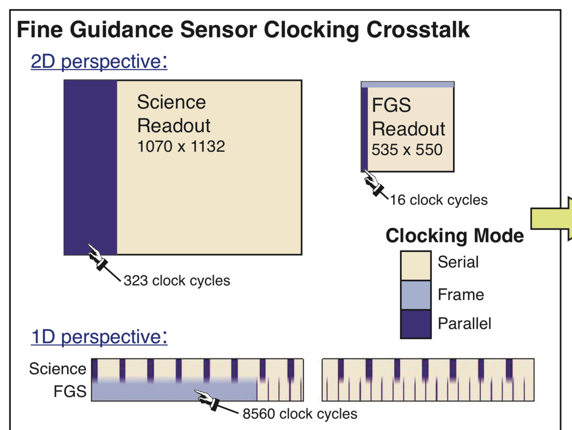


Column Dependence = SOL + C1 column + C2 column^2

SOL - Start of line ringing is determined from reverse- clocked data collected several times per quarter

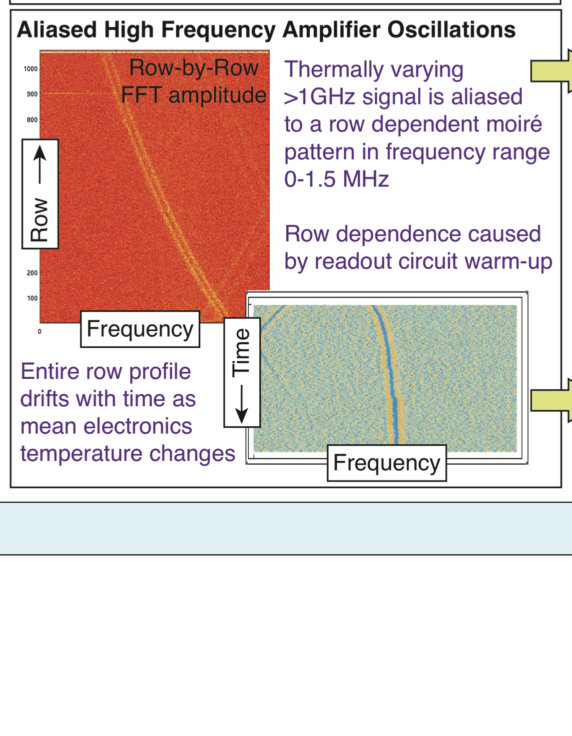


Fine Guidance Sensor Clocking Crosstalk



Crosstalk occurs during FGS frame and parallel clocking intervals; Repeats 5 times per science frame

Aliased High Frequency Amplifier Oscillations

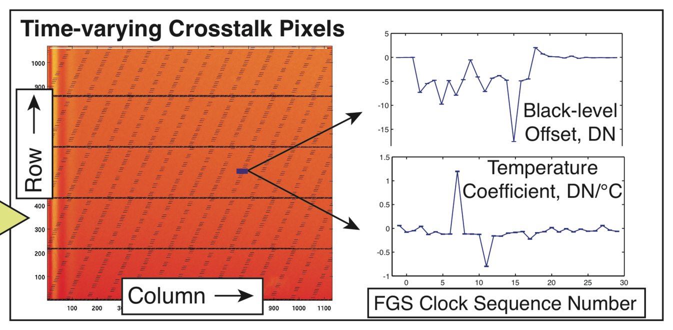


Thermally varying >1GHz signal is aliased to a row dependent moiré pattern in frequency range 0-1.5 MHz

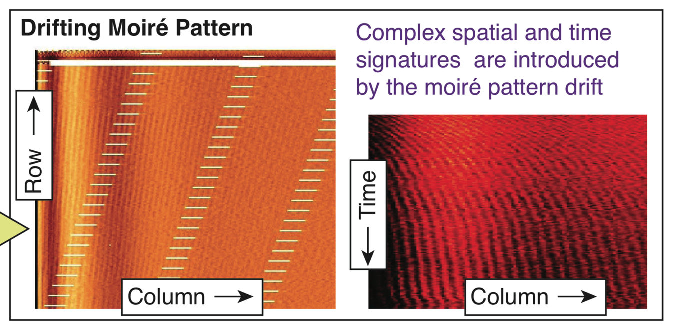
Row dependence caused by readout circuit warm-up

