Recovering saturated pixels blurred by CCD image smear

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Abstract

The effects of A/D saturation on the correction of image smear on frame-transfer CCD sensors are analyzed and shown to be proportional to the amount of image value lost by the A/D saturation. This analysis leads to a new correction algorithm that recovers the image values of the saturated pixels while removing the frame-transfer smear.

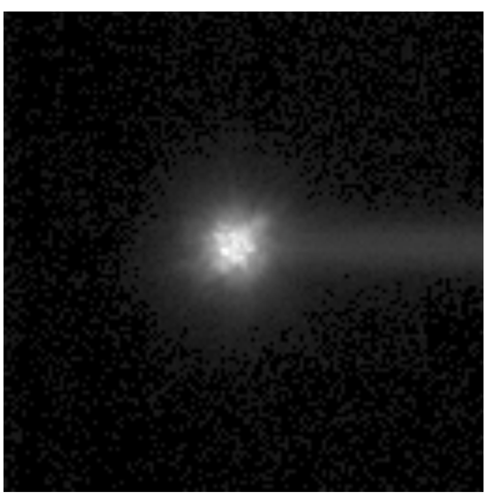
1. Introduction

When a pixel on an optical detector receives too much light and its value exceeds the dynamic range of the analog-to-digital converter, it will saturate. All that is recorded is that the value of the individual pixel exceeded the maximum value of the A/D converter. The actual value of the pixel is lost. There is one circumstance, however, in which the pixel value can be recovered, and that is when the image has been blurred by frame transfer smear.

Frame-transfer CCD sensors make an exposure and then transfer the charge image to a readout buffer. During the time it takes to transfer the charge to the readout buffer, the light-sensitive array continues to be exposed, thereby adding an additional linearly-smeared component of the object, which is roughly proportional to the ratio of the transfer time to the exposure time. See Figure 1 for an example image that has a small horizontal smear to its right.

Ordinarily, this smear would be considered a defect, but it actually opens an opportunity to recover the values of any saturated pixels. Because the image has been smeared across the CCD array, the brightest areas of the image that saturated in the exposed image have also been imaged all across the array in regions where it is not saturated.

This paper analyzes the effects of saturation in individual pixels on the smear correction algorithm. The analysis shows that a residual smear in the readout transfer direction remains after the smear correction is performed. The value of the smear is proportional to the loss in value in the saturated pixels. As a result, the saturated pixels can be restored by measuring the amount of the residual smear. The effects of saturated pixels on the smear correction algorithm are analyzed and illustrated with examples from saturated and unsaturated images of an unresolved star.



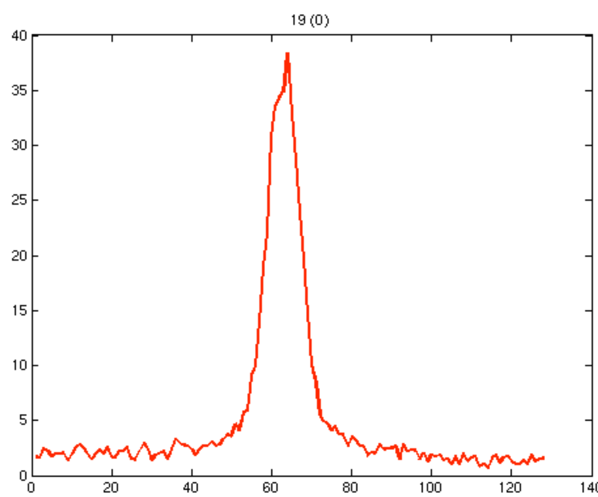


Fig. 1. Short-exposure image of HR 4630, Epsilon Corvi. A greatly enhanced image from a sequence of 2000 frames, taken at 210 frames/second. During the readout of the charge distribution, the CCD continues to be exposed, leading to the horizontal smear to the right of the star. The plot shows an average in digital counts of 10 columns of pixels, revealing a vertical cross-section of the smear, which is about 1% of the brightness of the star.

2. Frame-Transfer Smear

The image of the bright star Epsilon Corvi (HR 4630) in Figure 1 was taken on the evening of 19 April 2007 on the GEMINI sensor on the 1.6-meter telescope mount at the Air Force Maui Optical & Supercomputing Site (AMOS) on Haleakala. The image is one of 2,000 frames taken at 210 frames/second with an exposure time of 0.899 milliseconds and a field-of-view of 24 arc seconds. A clear filter was used to capture these short-exposure images.

