SPACE NAVIGATION AND FLIGHT DYNAMICS

INTEROFFICE MEMORANDUM

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To: OSIRIS-REx SPOC, MSA, & FDS; JPL Optical Navigation Group

From: Derek Nelson

Subject: OSIRIS-REx FDS Optical Navigation Image Corrections, Rev. B

References:

[1] *SPOC OSIRIS-REx Camera Suite (OCAMS) Uncalibrated / Calibrated Data Product Software Interface Specification*, UA-SIS-9.4.4-0300, Rev_3.0, University of Arizona / LPL, 04/12/2016.

[2] *1/2.5-Inch 5Mp CMOS Digital Image Sensor*, MT9P031 Data Sheet, Rev. G, Aptina Imaging.

[3] *TAGCAMS Pixel Layout and Dark Pixel Regions*, TAGCAMS_Pixel_Layout_v3.pptx, Version 3, KinetX SNAFD, 11/02/2016.

[4] *TAGCAMS Calibration Report*, MSSS-TAG-DOC-0103, Malin Space Science Systems, 07/07/2015.

Introduction

The OSIRIS-REx optical navigation (OpNav) process uses images of Bennu, stars, and other celestial bodies to perform spacecraft navigation and camera calibration functions. These images are acquired using various spacecraft cameras, each of which has its own image acquisition process. The raw images that are produced by the spacecraft imagers are downlinked and sent to the OSIRIS-REx Science Processing and Operations Center (SPOC), where they are packaged with relevant ancillary data and made available to the optical navigation team. The optical navigation function ingests these raw (Level 0, uncorrected) images. However, due to natural phenomena and various features of each camera, the raw image data obtained from the SPOC must be corrected internally within the optical navigation algorithms in order to optimize the image processing performance. Thus, an image correction process must be established for each type of image processed by the optical navigation function. This document describes the optical navigation image correction processes for each type of raw image that is ingested by the optical navigation algorithms. Since most of these corrections will be made internal within the FDS OpNav process and the corrected images are not typically rewritten as new FITS images, the FDS OpNav team does not expect to publish these corrected images. Thus, other users will need to duplicate the corrections within their own processes as they see fit.

Optical Navigation Image Types

The optical navigation function will use images from two sets of on-board cameras: OCAMS and TAGCAMS. The OSIRIS-REx Camera Suite (OCAMS) consists of three imagers: PolyCam, MapCam, and SamCam. PolyCam is the highest resolution imager, MapCam is the medium-resolution imager, and SamCam is the lowest resolution imager of the OCAMS suite. All three OCAMS cameras use the same model Charge-Coupled Device (CCD) for its detector, and thus detector-dependent corrections will be identical for each of the three cameras. Further details about the image correction processes for the OCAMS imagers is provided below.

The Touch-and-Go Camera System (TAGCAMS) consists of three imagers, two of which are dedicated specifically to optical navigation: NavCam1 and NavCam2. NavCam1 is also referred to as simply NavCam, and NavCam2 is also referred to as NFTCam. These names are used interchangeably. NavCam1 and NavCam2 are designed to be identical, redundant cameras that can be used interchangeably for optical navigation operations, if necessary. StowCam, the third imager of the TAGCAMS suite, is not used for optical navigation, and will not be discussed in this document. The NavCam1 and NavCam2 (referred to as "TAGCAMS" for the purpose of this document) correction processes and considerations are described in further detail below.

OCAMS Image Corrections

The Level 0 OCAMS images provided by the SPOC will be subject to the following corrections that are applied internally within the optical navigation function. The Level 0 OCAMS FITS files have "primary" and "image" FITS extensions. The "image" extension includes all of the image array data, including the masked and overscan pixels. This "image" extension is the raw, uncropped image. The "primary" image is not used by the optical navigation function, since it does not provide the dark/overscan pixel data.

A. Bias and Dark Correction using Masked Pixels

The bias offset and dark current present in each image are both corrected using the masked pixels present in each Level 0 OCAMS image. The mean DN value of each masked pixel region is subtracted from the corresponding active image region, resulting in a full corrected image. This correction can be described by the equation:

$$C_d = R - \frac{1}{n}\sum_{i,j} D_{ij} \tag{1}$$

where C_d is the corrected (and cropped) image, R is the raw active image array, D represents the masked dark pixel region, and n is the total number of pixels in the masked pixel region.

