Kepler photometric accuracy with degraded attitude control

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The present document describes the expected photometric accuracy which may be obtained from analysis of Kepler data in the case of degraded attitude accuracy.


The degraded attitude of Kepler

Based on information from Martin Still and Steve Howell (NASA Ames) we have specified three scenarios for a degraded attitude. Those are analysed below. The simulations of jitter and drift of Kepler are based on the description in section 3.7 in the Kepler Instrument Handbook (KSCI-19033, 15 July 2009, NASA Ames Research Center): http://keplerscience.arc.nasa.gov/calibration/KSCI-19033-001.pdf. The philosophy behind the simulated degraded attitude is first to create a simulation of the 3-axis stabilized pointing which follows the requirements shown in Figure 18 in the Kepler Instrument Handbook (see Figure 1 below).

Figure 1. From Kepler Instrument Handbook (figure 18, pg. 40). The figure indicate the 3σ RMS single-axis attitude error (combined jitter and drift). Reaction wheel jitter above 20 Hz is not included and will mainly affect the PSF.

The high frequency attitude noise is a result of spacecraft motion that can’t be removed by use of the guiding sensors and can therefore not be corrected by use of the reaction wheels. At low frequencies the main noise is drift and this is corrected almost entirely by the reaction wheels. In the simulations we therefore keep the
The three attitude scenarios are:

1. Over long time scales the attitude in pitch (X-coordinate) and yaw (Y-coordinate) is drifting around with a scatter of 0.5 arcsec.
2. Same as scenario 1 but with 1.0 arcsec scatter.
3. With a period of 13-15 minutes the attitude in yaw (Y-coordinate) is oscillating with a peak-to-peak amplitude of 3-4 arcsec. On top of this oscillation we add an additional jitter component similar to scenario 1 but with an amplitude of 0.2 arcsec.

Based on the attitude scenarios we constructed three ACS time series (in pitch and yaw. We ignore for the moment the roll component) with a time resolution of 1 sec. All data sets are 30 day long and contain the attitude offset in units of arcsec. Based on those time series data we construct images of a single star corresponding to integrations of 60 sec and 30 min.

The attitude in the three scenarios are shown in the figures below. Figure 2 show the first two days of each simulation (at the top of the figure we show the simulated attitude that is consistent with the requirements shown in figure 1).
Scenario 1 and 2 is basically a guided random walk (the drift component is 40-80 times higher than in the original mode of operation) while scenario 3 contains a periodic signal which will be seen in the photometric data.

**Figure 3.** The 3a attitude-RMS (one axis) for scenario 1. The figure can be compared to figure 1 (the original attitude specification).

**Figure 4.** The power density spectrum for a single axis attitude corresponding to the original Kepler specifications (see Figure 1). In the degraded simulations we mainly increase the low frequency component corresponding to excess signal from attitude guiding.
The CCD sensitivity

An important part of the simulation is the CCD sensitivity variation. There are three major components that are used to describe the relevant sensitivity variability. References are made to the Kepler Instrument handbook: http://keplerscience.arc.nasa.gov/calibration/KSCI-19033-001.pdf (KSCI-19033-001, 15 July 2009):

1. **Global pixel-to-pixel (inter-pixel) variations.** In the present simulation we use about 5% sensitivity variability peak-to-peak of a 30x30 pixel area. According to the Kepler Instrument Handbook table 9 one can expect a 1% standard deviation in the Photoresponse non-uniformity for the Kepler chips which is in agreement with a 5% peak-to-peak sensitivity variation. We assume that 80% of the global pixel-to-pixel variation can be removed via flat fielding (as discussed in the section 4.14 in the Kepler Instrument Handbook).

2. **Intra-pixel random variations.** In the present simulation we use 25% peak-to-peak variability within a pixel (on a scale corresponding to 1% of the pixel area).

3. **Sensitivity drop due to pixel-channel (intra-pixel drop due to the gate structure of the CCD chip).** In the present simulation we use 10% drop along 10% of the pixel in both the X- and Y-direction.

The corresponding sensitivity variability is shown in figure 5 below.

