

Cassini ISS Image Calibration: Theoretical Basis
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Revision 1. February 2002

I. Introduction

The purpose of this document is to provide a physical basis for the development of software to calibrate Cassini ISS images. It attempts to explain how the observed data numbers are related to quantities of physical interest to the scientist. Care has been taken to expose dependencies (such as the dependency of the light-flood residual bulk image on readout mode) which must be recognized and accounted for in the software.

I. Radiometric Calibration

This section describes the relationship between measured image values (DN for Data Number) and incident intensity I, and outlines the steps required to derive I from the DN values. Most filters are not sensitive to the polarization state of the target, and so the first section below will outline the method neglecting polarization. Polarization must be taken into account when polarizing filters are used, and the procedure for this will be describe in the section which follows.

To understand the processes involved it is useful to follow the light as it travels through the optical system, is converted to an electric signal and a data number and then is processed by the digital electronics.

The following definitions will be used:

Table 1
Definitions and Units

Ω	steradian	Solid angle sampled by one pixel
A	cm^2	Collecting area of camera optics ($0.25\pi d^2$, d is the primary mirror or lens diameter)
$C(f_1, f_2)$		Absolute sensitivity correction factor determined from in-flight calibration
$e_p(i, j)$	electrons	Electrons produced by photons striking the CCD
f_1, f_2		Filter 1 in wheel 1, filter 2 in wheel 2
$FF(i, j, f_1, f_2)$		Flat field relative sensitivity
g	electrons DN^{-1}	gain constant
$I(i, j, \lambda)$	photons $\text{cm}^{-2}\text{s}^{-1}\text{nm}^{-1}\text{sterad}^{-1}$	Intensity at (sample, line, wavelength)
line		The vertical coordinate (1:1024) of the image. Index j is used in this document for line number

QE(i,j,λ)	electrons photon ⁻¹	CCD Quantum efficiency
RBI(i,j,mode)	DN	Residual Bulk Image
sample		The horizontal coordinate (1:1024) of the image. Index i is used in this document for sample number.
t(i)	s	Shutter open time, depends on sample number
T _o (i,j,λ)		Optics transmission. Accounts for beam obscuration as well as losses at lens and mirror surfaces
T ₁ (i,j,λ)		Filter 1 transmission
T ₂ (i,j,λ)		Filter 2 transmission

The light that hits the CCD first passed through the camera optics and two filters, and the shutter. As a result of this process the number of photons incident on one pixel at location (i,j) is $A\Omega t(i)I(i,j,\lambda)T_o(i,j,\lambda)T_1(i,j,\lambda)T_2(i,j,\lambda)$. Note that the exposure time depends on sample number (i) because the shutter velocity is not uniform during the open and close. Note also that the actual shutter open time differs significantly from the commanded time for one of the exposures on each camera (20 ms for the WAC and 25 ms for the NAC).

Some of the photons (a fraction $QE(i,j,\lambda)$) that strike a pixel will be converted to electrons. The number of electrons generated by photons is given by

$$e_p(i,j) = A\Omega t(i) \int I(i,j,\lambda)T_o(i,j,\lambda)T_1(i,j,\lambda)T_2(i,j,\lambda)QE(i,j,\lambda)d\lambda \quad (1)$$

The optics and filter transmissions have spatial dependence because of low spatial frequency components (e.g. vignetting) and high spatial frequency components (dust particles). Calibration measurements are not able to determine the source of the spatial variations and so all spatial variations are lumped together and taken out of the wavelength integral. Henceforth we will call this lumped relative spatial dependency $FF(i,j,f_1,f_2)$. It is obtained with flat-field calibration measurements. It is a relative dependency because it is normalized to unity, i.e.