Entire row profile drifts with time as mean electronics temperature changes

Time-varying Crosstalk Pixels

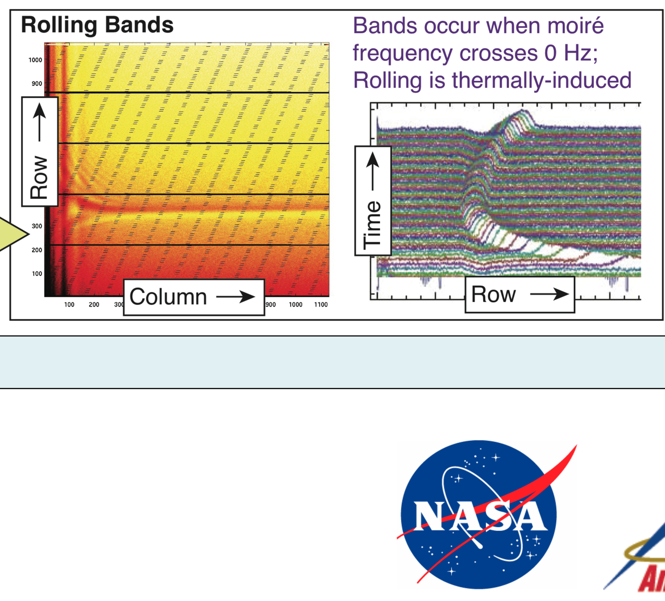


Drifting Moiré Pattern



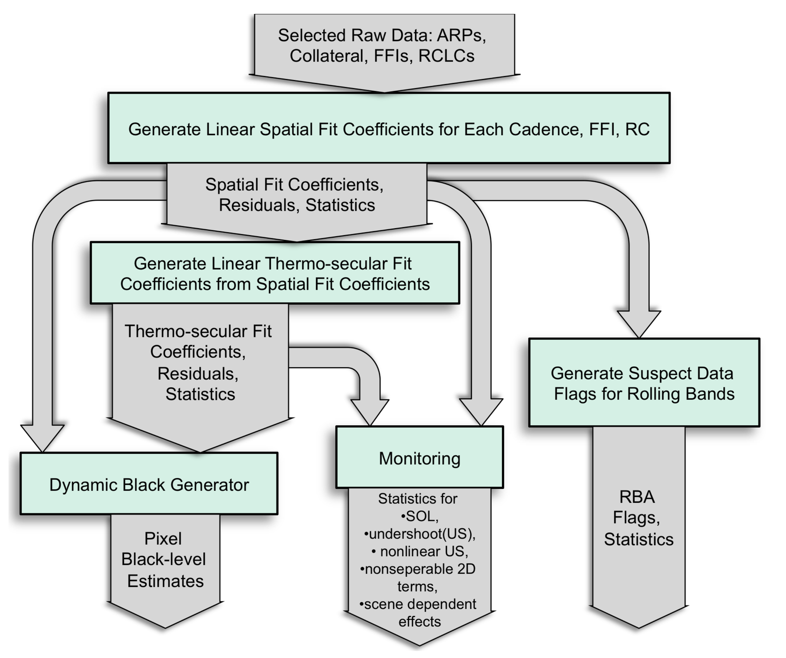
Complex spatial and time signatures are introduced by the moiré pattern drift

