
OSIRIS

Optical, Spectroscopic, and Infrared Remote Imaging System

OSIRIS calibration pipeline OsiCalliope

RO-RIS-MPAE-MA-007

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1 General aspects

1.1 Scope

This document describes the calibration pipeline for the images acquired by both OSIRIS cameras onboard the Rosetta spacecraft: the Wide Angle Camera (WAC) and the Narrow Angle Camera (NAC). The document describes the implemented procedures and algorithms in OsiCalliope v1.42.0 and higher. The pipeline software version is written in C++, and compiled as a standalone PC application. The pipeline also contains a database of the calibration parameters. The previous (obsolete) versions of the pipeline, developed before the CG comet operations, had been implemented as IDL scripts [RD5].

1.2 Applicable Documents

no.	document name	document no, Issue./Rev.
AD1	Software Interface Specifications for OSIRIS Science Products	RO-RIS-MPAE-ID-023 1/-
AD2	Rosetta-OSIRIS to Planetary Science Archive Interface Control Document	RO-RIS-MPAE-ID-015 4/b

1.3 Reference Documents

no.	document name	document no, Issue./Rev.
RD1	OSIRIS user manual	RO-RIS-MPAE-MA-004 D/s
RD2	Shutter parameters for exposure time calculation	RO-RIS-MPAE-TN-073 1/b
RD3	CCD Readout Board – (CRB)	RO-RIS-MPAE-SP-020 1/a
RD4	OSIRIS Calibration Report	RO-RIS-MPAE-RP-147 D/c
RD5	OSIRIS Calibration Pipeline Manual	RO-RIS-MPAE-MA-005, D/c
RD6	Low Level Software Interface between CRB and DPU	RIS-MPAE-ID-008, 2/k
RD7	Transfer function between the encoder measurement and the blades position of the FM WAC SHM	RO-RIS-UPD-TN-W333-219
RD8	Transfer function between the encoder measurement and the blades position of the FM NAC SHM	RO-RIS-UPD-TN-N333-213
RD9	OSIRIS camera linearity and saturation level	RO-RIS-MPAE-TN-078 1/a
RD10	OSIRIS camera bad pixel list	RO-RIS-MPAE-TN-080 1/a
RD11	OSIRIS camera bias levels	RO-RIS-MPAE-TN-079 1/b
RD12	Acquisition and processing of flat field images for OSIRIS calibration	RO-RIS-MPAE-TN-075 1/b
RD13	Determination of the absolute calibration coefficients to radiometrically calibrate OSIRIS images	RO-RIS-MPAE-TN-074 1/a
RD14	Osiris camera distortion correction parameters	RO-RIS-MPAE-TN-081 1/a
RD15	OSIRIS camera tandem ADC offset correction parameter	RO-RIS-MPAE-TN-088 D/-



1.4 Introduction

The OsiCalliope software has been developed to calibrate Rosetta OSIRIS images. It is part of the complete OSIRIS scientific data processing pipeline. This system contains different components that are responsible for:

- Downloading the data from the Data Delivery System (DDS)
- Generating raw images, with actual instrument hardware readouts (PDS Level 0)
- Generating raw images, with calibrated hardware parameters, and spacecraft position and pointing (PDS Level 1)
- Creating calibrated images for scientific analysis (OSIRIS Level 2 and higher)
- Producing additional image formats (JPEG, FITS, etc.)
- Generating reports and notifications

The current document defines the requirements and procedures to create calibrated images for scientific analysis, from the raw image data, hardware (imaging) configuration, and spacecraft pointing data.

1.5 Processing levels of the images

The OSIRIS data levels are (Figure 1):

- **Level 0:** PDS format, raw header (proprietary, non-standard labels), raw binary with 16 bit unsigned integer image data.
- **Level 1:** PDS format, calibrated header (standard labels), raw binary with 16 bit unsigned integer image data.
- **Level 2:** PDS format, calibrated header, radiometric calibrated 32 bit float image data in radiance units ($W m^{-2} sr^{-1} nm^{-1}$).
- **Level 2B:** (Optional) PDS format, calibrated header, radiometric calibrated 32 bit float image data in radiance factor (reflectance or I/F) units.
- **Level 2C:** (Optional) PDS format, calibrated header, radiometric calibrated 32 bit float image data in radiance units ($W m^{-2} sr^{-1} nm^{-1}$), solar stray light removal applied.
- **Level 2D:** (Optional) PDS format, calibrated header, radiometric calibrated 32 bit float image data in radiance factor (reflectance or I/F) units.
- **Level 3:** PDS format, calibrated header, radiometric calibrated 32 bit float image data, corrected for the camera optical distortion in radiance units ($W m^{-2} sr^{-1} nm^{-1}$).
- **Level 3B:** PDS format, calibrated header, radiometric calibrated 32 bit float image data, corrected for the camera optical distortion, in radiance factor (reflectance or I/F) units.
- **Level 3C:** PDS format, calibrated header, radiometric calibrated 32 bit float image data, corrected for the camera optical distortion in radiance units ($W m^{-2} sr^{-1} nm^{-1}$), solar stray light removal applied.
- **Level 3D:** PDS format, calibrated header, radiometric calibrated 32 bit float image data, corrected for the camera optical distortion in radiance factor (reflectance or I/F) units, solar stray light removal applied.
- **Level 4:** PDS format, calibrated header, radiometric calibrated 32 bit float image data, corrected for the camera optical distortion in radiance units ($W m^{-2} sr^{-1} nm^{-1}$), with comet CG geo-referencing data layers.



- **Level 4B:** PDS format, calibrated header, radiometric calibrated 32 bit float image data, corrected for the camera optical distortion in radiance factor (I/F or reflectance) units, with comet CG geo-referencing data layers.

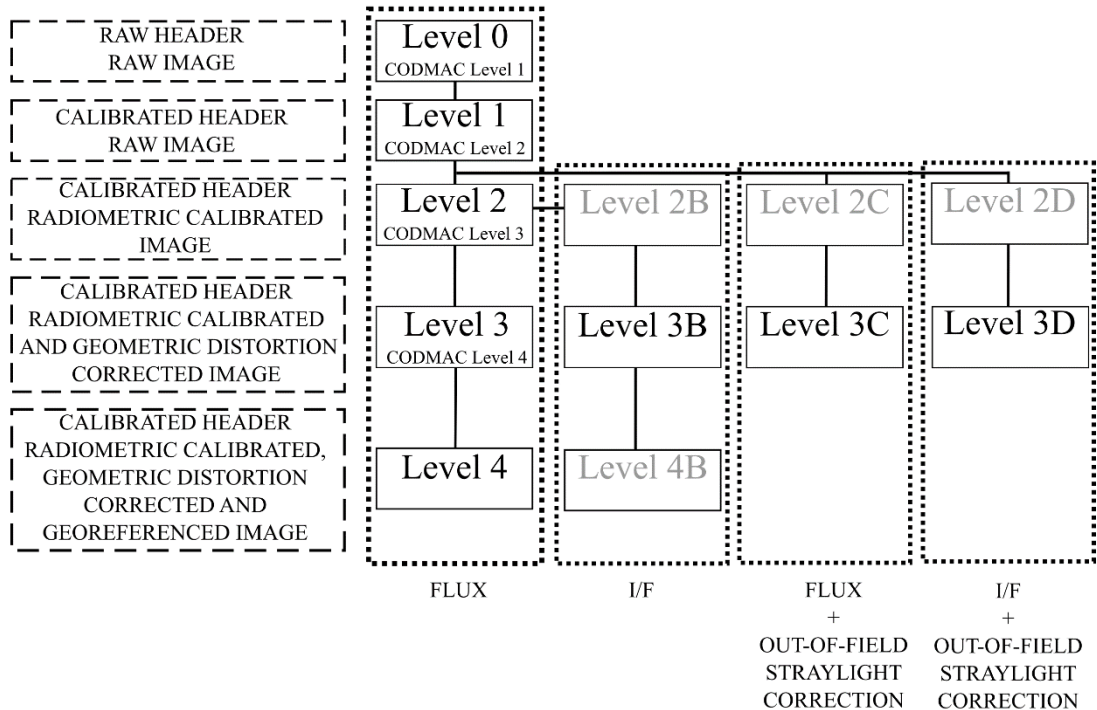


Figure 1 OSIRIS data levels

1.6 OSIRIS cameras

Both the NAC and the WAC use a 2k x 2k pixel backside illuminated full frame CCD as an image sensor [RD1]. The image area of the OSIRIS CCDs has 2048 columns and 2052 lines (2 + 2048 + 2). The readout serial register contains 2148 pixels (2 + 48 + 2048 + 48 + 2). The structure of the detector is shown on Figure 2.

