SHUTTER MAPPING CORRECTION FOR SHORT CCD EXPOSURES

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Abstract

Short exposures taken by CCD cameras with mechanical shutters can give field stars measurably different exposure times as a function of the position of the star in the field. For accurate photometry, the images need to be corrected for this error. The methods and formulas for correction are presented with an example of the significance of the correction.

1. Shutters

The ideal shutter in any camera, CCD or film, should open the camera aperture instantaneously to light, remain open for the required exposure time, and then instantly close the aperture. In practice some mechanical device such as an opaque screen is usually moved between the aperture and light-sensitive detector. Two problems are encountered with mechanical shutters. The mass of the shutter must be accelerated from rest to open and again to close. In the act of opening, some parts of the field of view receive light sooner than other parts. While closing, the first-mentioned parts are still receiving light after other parts are in the dark (Brandner *et al.* 1996).

Shutters usually fall into two types, iris and vane. An iris shutter opens from the center outward. A vane shutter moves from in front of the detector off to one side until the detector is unobstructed. Figure 1 illustrates the manner in which the two types of shutters uncover the field. The order in which the stars are exposed is listed in Figure 1. For the iris shutter, the center star is the first to be exposed and upon closing is the last to be covered. For the vane shutter, the star at the leftmost side of the field receives the longest exposure.

Let us assume that a shutter takes 0.1 second to open and close. During a 1000-second exposure there could be a difference of 0.1 second less exposure time for some stars in the field. That is a difference of 0.01 percent or the equivalent of 0.0001 magnitude error. Thus, in the case of a long exposure, we can safely ignore shutter corrections. If the exposure were 1 second, however, then the difference could be 10 percent, or 0.10 magnitude error. For CCD image photometry, this error is significant and must be corrected.

CCD cameras allow long exposures that can detect faint stars that were formerly unobservable with small telescopes. Why would anyone be concerned with short exposures? The star U Orionis is one of the eight four-color AAVSO variable fields and provides a good example of why a short exposure is sometimes needed.

U Ori is a Mira star with a period of 368 days. The spectral type varies from M6e to M9.5e—U Ori is a cool red star. At maximum light U Ori reaches CCDB=8.0, CCDV=6.5, CCDR=5.5, CCDI=2.5 . The comparison stars for U Ori range from 9th to 15th magnitude in all four colors.

During the exposure of a few minutes needed to obtain a good signal-to-noise ratio for the comparison stars, the I band image of the variable will be saturated. An exposure of 1 or 2 seconds is required to avoid overexposing the variable. The comparison stars are underexposed in this case. In order to obtain sufficient signal for the comparison stars, a number of 2-second exposures are made and later added together. Although the total exposure may be 10 or more seconds, the resultant image must be corrected for shutter inequalities encountered in a 2-second exposure.

Short exposures may be needed when taking sky flats. There is a short interval at dusk when the sky is at a convenient brightness for taking flat field images that are not saturated and do not show field stars. This interval may be too short to acquire multiple exposures in all colors. One could start earlier when the sky is brighter and use shorter exposures. These short exposures would have to be corrected for the shutter inequalities.