Rolling Bands



Bands occur when moiré frequency crosses 0 Hz; Rolling is thermally-induced

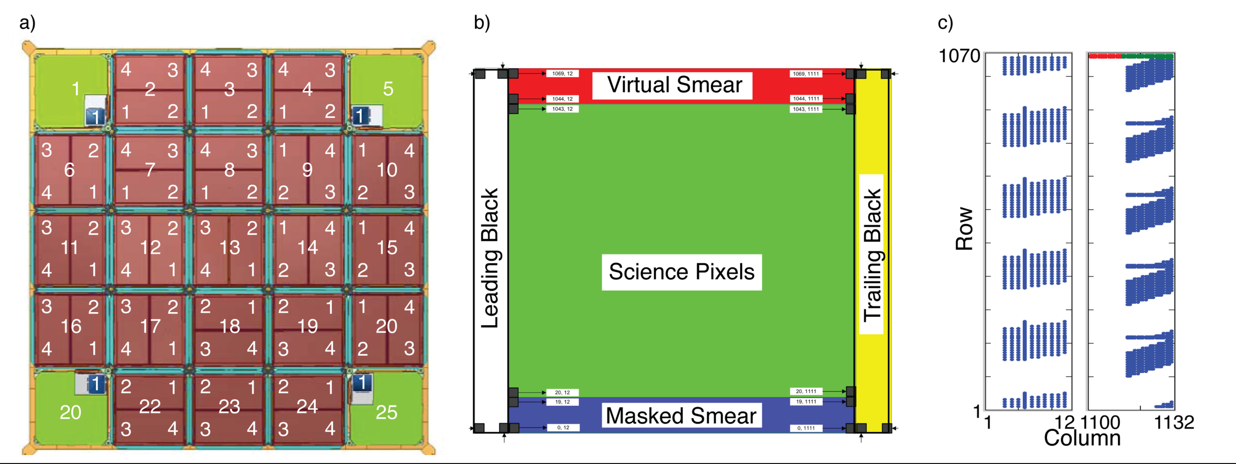
Dynablack Data Flow



Architecture diagram showing Dynablack elements as boxes and data product flow as arrows. Data flow is from top to bottom. The standard unit of work for dynablack is one focal plane channel (module output) for a duration of one quarter of long cadence data. Resulting calibration coefficients are applicable to either short cadence or long cadence data.

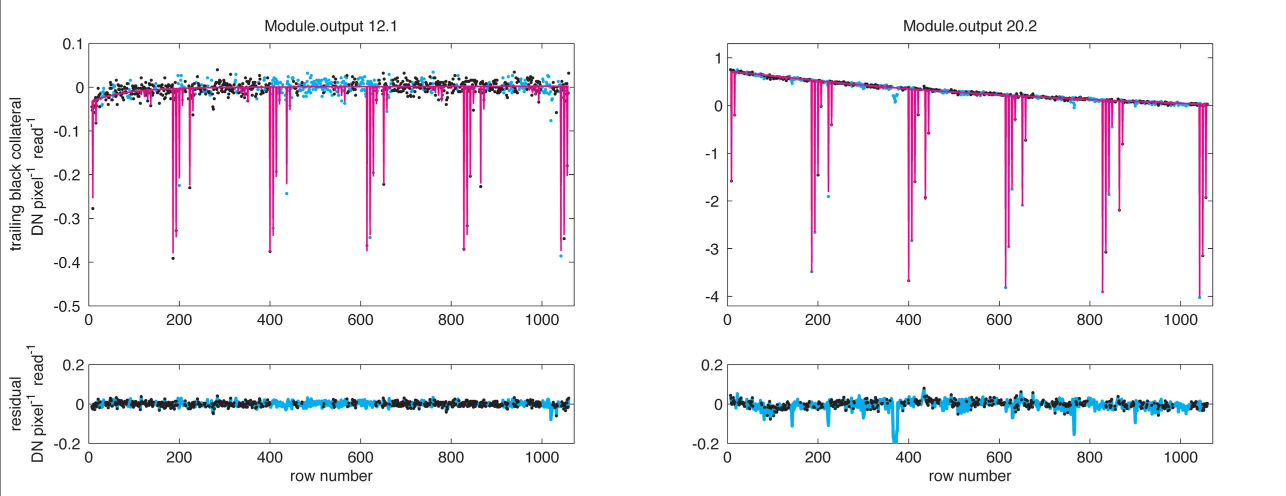
Dynablack Input Data

- **Full Frame Images** taken 3 time per quarter
- 3 **Reverse-clocked long cadences** taken 3 time per quarter - collects only specific artifact mitigation pixels
- **Collateral Data**
  - Trailing Black (Virtual Columns)
    - Summed across 14 columns (1119-1132)
  - Masked and Virtual Smear (Rows)
    - Summed over 12 rows each (7-18, 1047-1058)
- **Artifact Removal Pixels** (ARPs)
  - Cover time-varying FGS crosstalk
  - Also permit undershoot measurement following charge injection rows 1060-1063)