The GEMINI sensor [2] is a frame-transfer CCD sensor. Just before the exposure, the 128 x 128 pixel frame is cleared and a bias level established. After the exposure, the two-dimensional array of pixels is shifted to the left, one column at a time, into the readout buffer. Figure 2 shows the result after one column has been shifted into the readout buffer. The detector array continues to be exposed during this transfer, which takes 1 microsecond/column.

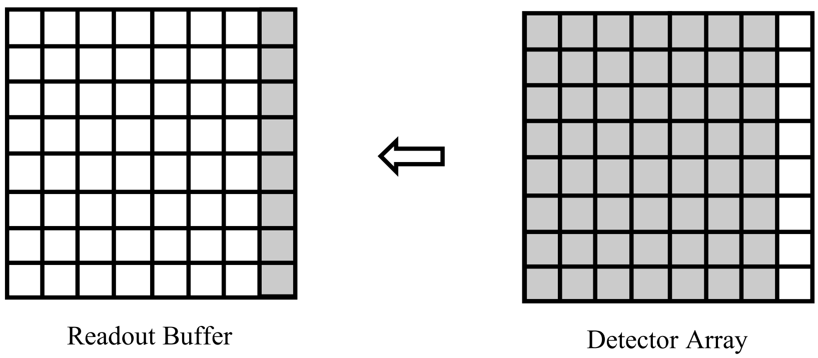


Fig. 2. Frame transfer. Image pixels are shifted to the left through the detector array into the readout buffer.

Since the detector array continues to be exposed during the frame transfer, the pixels being transferred receive additional exposure to the object. The effect is to smear the image in the direction opposite to the transfer.

The plot in Figure 1 shows a vertical cross-section through the smear. The peak value of 40 is 1% of the approximate peak value of the star image of 4,000. Under many circumstances, this 1% value is not visible in the displayed image. For example, if the image were linearly scaled between its maximum and minimum values and reduced to 8 bits, or 256 values, the smear would disappear into the background.

On the other hand, when trying to detect faint objects, the contrast is often significantly stretched, for example by taking the logarithm of the pixel value. In this case, the smear will be significantly enhanced and clearly visible. In the figures in this paper, the contrast detail has been stretched to reveal the smears. All the images in this paper have been enhanced in the same manner and to the same degree.

3. Correcting Frame-Transfer Smear

The problem of correcting frame-transfer smear was addressed in a paper by Ruyten[1]. He modeled the smear problem as the addition of a signal that is proportional to the linear sum of the pixels to one side of each individual pixel. If the original input image is $I(m, n)$ and the smeared image is $S(m, n)$, where m and n are the pixel numbers that vary from 1 to N, then $S(m, n)$ is modeled by:

$$S(m,n) = I(m,n) + a\sum_{k=1}^{m-1} I(k,n) \tag{1}$$

This equation assumes that the frame transfer is to the left and that the smear extends to the right. The constant a is equal to the ratio of the transfer time per pixel to the exposure time and can be determined empirically.

Solving Equation 1 for $I(m,n)$, one can write the original image values as the difference between the measured values and a new variable, $T(m,n)$, which is the sum of all of the original values to the left of the desired value.

