Calibration Description: OSIRIS-REx Camera Suite (OCAMS)
Dathon Golish and Bashar Rizk, April 1, 2018 – Version 1.0
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<u>**Acronym List**</u>
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CCD	Charge Coupled Device
DA	Detector Assembly
DN	Digital Number
FITS	Flexible Image Transport System
FM	Flight Model
FPA	Focal Plane Array
IDL	Interactive Data Language
L0	Level 0
L1	Level 1
L2	Level 2
MATLAB	Matrix Laboratory
OCAMS	OSIRIS-Rex Camera Suite
PDS	Planetary Data System
PTC	Photon Transfer Curve
RCC	Radiometric Calibration Constant
SIS	Software Interface Specification
SNR	Signal to Noise Ratio
SPOC	Science Processing and Operations Center
TVAC	Thermal Vacuum
UUT	Unit Under Test

<u>**Nominal OCAMS Calibration**</u>
OCAMS images acquired in flight and provided through the PDS experience several processing steps that convert the raw signal recorded in DN by the instruments in flight to the signal archived by the data repository. They begin life as electronically shuttered images recorded during the mission as individual electrons that correspond to the solar photons reflected from the surface of the Bennu, the Earth, the Moon, the planets and main-belt asteroids or as stellar photons from any of several thousand distant stars.

These processing steps are described below within individual sections. In summary they consist of bias/dark subtraction, charge-smear correction, flat-field normalization to convert the raw L0 images transmitted from the spacecraft and provided by the ground data system to L1 FITS files. Radiometric calibration converts L1 files into several different flavors of L2 (Figure 1), including a radiance (Rad), a spectral radiance (Spec Rad) and a reflectance (I/F) product. Versioning of the OCAMS pipeline is recorded in each image label in the Mission_area data_processing_information class ocams_pl_ver attribute.

The comments in this summary document are largely based on these sources. More extensive descriptions will be provided when the OCAMS team publishes the calibration of the OCAMS instruments, a process that is still on-going.

Figure 1 Flowchart of OCAMS Pipeline Processing
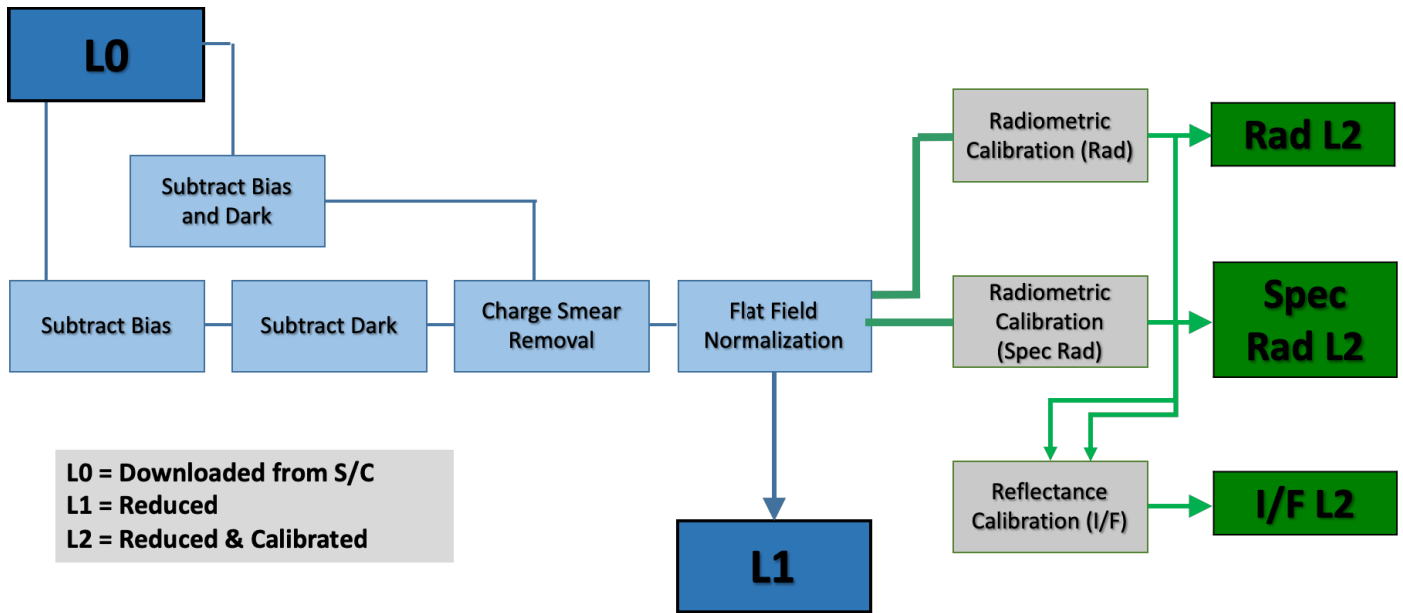
Some processing steps will refer to regions of the image that are used to correct the images. Those regions include the 1024x1024 active region (the image being corrected), the covered regions (physically CCD pixels that are masked and are not exposed to light), and overscan regions (virtual pixels that are created when the electronics perform empty reads at the end of each row). The transition and isolation regions are buffers between other regions to prevent signal leakage between them. The regions are shown in Figure 2 for reference. The calibration pipeline operates on the full image array unless otherwise stated.