The two extra lines at the bottom of the CCD (colored in red Figure 2) are discarded from the image. The two extra lines at the top of the CCD (colored in green in Figure 2), which are read out after the image data, are called overclocking lines.

The first two extra pixels in the serial register (colored in magenta in Figure 2) are ignored, thus 48 extra pixels (colored in light green in Figure 2) appear at both ends of the serial register. These pixels, which are read out before or after the image data, are called pre-clocked pixels and post-clocked pixels, respectively. Pre- and post-clocked pixels do not represent illuminated pixels of the CCD.

Pixel information outside the 2048x2048 image area is used for system testing and calibration of various engineering data. Overclocking lines can be used for charge transfer efficiency calculation, while pre-clocked and post-clocked pixels can be used to estimate the bias and the electronic noise level of the image.

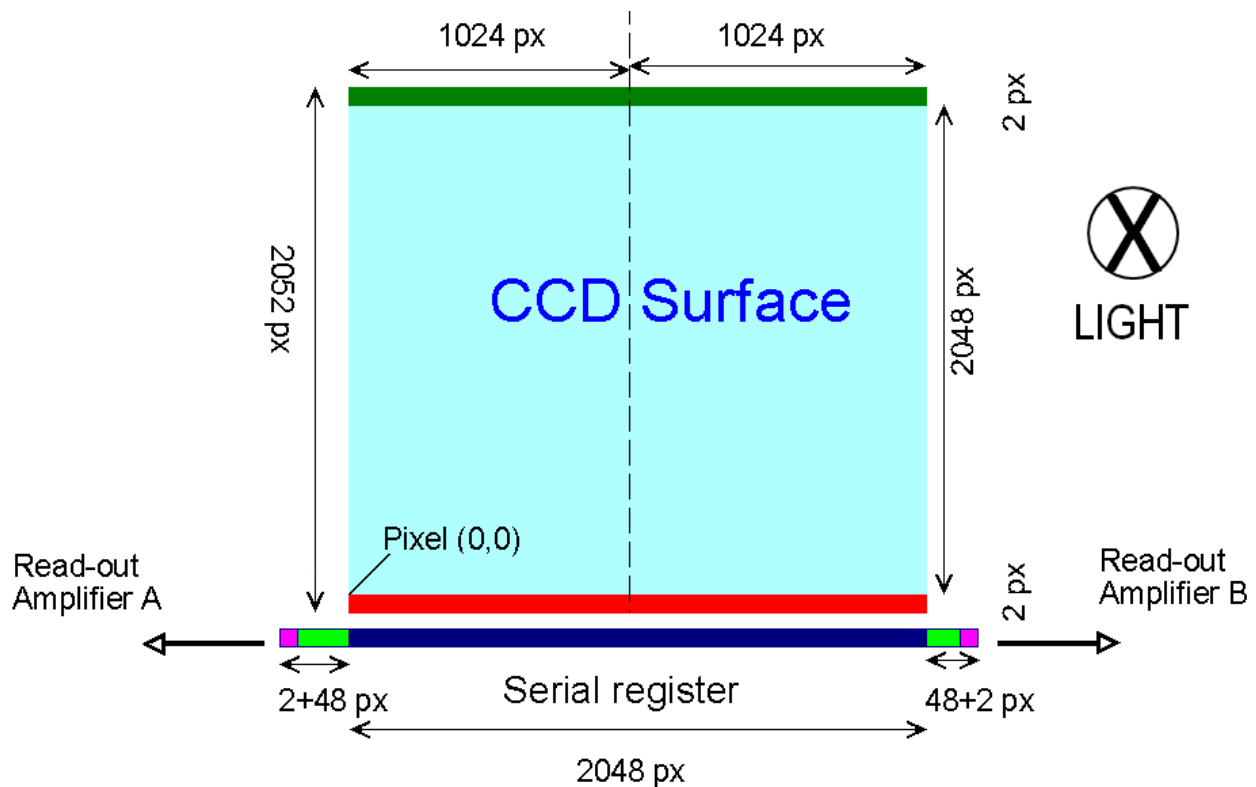


Figure 2 Structure of the OSIRIS CCDs

The readout electronics [RD3] of the cameras use a dual 14 bit Analogue to Digital Converter (ADC) configuration, providing a nominal 16 bit ADC system. The CCD readout is equipped with two amplifiers (A and B) which can be used individually or in parallel, for faster readout. The two amplifiers have slightly different operational parameters (offsets). During the image transfer from the detector chip, the first pixel to be read-out is the closest to the used amplifier. The on-board software re-arranges each line as if the CCD would have been read out through amplifier A. In this way, the first pixel in the image line corresponds always to pixel (0, 0).

In the image files the data is always stored in the CCD coordinate frame, where pixel (0, 0) is the closest pixel to amplifier A, independently from which amplifier is used. Lines are parallel to the serial register. The line numbers increase with distance from the serial register. Samples (columns) are perpendicular to the serial register. The sample numbers increase with distance from the edge of the CCD that contains read-out amplifier A.

During the imaging, neighboring pixels can be handled together, forming a larger (binned) virtual pixel. Binning results in reduced photon noise and increased sensitivity. In case of the OSIRIS CCD 1x1, 2x2, 4x4 and 8x8 binning can be used to connect 1, 4, 16 or 64 pixels.

Besides the full-frame imaging, which uses the full CCD area, windowing can reduce the image size, by transmitting only a smaller area of the CCD. This can drastically reduce the data volume through the communication channel. The OSIRIS cameras can do this either by hardware or by software. Software windowing acquires the full CCD area, and the on-board processor cuts out the required pixels for transmission. Hardware windowing reads out only a sub-frame of the CCD, which can also speed up the imaging sequence.

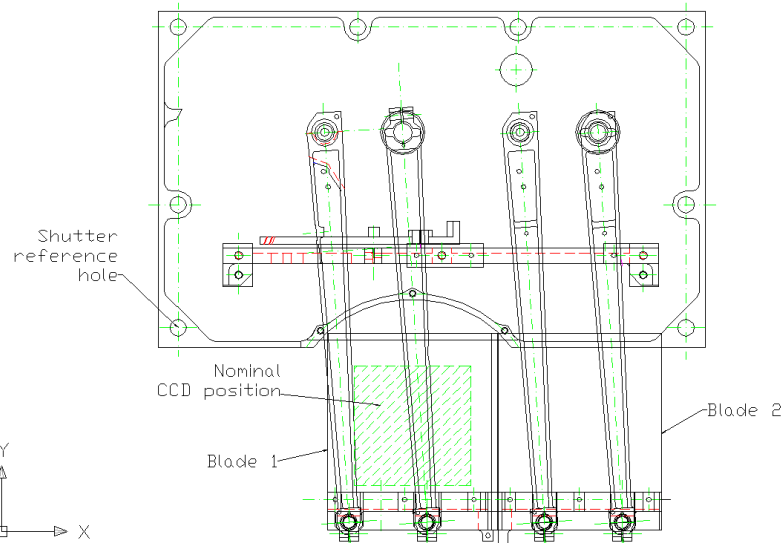


Figure 3 Shutter mechanism

The OSIRIS detectors are so called “full frame CCD”, which means that a mechanical shutter is necessary to control the exposure, and, during the image readout, the shutter must remain closed. The shutter blades [RD2] are operated by DC motors, and the shafts are equipped by optical encoders to give feedback about the blade positions and timings [RD7]. These “shutter pulse” values are necessary to precisely calculate the exposure time nonlinearities (Figure 3).

Both the NAC and the WAC are equipped with a dual filter wheel set, each wheel consisting of 8 positions. These wheel positions are used to select a transmission band for the WAC and a combination of band-pass, neutral density, or focusing optics for the NAC.

The main optical systems of the both cameras are off axis telescopes. A 3-mirror-system is used for the NAC and a 2-mirror-system for the WAC. The transmission and distortion of these optical systems have major impact on the image calibration.



2 The structure of the pipeline

The OSIRIS calibration pipeline application is “OsiCalliope.exe”. The software can be used either in interactive or in command line mode. In the latter mode it must receive the root folder of the observation (which contains the “.pds\level1” and “.geo” folders) as a parameter. The software generates higher-level images from the level 1 data.

The pipeline software loads the (level 1) images to be calibrated, one after the other, and executes the required calibration steps sequentially on the data. A PDS group OSICALLIOPE is inserted into the HISTORY section of the header of each image and the completed calibration steps are marked there with the applied parameters (and references) so that the process is transparent and repeatable. The main header processing flags are also set according to the finished calibration steps (group SR_PROCESSING_FLAGS).

