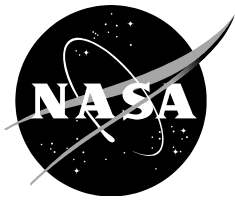


NASA/TP-2019-220321



Target Optimal Aperture Selection

Steve Bryson

Ames Research Center, Moffett Blvd, Mountain View, CA 94040

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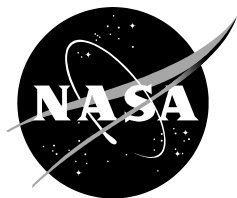
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Steve Bryson

Ames Research Center, Moffett Blvd, Mountain View, CA 94040

National Aeronautics and
Space Administration

*Ames Research Center
Moffett Blvd, Mountain View, CA 94040*

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Title:	Target Optimal Aperture Selection		
Author:	Steve Bryson	Signature:	
GS SE Approval:	Chris Middour	Signature:	
Science Approval:	Jon Jenkins	Signature:	
Distribution:	J. Jenkins, D. Caldwell, D Koch, W Borucki, J. Voss, R. Thompson, H. Chandrasekharan, K. Allen, S. Bryson, C. Middour, T. Klaus, M. Kote, D. Pletcher		

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0.1	added description of saturated pixels	12/16/08	Steve Bryson

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Overview

This document describes the computation of optimal pixels for planetary transit targets. The method we describe is based on that used in the End-to-End Model (ETEM), which simulates Kepler science output. An optimal aperture for a target is defined as the set of pixels which maximizes the signal-to-noise ratio (SNR) for that target. The optimal aperture for a target is determined by using catalog data to generate, for that target, a synthetic image with all background stars and signals and a second synthetic image with the target star's flux only. These images are incorporated into a noise model, from which the SNR of each pixel is computed. The pixels around a target are summed in an order that maximizes the SNR with each term. As dimmer and dimmer pixels contribute to this sum, the SNR reaches a maximum and further terms decrease the SNR. The set of pixels whose SNR sums to this maximum value defines the optimal aperture.

Applicable Documents

- KSOC-21008, Algorithm Theoretical Basis Document for the Science Operations Center
- KADN-26110, Commissioning: PSF Characterization
- KADN-26107, Target Aperture Mask Selection
- KADN-26026, Kepler Focal Plane coordinate conversion MATLAB version

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1 Introduction

Due to bandwidth considerations, data from all of the 84 million pixels in the Kepler focal plane cannot be stored for transmission for every cadence. Therefore specific objects (mostly stars) in the Kepler field of view called *targets* are identified, and groups of pixels around these objects, called *apertures*, are extracted for storage and eventual transmission. For some targets the required apertures are explicitly specified. For planetary transit targets the pixels are selected to maximize the signal to noise ratio of the sum of the pixel values for that target. The resulting collection of pixels is called an *optimal aperture*. There are many planetary transit targets whose optimal apertures should be computed each quarter, so the selection of optimal apertures is automated as described in this document.

In this section we briefly outline the computation of optimal apertures. The conceptual flow of this computation is shown in Figure 1. Details of this computation are given later in this document.