Figure 2 OCAMS CCD Region Layout
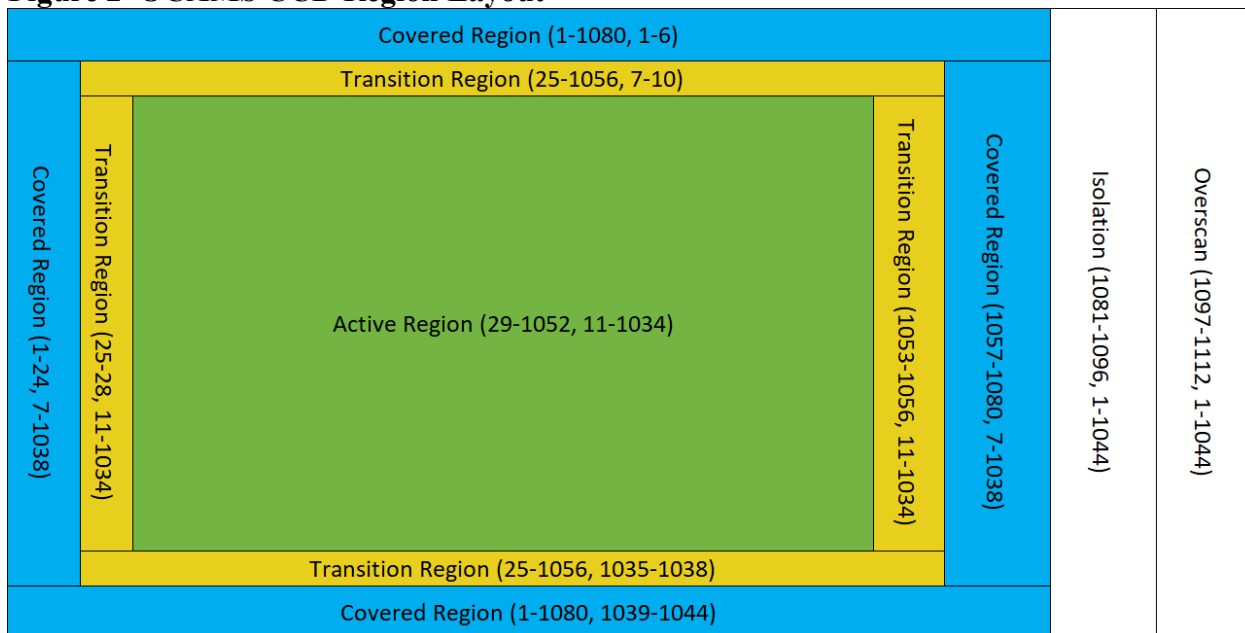
Bias (1112x1044 array size)

Bias subtraction is intended to remove the fixed offset applied by the readout electronics. A bias subtracted image (in the absence of dark or optically generated current) should have a mean value of 0.