“OsiCalliope.exe” also uses a configuration file describing the calibration database. This file is a PDS label format text file, listing all the input parameters and binary file references for the calibration process. The OsiCalliope configuration file is located in the \OSICALLIOPE\DATA\ folder, where “OSICALLIOPE” is the folder containing the “OsiCalliope.exe” file. The DATA folder contains additional folders and data files used by the calibration processes. The keys in the label are non-standard PDS keys using the namespace identifier WAC: and NAC: as reference to the specific OSIRIS camera.

All calibration files used by OsiCalliope to calibrate OSIRIS images are listed in Section 4.

The header keyword TARGET_TYPE sets whether calibration steps are applied to the image and higher levels are generated and stored. The following scheme is used:

1. TARGET_TYPE = CALIBRATION: all calibration steps are skipped, the image is stored only in level 1.
2. TARGET_TYPE = STAR: the heliocentric distance of the target is not available, thus the conversion to radiance units cannot be performed. Levels 3B and 3D cannot be generated, while all other levels are generated and stored.
3. TARGET_TYPE = PLANET and TARGET_TYPE = COMET: all calibration steps can be performed and all higher levels are generated and stored.

For all images, higher level images cannot be generated in the following cases:

1. The needed calibration file is missing.
OsiCalliope relies on the calibration database to calibrate the images. If the needed calibration file is not available, the calibration step cannot be completed. For example, this is the case when a non-standard filter combination is used to acquire the image, for which no flat field is available. No default calibration values are used. The only exception is the exposure time correction, where default values are available and used to calibrate images whenever needed. Images are stored only in level 1.
2. Incorrect shutter operation.
Type A, type C, and type D (only in normal shutter operation mode) shutter errors, and bad shutter pulses prevent the exposure time correction calibration step. When this happens, images are partially calibrated (only the exposure time correction is skipped) and stored in DN units as level 2X and level 3X.



The overview of the image level generation is shown in Figure 4 and the OsiCalliope calibration algorithm overview is shown in Figure 5, Figure 6, Figure 7, Figure 8, and Figure 9.

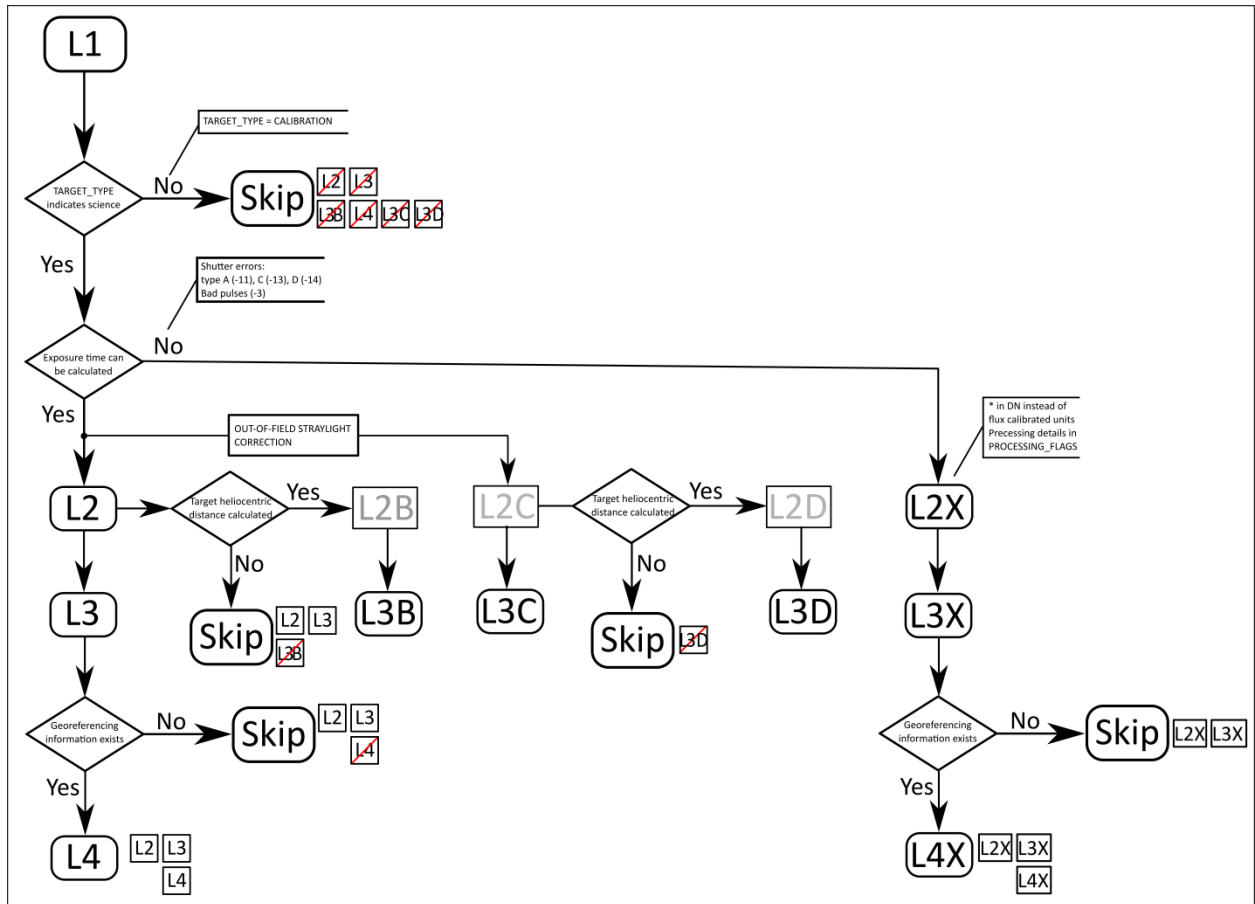


Figure 4 Overview of the image level generation.