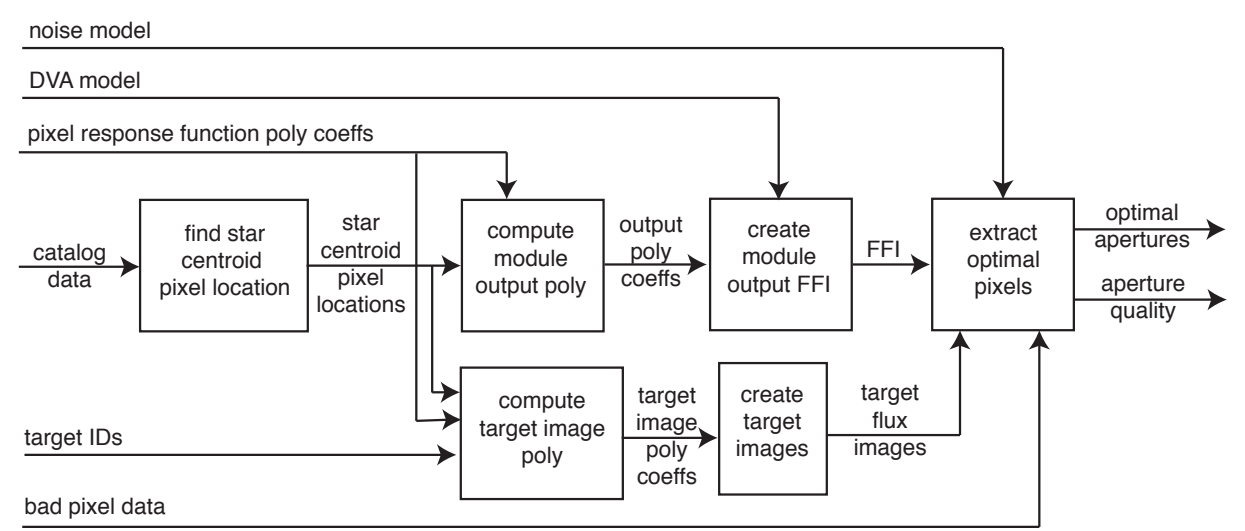


Figure 1: The conceptual flow of the computation of optimal apertures. A synthetic full-frame image (FFI) is created for the module output, and the target images are used to create a second FFI without the target stars. These FFIs are used to estimate the signal-to-noise ratio (SNR) of each pixel, allowing the selection of the pixel set that maximized the SNR of the total flux of each target.

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The computation of optimal apertures takes place for each Kepler output module, and is based on the generation of two synthetic full-frame images (FFIs) for that module: one FFI with all stars and a second FFI with the target stars removed (though still including the effects of target stars such as their smear). By comparing these two FFIs, we can determine the signal-to-noise ratio (SNR) of each pixel. By considering all the pixels in these two FFIs in a region around a target we can determine the pixel set whose sum maximizes the SNR for that target. The computation of a synthetic FFI uses several inputs:

- Data from the Kepler Input Catalog (KIC) for the stars that fall on that module.
- The pixels on which each star in the KIC fall, as determined by the geometry of the CCD in the Kepler optical system as well as pointing data and star aberration as determined by the spacecraft motion vector.
- The pixel response function (PRF) for that module determined during commissioning, represented as the coefficients of a two-dimensional polynomial. The PRF is determined by the optical point spread function (PSF) of the Kepler optical system, intra-pixel variability and geometric aspects of the focal plane.
- An estimation of the differential velocity aberration (DVA) of stars on the output module as a function of time and position.

In essence, for each star in the KIC that falls on the module output, a copy of the appropriate PRF scaled by the brightness of that star and smeared by to DVA motion is added to the FFI in the appropriate pixel location. Due to the large number of stars in the KIC and the resolution required to estimate the DVA motion, the direct computation of the FFI would be impracticably slow. To overcome this difficulty, both the PRF and the brightness of each pixel in the FFI is represented by two-dimensional polynomials, and most of the computations are performed in terms of the polynomial coefficients. The contributions from each individual star are added by adding the coefficients of the PRF's polynomial representation to the coefficients of the FFI pixel's polynomial representation. Once this process is complete the FFI is generated by evaluating the FFI's polynomial for each pixel. The FFI is completed by adding simulated spill-over of saturated pixels, effects of charge transfer, smear due to shutterless operation and zodiacal light.

The above computation of a synthetic FFI uses all the stars that fall on the module output. A subset of these stars are identified as target stars. For each target star a small image is created using the same procedures as those used to create the synthetic FFI, but

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using only the single target star's flux. These target images are used with the synthetic FFI to create an FFI with the target star's flux removed. When removing the flux from a target star when computing the second FFI, care is taken to retain the smear signal from the other target stars.

Once the two FFIs are computed, a rectangle of pixels around each target star is extracted. A noise model is used to estimate the noise in each pixel of the target's extracted rectangle. This noise model includes shot noise of the target, background signal, smear and zodiacal light as well as read and quantization noise. The signal to noise ratio (SNR) of each pixel is computed. As the SNR of each pixel is added to a running sum in decreasing order of value, the summed SNR will increase until pixels dominated by noise are added and the sum will start to decrease. The set of pixels that caused the summed SNR to increase defines the optimal aperture for that target.