The OCAMS detector regions and masked pixel array dimensions are presented in Fig. 1. The mean value of the *Left Covered* and *Bottom Left Covered* regions of the image is subtracted from the *Left Active* image region. The mean value of the *Right Covered* and *Bottom Right Covered* regions of the image is subtracted from the *Right Active* image region. The *Top Left Covered* and *Top Right Covered* regions are not used, because there seems to be charge transfer effects present that would bias the mean value of these regions. After these subtractions are applied to the active regions, the *Trans*, *Covered*, *Isolation*, and *Overscan* pixels are cropped from the image, leaving only the corrected 1024×1024 active array.

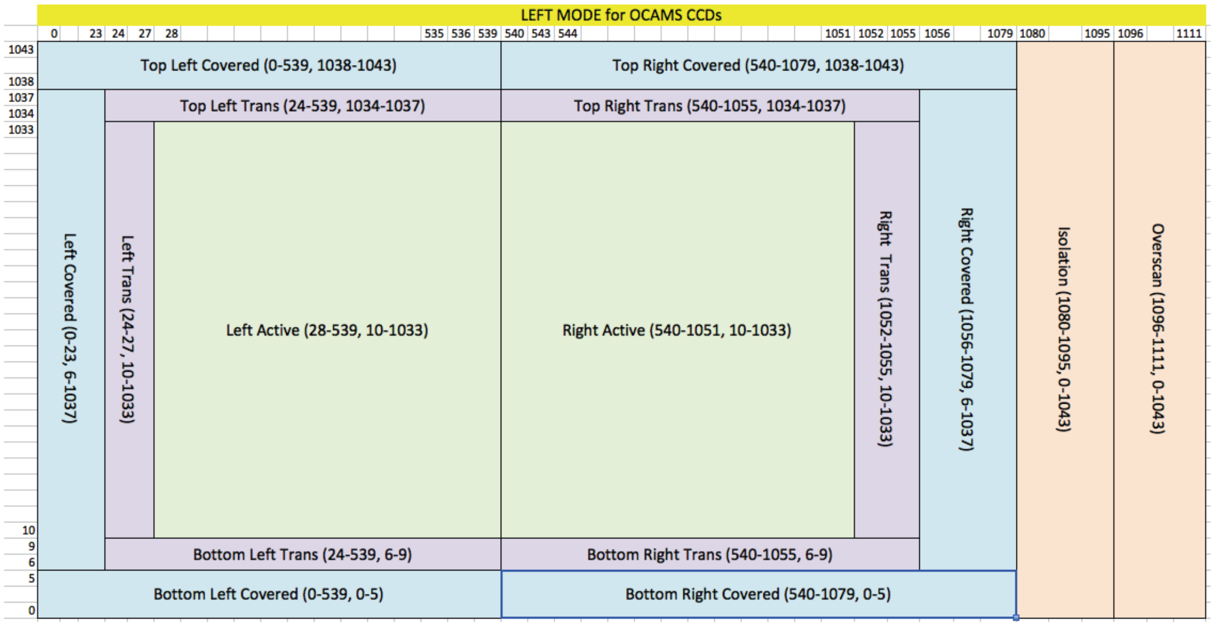

Figure 1: OCAMS Detector Layout [1]. Pixels from *Covered* regions are used to calculate the mean background DN values, which are subtracted from the corresponding active regions.

B. Flat-Field Correction

Pixel-to-pixel variations in response are corrected using a flat-field image that is applied to the full, dark-subtracted 1024×1024 image array. An official flat-field will be generated individually for PolyCam, MapCam, and SamCam, and each flat-field will be applied to images from the corresponding camera. The flat-field is applied by dividing the individual dark-corrected image DN pixel values by the corresponding flat-field pixel values. This can be described by the equation:

$$C_{d,f,ij} = \frac{C_{d,ij}}{F_{ij}} \tag{2}$$

where F is the flat-field and $C_{d,f}$ is the bias/dark-corrected, flat-fielded image.

C. Image Projection Corrections over Temperature

The optical navigation team will be using the infinity focus position for PolyCam (focus position 17371), the panchromatic (PAN) filter for MapCam, and Filter #1 for SamCam. The following statements refer only to these OCAMS focus/filter positions that will be used for optical navigation operations.

C..1 Effective Focal Length Scale Correction

The effective focal length of each OCAMS focus/filter position used for optical navigation is not expected to significantly change over the operational temperature range. Thus, no corrections will be made to the OCAMS effective focal lengths. This will be reevaluated after analyzing in-flight calibration data.

C..2 Geometric Distortion Parameters Corrections

The geometric distortion parameters for each OCAMS focus/filter position used for optical navigation are not expected to significantly change over the operational temperature range. Thus, no corrections will be made to the OCAMS distortion parameters. This will be reevaluated after analyzing in-flight calibration data.