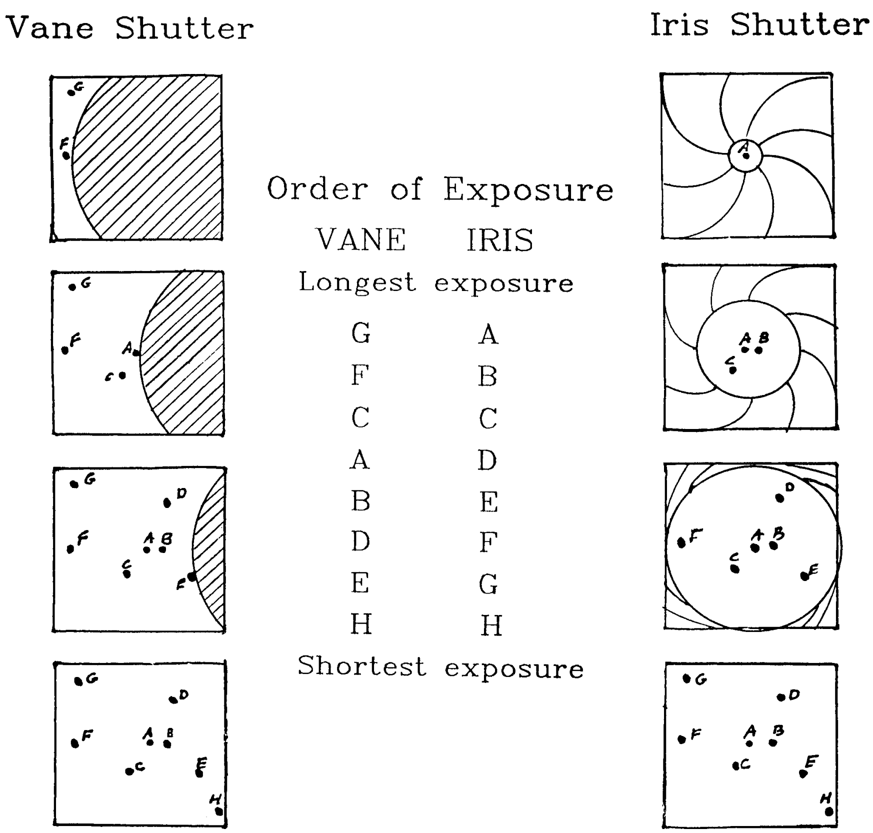

Figure 1. Illustration of vane and iris shutters opening and the order in which field stars receive different exposures. When a shutter opens, time advances down the page. When closing, time advances up the page.

2. Calibrations

The first thing to determine is the correlation between the exposure time selected from the CCD camera control software and the time the shutter is actually open. This can be found by making a series of exposures of an illuminated dome screen. This screen need not be illuminated as uniformly as a flat-field screen but the illumination

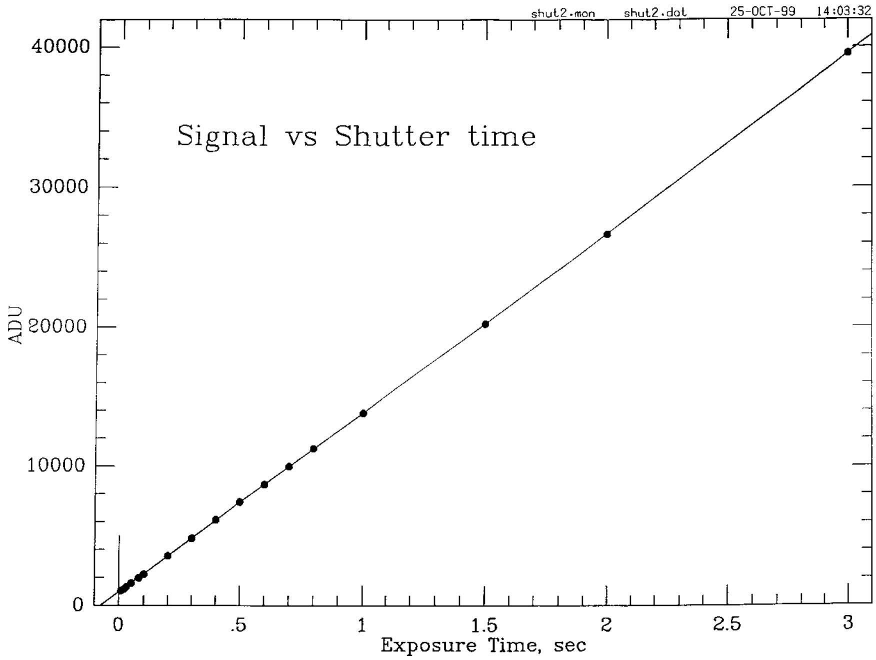

Figure 2. Mean signal from flat field screen for center 30 x 30 pixels vs exposure time selected from camera software. Signal is a linear function of time. A 75-millisecond correction should be added to the selected time to obtain actual shutter time, as noted by the line not passing through the exact origin of the graph.

must be constant during the exposure series. To achieve this constant illumination, try alternating the longer and shorter exposures rather than starting with long and progressing to short. Figure 2 shows the mean signal of the center 30 x 30 pixel area of a 1024 x 1024 CCD array with an iris type shutter as a function of selected exposure time. The center part of the array was chosen since this area has the least exposure time correction for an iris shutter. With a vane shutter one would choose the area that is exposed first for this test.

The response is quite linear, as would be desired. Notice that the time coordinate intercept is -0.075 second. A time correction of 75 milliseconds should be added to the selected exposure times.