Bias subtraction is applied in the following way:

A master bias file (1112x1044) is created from bias images taken either on the ground or coincident with the images being corrected. The master bias file used is recorded in the reference list section of the data product label. The algorithm performs pixel-wise subtraction (e.g. a straight array subtraction) of the master bias file (*Bias*) from the image being processed (*Raw*), as shown in Equation 1.

$$Tmp_{ij} = Raw_{ij} - Bias_{ij} \tag{1}$$

After subtracting the master bias, to account for bias variations at the moment of acquisition, overscan columns are used to update the bias correction. The overscan columns are not physical pixels; they are empty reads of the readout electronics, which should contain only the bias offset plus read noise. The overscan columns are the last 16 columns read out by the detector. The overscan columns having been corrected by Equation 1, the master bias, so any residual signal should be the in-situ bias variation. To correct for the in-situ variation, the median of the 16 overscan columns (see Figure 1) are taken on a row-wise basis and then the column vector of the results is box-car smoothed[1]. The size of the kernel is user controllable, but the default is 51 pixels. This large default is chosen to smooth the impact of extended cosmic ray hits that can cover several pixels. Although cosmic ray hits cannot affect the overscan columns, this operation is kept consistent with the Dark and Bias/Dark algorithms (which can be affected by cosmic rays). The smoothed result is subtracted on a row-wise basis, as shown in Equations 2-4.

$$overscan_i = median\{Tmp_{i,1} \dots Tmp_{i,24}, Tmp_{i,1057} \dots Tmp_{i,1080}\} \tag{2}$$

$$\overrightarrow{overscan'} = boxcar(\overrightarrow{overscan}, 51) \tag{3}$$

$$\overrightarrow{Corrected_i} = \overrightarrow{Tmp_i} - \overrightarrow{overscan'} \tag{4}$$

Dark (1112x1044 array size)

Dark subtraction removes the signal generated not by photons, but by phonons, thermal excitations in the detector material. Dark signal is removed in a way similar to bias signal:

A master dark file (1112x1044) is created from dark images taken coincident with the images being corrected. The master dark file used is recorded in the reference list section of the data product label. The

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[1] The standard IDL function SMOOTH is applied, using the EDGE_TRUNCATE option. The IDL SMOOTH function returns a copy of the input array smoothed with a boxcar average of the specified full width

$$W = \begin{cases} width & \text{if width is odd} \\ width + 1 & \text{otherwise} \end{cases}$$

We use the "EDGE_TRUNCATE" option, under which the edge pixels are assumed to be replicated as many times as necessary to complete the boxcar. The equation is thus:

$$R_i = \frac{1}{W} \sum_{j=0}^{W-1} A_{i+j-\text{floor}(\frac{W}{2})}$$

Where A_k is taken as the edge pixel A_0 or A_{N-1} if the subscript quantity $k = i + j - \text{floor}(\frac{W}{2})$ is < 0 or $> N - 1$, respectively

algorithm performs pixel-wise subtraction (e.g. a straight array subtraction) of the master dark file (*Dark*) from the image being processed (*Raw*), as shown in Equation 5. The advantage to this method is that it corrects pixel-to-pixel variation in the dark current, which can vary across the detector. Note that the input to this process has likely been bias corrected, but is referred to here as *Raw*, without that assumption.

$$Tmp_{ij} = Raw_{ij} - Dark_{ij} \tag{5}$$

After subtracting the master dark, to account for dark current variations at the moment of acquisition, covered columns are used to update the dark correction. There are 24 covered columns on either side of the active region (48 columns total, indicated in blue on Figure 1). Because the covered columns are physical pixels, they are susceptible to both hot pixels and cosmic ray hits. To prevent their contribution to the correction, the covered columns are scrubbed for bad pixels. Bad pixels are identified as those pixels that are statistically different than their neighbors. Specifically, the mean and standard deviation are calculated for a 10x10 pixel window and pixels that are more than 5 standard deviations higher than the mean are identified as bad. The 10x10 pixel window is swept across the covered columns in 5 pixel steps to find all bad pixels using their local statistics. Bad pixels are corrected by replacing their value with the mean of their 4 nearest neighbors. A bad pixel map is provided in the OCAMS bundle Calibration collection; however the map is provided only as a reference, and is not used specifically in the calibration. The covered columns have themselves been corrected by the master dark; any residual signal in those columns represent instantaneous dark current variation. To correct for that variation, the median of the 48 covered columns are calculated on a row-wise basis and then the column vector of the results is box-car smoothed as with bias correction. The smoothed result is subtracted on a row-wise basis, as shown in Equations 6-8.