$$I(m,n) = S(m,n) - aT(m-1,n) \quad (2)$$

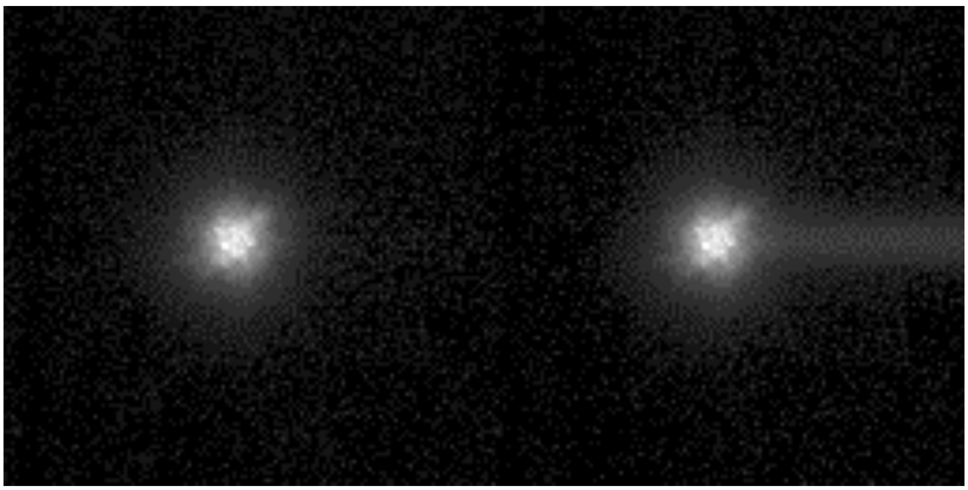
where

$$T(m,n) = \sum_{k=1}^{m} I(k,n) \quad (3)$$

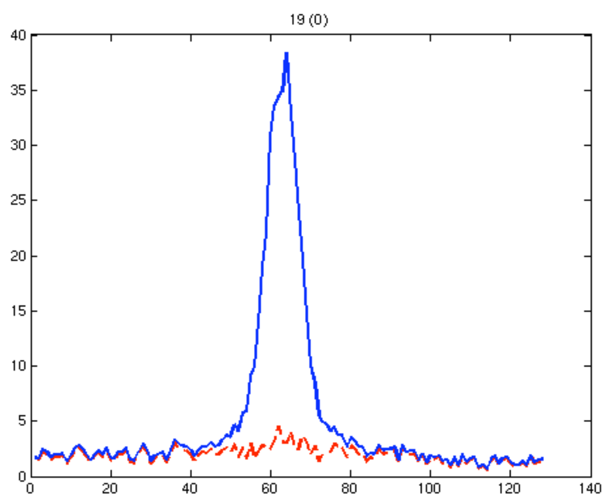
or

$$T(m,n) = T(m-1,n) + I(m,n) \quad (4)$$

Equations 2 and 4 are applied iteratively starting with the first column, $m = 1$, with $T(0,n)$ defined as identically zero. As each column is calculated, the variable $T(m,n)$ contains the known values determined in the previous iterations. Since the smeared image was created by iteratively adding the object information into the shifted image, the smear is removed by iteratively subtracting it in the opposite direction.



a)



b)

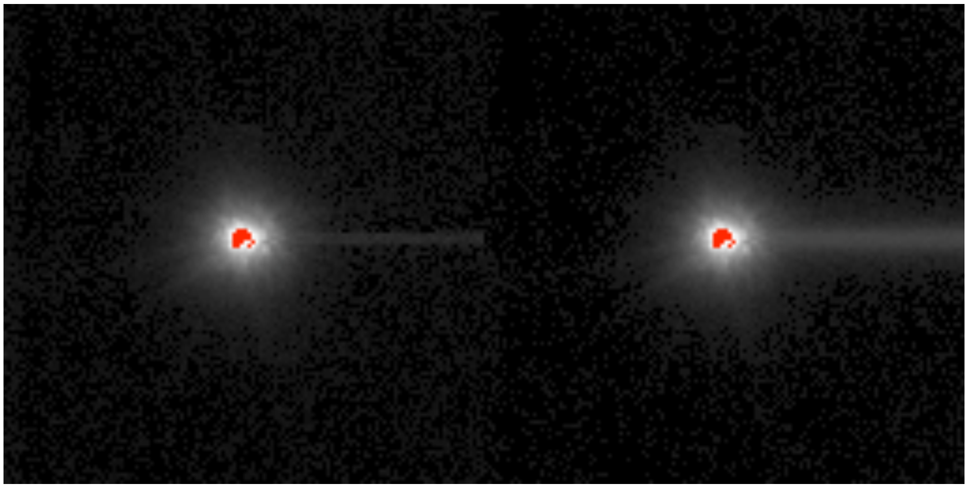
Fig. 3. Smear removal. In part a) the original smeared image is shown on the right and the post-processed image to remove the smear is shown on the left. In part b), the cross-section of the smear shows that the smear is completely removed. The blue solid line is through the original image, while the red dashed line is through the corrected image.

The images need to be corrected for bias and dark current before this algorithm is applied. The smearing of the object does not apply to the bias or dark current values. For the GEMINI sensor, the readout is accomplished in four parallel ports, oriented horizontally. There are four additional columns, adjacent to the 128 x 128 detector array, that are not light sensitive. These four columns can be used to measure the amount of bias in each row for the detector array. A series of dark exposures is used to measure the dark current component.

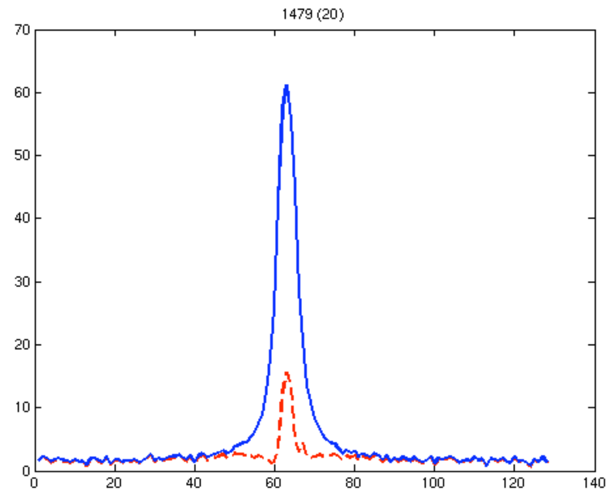
Figure 3 shows the result of applying this smear correction algorithm to one of the GEMINI frames. The frame shown on the right side of Figure 3a) contains no saturated values. The maximum value in this image is 3984, where the saturated or maximum value of the 12-bit A/D converter is 4095.