This correction for the effective exposure time is most significant when observing single bright standard stars that require very short exposures. A 1.0-second exposure on such a star would really be exposed for 1.075 seconds, making the star appear 0.078 magnitude too bright when compared with stars in longer exposures!

After finding the shutter time correction, take a number of short (0.3 second) and long (3.0 second) exposures. The illumination of the screen should not change during this series of exposures. Again, errors will be minimized if the short and long exposures are taken alternately. Enough short exposures need to be taken to ensure an image with an adequate signal-to-noise ratio (Zissell 1996).

These exposures are corrected for bias and dark signal only. The short and long exposures are each averaged to produce a mean short and long image.

3. Correction Formula

The primary assumption from which the correction formula will be derived is that the rate of photons falling on a pixel is the same for a short or long exposure. Figure 3 shows the derivation. The subscripts s and l refer to short and long exposures. The subscript c refers to a corrected value, o refers to the observed value. R is the rate of photon detection, S is the total signal for a particular pixel after an exposure of t seconds. t is the maximum time that the shutter stays open. Sm is the "Shutter Map" correction to the maximum exposure and has units of seconds.

R, S, Sm can also be thought of as representing an individual pixel or the total array of pixels, the image itself. The subscripts i and j could be added to the symbols R, S, Sm to represent the pixel in the ith row and jth column. These subscripts would just make the equations harder to read so they are omitted. In practice, the symbols R, S, Sm represent entire image arrays.

Shutter Mapping Formula

$$R_{cs} = R_{cl} \qquad \text{Signal Rate (ADU/sec)} \qquad (1)$$

$$R_{cs} = \frac{S_{cs}}{t_s} = \frac{S_{os}}{t_s - Sm} = \frac{S_{ol}}{t_l - Sm} = \frac{S_{cl}}{t_l} = R_{cl} \qquad (2)$$

$$S_{os} t_l - S_{os} Sm = S_{ol} t_s - S_{ol} Sm \qquad (3)$$

$$Sm (S_{os} - S_{ol}) = S_{os} t_l - S_{ol} t_s \qquad (4)$$

$$Sm = \frac{S_{os} t_l - S_{ol} t_s}{S_{os} - S_{ol}} \qquad (5)$$

$$\frac{S_{cs}}{t_s} = \frac{S_{os}}{t_s - Sm} \Rightarrow S_{cs} = \frac{S_{os} t_s}{t_s - Sm} = \frac{S_{os}}{\left(1 - \frac{Sm}{t_s}\right)} \qquad (6)$$

$$\frac{S_{cl}}{t_l} = \frac{S_{ol}}{t_l - Sm} \Rightarrow S_{cl} = \frac{S_{ol} t_l}{t_l - Sm} = \frac{S_{ol}}{\left(1 - \frac{Sm}{t_l}\right)} \qquad (7)$$

Figure 3. Derivation of shutter correction formula. R is rate of photon detection in ADU/sec, S is total observed signal in ADU. Maximum exposure time is t. Subscripts c, o, s, l refer to corrected, observed, short, and long values, respectively. Sm is the shutter-map time correction in seconds.

Equation 1 equates the Rate of photon detection for a short and long exposure.

Equation 2 shows that the signal rate equals the corrected total signal divided by the maximum shutter time or the observed signal divided by the corrected exposure time for both the short and long exposure.

Equation 3 and 4 show the algebra leading to solving for the variable Sm, the correction to the maximum exposure time.

Equation 5 is the working equation for calculating the shutter map image, Sm. The short and long mean exposures are multiplied by the long and short exposure times, respectively. The difference in the multiplied images is then divided by the difference between the original short and long images. The image Sm has intensities in units of seconds. The values of the pixels in Sm will be negative since we originally subtracted Sm from t. Had we added the Sm correction, Sm would have positive values. The corrected exposure time for a pixel will be shorter than the maximum time, t, except for the pixels exposed to first and last light.

Figure 4 shows the time correction image, Sm, for the iris type shutter supplied with the Photometrics CH250 camera. Bright areas have a longer exposure time than darker areas.

Figure 5 is a contour plot of Sm with minimum value at center. The pattern characteristic of a five blade shutter is obvious.

Figure 6 is a histogram of Sm and has a mean value of 0.012 second with a range from 0 to 0.025 second. The Y axis denotes the number of pixels that have a value given on the X axis. Note that the extreme ends of the X axis representing the least and maximum correction both have the fewest number of pixels. These pixels are located at the very center and far corners of the array, respectively.