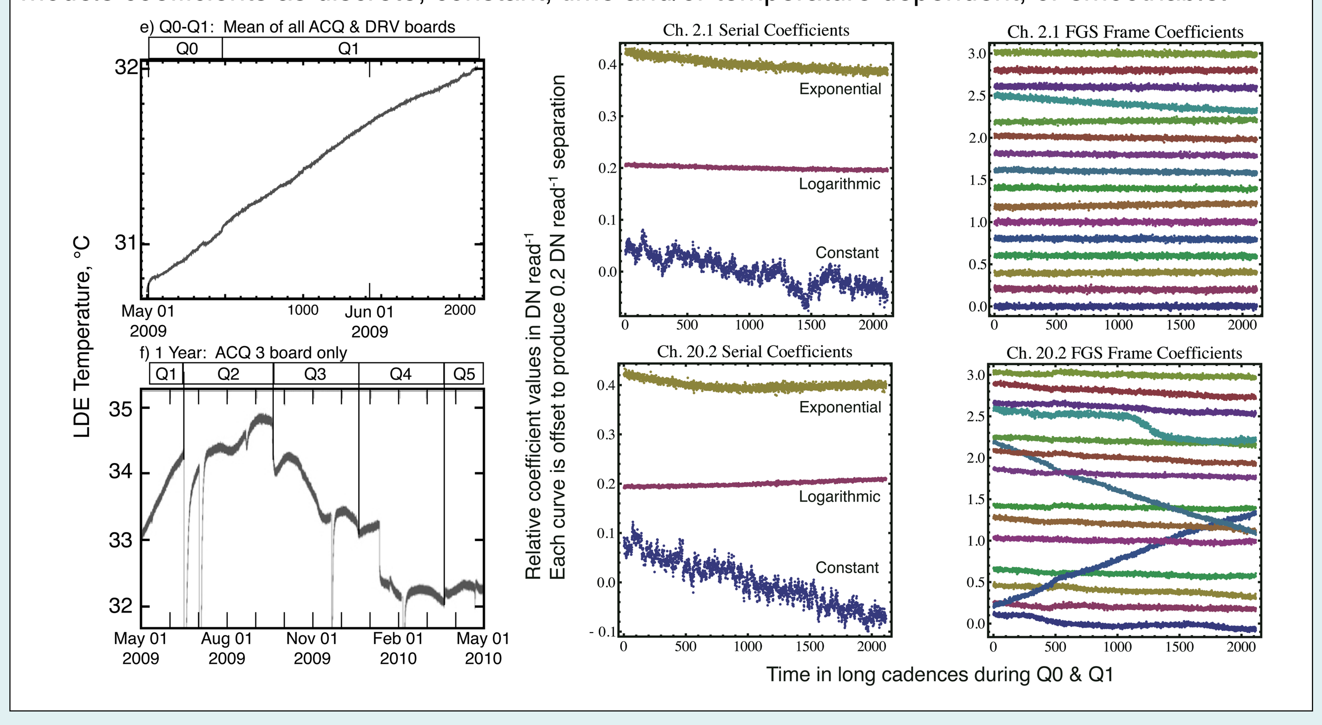
Fitting for Cadence-by-Cadence Black Level Model Coefficients

Comparison of fit curves (red) and data (black) comparing trailing black collateral for channels 12.1 and 20.2 for one representative Q1 long cadence. The scales include an arbitrary constant offset. The light blue points are data and residuals from regions excluded from the fit because of increase likelihood of scene dependent bias due to stars with pixel values >5000 DN read^{-1} within 400 columns of the trailing black in the excluded rows. The density of stars is higher in channel 20.2 in Q1, so the likelihood of stars very close to the trailing black is higher, leading to the evident higher number of obvious outliers in the excluded region in that channel.



Handling Black-Level Model Coefficients over Multiple Cadences

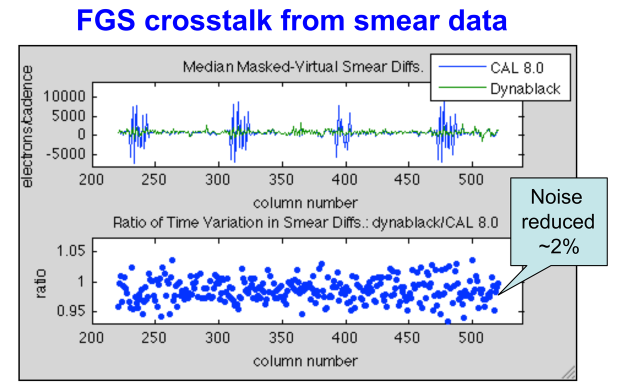
Behavior of spatial fit coefficients vs. time for channels 2.1 and 20.2. An adaptive fitting algorithm models coefficients as discrete, constant, time and/or temperature dependent, or smoothable.