$$covered_i = median\{Tmp_{i,1} ... Tmp_{i,24}, Tmp_{i,1057} ... Tmp_{i,1080}\} \tag{6}$$

$$\overrightarrow{covered'} = boxcar(\overrightarrow{covered}, 51) \tag{7}$$

$$\overrightarrow{Corrected_i} = \overrightarrow{Tmp_i} - \overrightarrow{covered'} \tag{8}$$

Bias + Dark (1112x1044 array size)
For the majority of the OCAMS images taken in flight, even star fields, bias levels have dominated the dark current, which is measurable but rather inconsequential. As a result, the bias + dark correction can be conveniently and effectively applied together. The master bias+dark files (1112x1044) are tagged with the time period and exposure time for which they are relevant and used to process images acquired within that period and with identical exposure times. The combined BiasDark calculation is performed in the same way as with the bias and darks individually (i.e. subtract BiasDark master and then update via covered columns using Equations 6 – 8). As the BiasDark method uses Equations 6 – 8, the overscan regions of the detector are not explicitly used.

Charge Smear
Charge smear is the result of signal being generated when exposed to light during the frame transfer of pixel wells both on and off the active area. It is most noticeable when a very bright object, whether point source or extended source, is resident within the camera's field of view, requiring a very short exposure time. The exposure time is short enough to be comparable to the time required to clock the pixels on and off the array. As a result, an extended line is recorded above and below the bright source, marking the charge collected by each of these pixels as a bright object's image is trailed across them. In order to be radiometrically accurate, removing charge smear signal requires reducing the effective exposure time of the image. This effective exposure time (found in the L1 reduced image product in the effective_exposure attribute), calculated as the actual exposure time subtracted by the frame transfer time (1.044 ms) is tracked in the header (EXPEFF) of the FITS file and used directly by the radiometric corrections later in the pipeline.

The signal recorded by the detector due to the full imaging operation (exposure time and frame transfer time) can be measured by summing the signal on a column-wise basis. This sum is the full amount of charge accumulated. A fraction of that charge (the ratio of the row transfer time to the integration time) will be distributed to each pixel in the column. A first order correction for charge smear is to subtract that fraction of the total signal off of every pixel in a given column. However, this correction is an overestimate because it includes the signal generated by charge smear itself. We can solve for the true amount of charge smear in the following way. The total signal measured by a given pixel is the combination of the true signal from its location in the scene and the charge smear from locations above and below it.

$$S = \widehat{S} + E \tag{9}$$

where S is the measured signal, $\widehat{S}$ is the actual signal, and E is the contribution from charge smear. For pixel (i,j), the charge smear contribution is proportional to the sum of the actual signals in that column.

$$S_{i,j} = \widehat{S}_{i,j} + \epsilon \sum_i \widehat{S}_j \tag{10}$$

where (i,j) is the (row, column) of the pixel location and ε is the ratio of row transfer time to exposure time (i.e. how long each pixel is exposed to the other locations in the scene as the frame is transferred). The signal measured in a column is then the sum of all pixels in that column.

$$\sum_i S_j = \sum_i \left(\widehat{S}_{i,j} + \epsilon \sum_i \widehat{S}_j \right) \tag{11}$$

$\sum_i S_j$ is the sum of the jth column in the image. It is an input to the solution, so will be represented as the variable Y. We substitute this in, as well as substituting $\widehat{S} = S - E$.

$$Y_j = \sum_i \left((S_j - E_j) + \epsilon \sum_i (S_j - E_j) \right) \tag{12}$$

Again we can substitute the measured signal in the column, Y.

$$Y_j = \sum_i \left(S_j - E_j + \epsilon Y_j - \epsilon \sum_i E_j \right) \tag{13}$$

The sum of the charge smear term over the column is merely the charge smear term, summed N_{row} times (the number of rows, 1044).

$$\sum E = N_{row} * E \tag{14}$$

We can therefore substitute further and distribute the summing operation.

$$Y_j = \sum_i S_j - \sum_i E_j + \sum_i \epsilon Y_j - N_{row} * \epsilon \sum_i E_j \tag{15}$$

$$Y_j = Y_j - N_{row} * E_j + N_{row} * \epsilon * Y_j - N_{row}^2 * \epsilon * E_j \tag{16}$$