This computation of optimal apertures is based on a method implemented in the End-to-End Model (ETEM), described in KSOC-21008, "Algorithm Theoretical Basis Document for the Science Operations Center", which is used to generate synthetic Kepler data. This model has undergone independent review and verification. The method we describe in this document is very similar to that in ETEM, with the primary difference being the source of the pixel response function: in ETEM the PRF is computed based on input models of the PSF, the intra-pixel variability and does not include spacecraft pointing jitter. In ETEM pointing jitter is added later in the computation of the FFI. In the method described here the PRF is measured directly based on dithered FFIs taken during commissioning as described in KADN-26110 "Commissioning: PSF Characterization". These PRFs will include the effects of spacecraft pointing jitter.

Once the optimal aperture for that target is found, it is compared with a list of bad pixel information. The presence of bad pixels in an optimal aperture is reported, along with that aperture's signal to noise ratio.

The output of the optimal aperture computation is sent to the aperture mask selection algorithm, described in KADN-26107, "Target Aperture Mask Selection", for the selection of actual apertures that are sent from the spacecraft.

2 Computing a Synthetic FFI

The primary inputs to the computation of the module output's FFI are data about the stars that fall on the output and the pixel response function for that output. The star data must

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be converted into pixel locations before it can be used.

Relevant data for stars that fall on the module output are provided to the optimal aperture computation by the pipeline framework. This data includes the star's celestial coordinates (Right-Ascension and Declination) and stellar magnitude. The coordinates are converted to the pixel location, including sub-location on a 10×10 sub-pixel grid, by the RADec2Pix library call described in KADN-26026, "Kepler Focal Plane coordinate conversion MATLAB version". This conversion includes stellar aberration due to spacecraft motion. The result is the location of the star's centroid on the module output's pixels.

The flux measured by a pixel is determined by several things, of which the following are dominant:

- The location of the centroid of stars whose light falls on the pixel, including which pixel and where on that pixel that centroid is located (the sub-pixel location).
- The optical point-spread function (PSF), which spreads the light from a star over several pixels.
- Intra-pixel variability, which causes variations in the measured flux as the star's centroid moves within the pixel.

The PSF combined with the intra-pixel variability causes the pixel to be very sensitive to small motions of a star's centroid. These motions include spacecraft pointing jitter and differential velocity aberration and can be a significant source of signal noise and uncertainty. Therefore it is important to characterize each pixel's response to image motion on a sub-pixel scale. We call the function describing the pixel's response to motion the *pixel response function* (PRF). Our strategy is to use pre-determined PRFs, the catalog input data and an estimate of the offsets ($\Delta x, \Delta y$) over time to compute a synthetic full-frame image (FFI). This FFI will be used to estimate the set of pixel that provide an optimal signal for a target. Since the PRF is expected to be determined during commissioning using long-cadence FFIs, components of the mean motion due to spacecraft pointing jitter and any other effect that occurs on a single long-cadence time scale will be included in the PRF. Motion over longer time scales is explicitly accounted for by making the offsets ($\Delta x(t), \Delta y(t)$) time dependent.

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2.1 Representing a Pixel's Dependence on Motion with a Polynomial

As mentioned above, the pixel response function depends sensitively on the sub-pixel location of the star centroid. We approximate this dependence by characterizing (during commissioning) the PRF on a 10×10 sub-pixel grid, so each pixel has 100 pixel response functions assigned to it. For each sub-pixel location the PRF is defined on a domain of pixels, which in ETEM is taken to be 11×11 pixels centered on the star centroid. In actual implementation this shape may be too small and will be determined by further analysis. In this document we will use 11×11 size for illustration.

For the moment, to simplify our notation, we ignore the time and space dependence of $(\Delta x, \Delta y)$. We are computing the brightness of a pixel given the starlight that falls on that pixel and the offsets of the star images $(\Delta x, \Delta y)$. The basic strategy is to develop polynomial functions of $(\Delta x, \Delta y)$ for each pixel. This information is encoded into the pixel response function $R_{i,j}^\alpha$ for each pixel (i, j) and a sub-pixel location α on the 10×10 sub-pixel grid. We represent $R_{i,j}^\alpha$ as a two-dimensional polynomial on the 11×11 pixel domain as

$$R_{i,j}^\alpha = \sum_{k=1}^N c_{\text{pix},k}^{\alpha,i,j} X_k(\Delta x, \Delta y)$$