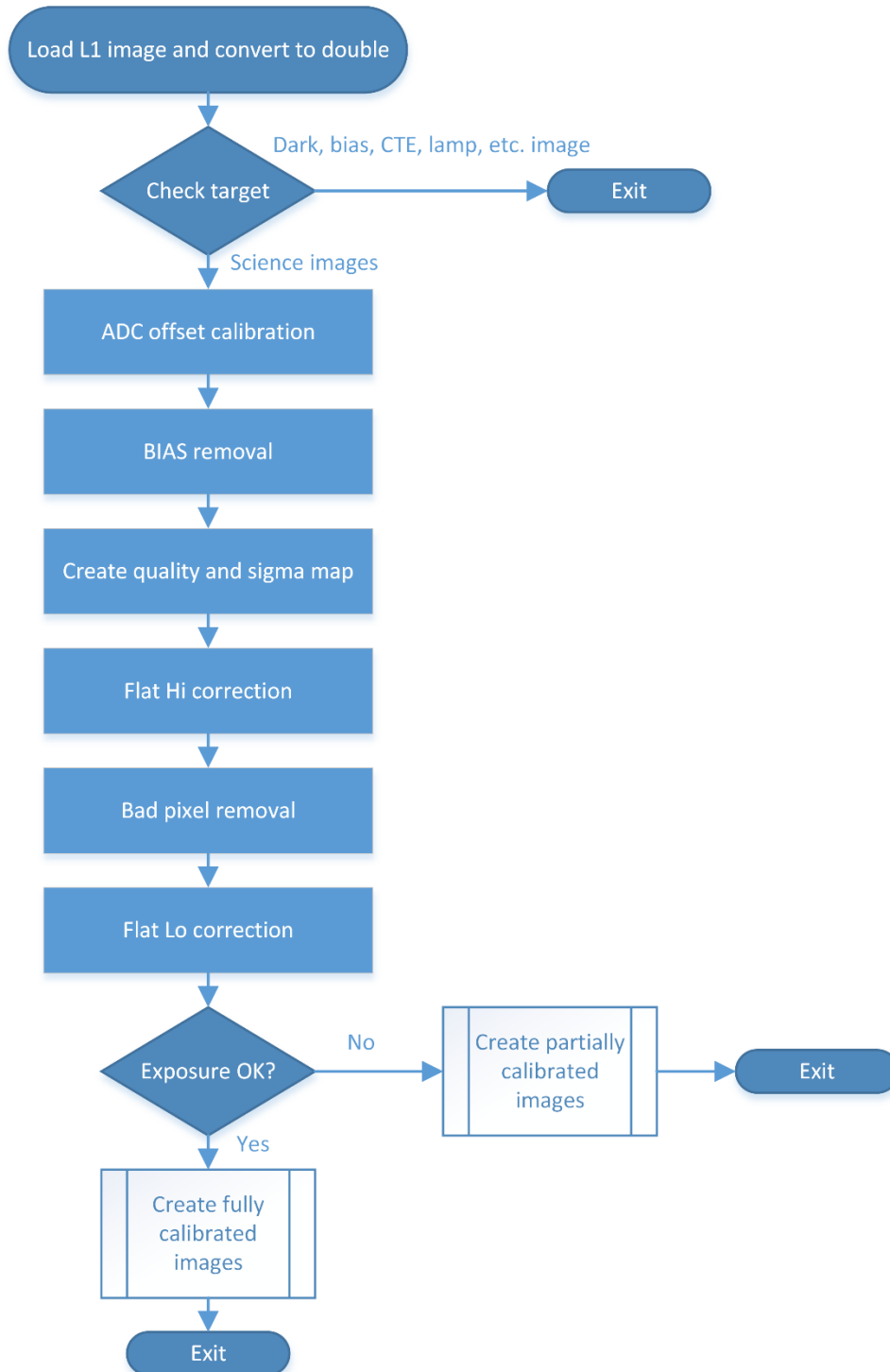


Figure 5 OsiCalliope main image calibration algorithm

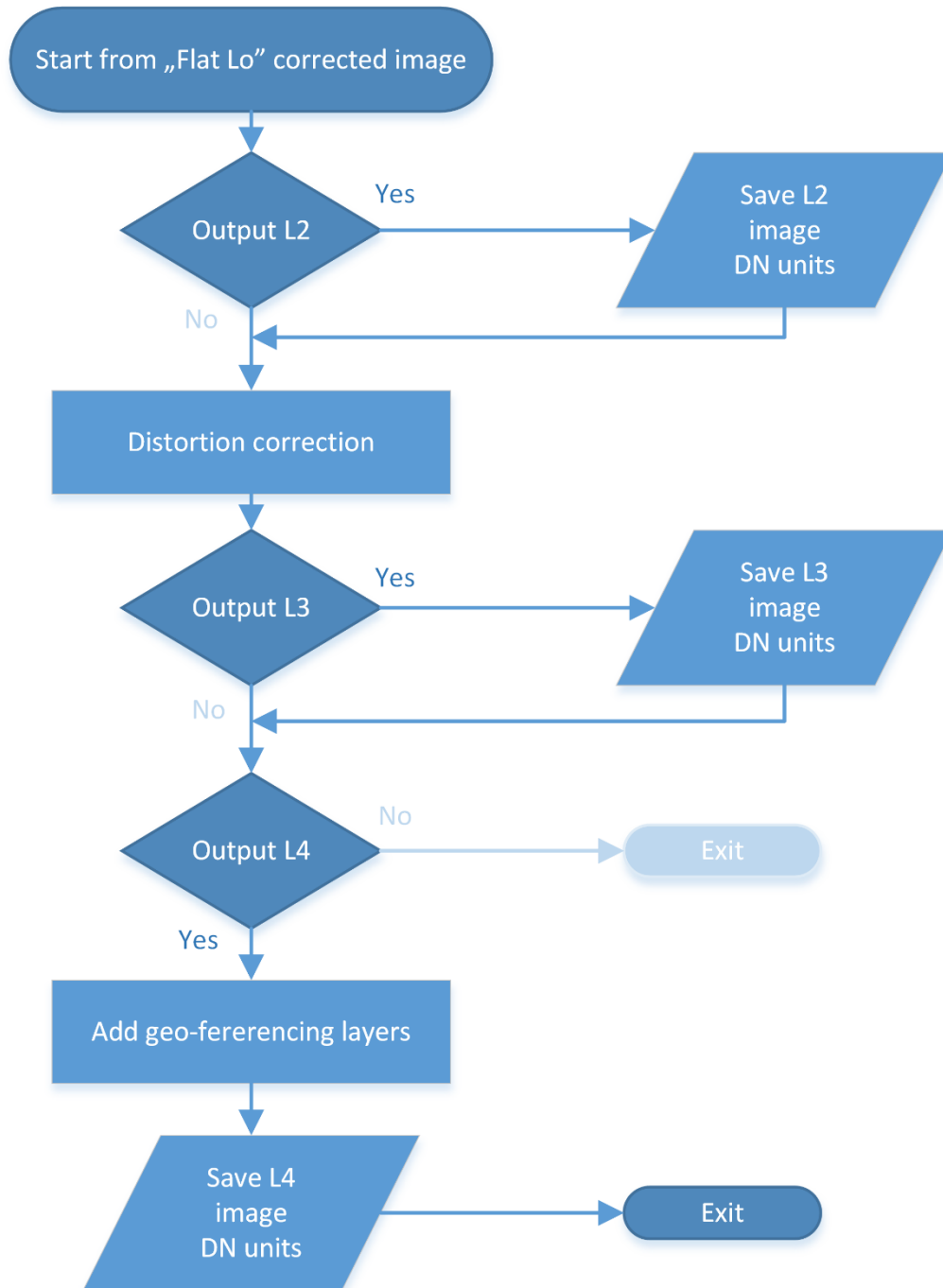


Figure 6 OSIRIS partial calibration steps – in case valid exposure time correction cannot be calculated.