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**Figure 5.** The lower left corner show the combined detector sensitivity variation in the present simulation including global variations as well as intra-pixel and pixel-channel sensitivity drop. The upper left corner show the global sensitivity variations at the same scale as used in the lower left corner. The upper right corner shows the global pixel-to-pixel variability using a finer scale. The lower right show the sensitivity variability without the pixel-channel sensitivity drop.
Simulating the photometric performance

Using the simulated attitude as well as the simulated sensitivity variability we finally use a stellar PSF (simulating the Kepler PSF) and create images which are then analysed. In figure 6 we show an example of a 30x30 pixel image and in figure 8 we show the extracted photometric variability the series in scenario 1. The photometric analysis is done using three different apertures (defined in the software) and we also measure the position of the PSF on the CCD which can then be compared to the attitude input.

**Figure 6.** A single simulated CCD-frame showing a single star in the chip.

**Figure 7 (below).** Figure 15 from the Kepler Instrument handbook (KSCI-19033) showing the PSF (or PRF) for a point source in the focal plane (detected by use of Kepler).

**Figure 8.** Extracted raw photometric variations using the attitude variations as described in scenario 1. No photon noise is included in this time series and no intrinsic stellar variability is included. This should be compared to figure 9 (showing the photometric variability due to attitude variability in the original mode of operation).
Figure 9. Simulated photometric variability due to pointing variations corresponding the RMS attitude errors in the original mode of operation for Kepler.

Figure 10. Extracted raw photometry using the simulated attitude for scenario 2.
As part of the data analysis of the simulated data we also determine the position of the star on the CCD. We may therefore compare the input attitude to the measured position. In figure 12 below we show an example of the measured stellar position for the simulation of scenario 1.

**Figure 11.** Extracted raw photometry using the simulated attitude for scenario 3

**Figure 12.** The measured position of the stellar profile. The X-coordinate is shown at the top and the Y-coordinate at the bottom. The black curve show the input attitude. On top of this curve we show the measured position. The measured positions are also shown below the input attitude for comparison.
The noise in the power spectrum

Based on the simulations we can then calculate the noise level in the power spectrum. This noise should be compared with the stellar signal. A more detailed analysis of this will also follow in a later version of the present document.

In figure 13 and 14 we show the power density spectrum (PDS) in units of ppm\(^2/\mu\text{Hz}\). Those figures are based on the simulated data for scenario 1. It is clear that power density is orders of magnitudes higher than the noise level for the brightest Kepler stars. As discussed in a the next section we could however remove some of the photometric noise by modelling the sensitivity as a function of the intra-pixel and inter-pixel position.

![Graph of power density spectrum](image)

**Figure 13.** Power density spectrum for attitude scenario 1. The power density follow a \(1/f^{1.5}\) spectrum with high noise a low frequency. The power level should be compared to the stellar signal and stellar background noise for e.g. solar-like stars which is shown in figure 15.
Figure 14. Same as figure 13. In this plot the power density is shown in linear units.

Figure 15. A number of power density spectra for bright Kepler stars (from Chaplin et al.). The intrinsic noise level is in most cases below the noise shown in figure 14.
Figure 16. The power density spectrum for the attitude induced photometric noise during the nominal mission and for scenario 1, 2 and 3.
Using the data to model the intra- and inter-pixel sensitivity

The photometric variability seen in figure 8, 9, 10 and 11 is caused by intra- and inter-pixel sensitivity variations across the detector. Using the measured position of the star on the chip we may be able to use the data to construct a model for the intra- and inter-pixel variability. In order to do this we need to consider both the intrinsic stellar variability (due to transits, stellar rotation, oscillations and granulation) and the variability due to the detector sensitivity variability. We describe the photometric signal as the sum of three components:

\[ data(t) = noise + stellar(t) + \text{CCD}_{\text{sensitivity}}(x(t), y(t)) \]

The basic idea is then to build a model the CCD sensitivity and correct the data for this component leaving the intrinsic noise and the stellar variability.