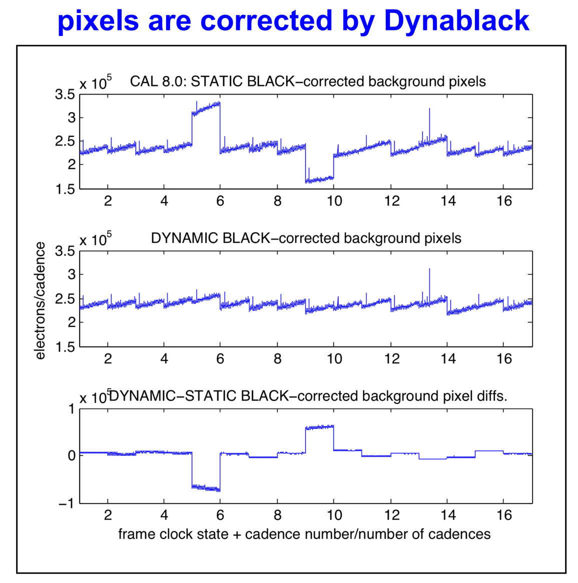
CAL Results and Effect on Background Pixel Time Series

Derived black-level corrections are applied to smear data in CAL and both black and smear corrections are applied to background pixels. Black, smear and background corrections are applied to science target pixels. The plots below compare CAL 8.0 with Dynablack using differences between masked and virtual smear pixels and FGS crosstalk-affected background pixel time series from a Q3 month Module 10 Output 2. (Note: 600 electrons/cadence is the level to affect a Kp =12 star by 20 PPM).

Dynablack correctly removes FGS crosstalk from smear data

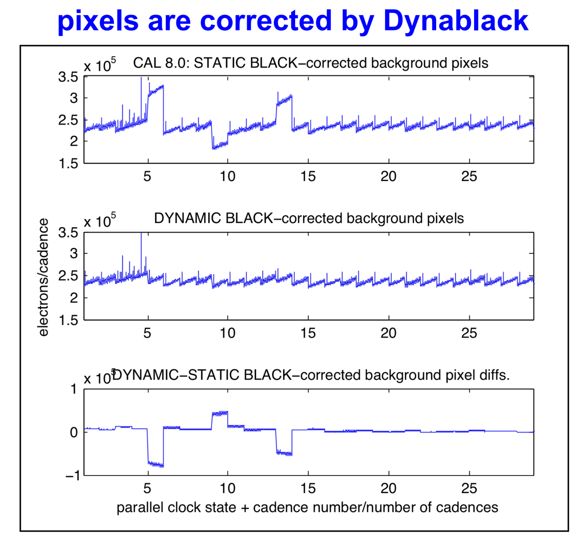


Frame FGS crosstalk-affected background pixels are corrected by Dynablack

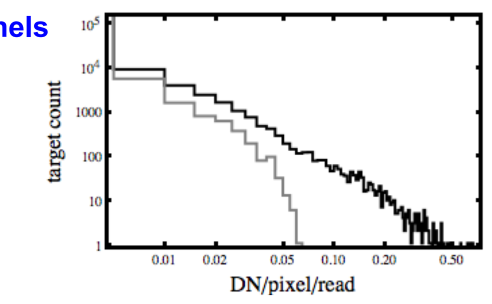


The dynamic black corrected CAL results have not yet been run through the remain pipeline elements, and the direct effect on target pixels is difficult to demonstrate because of the comparatively large motion-dependent variation of individual pixel time series. We can predict the effect on each target from the distibution of FGS clock states in the optimal apertures. Below is a histogram of peak-to-peak dynamic 2D black corrections per science target for all channels during Q1. The contribution of smear effects is shown in gray. Approximately 4% of targets are affected by > 0.02 DN/pixel/read (the level to affect a Kp =12 star by 20 PPM). [3]

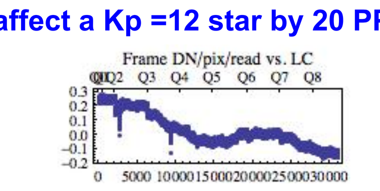
Parallel FGS crosstalk-affected background pixels are corrected by Dynablack



Histogram of Q1 peak-to-peak dynamic 2D black corrections per science target for all channels