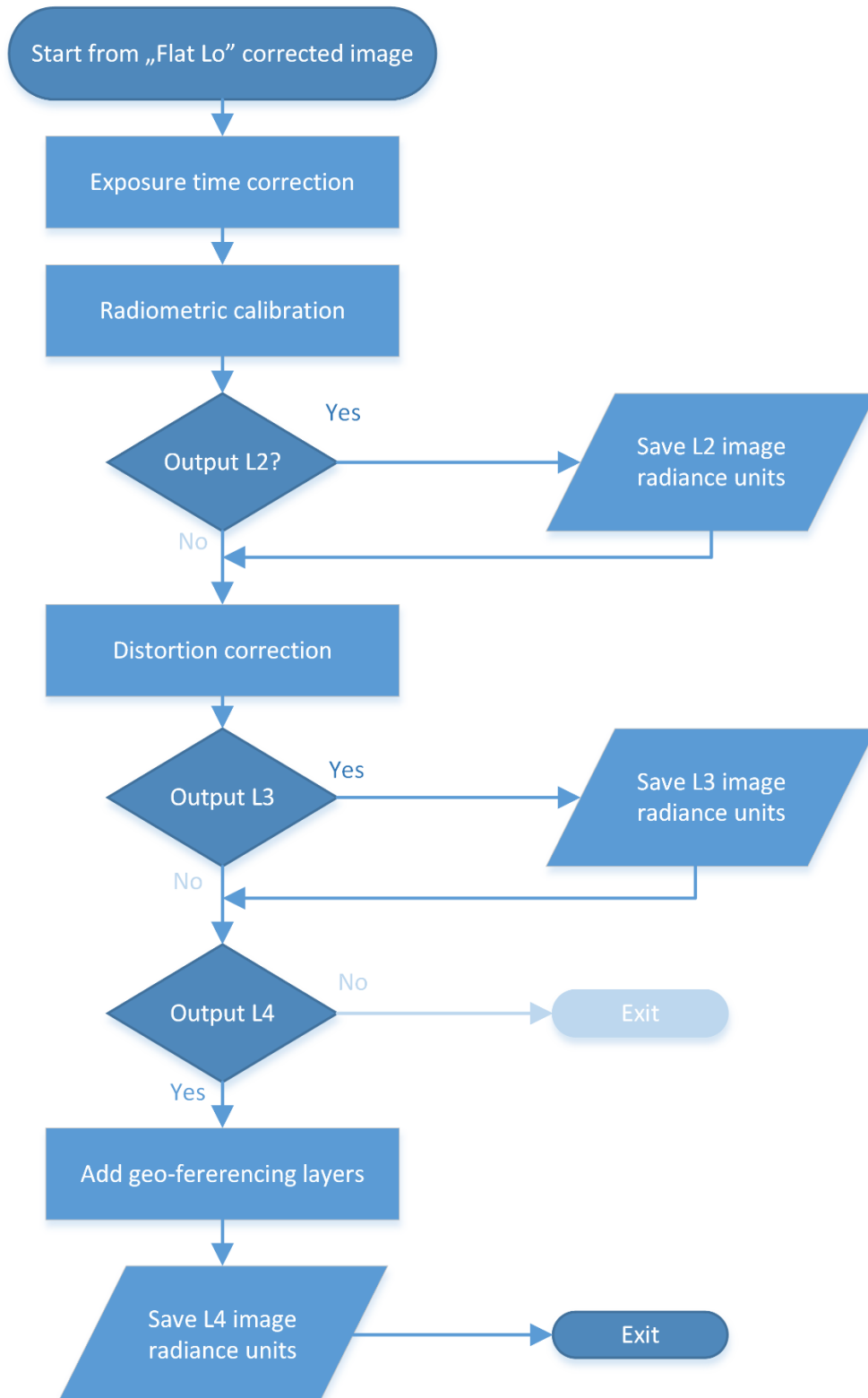


Figure 7 OSIRIS full calibration steps for images in radiance units

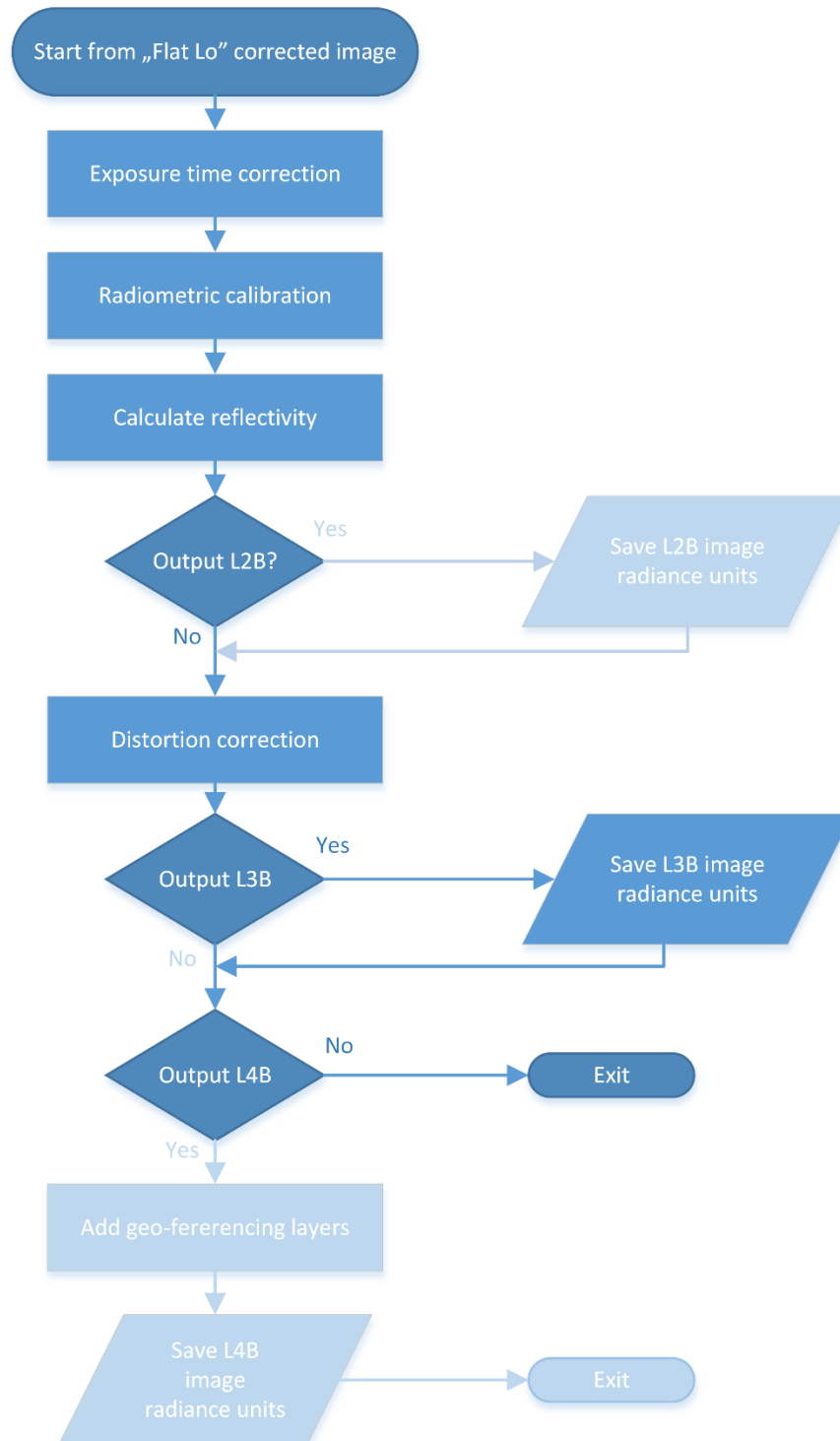


Figure 8 OSIRIS full calibration steps for images in reflectance (I/F) units

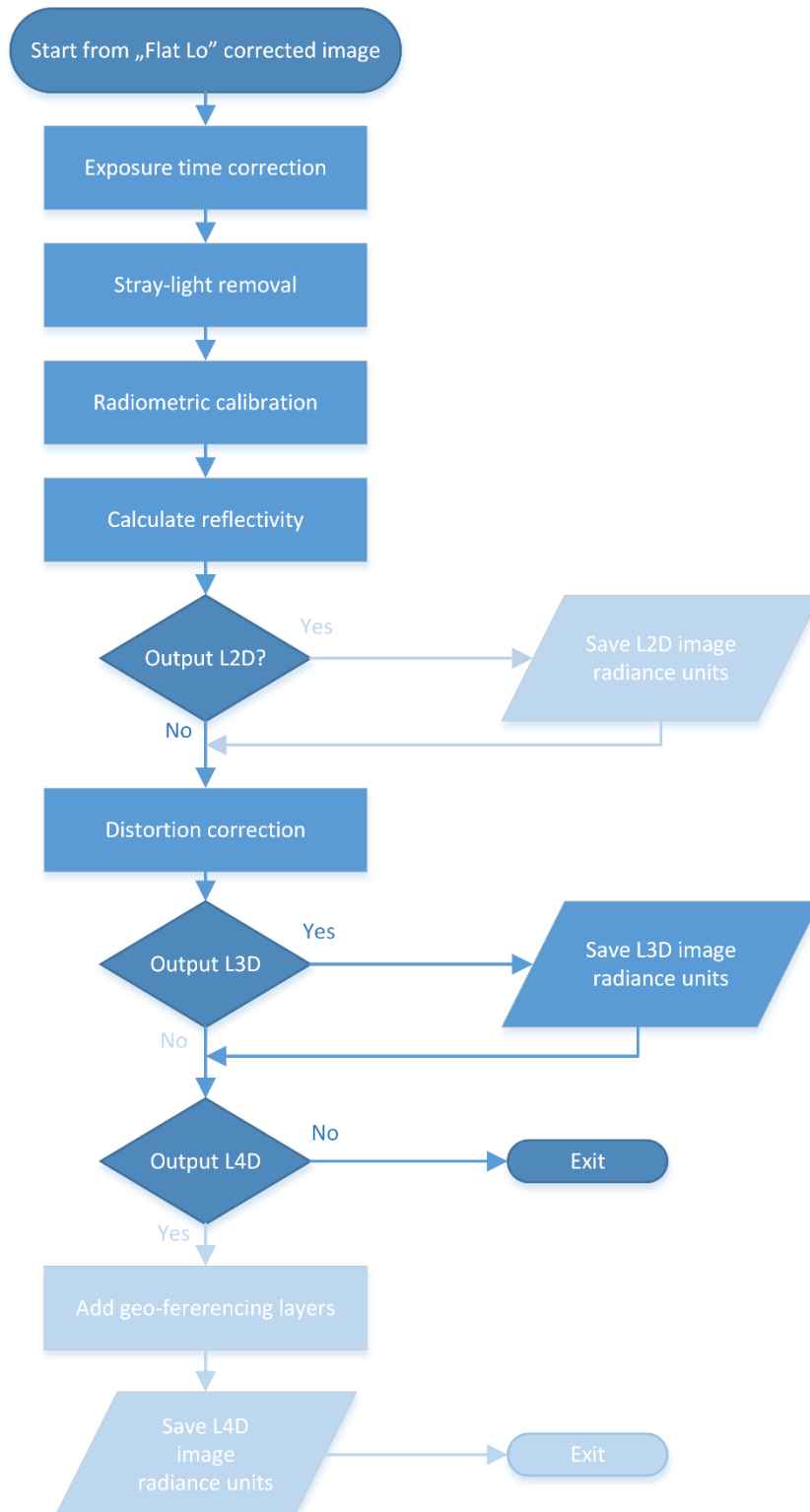


Figure 9 OSIRIS full calibration steps for solar stray-light corrected images in reflectance units



3 Pipeline procedures and algorithms

3.1 Level 1 image pre-processing

The first step of the OsiCalliope calibration pipeline is reading the Level 1 image. The image header and binary is checked for errors. In case of errors, or if the header indicates that no higher levels are needed, the procedure aborts, with the explaining message log information.

The image binary is converted from WORD (16 bits) to DOUBLE (64 bits) format. The software uses this format only internally; the final storage format is PC_REAL (32 bits). The additional binary content of the level 1 data such as the overclocking lines, pre- and post-clocked pixels are not stored in the higher levels.