By trial and error, a value of $a = 0.0011$ was determined to completely remove the smear. This is exactly what theory predicts, i.e. a = time to shift a column divided by the integration time = $1/899 = .0011$. No smear is visible in the corrected image on the left side of Figure 3a). The contract enhancement applied to the corrected image is the same as that applied to the smeared image, so any remaining smear would be visible in the image.

The plot in Figure 3b) shows vertical cross-sections through the smear regions of both the original and corrected images. From the plot, it is clear that the smear has been removed down to the level of the background in the image. The cross-sectional plots do not reflect the contrast enhancement that was applied to the displayed images in part a).



a)



b)

Fig. 4. Smear removal in the presence of saturated pixels. The 20 red pixels in the image centers in part a) are saturated, i.e. they all have the value 4095. The smear removal algorithm, when applied to the image on the right, leaves a residual smear (left image) that is proportional to the image value that is missing in the saturated regions.

When the smear removal algorithm is applied to an image with saturated pixels, as shown in Figure 4, the smear is not completely removed. The amount of the smear is based on the actual light impinging on the detector array, while the correction algorithm can only correct using the saturated value that was recorded in the image array. Since the saturated value is smaller, it cannot completely remove the smear. Based on this idea, it is possible to determine how much was lost in saturation by the amount of smear left by the correction algorithm. A detailed analysis is given in the next section of the amount of residual smear remaining after the smear correction algorithm is applied to an image containing saturated pixels.

4. Correction Algorithm in the Presence of Saturated Pixels

If the measured image has no saturated pixels, then the correction properly restores the image to its original exposure values. On the other hand, if a measured pixel value exceeds the maximum value of the A/D converter, then the true measured pixel value is unknown and the true value is not used in the restoration of the image values. This leads to errors in the smear removal algorithm, which leave a residual smear. The errors created by the smear removal algorithm, due to a saturated pixel, are shown below in Figure 5.

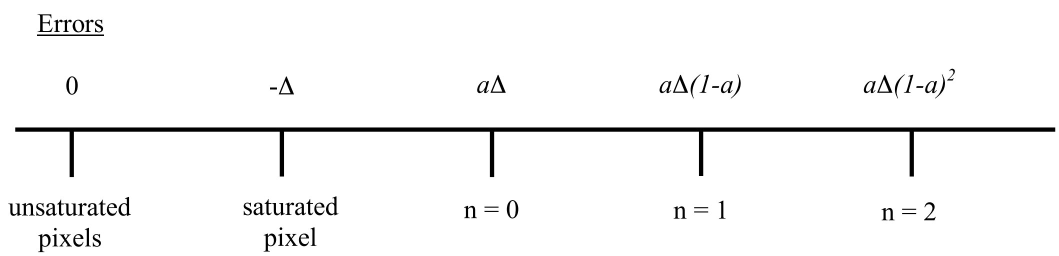


Fig. 5. Errors by applying algorithm. The initial error, Δ, made at a saturated pixel is spread to the following pixels.

Just before the saturated pixel, the correction algorithm subtracts all the known image values to the left that were determined in the earlier calculations. There is no error at that location.

At the saturated pixel, the measured value exceeded the maximum value by an amount, Δ. When the sum of the earlier true values is subtracted from the maximum value at the saturated pixel location, the restored value is the true value minus Δ. The error at the saturated pixel location is therefore just equal to -Δ.

According to Equation 2, the restored value at position, $n=0$, is determined by subtracting a times the sum of the previous true values. Since that sum is smaller by an amount, -Δ, the restored value is larger by an amount of $a\Delta$.