where $i, j = 1, \dots, 11$, $X_k(\Delta x, \Delta y)$ is the polynomial basis for the k th term and N is the number of terms, which depends on the order of the polynomial. For example, for a second-order polynomial we could take $X_1(\Delta x, \Delta y) = 1$, $X_2(\Delta x, \Delta y) = \Delta x$, $X_3(\Delta x, \Delta y) = \Delta y$, $X_4(\Delta x, \Delta y) = \Delta x^2$, $X_5(\Delta x, \Delta y) = \Delta y^2$, $X_6(\Delta x, \Delta y) = \Delta x \Delta y$ so $N = 6$. The coefficients $c_{\text{pix},k}^{\alpha,i,j}$ are pre-determined by fitting to jittered real FFIs from the spacecraft during commissioning as described in KADN-26110, "Commissioning: PSF Characterization".

We first compute the brightness of a pixel at row r and column c without the pixel response function by, for each sub-pixel position α , adding the flux f_s of each star s in the set S of stars whose centroids fall on that pixel at that sub-pixel location:

$$b_{r,c}^\alpha = \sum_{s \in S} f_s.$$

The effect of the pixel response function, which spreads the light from an individual star over several pixels, is included via convolution which gives the brightness of the pixel $p_{r,c}^\alpha$:

$$p_{r,c}^\alpha = \sum_{i=1}^{11} \sum_{j=1}^{11} b_{r-i,c-j}^\alpha R_{i,j}^\alpha$$

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$$\begin{aligned}
 &= \sum_{i=1}^{11} \sum_{j=1}^{11} b_{r-i, c-j}^{\alpha} \sum_{k=1}^N c_{\text{pix}, k}^{\alpha, i, j} X_k(\Delta x, \Delta y) \\
 &= \sum_{k=1}^N \sum_{i=1}^{11} \sum_{j=1}^{11} c_{\text{pix}, k}^{\alpha, i, j} b_{r-i, c-j}^{\alpha} X_k(\Delta x, \Delta y)
 \end{aligned}$$

If we define

$$c_{\text{ccd}, k}^{\alpha, r, c} = \sum_{i=1}^{11} \sum_{j=1}^{11} c_{\text{pix}, k}^{\alpha, i, j} b_{r-i, c-j}^{\alpha}, \quad (1)$$

which expresses the ccd pixel coefficients $c_{\text{ccd}, k}^{\alpha, r, c}$ as a convolution, then we have a polynomial expression for $p_{r, c}^{\alpha}$:

$$p_{r, c}^{\alpha} = \sum_{k=1}^N c_{\text{ccd}, k}^{\alpha, r, c} X_k(\Delta x, \Delta y).$$

The total brightness of the pixel, $p_{r, c}$, is obtained by summing the contributions from each sub-pixel position:

$$p_{r, c} = \sum_{\alpha} \sum_{k=1}^N c_{\text{ccd}, k}^{\alpha, r, c} X_k(\Delta x, \Delta y) = \sum_{k=1}^N c_{\text{ccd}, k}^{r, c} X_k(\Delta x, \Delta y).$$

where

$$c_{\text{ccd}, k}^{r, c} = \sum_{\alpha} c_{\text{ccd}, k}^{\alpha, r, c} = \sum_{\alpha} \sum_{i=1}^{11} \sum_{j=1}^{11} c_{\text{pix}, k}^{\alpha, i, j} b_{r-i, c-j}^{\alpha} \quad (2)$$

are the coefficients of the polynomial giving the pixel brightness.

In other words, we can find the coefficients of a polynomial expression for the brightness of each pixel, giving that pixel's brightness as a function of offsets of the light falling on that pixel, by convolving the flux centered on each of that pixel's sub-pixel position with the coefficients of the pixel response function for that sub-pixel position, and summing over the sub-pixel positions.. For a given offset, which will in general depend on the pixel, evaluating $p_{r, c}$ at pixel (r, c) gives the brightness of the pixel after a single (long-cadence) integration.