3.2 Correction of tandem ADC offset

3.2.1 Methods

Both NAC and WAC are equipped with two 14 bits ADCs for each readout channels (ADC-LOW and ADC-HIGH) to digitize the CCD pixel signal. The readout electronics can use the ADCs separately (either ADC-LOW or ADC-HIGH) or together in a dual 14 bits ADC configuration (ADC-TANDEM). The latter option gives a quasi-16 bits dynamical range, which is resolved using a sub-ranging technique. The signal is split between the two ADCs as follows [RD3]:

Where:

$0 \leq DN < ADC_SW_DN \quad ==> \text{ADC-LOW is used}$

$ADC_SW_DN \leq DN < 2^{16} \quad ==> \text{ADC-HIGH is used.}$

ADC_SW_DN is the switch-over value, set to 16384 (0x4000) = 2^{14}

DN is the analog digital converter (ADC) output value

The two ADCs are adjusted to cover a continuous range linearly but, there is a few DN's offset between them. To correctly handle this, the calibration process must determine the readout channel (A or B) and the corresponding ADC unit (ADC-LOW or ADC-HIGH). Then the following correction is applied for pixels having a DN value **ADC_SW_DN** or greater:

$$PX_C = PX_O - ADC_{offset}$$

Where:

PX_C : is the corrected pixel intensity

PX_O : the original pixel intensity

ADC_{offset} : the offset value of the matching ADC (see below)

3.2.2 Parameters

The correction constants were determined during the ground campaign [RD15] and stored in the OSICALLIOPE_V???.TXT configuration file under the following keys:



Amplifier A (single channel)	Amplifier B (single channel)
ADC_OFFSET_A	ADC_OFFSET_B
Amplifier A (dual channel)	Amplifier A (dual channel)
ADC_OFFSET_DA	ADC_OFFSET_DB

Note that the values are different for single channel (A or B) readout and dual channel (A and B) readout!

3.2.3 Header records

In the PDS header and HISTORY:

ROSETTA:ADC_OFFSET_CORRECTION_FLAG = TRUE

The applied ADC correction values for the left and right half (A and B amplifier) of the image are stored in the HISTORY section:

ADC_OFFSET_VALUES = (44.000, 48.000) (example)

3.3 Subtraction of bias

3.3.1 Methods

Ground calibration and in-flight tests indicated that the actual bias value of the OSIRIS cameras depends on the operation mode and the AD converter operating temperature. The following correction is applied:

$$PX_C = PX_O - BIAS_{OM,T_0} + (T_{ADC} - T_0) C_T$$

Where:

- PX_C** : is the corrected pixel value
- PX_O** : the original pixel value
- BIAS_{OM,T₀}** : bias constant for the specific operational mode, at T₀ temperature of the AD converter.
- T₀** : bias constant reference temperature.
- T_{ADC}** : the current temperature calculated as the average of the two ADC temperature sensors on the CCD readout board.
- C_T** : bias temperature dependency factor

The analysis of bias frames indicated that the bias value is constant throughout the CCD for a given operational mode and CCD temperature [RD11]. However this value changes with hardware window size, binning and amplifier channel. The bias is also slightly temperature dependent. The **BIAS_{OM,T₀}** values are therefore individually determined for the frequently used operational modes [RD12]:

- Hardware window sizes: 2048x2048, 1024x1024, 512x512, 256x256, 128x128, 64x64
- Binning modes: 1x1, 2x2, 4x4, 8x8
- Optimized sync modes for the respective binning



3.3.2 Parameters

The bias data file [RD11] used by OsiCalliope is listed in Sec. 4.

The correction constants (**BIAS_{OM,T0}**) are determined during inflight calibration campaigns, and stored with the following key schemes:

BIAS_Wn_Bn_An_Snn for single channel readout

BIAS_Wn_Bn_Dn_Snn for dual channel readout

where:

W : Windowing mode, n = 0 software windowing, n = 1 hardware windowing,

B : Binning mode: n = 1 for 1x1, n = 2 for 2x2, n = 4 for 4x4 or n = 8 for 8x8

A or **D** : Amplifier or dual channel n = A or n = B

S : CRB to power converter synchronization mode nn = 00-31

The bias error (standard deviation) is also stored similarly:

SDEV_Wn_Bn_An_Snn for single channel readout

SDEV_Wn_Bn_Dn_Snn for dual channel readout

The nominal temperature of the bias calibration constants (**T₀**) is stored in Kelvin as well as the temperature coefficient (**C_T**) [DN/K]:

BIAS_A_TEMPERATURE = **281.1** (example)

BIAS_A_TEMP_FACTOR = **0.7**

3.3.3 Header records

In the PDS header and HISTORY:

ROSETTA: BIAS_CORRECTION_FLAG = TRUE

The applied bias correction values for the left and right half (A and B amplifier) of the image are stored in the image header HISTORY section:

BIAS_FILE = ("WAC_FM_BIAS_V01.TXT", "0.0") (example)

BIAS_TEMP = (297.7, 297.7)

BIAS_BASE_VALUES = (240.742, 240.742)

BIAS_TEMP_DELTA = (3.268 <DN>, 3.268 <DN>)

3.4 Removal of coherent noise

3.4.1 Methods

The NAC and WAC signal chains are exposed to noise generated in the CCD readout board (CRB) power converter modules and in the data processing unit (DPU) power converter module. The CRB power converter modules are considered the dominant noise source.

Both, NAC and WAC CRB power converter modules are synchronised with the corresponding pixel readouts. The converters contain two primary switches in push-pull, where one switch is active for the even pixels while the other switch is active for the odd pixels. Both switches



produce different noise effects. Thus, we have different coherent noise on odd and on even pixels, which produces a black-and-white pattern upon the image data with amplitudes of up to 25 DN. This pattern is vertically structured if extra pixels are not included, while it is diagonally structured if the extra pixels are included.

The magnitude of the coherent noise is determined based on full frame images of the calibration sequences:

MTP003/STP003_CALIB_BIAS_001 and **MTP003/STP003_CALIB_BIAS_002**

The following steps were used to process the images:

- Bad pixels removed
- Cosmic particle effects were manually removed by the 5x5 bad pixel region removal procedure
- Images were cropped to 2000x2000 pixel size
- The standard deviation of the pixel values was calculated

Possible noise removal algorithms are currently under evaluation, but no coherent noise removal procedure is currently implemented in the pipeline.

3.4.2 *Parameters*

Coherent noise standard deviation (E_c):

NAC: 7.6 DN

WAC: 7.1 DN

These values are used in the sigma map error calculation.

3.4.3 *Header records*

In the PDS header and HISTORY:

ROSETTA:COHERENT_NOISE_CORRECTION_FLAG = FALSE

3.5 *Removal of dark current*

3.5.1 *Methods*

A standard dark current subtraction is not implemented in the pipeline.

Dark frames with exposure times between 1 s and 1200 s have been acquired to investigate the dark current behavior. Between May and December 2014, the CCD temperature was in the range 148-150 K; the measured dark charge is $< 0.006 e^-/s$ that correspond to < 0.002 DN/s. Even for long coma exposures (typically 300s), the dark current is much smaller than the readout noise at the current operational temperature; therefore no dark current correction is necessary.

3.5.2 *Header records*

In the PDS header and HISTORY:

DARK_CURRENT_CORRECTION_FLAG = FALSE



3.6 High spatial frequency flat fielding

3.6.1 Methods

The flat field corrects for the non-uniform sensitivity of the camera across the image plane. Two main forms of non-uniformities are present:

- A pixel-to-pixel sensitivity variation across the image, due to the size difference and electrical characteristics of the individual CCD pixels and to dust particles on the CCD chip surface;
- A lower spatial frequency variation that is caused by the optical properties of the camera and the filters.

To correct the OSIRIS images, we have introduced a new technique that consists in correcting the two types of non-uniformities in two steps. First the pixel-to-pixel sensitivity variations are removed and then the lower spatial frequency variations.

The high spatial frequency flat fielding is done by multiplying the original image with the “FLAT_HI” image.

3.6.2 Parameters

The flat image files [RD12] used by OsiCalliope are listed in Sec. 4.

3.6.3 Header records

In the PDS header and HISTORY:

ROSETTA:FLATFIELD_HI_CORRECTION_FLAG = TRUE

In the HISTORY section, the applied flat image file is also listed:

FLAT_HI_FILE = ("WAC_FM_FLATHI_00_V01.IMG", "0.0") (example)

3.7 Removal of bad pixels

3.7.1 Methods

Logically bad pixel removal should precede the flat fielding, but since its algorithm relies on the corrected neighboring pixel values, the high spatial frequency flat field correction is done first.

