VIMS Saturn Occultations Centering Algorithm

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Abstract

Tracking the center of a star in a VIMS image is a difficult task because the PSF of the star is less than one pixel. Still, the star is rarely centered in a pixel, and so centering can be achieved by looking at how much light spills into the neighbors of the brightest pixel. Fortunately, the Pixel Response Function (PRF) is well-defined for the single VIMS spatial pixel as a function of the angle between the center of the pixel and the star. This has been done by slewing the spacecraft so that the star raster-scans across the pixel. From these, we can calculate the theoretical relative brightnesses of the pixels on either side of the brightest pixel relative to the brightest pixel, and compare this to the measured value in the VIMS frame. The ultimate goal of the procedure outlined in this document is to produce a metric of the theoretical relative brightnesses of the critical pixels as a function of the position of the star, so that we can compare this to the actual relative pixel brightnesses and constrain the position of the star in the focal plane.

1 Coordinate System Definition

The first step is to define a coordinate system that we will use to describe the location of the center of the star's image on the detector. This coordinate system will necessarily be related to the pixel grid (Figure 1. We will define this coordinate system first in terms of pixel number, then convert it to angular displacement.

Detecting when the center of the image of a star is aligned with the center of a pixel is difficult compared to detecting when the center of the star is on the boundary between two pixels. When the center of the star is on the boundary between two pixels, the two pixels receive the same flux from the star. Further, this allows someone working with the data to easily determine which pixel the star is currently in by looking at the position of the center. The value before the decimal point tells you which pixel is brightest, and the value after the decimal point tells you how far through the pixel the star has moved. See Figure **??**.

We can then convert this coordinate system from pixel locations to angular displacements by multiplying by the angular width and height of the pixel in whichever observing mode is associated with the data.

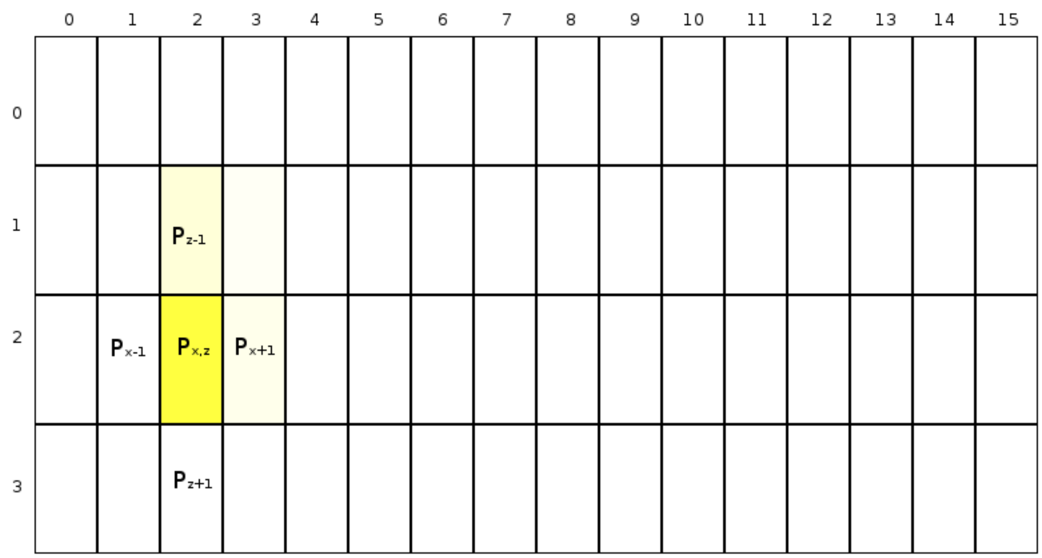

Figure 1: The pixels on the Cassini VIMS instrument are 0.5x0.25 milliradians for images taken in high-resolution mode. They are 0.5x0.5 milliradians for images taken in low-resolution mode. This is a diagram of the instrument field-of-view for a 16x4 high-resolution imaging-mode occultation, such as that for the AlpOri occultation of rev270s99. The pixels used in the calculation of the metric R are labeled.

2 Selecting the Comparison Pixel

We calculate the brightest pixel, $P^x = P^z$, using the brightest pixel algorithm described in the code document. Then we mark "transitions" when the brightest pixel moves from one position to the next. We use the position of the brightest pixel beyond the nearest transition as the comparison pixel. See the code document for the full write-up, or I should combine these documents at some point (likely).