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2.2 Time Dependence of the Offsets $(\Delta x(t), \Delta y(t))$

We now consider the effect of the time dependence of the offsets $(\Delta x(t), \Delta y(t))$. This causes the brightness of each pixel to become time dependent as

$$p_{r,c}(t) = \sum_{k=1}^N c_{\text{ccd},k}^{r,c} X_k(\Delta x(t), \Delta y(t)).$$

For purposes of determining the optimal aperture over a long time period T such as a quarter, we wish to create an FFI that integrates the pixel flux over that time period, divided by the number of integrations $N_T = T/\Delta t$ in that time period, where Δt is the integration time. If we divide T into integration intervals $[T_n, T_{n+1}]$ (where $T_{n+1} = T_n + \Delta t$ and $T_1 = 0$ and $T_{N_T} = T$) then we can write this integral as

$$\frac{1}{N_T} \int_0^T p_{r,c}(t) dt = \frac{1}{N_T} \sum_{n=1}^{N_T} \int_{T_n}^{T_{n+1}} p_{r,c}(t) dt.$$

Motions on the single integration time scale are already included in the pixel response function, so the integral $\int_{T_n}^{T_{n+1}} p_{r,c}^b(t) dt$ is replaced by the polynomial representation of $p_{r,c}(t)$ multiplied by Δt :

$$\begin{aligned} \frac{1}{N_T} \int_0^T p_{r,c}(t) dt &= \frac{1}{N_T} \sum_{n=1}^{N_T} \sum_{k=1}^N c_{\text{ccd},k}^{r,c} X_k(\Delta x(t_n), \Delta y(t_n)) \Delta t \\ &= \sum_{k=1}^N c_{\text{ccd},k}^{r,c} \frac{1}{N_T} \sum_{n=1}^{N_T} X_k(\Delta x(t_n), \Delta y(t_n)) \Delta t \\ &= \sum_{k=1}^N c_{\text{ccd},k}^{r,c} \langle X_k(\Delta x, \Delta y) \rangle_t \Delta t \end{aligned}$$

where $\langle \dots \rangle_t$ denotes the average with respect to time. We therefore can account for the effect of time-dependent motions by evaluating the pixel polynomial $p_{r,c}$ on the time average of the polynomial basis functions and multiplying by Δt .

2.3 Computing the time and space dependence of the offsets $\Delta x(t)$ and $\Delta y(t)$

The primary source of long-term motion is expected to be differential velocity aberration (DVA), which is determined by changes in the velocity vector of the spacecraft and position

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of a star's image on the focal plane. This is expected to have very slow variation in both space and time, and so can be approximated by low-order polynomials. Following ETEM, spatial variation on each module output is measured on a 5×5 grid which we label with the indices (u, v) . First, the aberrated celestial coordinates at the start of the motion time period of each grid point are determined via the Focal Plane Characterization library call Pix2RADec. These coordinates are then corrected for velocity aberration with the Focal Plane Characterization library call unaberrate. Then for each long cadence in the time interval of interest, the Focal Plane Characterization library routine RADec2Pix is called for each grid point (u, v) , which returns the pixel and pixel sub-position of the aberrated celestial coordinates at that time. This aberrated result is subtracted from the initial position of the grid point, delivering the offsets $(\Delta x_{u,v}(t_n), \Delta y_{u,v}(t_n))$. The basis functions $X_k(\Delta x_{u,v}(t_n), \Delta y_{u,v}(t_n))$ are then computed as described below and stored for each cadence. To find the k th time-averaged basis function at a pixel (r, c) , the k th stored basis functions on the 5×5 grid are averaged over time and used to form a two-dimensional polynomial that is evaluated at (r, c) . Specifically, the system of equations

$$\sum_{l=1}^M c_{\text{offset},l}^k Y_l(u, v) = \langle X_k(\Delta x_{u,v}, \Delta y_{u,v}) \rangle_t, \quad u, v = 1, \dots, 5$$

is solved, for each k th term in the pixel polynomial, for the least-squared coefficients $c_{\text{offset},l}^k$ where $Y_l(u, v)$ are the M polynomial basis function for this offset polynomial. $Y_l(u, v)$ may or may not be the same as the basis functions $X_k(\Delta x, \Delta y)$ for the pixel polynomial representations above. The time-averaged value of the offset basis function at pixel (r, c) is then given by the polynomial evaluation (after a suitable transformation to make sure that (u, v) and (r, c) are in the same coordinate units)

$$\langle X_k(\Delta x_{r,c}, \Delta y_{r,c}) \rangle_t = \sum_{l=1}^M c_{\text{offset},l}^k Y_l(r, c). \quad (3)$$

We can now finally write the complete formula for the brightness of each pixel in our synthetic FFI:

$$p_{r,c}(t) = \sum_{k=1}^N c_{\text{ccd},k}^{r,c} \langle X_k(\Delta x_{r,c}, \Delta y_{r,c}) \rangle_t \Delta t, \quad (4)$$

which is built from equations (2) and (3). Once the time-averaged offsets are computed, as described in the next section, equation (4) is evaluated pixel by pixel to generate the

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complete FFI. This FFI is completed by including the effects of spill-over of saturated pixels, charge-transfer, smear and zodiacal light.