Bad pixels are areas of the CCD surface that provide invalid DN values. They can be individual pixels, or group of pixels (lines, rows, or areas). Bad pixels can be handled by the on-board spacecraft software, by the calibration pipeline, or both. The calibration pipeline can provide more sophisticated correction methods than the on-board software.

The PDS header flag: **BAD_PIXEL_REPLACEMENT_FLAG** in the group **SR_PROCESSING_FLAGS** indicates the presence of the spacecraft processing.

3.7.2 Parameters

The bad pixel lists [RD10] for the NAC and WAC used by OsiCalliope are listed in Sec. 4.

The list indicates the position of the bad pixels, and the correction method in the following form:

area_type = (x, y, method) or **area_type = (x, y, h, w, method)**

For single pixels:



PIXEL = (10, 10, MEDIAN_CORR) (example)

where: 10, 10 is an example of the column and row coordinates, and MEDIAN_CORR or AVERAGE_CORR is the correction method: median or average of the neighboring 8 pixels.

For columns:

COLUMN = (994, 0, SHIFT_L_CORR) (example)

where: 994, is the column number and 0 is the starting line. If the second coordinate is larger than 0, it specifies the length of the corrected cluster, starting from line 0. MEDIAN_CORR or AVERAGE_CORR replaces each pixel of the column with the median or average of the neighboring 6 good pixels. SHIFT_L_CORR or SHIFT_R_CORR handles hot or dim columns, by shifting its DN values to have the same median as the Left or Right neighbor's.

Bad column number 995: The neighboring columns are also slightly affected by the higher charge of this bad column. The following correction method shifts the affected neighboring columns, than corrects the bad one.

COLUMN = (994, 0, SHIFT_L_CORR) (example)

COLUMN = (996, 0, SHIFT_R_CORR)

COLUMN = (995, 0, MEDIAN_CORR)

Rectangular areas, such as the 9x9 pixels (blob) area close to the physical center of the NAC, are also handled:

REGION_R = (915, 970, 20, 20, NO_CORR) (example)

Hot pixels, columns and rectangular areas are also marked as **PIXEL**, **COLUMN** or **REGION_R**. The **NO_CORR** key means no correction method, just an indication in the quality map.

3.7.3 Header records

In the PDS header and HISTORY:

ROSETTA:BAD_PIXEL_REPLACEMENT_GROUND_FLAG = TRUE

In the HISTORY section, the applied bad pixel file is also listed:

BAD_PIXEL_FILE = ("WAC_FM_BAD_PIXEL_V01.TXT", "0.0") (example)

3.8 Low spatial frequency flat fielding

3.8.1 Methods

Low spatial frequency flat fielding is used to remove sensitivity non-uniformities in the image plane that are caused by the filters and the optical system itself. The low spatial frequency flat fielding is done by multiplying the original image with the "FLAT_LO" image.

3.8.2 Parameters

The flat image files [RD12] used by OsiCalliope are listed in Sec. 4.

3.8.3 Header records

In the PDS header and HISTORY:

ROSETTA:FLATFIELD_LO_CORRECTION_FLAG = TRUE



In the HISTORY section, the applied flat image file is noted:

FLAT_LO_FILE= ("WAC_FM_FLATLO_12_V01.IMG", "0.0") (example)

3.9 Correction of solar stray-light

3.9.1 Methods

Solar stray-light effect is removed in images acquired at solar elongation less than 90°. However, for dataset consistency all higher level images are generated, independently from the solar elongation. The correction is based on pre-determined stray-light reference image files. The files are created from in-flight stray-light calibration sequences, for individual filters. The reference files are assembled from several stray-light images, with gradually increasing solar elongation positions. They are scaled to 1 s exposure, and 1 AU solar distance. In case of filter combinations not having a dedicated stray-light calibration sequence, intensity scaling was applied, based on the absolute calibration factor and the solar irradiation value.

The actual subtracted solar stray-light contribution at a given solar elongation is determined by parabolic interpolation of the reference image components. This simple correction is always possible, because due to flight operation rules, the Sun is always perpendicular to the solar panels, thus the Sun is always on the meridian of the spacecraft.

The following correction is applied for each pixels of the image:

$$PX_C = PX_O - PX_{iSoISL} * t_{exp} / d^2.$$

Where:

- PX_C** : is the corrected pixel value
- PX_O** : the original pixel value
- PX_{iSoISL}** : is the solar stray-light image, interpolated for the actual solar elongation of the camera.
- t_{exp}** : exposure time in seconds.
- d** : is the solar distance in AU

3.9.2 Parameters

The method for generating the solar stray-light reference images [RD16] and files used by OsiCalliope are listed in Sec. 4.

3.9.3 Header records

In the PDS header and HISTORY:

ROSETTA:OUTFIELD_STRAYLIGHT_CORRECTION_FLAG = TRUE

In the HISTORY section, the applied flat image file is noted:

SOL_STL_IMG = ("WAC_FM_SOL_STL_12_V01.IMG", "0.0") (example)



3.10 Normalization of the exposure time

3.10.1 Methods

Each image is normalized to 1 second exposure. The normalization is done line by line, based on the calculated CCD illumination [RD2]. The correction method is determined based on the header keyword **SHUTTER_OPERATION_MODE**, the shutter pulse values, and the header keyword **ERROR_TYPE_ID**.

1) **SHUTTER_OPERATION_MODE = NORMAL**

This is the default shutter mode, both shutter blades are operated according to the original specs [RD1].

If **ERROR_TYPE_ID** is equal to **LOCKING_ERROR_A**, **UNLOCKING_ERROR_C**, or **SHE_RESET_ERROR_D**, the exposure correction is not possible and **EXPOSURE_CORRECTION_TYPE** is reported as **UNCORRECTED_SHUTTER_ERROR_A**, **UNCORRECTED_SHUTTER_ERROR_C**, and **UNCORRECTED_SHUTTER_ERROR_D**, respectively. An **ERROR_TYPE_ID** equal to **MEMORY_ERROR_B** does not prevent the exposure time correction.

In case of successful exposure, the correction is the following:

$$\text{exp_time}_{\text{effective}} = \text{exp_time}_{\text{commanded}} + \Delta t \quad (1)$$

Where:

exp_time_{effective}	:	is the effective exposure time per line
exp_time_{commanded}	:	is the commanded exposure time
Δt	:	is a correction of the actual shutter blade velocity variation during the exposure, calculated for each individual CCD line

If the image data contains valid and complete shutter pulse information, it will be used to calculate the correction factor Δt and the correction mode is **EXPOSURE_CORRECTION_TYPE = NORMAL_PULSES**. Otherwise a default correction factor Δt , constant for all lines of the CCD, is used and the correction mode is **EXPOSURE_CORRECTION_TYPE = NORMAL_NOPULSES**. These values are calculated for each camera from the in-flight linearity test [RD9] and listed in RD2.

The **NORMAL_PULSES** exposure time calculation uses the following algorithm:

- The shutter pulse array contains the number of clock pulses (2.1MHz) at certain encoder (angular) positions of the shutter blade arm.
- The encoder positions are transformed into shutter blade positions by the shutter blade transfer functions [RD7].
- The blade position – time function is calculated [RD2]
- The exposure time correction factor Δt is calculated as the difference of the above functions for the two blades at a certain CCD position.
- The linewise effective exposure time $\text{exp_time}_{\text{effective}}$ is calculated using Eq.(1).
- The average of these values is the **MEAN_EFFECTIVE_EXPOSURETIME**.
- For the normalization, every image pixels value is divided by the effective exposure time $\text{exp_time}_{\text{effective}}$.



The **MEAN_EFFECTIVE_EXPOSURETIME** is stored in the HISTORY section of the PDS header.

From November 2015 the WAC shutter failure required the introduction of new shutter operation modes. In ballistic modes, the commanded shutter blade travel is shorter than the full travel path, and the blade(s) do not reach the locking position at the end of the run.

2) SHUTTER_OPERATION_MODE = BALLISTIC

This is a single shutter blade operation mode, with motor driven first shutter blade opening and spring force driven closing. The second shutter blade does not move. This results in a relative short exposure time, and highly non-uniform CCD illumination. The correction method is dependent on the existence of the shutter pulses.