Finally, we can solve for the charge smear term, which will convert the measured signal of any pixel in the jth column to the actual signal.

$$E_j = \frac{\epsilon Y_j}{N_{row}\epsilon + 1} \tag{17}$$

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In practice, we have seen that this does not perfectly correct charge smear. To improve the correction, we use the covered rows to evaluate the residual. If the above algorithm perfectly predicted charge smear, the covered rows would have a mean signal of zero (assuming bias and dark signals have already been removed). Mean signal above or below zero in the covered rows indicate under- or over-correction in the charge smear algorithm. We can therefore modify the magnitude of the correction in the appropriate direction and repeat the correction. This continues iteratively until the mean signal in the covered row region is minimized (i.e. iterate correction by 1% steps until an error inflection is reached. The correction with the minimum error value is used). This method is less susceptible to the small number of covered rows, because we can average all the columns together to improve our statistics. The iterative algorithm leads to near complete removal of charge smear.

For EGA images, an alternative charge smear correction method was necessary due to the very short exposure times (see the 'Icicles' caveat). One of two methods are used, both of which require user intervention to choose a portion of the image to use to generate the correction. In the 'guided' method, the user provides the row and column values for the four corners of a rectangle that contain only charge smear (i.e. off the limb of the Earth/Moon, looking at dark sky). The median (along the columns) of the pixels within that rectangle are used to create a correction vector that is subtracted off of the entire image. Columns outside the rectangle will have a correction of zero. The 'in-situ' method is used for EGA images that do not have any dark sky in the image. The user provides the starting and ending columns (the row values are ignored and can be provided as zeros) of a region of the image that has a relatively uniform scene (i.e. uniform clouds). The intention is that the variation in this uniform region is representative of charge smear and can be used to generate a correction. Clearly this method can only be as effective as the uniformity of the background, but there are some EGA images for which this is the only option. The median of the rows indicated by the column limits is calculated to create a column-wise charge smear correction. The methods and values used for EGA images are provided in the table below.

Table 1 EGA Charge Smear Correction Settings

Camera	**Start Date/Time**	**Stop Date/Time**	**Method**	**Starting Column**	**Ending Column**	**Starting Row**	**Ending Row**
MapCam	2017-09-22 23:38:40.000	2017-09-22 23:39:00.000	Guided	0	1111	1014	1023
MapCam	2017-09-22 23:41:30.000	2017-09-22 23:41:50.000	Guided	0	1111	1	9
MapCam	2017-09-23 00:03:05.000	2017-09-23 00:03:26.000	Guided	0	1111	114	1023
MapCam	2017-09-23 00:04:03.000	2017-09-23 00:04:23.000	Guided	0	1111	1025	1035
PolyCam	2017-09-22 23:17:17.000	2017-09-22 23:19:50.000	Guided	0	1111	210	240
PolyCam	2017-09-22 23:17:16.000	2017-09-22 23:17:17.000	Insitu	0	0	740	785
PolyCam	2017-09-23 00:10:40.000	2017-09-23 00:10:42.000	Insitu	0	0	270	1020
SamCam	2017-09-22 23:31:01.000	2017-09-22 23:57:16.000	Guided	0	1111	1014	1023
MapCam	2017-09-25T00:00:00.000Z	2017-09-25T05:00:00.000Z	Guided	0	1111	100	200
PolyCam	2017-09-25T00:18:00.000Z	2017-09-25T00:19:06.000Z	Guided	0	1111	100	200