The background-corrected brightness of these two pixels is divided to arrive at R_{data}

3 The Metric

We measure the direction to the star by modeling which two pixels might be sharing starlight, then taking the ratio of their de-noised signal R_{data}. We compare this ratio to the same ratio calculated from the PRF scans $R_{scans}(t)$ at each time step t. We calculate the value of $t = t_0$ for which $\chi^2 = (R_{data} - R_{scans}(t_0))^2$ is minimized, and then calculate $\theta(t_0)$ which is the offset of the star from the center of the pixel at t_0.

$$R^x_{data} = \frac{P^{x\pm1}}{P^x} \tag{1}$$

And in the z direction this ratio is defined as:

$$R^z_{data} = \frac{P^{z\pm1}}{P^z} \tag{2}$$

Where $P^x = P^z$ is the brightness of the brightest pixel (integrated over some wavelength range), and $P^{x\pm1}$ and $P^{z\pm1}$ are those of the adjacent pixels in each direction, as shown in Figure 1.

This metric has many properties which make it useful. Theoretically, it should be monotonically increasing or decreasing as the star position increases steadily in pixel position. For PSFs smaller than a pixel, there will be a plateau at zero where there is no light observed in the neighboring pixel. Away from this plateau (near the pixel boundaries) we have the best sensitivity to the position of the star. At metric values $R = 1$ the center of the star's PSF straddles the boundary with the neighboring pixel and we have the most sensitivity.

4 The Pixel Scans

We have scans of the sensitivity of VIMS's spatial pixel as a function of the position of the star relative to the center of the pixel created by slewing the spacecraft around in a raster-scan pattern as shown in Figure 2.

NOTES: I am currently only using x-scan 7 (near the middle), and only for the observations where the spacecraft's motion was aligned with the x-axis. These central scans saturate the pixel at the very shortest wavelengths. This impacts one of the observed band-passes in my code. I have plans to select the best scan in each direction that I need to develop further.

5 Calculating the Theoretical Metric from the Scans

One of the most well-constrained and precisely repeatable parts of the VIMS camera is the interpixel distance, θ_{pix} (Phil Nicholson, private communication). Therefore, we should be able to reliably calculate the theoretical metric along a scanline from the scanned data using the following formula:

$$R_{scans}(t) = \frac{PRF(t \pm \frac{\theta_{pix}}{\dot{\theta}_{spacecraft}})}{PRF(t)} \tag{3}$$

where θ_{pix} is the fixed interpixel distance and $\dot{\theta}_{spacecraft}$ is the fixed spacecraft velocity during the scan.

The buffer provided in each scan provides a domain of the metric that extends beyond the edge of the pixel so that we can still test those values for completeness of the fitting algorithm described in the next section.

6 Fitting the Experimental Metric to the Theoretical

Now we have a map of the metric along each scan extending beyond the edges of each pixel, and the observed value of the metric.

Next, we calculate the t_0 for which $\chi^2 = (R_{data} - R_{scans}(t_0))^2$ is minimized, and then calculate $\theta(t_0)$ which is the offset from the center of the pixel at t_0.

7 Results

In Figure 3, you can see the results of one of these centering runs for the occultation AlpOri271S99.