$$\frac{1}{N^2} \sum_{j=1}^N \sum_{i=1}^N FF(i,j,f_1,f_2) = 1.0$$

The dependence on f_1 and f_2 reflects the fact that the FF depends on the filter 1 and filter 2. Then equation (1) becomes

$$e_p(i,j) = C(f_1,f_2)A\Omega t(i)FF(i,j,f_1,f_2) \int I(i,j,\lambda)T_o(\lambda)T_1(\lambda)T_2(\lambda)QE(\lambda)d\lambda \quad (2)$$

In equation (2) $T_o(\lambda)$, $T_1(\lambda)$, and $T_2(\lambda)$ refer to transmissions averaged over the focal plane. These were measured as part of the calibration procedure. A new term $C(f_1, f_2)$ was introduced into equation (2). It is a correction factor to account for the fact that there are errors in the calibration measurements of absolute sensitivity. This factor will be determined from in-flight absolute calibration of standard stars and other objects whose radiometric flux or intensity is independently calibrated. If the ground calibration measurements are accurate it should be close to unity.

Other processes add to or reduce the number of electrons in a pixel. Residual bulk image (RBI) from preflash and (at a very low level) previous exposures, and dark current add electrons. If anti-blooming is on electrons can be shifted from one pixel to an adjacent pixel containing traps. The pixel with the traps will accumulate electrons at the expense of its neighbor. The neighbor is always the adjacent pixel in the line direction.

Dark current is usually negligible except at the edge of the image. However, an uncompressed unsummed image will read out partially into memory and then wait since the camera memory cannot store an entire image. If the bus rate is low the remaining image may sit on the CCD for many seconds. During this time dark current at the edge of the frame builds up. Since the image is partially read out, what was line 337 waits at the edge of the CCD where dark current builds rapidly. The line waiting at the edge of the frame depends on the data rate and possibly also whether compression is used. Line 337 was observed to have bright pixels in uncompressed calibration frames taken in the lab, all at a rate of 60.9 kilo-bits per second. All lines after 336 contain enhanced RBI electrons from the time spent waiting.

The RBI from the part of the image remaining on the chip also builds up. Therefore the resulting dark current and RBI pattern has a complicated spatial structure and depends on how the chip was read out, which in turn depends on the data rate, the summation mode, exposure time, which camera was read first after simultaneous shuttering, and compression. The only way to remove the unwanted signal is to take a series of dark frames in each mode used during the image sequence. Here mode refers to all the factors which influence the time spent on the chip and the read pattern. These factors include exposure time, summation mode, compression mode, framing time, readout rate, etc. A potentially very large number of dark frames with different parameters must be obtained and returned. The frequency with which new frames need to be obtained is to be determined during flight.

The CCD contains a summation well. On-chip summation of 2X2 or 4X4 pixels can be commanded. Data volumes in these summation modes are small enough that the entire chip can be read to memory.

Voltages on the chip are set so that the zero level (no electrons in the pixel) will produce a positive DN value. This is called the bias level. It should not change except over long time periods or after a voltage reset. It can be measured for each frame from the over-clocked pixels. Calibration data taken in the thermal vacuum chamber revealed that the bias level, as revealed by over-clocked pixels, increases with increasing exposure time. The reason

for this is unknown. For gain state 3 the bias level is a function also of the electronics temperature. To ensure that the correct bias level is subtracted, the bias level should be obtained from the over-clocked pixels for each frame. The best measure of the bias level is to average as many over-clocked pixels as possible.

The summation well is deep enough to accommodate 2X2 summation moderately well, but is not adequate for 4X4 summation in the lowest gain state. DN values above about 1600 in the lowest gain state depart from the linear coefficients derived from low DN levels. Nonlinearity is noticeable in other gain states as well. It is least severe for the highest gain state. Departures from linearity are recorded as one of the calibration products, but the (quadratic) terms in the response curve were not derived. Both linear and quadratic terms are different for each pixel. A separate file containing maximum allowed DN needs to be checked to make sure the DN value for any pixel is not above the DN range over which calibration is accurate to 1% or better.