PolyCam	2017-09-25T00:19:06.000Z	2017-09-25T00:21:54.000Z	Guided	0	1111	600	1000
PolyCam	2017-09-25T00:21:55.000Z	2017-09-25T05:00:00.000Z	Guided	0	1111	100	200
SamCam	2017-09-25T00:00:00.000Z	2017-09-25T05:03:00.000Z	Guided	0	1111	100	200
MapCam	2017-09-28T00:00:00.000Z	2017-09-28T02:00:00.000Z	Guided	0	1111	750	1000
PolyCam	2017-09-28T00:29:00.000Z	2017-09-28T00:29:25.000Z	Guided	0	1111	200	400
PolyCam	2017-09-28T00:29:25.000Z	2017-09-28T00:29:28.000Z	Guided	0	1111	800	1000
PolyCam	2017-09-28T00:32:27.000Z	2017-09-28T00:32:33.000Z	Guided	0	1111	750	1000
PolyCam	2017-09-28T00:32:33.000Z	2017-09-28T00:33:00.000Z	Guided	0	1111	200	400
PolyCam	2017-09-28T02:00:00.000Z	2017-09-28T03:00:00.000Z	Guided	0	1111	950	1000
MapCam	2017-10-02T00:00:00.000Z	2017-10-02T03:00:00.000Z	Guided	0	1111	750	1000
PolyCam	2017-10-02T00:00:00.000Z	2017-10-02T01:00:00.000Z	Guided	0	1111	800	1000

Flat Field (1024x1024 array size)

Flat field corrects for the spatial variation in optical responsivity across the detector itself. It can account for both slowly varying and rapidly-varying (pixel-to-pixel) relative responsivities. It is currently only corrected by applying a master flat field acquired on the ground. The master flat field (1024x1024) used is indicated in the data product label reference list. The master flat field is calculated as the inverse of the system response to a spatially uniform scene. Therefore, the master flat field (*Flat*) is applied by multiplying it against the image to be corrected (*Raw*), as shown in Equation 18. Note that the input to this process has likely been bias/dark corrected, but is referred to here as *Raw*, without that assumption.

$$Corrected_{ij} = Raw_{ij} * Flat_{ij} \tag{18}$$

Laboratory Radiometric Calibration to Radiance (Rad 250-1100 nm) (1024x1024 array size)

Radiometric calibration to radiance converts the signal rate in DN/sec between 250 and 1100 nm to the radiance of the detected field in W m^{-2} sr^{-1} by applying radiometric calibration constants determined on the ground. These conversions were used for laboratory calibrations during ground testing. These constants are expressed in terms of signal, per second, per unit of radiance. Therefore, to convert to radiance, the measured signal (*DN*) is divided by the radiometric calibration constant (*RCC*) and by the effective exposure time (t_{exp}) of the image, as shown in Equation 19. The effective exposure time, as described in the Charge Smear section, is recorded in milliseconds. However, the RCC is calculated in terms of seconds, so the effective exposure time must be converted to seconds before use in Equation 19. The RCC is temperature-dependent, so is scaled based on the temperature of the CCD at the time of image acquisition (see Equation 21).

$$Radiance_{ij} = \frac{\left(\frac{DN_{ij}}{t_{exp}}\right)}{RCC} \tag{19}$$

Table 2 OCAMS Radiance Responsivities to reflected solar light between 250 and 1100 nm in (DN/sec) / (Wm^{-2}sr^{-1})

MapCam	Pan	Pan-30	b	v	w	x
	437451	430277	48035	59484	84110	54441
PolyCam	Pan					
	320852					
SamCam	Pan 1	Pan 4	Pan 5	Diopter		
	150829	152679	151077	153902		

Radiometric Calibration to Radiance (1024x1024 array size)

For the panchromatic filters, radiometric calibration to radiance converts the signal rate in DN/sec to radiance detected in W m^{-2} sr^{-1} at the band center of each of the filtered optical pathways possessed by the OCAMS instruments, as shown in Equation 19.

Table 3 OCAMS Panchromatic Filter Radiance Responsivities to reflected solar light within the band (DN sec^{-1}) / (W m^{-2} sr^{-1})

MapCam	Pan	Pan-30	
	865142	864489	
PolyCam	Pan		
	658338		
SamCam	Pan 1	Pan 4	Pan 5	Diopter
	301088	304742	301583	307223

Radiometric Calibration to Spectral Radiance (1024x1024 array size)

For the color filters, radiometric calibration to spectral radiance converts the signal rate in DN/sec to spectral radiance in W m^{-2} µm^{-1} sr^{-1} at the band center of each of the filtered optical pathways possessed by the OCAMS instruments, as shown in Equation 19.