TAGCAMS Image Corrections

The Level 0 TAGCAMS images provided by the SPOC will be subject to the following corrections that are applied internally within the optical navigation function. The Level 0 TAGCAMS FITS files only include one FITS extension, the "primary" extension.

A. Channel-wise Offset and Dark Correction using Masked Pixels

The bias offsets and dark current present in each image are both corrected using a subset of masked pixels present in each Level 0 TAGCAMS image. Due to the Bayer pattern design of the detector and corresponding on-chip data processing algorithm, a fixed pattern offset can be observed in the TAGCAMS images. In addition to each of the four Bayer channels having a unique offset, there is also a repeating even-odd column dependency. This results in a total of 8 different offsets that must be considered when correcting the biases and dark current within each image. Each of the 8 mean offsets are calculated using a particular subset of the masked dark pixel region in an image. Each of the 8 mean DN values are then subtracted from the corresponding set of pixels within the active image region, resulting in a full corrected image. For each of the 8 values, the correction can be described by the equation:

$$C_{d,c} = R_c - \frac{1}{n_c} \sum_c D_c \tag{3}$$

where C_d is the corrected (and cropped) image, R is the set of raw active image pixels, D is the set of usable masked pixels, n is the total number of usable masked pixels, and subscript c denotes the offset index (1-8).

The TAGCAMS detector regions and masked pixel array dimensions are presented in Fig. 2 and Fig. 3, respectively. A sample subarray showing the TAGCAMS pattern offsets and enumerated offset indices is presented in Fig. 4. After each of the mean offsets are subtracted from the corresponding set of active pixels, the masked and unused active border pixels are cropped from the image, leaving only the corrected 2592×1944 active array.

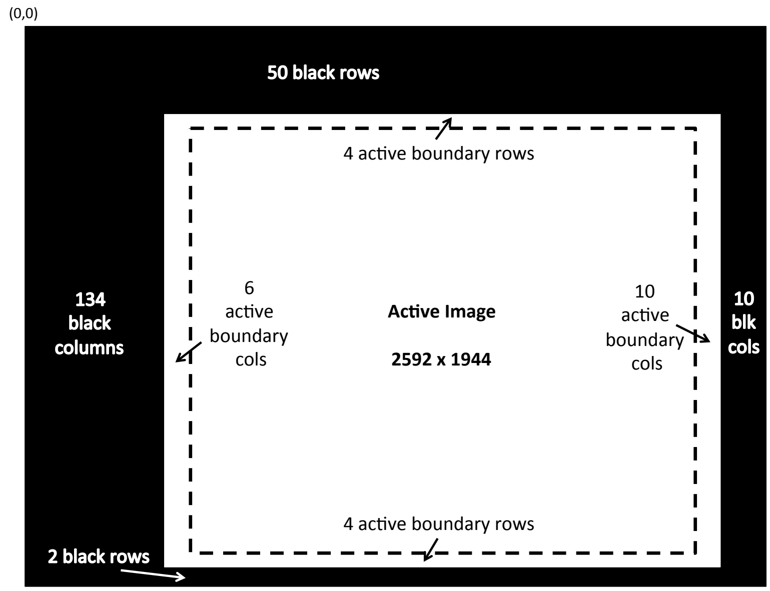

Figure 2: TAGCAMS Detector Layout [2, 3]