The electrons on the CCD are shifted to an output register and then to the analog-to-digital converter (ADC). The ADC also picks up a non-steady signal in the 2-3 HZ frequency range coming from the spacecraft bus or some obscure source. The signal is small but very noticeable on scenes with low intrinsic signal (dark sky). For most images the only information on the amplitude and phase of this signal comes from overclocked pixels. The calibration software analyzes these and removes the 2-3 Hz noise to within statistical uncertainty. During the first several years of cruise (until mid-2002) only one overclocked pixel per line was recorded in the image file. During the latter part two values are reported for each line, the sum of the first six overclocked pixels and the sum of the last two overclocked pixels. The calibration software needs to recognize both cases.

Although the statistical uncertainty in the 2-Hz signal is improved by summing eight overclocked pixels, there is still some residual 2-Hz noise in the calibrated image. Some scenes (star images, dark sky, dark current exposures) contain large areas of the image where the light incident on the chip is negligible compared to the 2-Hz noise. In that case one can use an optional routine which more accurately measures the 2-Hz noise. The 2-Hz signal is not visible in the two lowest gain states.

In-flight images also show additional weak coherent noise patterns which appear as wave trains with arbitrary orientation. These patterns are most evident in low signal images. At this time we do not have a generic algorithm to handle the general case. Some team members have been able to remove coherent noise on an ad-hoc basis by Fourier filtering.

The ADC introduces a bias in the DN levels because of a process called uneven bit weighting. Instead of a one-to-one linear correspondence between input signal and output DN, some of the DN values are under-populated and some are over-populated. Four gain states are available. The uneven weighting is different for each of the gain states.

Data from the ADC are 12-bit numbers. These can be sent to memory or passed through one of the 12-to-8 tables. One of the tables approximates a square-root function. The other takes the 8 least significant bits.

Eight-bit data can be passed through one of two compressors. One is a lossless Huffman compressor. The other is a lossy cosine transform compressor.

Radiometric calibration requires the following steps which reverse the effects of each of the processes listed above:

- (1) Decompression if compression was used.
- (2) Conversion from 8 to 12-bit words if a 12-to-8 table was used.
- (3) Correction for uneven bit weighting using a table appropriate for the gain state. This step is not done if 12 to 8 table was used because of information lost in the 12 to 8 table mapping.
- (4) Bias subtraction using overclocked pixel values (average of many to improve statistics)
- (5) 2-Hz noise subtraction using overclocked pixel values or an optional code that uses image values.
- (6) Subtraction of appropriate dark frame containing RBI and dark current corresponding to the exposure time, summation mode, gain state, and readout mode of the image. This frame has had its own bias value already subtracted and may contain some negative DN values. The dark image may be generated from coefficient files and a code which contains a model for dark current and RBI production.
- (7) Correction for bright/dark differences in anti-blooming mode.
- (8) Correction for nonlinearity for the appropriate gain state.
- (9) Multiply by the gain constant g . The result will be $e_p(i,j)$ as given by equation (2).
- (10) Divide the frame by the factors $C(f_1, f_2)A\Omega t(i)FF(i,j, f_1, f_2)$
- (11) Divide the image values by $\int T_o(\lambda)T_1(\lambda)T_2(\lambda)QE(\lambda)d\lambda$. The resulting image will be an array of intensities averaged over the passband of the filter with a weighting function $T_o(\lambda)T_1(\lambda)T_2(\lambda)QE(\lambda)$
- (12) The quantity I/F is often desired for solar system objects, where πF is the incident solar flux. The appropriate value of F is the passband averaged F weighted the same way as the intensity, namely

$$F = \frac{\int F_1(\lambda)T_o(\lambda)T_1(\lambda)T_2(\lambda)QE(\lambda)d\lambda}{\pi D^2 \int T_o(\lambda)T_1(\lambda)T_2(\lambda)QE(\lambda)d\lambda}$$

In the above equation F_1 is the solar flux at 1 AU and D is the distance between the sun and target body in AU.