2.4 Computing the Target Images

We need to compute images due solely to each target on squares of 11×11 pixels, one for each target. The flux from any particular target with flux f will fall on a single pixel (r, c) at a particular sub-pixel location α . In this case the convolution (1) reduces to simply multiplying the pixel coefficients $c_{\text{pix},k}^{\alpha,i,j}$ by the target flux f , with the effect of creating a copy of the pixel response function (defined itself on an 11×11 array) for this sub-pixel location scaled by the target flux. Then the pixel brightness formula corresponding to equation (1) becomes

$$p_{i,j} = \sum_{k=1}^N c_{\text{pix},k}^{\alpha,i,j} f X_k(\Delta x, \Delta y).$$

If we define

$$c_{\text{target},k}^{i,j} = c_{\text{pix},k}^{\alpha,i,j} f,$$

then we have the polynomial expression for the target image brightness $p_{r,c}$ evaluated over the time-averaged motions as in equation (4)

$$p_{i,j} = \sum_{k=1}^N c_{\text{target},k}^{i,j} \langle X_k(\Delta x_{r,c}, \Delta y_{r,c}) \rangle_t.$$

We do not need to perform the sum over the sub-pixel locations because f is non-zero for only the target's sub-pixel location α , so all other sub-pixel locations do not contribute.

3 Determining the Optimal Aperture

Once the synthetic FFIs, one with and the other without targets, are available, we are in a position to determine the pixels that optimize the SNR for each target. First we subtract the target-only FFI from the module output FFI, providing a background-only FFI. For each target, the 11×11 pixel image around each target is extracted from each FFI type. The pixel values p_{target} in the target-only image define the signal of each pixel, while the pixel

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values p_{back} in the image-only FFI provides the background signal. The SNR of each pixel is estimated as

$$SNR = \frac{p_{\text{target}}}{\sqrt{p_{\text{target}} + p_{\text{back}} + \nu_{\text{read}}^2 + \nu_{\text{quant}}^2}}$$

where ν_{read} is the read noise and ν_{quant} is the quantization noise. This formula includes the Poisson shot noise of the photon signals, which has a variance equal to the flux.

The SNR computed on the 11×11 pixel image is then summed in a way to estimate the collection of pixels which maximizes the SNR. This is done by, at each step of the sum, checking the remaining unsummed pixels and choosing the pixel that results in the greatest increase in SNR of the sum. Initially the summed SNR will increase, until dim pixels, which are dominated by noise, are added and the sum begins to decrease. The pixels included when the summed SNR reaches its maximum defines the optimal aperture. This approach is further discussed in Section 4.4 of KSOC-21008, "Algorithm Theoretical Basis Document for the Science Operations Center".

3.1 Treatment of Saturated Pixels

Saturated charge is spilled along columns, with the fraction of charge spilled up determined by the saturationSpillUpFraction parameter obtained from FC constants. The fraction spilled down is $1 - \text{saturationSpillUpFraction}$. If the saturated charge spills N pixels, then $N \cdot \text{saturationSpillUpFraction}$ pixels are spilled up the column, and $N \cdot (1 - \text{saturationSpillUpFraction})$ are spilled down the column. These pixel values are set to the saturation value in the synthetic image created by TAD/COA.

Because ground test indicates that the well depth and saturation spill direction varies across the focal plane, including variation within a module output, TAD adds a buffer to the optimal aperture for saturated targets. The buffer size is controlled by the input module parameter saturationSpillBufferSize. This buffer is applied equally up and down the column. This parameter is in the same units as saturationSpillUpFraction, so if the saturated charge spills N pixels, then the buffer extends $N \cdot \text{saturationSpillBufferSize}$ pixels both up and down the column. This buffer is added to the target's optimal aperture, but the pixel values themselves are not changed. If the buffer size is smaller than the optimal aperture in either direction, then the buffer size is ignored in that direction.