4. Applying the Shutter Correction

Equation 6 (for short exposures) or 7 (for long exposures) in Figure 3 is the working equation for applying the shutter correction to an observed image. The image Sm is stored and a copy backed up on the hard drive. Before applying the correction, create and store a "unity" image where all pixels have the value 1.000 . This can be done by dividing an image into itself and saving the result as "one." A better method would be to multiply an image by zero and add one to the result. This avoids the problem of "divide by zero" errors for bad pixels.

To correct a short observed exposure, S_{os}, divide Sm by the maximum exposure time, t_s, subtract the result from the unity image, and divide that result into S_{os}. One could drop the subscript s or l since the equation is valid for any length exposure. As the exposure time increases, the denominator of the righthand part of equation 6 or 7 approaches 1.000.

5. Example of Shutter Correction

Figure 7 is an actual CCD image of the VX Gem field with the bright variable in the center of the field. The image was corrected for bias and dark before the shutter map correction was applied. Then the flat field correction was applied. A copy of the Sm image and the contour plot were overlaid to show where the corrections would be most significant.

The numbers in the field are the magnitude difference between the stars in the corrected and uncorrected images. Note that with the iris shutter, differences are least for the central stars. The actual corrections in magnitudes range from 0.000 in the center to -0.05 or -0.06 near the edges. The negative signs indicate that the stars become brighter when corrected.

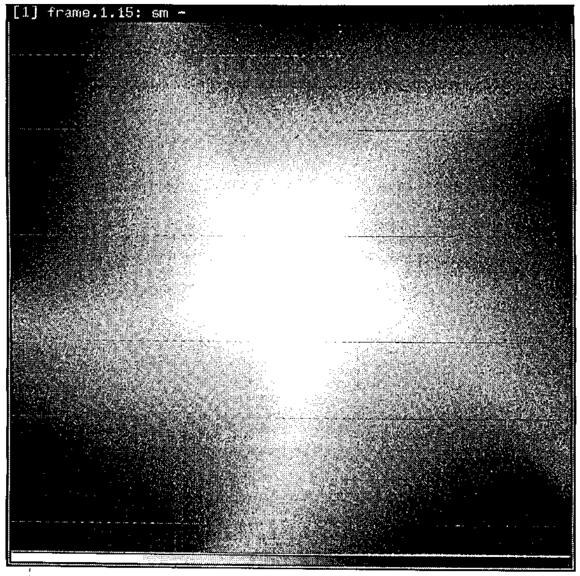

Figure 4. Shutter Correction Image, Sm for iris shutter. Darker parts of image indicate shorter effective exposure times.

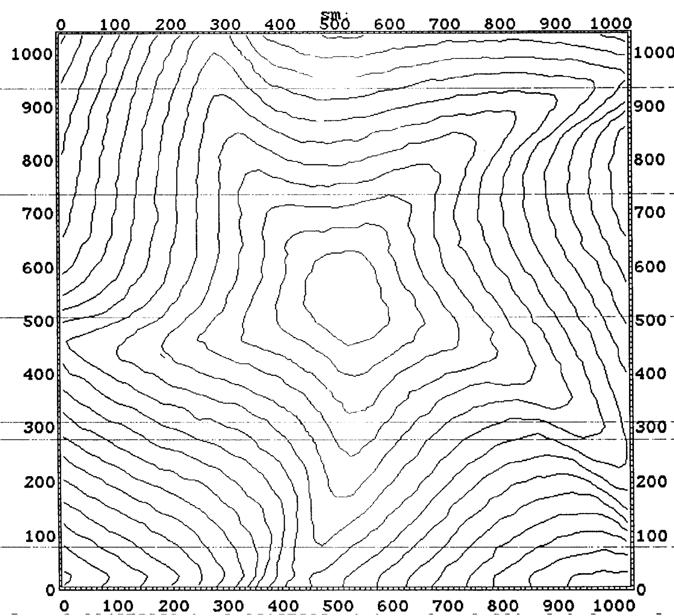

Figure 5. Contour map of Shutter Correction Image shown in Figure 4. The pattern from the five blade shutter is obvious.