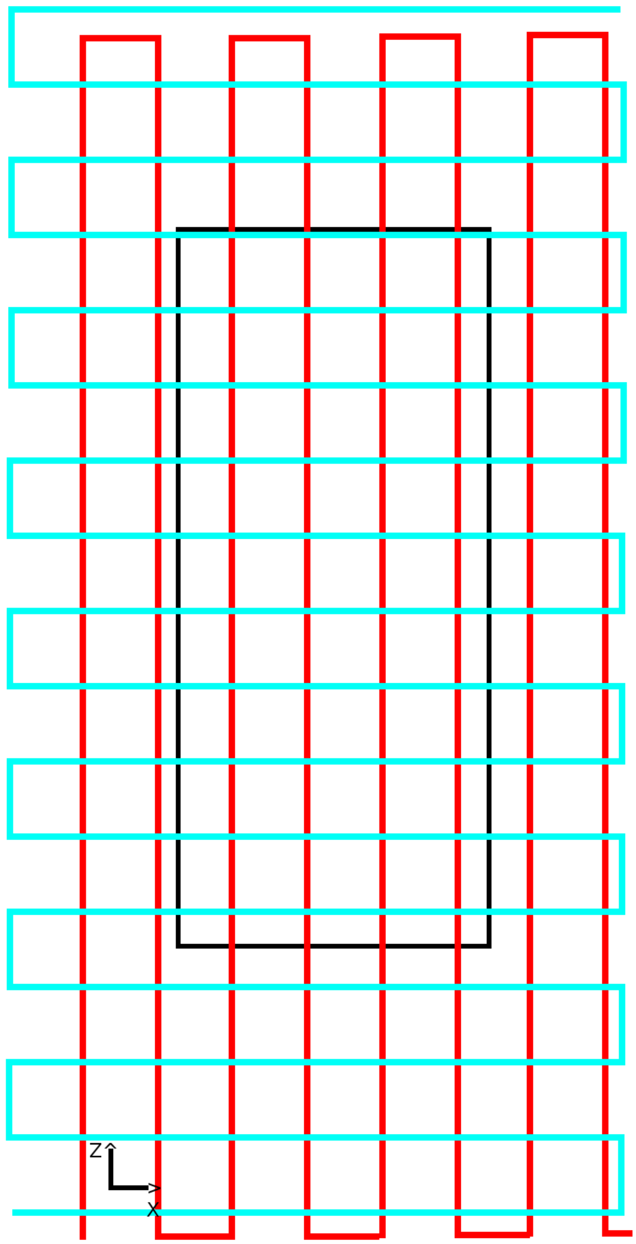

Figure 2: Black Box is pixel, Red scans are Z scans, Cyan scans are X scans. The spacecraft was slewed such that the center of the star passed along the paths shown by the scan-lines.

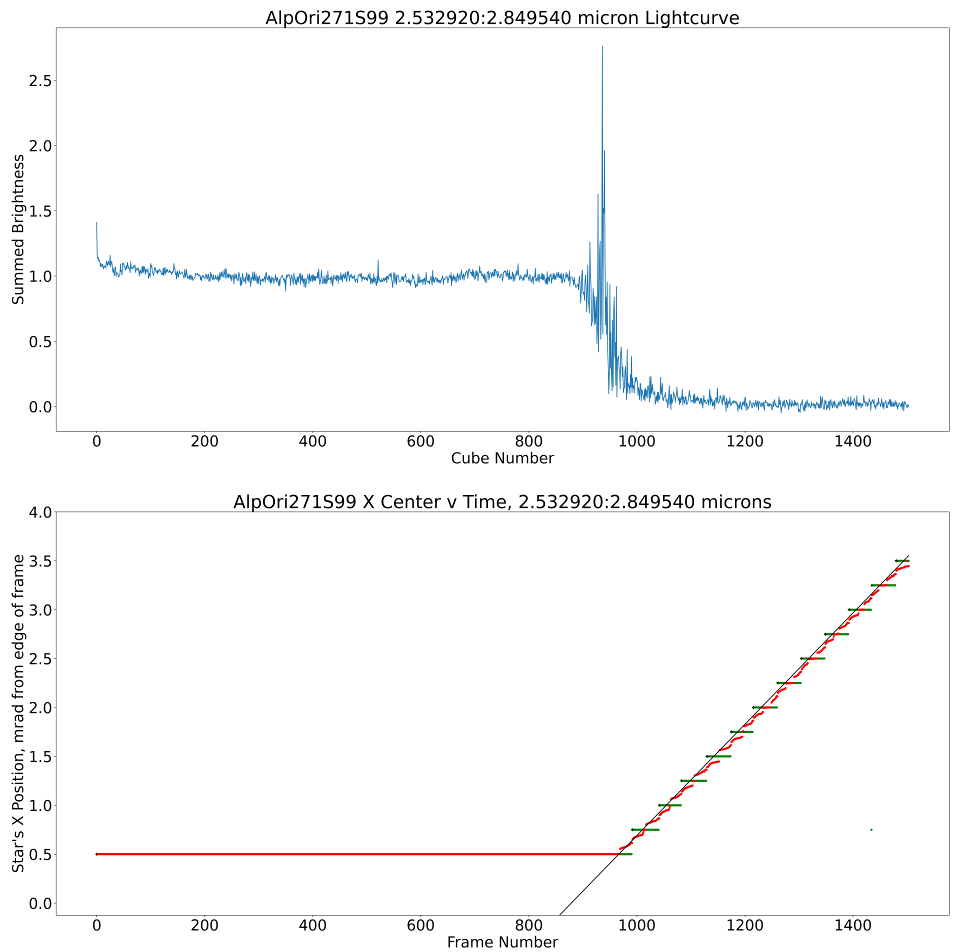

Figure 3: (top) Occultation light curve as AlpOri passed behind Saturn from the vantage point of Cassini VIMS on rev 271.
(bottom) In green, you can see the step-wise brightest pixel centering that had resolution of one pixel. In red, you can see the centering calculated as a result of the algorithm described in this paper. The plus signs mark where the transitionfinder() function marked pixel transitions. The black line marks the calculated position of the limb of Saturn, which is where the refracted light should appear to come from.