Table 4 OCAMS MapCam Color Filter Spectral Radiance Responsivities to reflected solar light within the band (DN sec^{-1}) / (W m^{-2} µm^{-1} sr^{-1})

MapCam	b	v	w	x
	24644	32443	60085	55314

As with all silicon-based detectors, the responsivity of the OCAMS CCDs are thermally dependent and that dependence is coupled with wavelength. The responsivities listed above for the OCAMS cameras were measured at room temperature, but flight operations will take place at colder temperatures. As such, responsivity has a linear temperature dependence for each filter. When OCAMS images are converted to radiance, the responsivity term is first adjusted for this dependence, listed in Table 5.

Table 5: Thermal-spectral responsivity dependence

Camera / Filter	Thermal-spectral responsivity slope (°C^{-1})	Reference Temperature (°C)

MapCam / b'	-0.0014	30.2
MapCam / v	-0.00075	30.0
MapCam / w	0.00053	30.1
MapCam / x	0.003	26.6
MapCam / pan	0.00075	28.6
PolyCam / pan	0.00075	27.2
SamCam / pan	0.00075	29.6

$$tsr' = \left(1 + \left(T_{ccd} - T_{ref}\right) * tsr\right) \tag{20}$$

$$RCC' = RCC * tsr' \tag{21}$$

where T_{ccd} is the temperature of the CCD (MCCCDTMP, PCCCDTMP or SCCCDTMP label attribute) at the time of the image, T_{ref} is the temperature at which the nominal responsivity was measured, tsr is the slope of the temperature-spectral responsivity dependence, RCC (see Eq. 19) is the nominal responsivity for that filter at the reference temperature, and RCC' is the adjusted responsivity. Radiance calculated using RCC' is the responsivity reported in the OCAMS L2 data products.

Radiometric Calibration to Reflectance (I/F)

From the values in Table 3 and 4, combined with the solar irradiance standards displayed in Table 6, the I/F of each observed surface can be produced using the relationship:

$$\frac{I}{F} = L * \pi * \frac{D_{sun}^2}{F_{band}} \tag{22}$$

where

D_{sun} is the range to the Sun (AU); this is derived from the mission profile, passed through the image header which uses the tool spatialgen to produce the range;

L is the radiance measured by the OCAMS detector within the band at the pixel (W/m2/sr or W/m2/sr/um);

F_{band} is the Sun's irradiance or spectral irradiance within the band at 1 AU illuminating the surface at the location of the pixel (See Tables 6 or 7).

Table 6 Solar Irradiances (W m^{-2}) used in converting to I/F

MapCam	Pan & Pan-30
	501.049
PolyCam	Pan
	490.6251
SamCam	Pan 1, 4, 5, Diopter
	504.3337

Table 7 OCAMS Solar Irradiances (W m^{-2} μm^{-1}) used in converting to I/F

MapCam	b	v	w	x

	2003.167	1837.798	1426.860	993.7742

It should be noted that the calculation of the L2 I/F images (in units of reflectance) depends on the amount of solar flux incident on the surface, which in turn depends on the distance from the Sun to the target. In the OCAMS calibration pipeline, the distance used is the distance from the Sun to the OSIRIS-REx spacecraft (sc2sun_range_km label attribute, SCSUNRNG FITS header keyword), which will be slightly different. However, for even the earliest resolved images of Bennu, the difference between the two distances is < 0.1%. For all of Proximity Operations, the difference is < 0.00001%. The only other target for which reflectance is meaningful is the Moon during the Earth Gravity Assist. For the Moon images on 09/25/2017, which have been used to radiometrically verify the cameras, the difference is ~0.5%. For the Moon images on 10/02/2017, the difference is ~3%. However, in these images the Moon subtends only a few pixels, therefore it is not expected that those data will ever be used for radiometry. As a result, the OCAMS calibration pipeline will not be changed to use distance-to-target in the calculation of the I/F L2 images.

Availability of Calibration Files on SPOCFlight

Internally, calibration files are distributed to the team in a convenient fashion by making them available on SPOCFlight. On this system, one selects Engineering→Calibrations→Select Instrument→ocams, Select Calibration→ (one of several choices). They are time-tagged with a Start and Stop Date (e.g., 20160301100000 for yyymmddhhmmss) to delimit the time period over which they are intended to apply. *These files are available to PDS users in the OCAMS Bundle Calibration collection. Files used to correct a particular image are listed in that image's label reference list.*