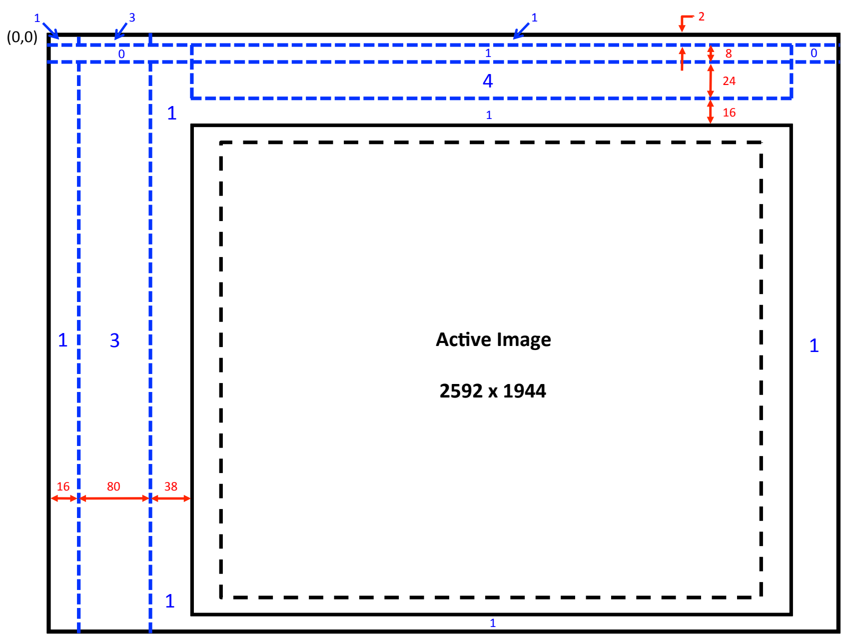

Figure 3: TAGCAMS Dark Pixel Region Dimensions [3]. The black borders represent the standard array boundaries as presented in Fig. 2, the blue borders and text represent the dark pixel region boundaries and region ID numbers, and the red annotations represent the dark pixel region dimensions in units of pixels. Region #4 is used to calculate the mean DN offsets for each of the 8 offset indices. More information about each region can be found in Ref. [3].

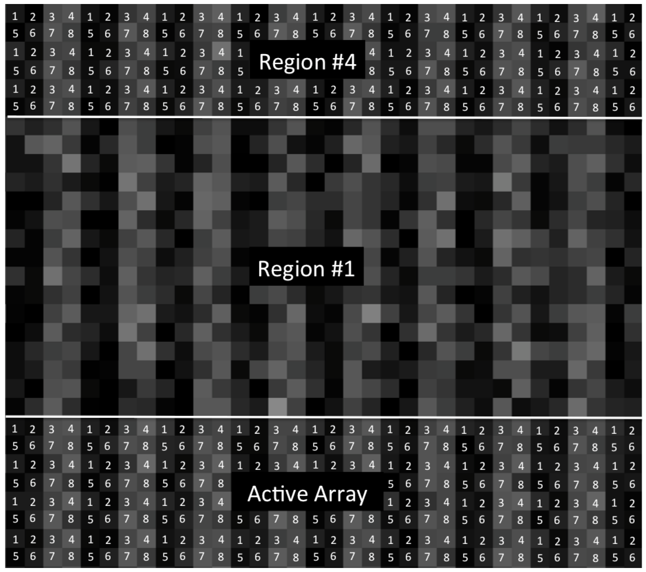

Figure 4: Sample subarray of a raw TAGCAMS image showing a sample of the usable masked dark pixels (Region #4), unusable dark pixels (Region #1), and active pixels [3]. Pixels from Region #4 are used to calculate the mean DN value of each of the 8 offset indices. The white numbers denote the channel indices in Region #4 and the active image array. The 8 mean DN values calculated using the Region #4 pixels are each subtracted from their corresponding offset indices in the active array.

B. Flat-Field Correction

Pixel-to-pixel variations in response are corrected using a flat-field image that is applied to the full, dark-corrected 2592 $\times$ 1944 image array. An official flat-field will be generated individually for NavCam1 and NavCam2, and each flat-field will be applied to images from the corresponding camera. The flat-field is applied by dividing the individual dark-corrected image DN pixel values by the corresponding flat-field pixel values. This can be described by the equation:

$$C_{d,f,ij} = \frac{C_{d,ij}}{F_{ij}} \tag{4}$$

where F is the flat-field and $C_{d,f}$ is the offset/dark-corrected, flat-fielded image.

C. Image Projection Corrections over Temperature

C..1 Effective Focal Length Correction

Based on thermal vacuum testing performed by the TAGCAMS manufacturer (Malin Space Science Systems) in June 2015, the effective focal length of each TAGCAMS imager is expected to change over the range of operational temperatures [4]. As a result, in-flight distortion calibration images will be taken at multiple temperatures in order to characterize the effective focal length change over temperature. An effective focal length will be estimated at each calibration temperature, resulting in an effective focal length vs. temperature curve. During OpNav operations, this curve will be interpolated to determine the effective focal length at a given OpNav image temperature. This approximate effective focal length will then be applied to calculations using that particular image. An example effective focal length vs. temperature curve is provided in Fig. 5.