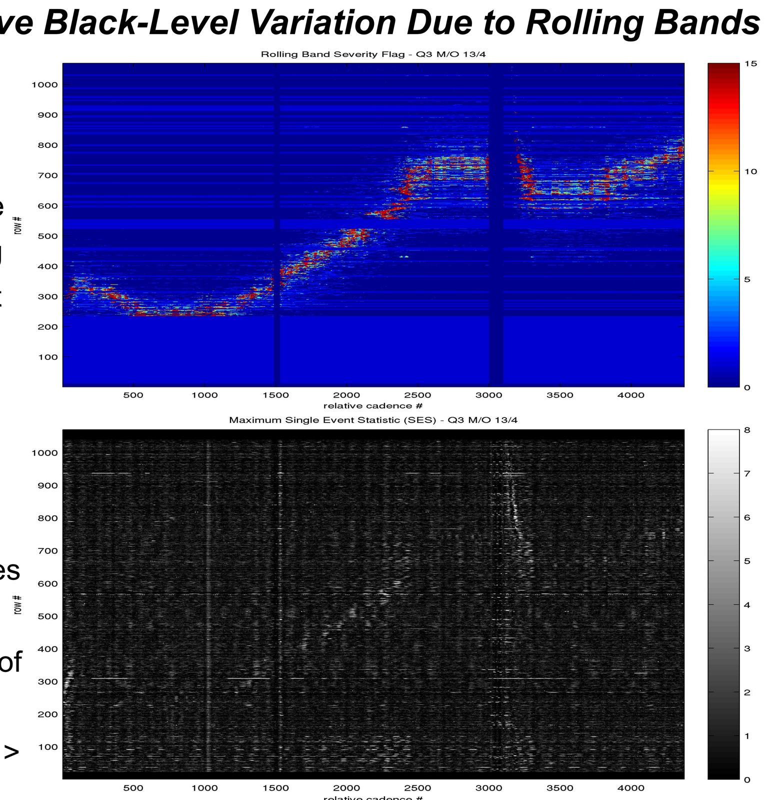


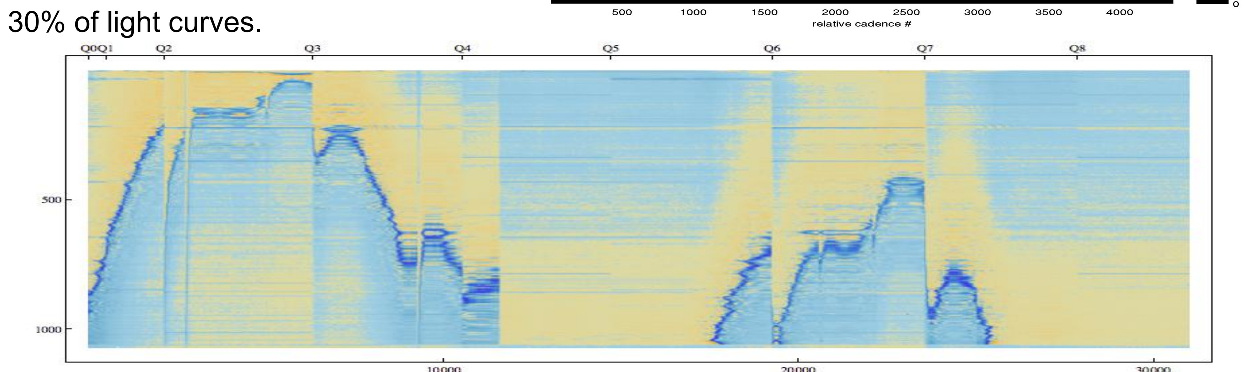
Ch 10.2 long term trend in FGS crosstalk (0.02 DN/pix/read is the level to affect a Kp =12 star by 20 PPM)



Flagging Intervals of Excessive Black-Level Variation Due to Rolling Bands

Rolling band flagging results from channels 13.4 for Q3 show a strong rolling band for the entire quarter. Colors represent a 4-bit severity code with values 2-16 indicating increasing rolling band severity. The max. transit search single event statistic figure indicates that the rolling bands are often interpreted by the pipeline as having enhanced transit probability. Flagging them may reduce the false positive rate. Below, dark blue features indicate long term rolling band trends in Ch 13.4, which recur annually. 49 of 84 sky groups contain rolling bands over ~50% of rows, which may affect > 30% of light curves.





References

[1] Jenkins, J.M., et al., "Overview of the *Kepler* Science Processing Pipeline," ApJL, 713 (2), L87-L91 (2010).
[2] Caldwell, D. A., et al., "Instrument Performance in *Kepler*'s First Months," ApJL, *713*, L92-L96. (2010).
[3] Kolodziejczak, J. J., et al., "Flagging and Correction of Pattern Noise in the Kepler Focal Plane Array," *Proc. SPIE*, 7742, 38 (2010).

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