The model we use is based on calculating a local weighted mean value at a given measured position \((x(t), y(t))\). We want to avoid that the model is sensitive to data outliers and to intrinsic variability and this is ensured by constructing an iterative calculation of the mean value:

We first calculate the mean value as the weighted mean, where the weight for the data in order to calculate the mean value at position \((x_0, y_0)\) at time \(t_0\) is defined as:

\[ W(t, x, y) = \left( 1 - \frac{1}{1 + \left( \frac{t - t_0}{\Delta t} \right)^6} \right) \cdot \frac{1}{1 + \left( \frac{x - x_0}{\Delta x} \right)^6} \cdot \frac{1}{1 + \left( \frac{y - y_0}{\Delta y} \right)^6} \]

The values for \(\Delta t\), \(\Delta x\) and \(\Delta y\) specifies the resolution of the model. The three parameters are:

- \(\Delta t\): The minimum allowed separation in time between a given data point and \(t_0\)
- \(\Delta x\): The maximum distance to \(x_0\) in the measured stellar position (x-coordinate) on the detector
- \(\Delta y\): The maximum distance to \(y_0\) in the measured stellar position (y-coordinate) on the detector

We now calculate the mean value using all the data in the time series \(data(t)\) and the weight \(W(t,x,y)\):

\[ \mu(t_0, x_0, y_0) = \frac{\sum_{i=1}^{N} W(t_i, x_i, y_i) \cdot data(t_i)}{\sum_{i=1}^{N} W(t_i, x_i, y_i)} \]

The next step is to calculate the mean deviation from the mean value:

\[ \Delta(t_0, x_0, y_0) = \frac{\sum_{i=1}^{N} W(t_i, x_i, y_i) \cdot |data(t_i) - \mu(t_0, x_0, y_0)|}{\sum_{i=1}^{N} W(t_i, x_i, y_i)} \]

In order to avoid the influence of outliers in \(data(t)\) we finally optimize the weights by use of the mean and the mean deviation:

\[ W(t, x, y, data(t)) = \left( 1 - \frac{1}{1 + \left( \frac{t - t_0}{\Delta t} \right)^6} \right) \cdot \left( 1 + \left( \frac{x - x_0}{\Delta x} \right)^6 \right) \cdot \left( 1 + \left( \frac{y - y_0}{\Delta y} \right)^6 \right) \cdot \frac{1}{1 + \left( \frac{data(t) - \mu(t_0, x_0, y_0)}{C_\Delta \cdot \Delta(t_0, x_0, y_0)} \right)^6} \]

The \(C_\Delta\)-coefficient specifies the range of data clipping (sigma-clipping).
We finally calculate the model for the CCD-sensitivity at position \((x_0,y_0)\) at time \(t_0\):

\[
model(t_0,x_0,y_0) = \frac{\sum_{i=1}^{N} W(t_i,x_i,y_i,\text{data}(t_i)) \cdot \text{data}(t_i)}{\sum_{i=1}^{N} W(t_i,x_i,y_i,\text{data}(t_i))}
\]

In the next version of the present document we will run a series of simulations where we include additional noise source (photon noise and stellar intrinsic “noise”) as well as signals (transits and oscillations) to fully understand the impact of the sensitivity correction.

The first analysis indicates that we can correct the raw photometry and reach a noise level very similar to the instrumental noise in the nominal mission (fully 3-axis stabilized).

Below we show in figure 17, 18 and 19 the results of using two different set of parameters for modelling the detector sensitivity. In model A we use \(\Delta t = 0.1\) d, \(\Delta x = 0.05\) pix, \(\Delta y = 0.05\) pix and \(C_{\Delta} = 1.0\) and in model B we use \(\Delta t = 0.1\) d, \(\Delta x = 0.02\) pix, \(\Delta y = 0.02\) pix and \(C_{\Delta} = 1.0\). More analysis is needed in order to fully understand the properties of modelling and correcting for the photometric variations due to detector sensitivity variations. It is however clear that model B provide a much better correction than model A. Both models however are able to lower the noise significantly.

**Figure 17.** The simulated time series photometry for Scenario 1. At the top we show the raw photometry and below we show the corrected photometry using model A and model B.
*Figure 18.* The simulated time series photometry for Scenario 1. At the top we show the raw photometry and below we show the corrected photometry using model A and model B. The plot show a zoom of one day out of the simulated 30 day time series.
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Figure 19. The power density spectrum (PDS) of the simulated time series photometry for Scenario 1. At the top we show the PDS of the raw photometry and below we show the PDS for the corrected photometry using model A and model B.

Based on Figure 19 we conclude that Kepler will be able to deliver photometry of similar quality as we have obtained during the nominal mission if the degraded attitude is similar to the one described in scenario 1.