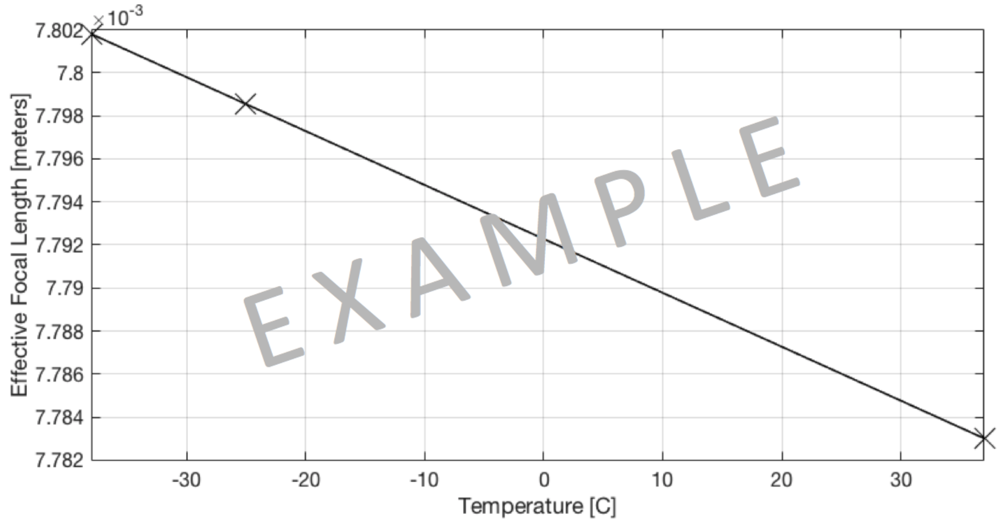

Figure 5: Example Effective Focal Length vs. Temperature curve. The black $\times$ markers denote the effective focal lengths estimated using in-flight calibration images. This curve will be interpolated at operational OpNav temperatures to determine the approximate effective focal length for each image.

C..2 Geometric Distortion Parameters Corrections

The geometric distortion parameters for the TAGCAMS imagers are not expected to significantly change over the operational temperature range. Thus, no corrections will be made to the TAGCAMS distortion parameters. This will be reevaluated after analyzing in-flight calibration data.

Hot/Cold Pixel Handling

Over-responsive (hot) and under-responsive (cold) pixels for each OCAMS and TAGCAMS imager will be monitored over the course of the mission, and a hot/cold pixel map will be continuously maintained and updated as pixel responses change over time. Each pixel map will have the same dimensions as the cropped image array (1024 $\times$ 1024 for OCAMS and 2592 $\times$ 1944 for TAGCAMS), and will identify pixels as either over-, under-, or normally-responsive.

For both star-based and landmark-based OpNav processing using KXIMP and SPC, respectively, this pixel map will be converted into a similar map that assigns each pixel with a binary "good" or "bad" identification. Hot and cold pixels will be identified as "bad" and normally-responsive pixels will be assigned as "good." For KXIMP, this map will be used to determine if a star should be ignored by the attitude estimation, based on its proximity to a bad pixel. For SPC, the bad pixel map will be ingested and image data from bad pixels will be ignored by SPC calculations.

Camera Frame Alignment Modeling over Temperature

The alignment of each OCAMS and TAGCAMS camera frame relative to the spacecraft frame is expected to shift over the range of operational temperatures. Since this camera to spacecraft rotation is generally assumed to be fixed (defined in a static frames kernel), this dependency on temperature could introduce a mismodeling of the true camera to spacecraft rotation. This mismodeled rotation negligibly affects star-based OpNav processing, since the inertial attitude is estimated using stars in the image. However, if an inertial reference is not present in a given image, the mismodeled camera to spacecraft rotation would translate into a mismodeling of the camera to inertial frame rotation matrix, which could degrade OpNav performance. Since landmark-based OpNav images do not have an inertial reference, the camera to spacecraft rotation must be well-characterized over temperature to optimize landmark-based OpNav performance.

The camera to spacecraft rotation temperature-dependency will be characterized using in-flight calibration and OpNav images. Using star images, the OpNav-derived camera attitude estimates can be compared to the GNC-derived reconstructed camera attitude predictions (assuming the nominal camera to spacecraft alignment). The differences between these two attitude estimates can be compiled over various temperatures, and a camera to spacecraft alignment as a function of temperature can be generated.

This camera alignment vs. temperature model can further be used to predict the alignment at any operational temperature, using an interpolation technique. As a result, a SPICE C-kernel representing the corrected camera to spacecraft rotation as a function of time can be generated using camera temperature telemetry. This corrected camera to spacecraft rotation can then be used as a replacement of the static rotation defined in the frames kernel.

While this calibration is not in the baseline OpNav operations concept (and not required for OpNav success), the FDS team expects to analyze the camera frame alignment as a function of temperature and will implement the correction if it is expected to significantly improve OpNav performance.

Summary

Due to natural phenomena and various features of each OSIRIS-REx imager, the optical navigation function needs to apply the presented image corrections to Level 0 OCAMS and TAGCAMS images in order to optimize optical navigation performance. The effectiveness and relevance of each correction will be continually assessed throughout flight operations using an ensemble of calibration, optical navigation, and (if necessary) science images.

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