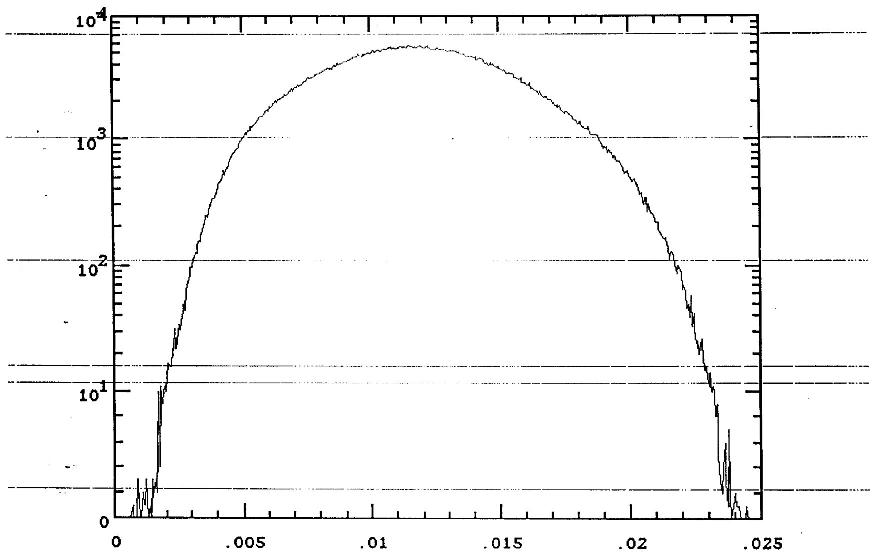

Figure 6. Histogram of Shutter Correction Image. Corrections range from near zero correction at center of image to 0.025 sec correction at the corners of the image.

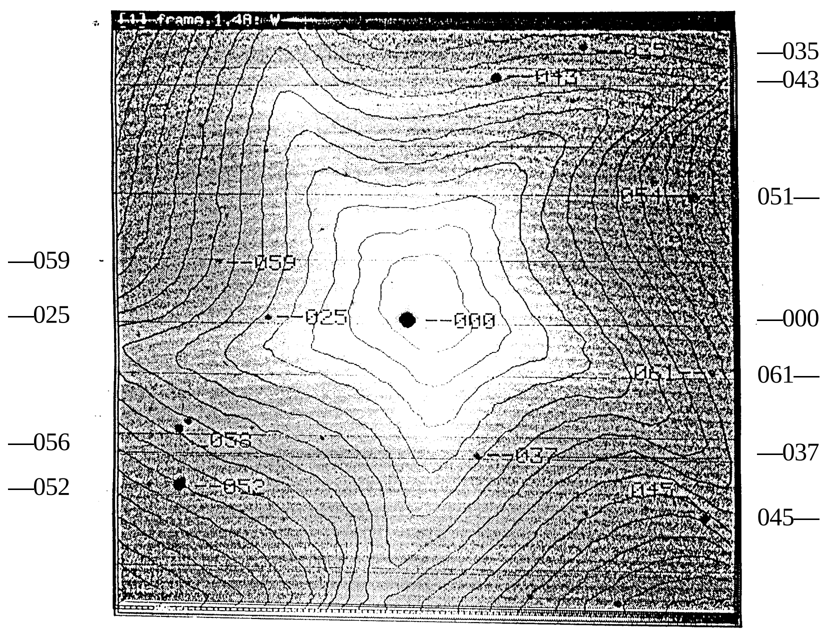

Figure 7. Image of VX Gem with shutter correction image and contour superimposed. The numbers indicate the magnitude differences between shutter-corrected and non-shutter corrected images. Note the differences become more significant toward the edges.

6. Conclusions

As illustrated above, shutter error corrections can be significant in certain situations. Every CCD observer should at least determine if there is a time correction needed for the times selected from camera control software. If one takes short exposure images of single standard stars, one should find where to locate the star in the field to minimize shutter errors.

Some CCD systems do not use a mechanical shutter but instead employ an array with one half of the chip covered with an opaque screen. At the conclusion of an exposure, the charge in the uncovered pixels is transferred rapidly to the covered pixels where the image is then read out. This shifting of the image only takes a few milliseconds. The shutter inequality correction would be insignificant in this case, although one should check for the time-delay error.

References

Brandner, W., Lehmann, T., Schöller, M., Weigelt, G., and Zinnecker, H. 1996, *The ESO Messenger*, **83**, 43.

Zissell, R. E. 1996, *J. Amer. Assoc. Var. Star Obs.*, **24**, 26.