At all subsequent positions, the error, $E(n)$, will be $-a$ times the sum of all the previous errors. The error just before, $E(n-1)$, is already equal to $-a$ times the sum of the errors before it, so the new error, $E(n)$, is the sum of the previous error, $E(n-1)$, and $-a$ times that same previous error, or $(1-a)E(n-1)$. In other words,

$$E(n) = (1-a)E(n-1) \tag{5}$$

Since

$$E(0) = a\Delta \tag{6}$$

therefore

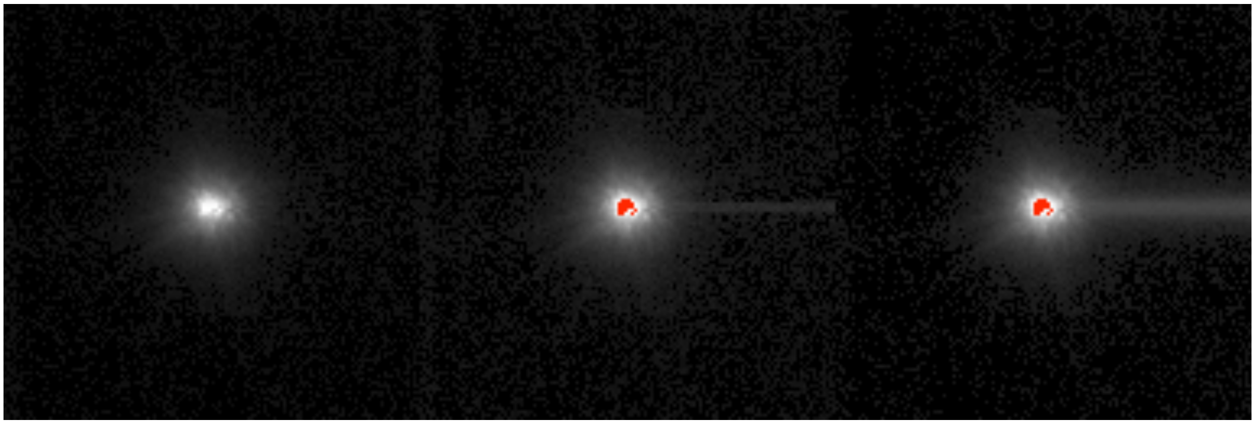
$$E(n) = a\Delta(1-a)^n \tag{7}$$

The error, as a function of position, n, is a constant times another constant to the power n. In the case considered in this paper, where the constant a is a very small number, 0.0011, and the farthest pixel away from the saturated pixels in the center is only 64 pixels, the term in the parentheses raised to the power n is only 0.93 at the edge of the image, or a drop of only 7% from the center.

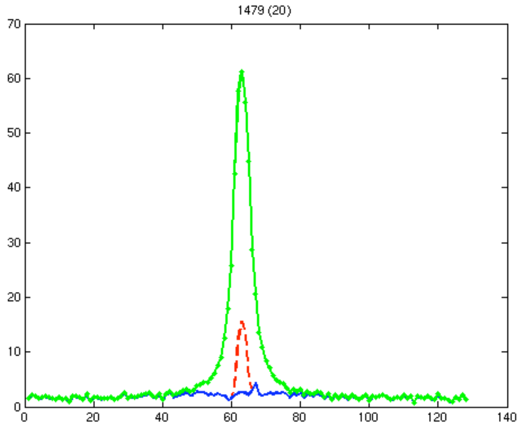
This means that, to a reasonable approximation, the smear has a constant value of approximately $a\Delta$. In other words, the amount lost due to saturation, Δ, can be determined by dividing the magnitude of the residual smear by a.

In the example shown in Figure 5, only one saturated pixel with a single loss of Δ was considered. If a second saturated pixel existed on the same row, clearly the contributions of the two pixels would simply add. The amount of residual smear contains the sum of the saturation losses at all of the saturated pixels in that row.

In Figure 6, the residual smear is removed by measuring the amount of residual smear, dividing it by *a*, and adding it back into the saturated pixels, splitting it equally between all the saturated pixels on a given row. When the smear correction algorithm is applied to the newly augmented image, a restored image results that has no residual smear. The amount added to the saturated pixels was 30% of their total value and 10% of the total value of the entire image.



a)



b)

Fig. 6. Restoring the saturated pixels. In the far left image in part a), the pixels were augmented by an amount determined from a measurement of the residual smear in the middle image. The additional digital counts added to the saturated pixels were sufficient to remove the residual smear leaving the cleaned image on the left. The plot compares all three smear regions. The blue solid line shows the absence of a smear in the final corrected image.

5. Conclusions

When a smear removal algorithm is applied to an image with saturated pixels, a residual smear remains that is approximately a constant across the image and is proportional to the information lost due to saturation. Using this constant of proportionality, the sum of the true values of all the saturated pixels on any given row can be recovered.

6. References

1. Ruyten, Wim, "Smear correction for frame transfer charge-coupled-devise cameras", Optics Letters, vol. 24, no. 13, pp. 878-880, July 1, 1999.
2. Stribling, Bruce, "Photometric calibration of short exposure imagery", *Proceedings AMOS conference*, 2001.