If pulse data is present, the correction mode **EXPOSURE_CORRECTION_TYPE = BALLISTIC_PULSES** is used. The exact exposure time calculation is based on the pulse information similarly to the **NORMAL_PULSE** mode, but using only the data of the first blade. The exposure time calculation uses the following algorithm:

- The shutter pulse array contains the number of clock pulses (2.1MHz) at certain encoder (angular) positions of the shutter blade arm.
- The turning point of the first blade is determined
- The encoder positions are transformed into shutter blade positions by the shutter blade transfer functions [RD7].
- The blade position – time function is calculated [RD2]
- The exposure time correction factor Δt is calculated as the difference of the above functions for shooting and the returning first blade.
- The linewise effective exposure time $\text{exp_time}_{\text{effective}}$ is calculated using the following equation:

$$\text{exp_time}_{\text{effective}} = \Delta t \quad (2)$$

Where:

exp_time_{effective} : is the effective exposure time per line

Δt : is the actual exposure time per CCD line
calculated as the time difference of the shooting and the returning blade

- The average of $\text{exp_time}_{\text{effective}}$ is the **MEAN_EFFECTIVE_EXPOSURETIME**.
- For the normalization, every image pixels value is divided by the effective exposure time $\text{exp_time}_{\text{effective}}$.

If valid pulse data is not available **EXPOSURE_CORRECTION_TYPE = BALLISTIC_NOPULSES** is used. The illumination non-uniformity is corrected based on a pre-determined shutter profile. The profile is an averaged result of several **BALLISTIC_PULSES** test images (STP095_SHUTTER_PULSE_001, STP101_SHUTTER_TEST, STP102_SHUTTER_TEST), depending on the mission time. The correction data and their applicable time periods are given in [RD2].

3) SHUTTER_OPERATION_MODE = BALLISTIC_STACKED

To achieve longer exposure times, several ballistic exposures are commanded without reading out the CCD. The image readout is commanded after the last shutter operation, “stacking” up several individual ballistic exposures. This operation mode does not allow the recording of the



pulse information, so the correction method is always **CORRECTION_TYPE = BALLISTIC_STACKED_NOPULSES**, a **BALLISTIC_NOPULSES** type correction, which correctly takes into account the number of exposures.

4) SHUTTER_OPERATION_MODE = BALLISTIC_DUAL

In this case both blades are used, with motor operated first and second shutter blade opening and spring force driven closing. The shutter blades stop before the end of the full travel path, not reaching the locking position. This allows only very short exposure times (<20ms). As in SHUTTER_OPERATION_MODE = NORMAL, if the image data contains valid and complete shutter pulse information, it will be used to calculate the correction factor Δt and the correction mode is **EXPOSURE_CORRECTION_TYPE = NORMAL_PULSES**. Otherwise a default correction factor Δt , constant for all lines of the CCD, is used and the correction mode is **EXPOSURE_CORRECTION_TYPE = NORMAL_NOPULSES**.

3.10.2 Parameters

The exposure correction files [RD2] used by OsiCalliope are listed in Sec. 4.

3.10.3 Header records

In the PDS header and HISTORY:

ROSETTA:EXPOSURETIME_CORRECTION_FLAG = TRUE

In the HISTORY section, the exposure method, the mean effective exposure time, and the applied exposure correction, type and file is noted:

```

SHUTTER_OPERATION_MODE           = BALLISTIC           (example)
EXPOSURE_CORRECTION_TYPE         = BALLISTIC_PULSES
MEAN_EFFECTIVE_EXPOSURETIME      = 0.0933 <s>
EXPOSURE_CORRECTION_FILE = ("WAC_FM_EXP_20160405_V01.TXT", "0.0")

```

3.11 Radiometric calibration

3.11.1 Methods

The last step to achieve radiometric calibrated images is the conversion from DN/s to radiance units ($W\ m^{-2}\ sr^{-1}\ nm^{-1}$). This is done by dividing the image by the **ABSCAL_FACTOR**.

$$PX_{rad} = PX_o / ABS_CAL$$

Where:

PX_o : the original pixel value (in DN/s)

PX_{rad} : the pixel value in radiance units ($W/m^2/sr/nm$)

3.11.2 Parameters

The calibration constants (**ABSCAL_FACTOR**) for the radiometric calibrations are obtained from the observation of standard stars – usually Vega – [RD13]. The radiometric calibration coefficients used by OsiCalliope are listed in Sec. 4.



3.11.3 Header records

In the PDS header and HISTORY:

ROSETTA:RADIOMETRIC_CALIBRATION_FLAG = TRUE

The applied absolute calibration file, correction factor, and binning multiplier are listed in the HISTORY:

ABSCAL_FILE = ("WAC_FM_ABSCAL_V01.TXT", "0.0") (example)

ABSCAL_FACTOR = 1.233e+008

BINNING_FACTOR = 1

3.12 Conversion to radiance factor units

3.12.1 Methods

The radiance factor image (reflectivity or I/F) is calculated dividing the radiometric calibrated image by the solar flux scaled to the heliocentric distance of the target.

$$PX_{rf} = \pi \cdot d^2 \cdot PX_{rad} / SFX$$

Where:

PX_{rf} : the pixel value in radiance factor units (1)

PX_{rad} : the original pixel value in radiance units (W/m²/sr/nm)

d : the target solar distance in AU

(calculated from PDS header Sun and target position)

SFX : the solar flux or irradiance at 1 AU at the central wavelength of the filter used (W/m²/nm).

3.12.2 Parameters

The solar flux values (SFX) [RD13] used by OsiCalliope are listed in Sec. 4.

3.12.3 Header records

In the PDS header and HISTORY:

ROSETTA:REFLECTIVITY_NORMALIZATION_FLAG = TRUE

The applied solar distance and solar flux values are listed in the HISTORY:

SOLAR_FLUX = 1.289 <W/m²/nm> (example)

SOLAR_DISTANCE = 1.2582921 <AU> (example)

3.13 Correction of geometric distortion

3.13.1 Methods

Both the NAC and WAC optical layouts are off-axis mirror systems, which provide high transmittance and near diffraction limited performance, with low geometrical optical aberrations. However, this layout has a significant geometrical distortion which must be corrected.



The correction is performed by resampling the images according to the nonlinear distortion function of the relevant camera, as if it would be acquired by a distortion free camera. The image resampling is done by the bi-linear algorithm, and since the original image is in radiance or reflectance unit, the result is also considered radiometrically corrected on the large scale.

The resampling is based on a two dimensional third-order polynomial fit:

$$X_i = \sum_{i,j} kx_{i,j} \cdot X_0^j \cdot Y_0^i$$
$$Y_i = \sum_{i,j} ky_{i,j} \cdot X_0^j \cdot Y_0^i$$

Where (x_i, y_i) , the undistorted coordinates are expressed as a function of the actual image coordinates (X_0, Y_0) . The coefficients for distortion removal (kx and ky) are the coefficients of the third-order polynomial fit. To obtain the corrected level 3 images, the level 2 images are wrapped according to the tabulated kx and ky distortion removal coefficients.

3.13.2 Parameters

The geometric distortion correction files [RD14] used by OsiCalliope are listed in Sec. 4.

3.13.3 Header records

In the PDS header and HISTORY:

ROSETTA:GEOMETRIC_DISTORTION_CORRECTION_FLAG = TRUE

The applied distortion correction file, together with the correction method used and the average distortion correction, are listed in the HISTORY:

GEOMETRIC_CORRECTION_FILE = ("NAC_FM_DISTORTION_V01.TXT", "10.0")

GEOMETRIC_CORRECTION_METHOD = (POLY3_2D, POLY3_2D)

GEOMETRIC_CORRECTION_AVERAGE = 5.02

3.14 Generate sigma map and quality map

In addition to the calibrated frame, the pipeline also creates for each image a map with error estimates and quality indicators.

3.14.1 Sigma map

The sigma map (error estimate map) is a float image with the same dimension as the image itself. For each pixel, its error is determined by the Poisson error E_p , and the readout (coherent) noise E_c :

$$error_{i,j} = \sqrt{E_p^2 + E_c^2}$$
$$E_p = \frac{\sqrt{N_{i,j}}}{N_{i,j}}$$

where $N_{i,j}$ is the intensity of the pixel with coordinates (i, j) in number of electrons. Since the Poisson statistics are done using the intensity in number of electrons, the image intensity has to be converted from DN to number of electrons and this is done using:



$$I_{e^-} = I_{DN} \cdot gain$$

where I_{e^-} and I_{DN} are the intensity in number of electrons and DN, respectively, and gain is the number of electrons per DN (for OSIRIS WAC and NAC gain = 3.1 e⁻/DN in HIGH gain mode and gain = 15.5 e⁻/DN in LOW gain mode).

$$\text{NB: } N_{i,j} = I_{e^-, (i,j)}, \sum_{i,j} N_{i,j} = I_{e^-}$$

For radiance factor images, the value is calculated by scaling the radiance image error similarly as the radiance factor (I/F) value.

3.14.2 Quality map

The PIXEL QUALITY MAP is an 8-bit image with the same dimension as the image itself and contains a quality estimate of each pixel. The quality map exists for level 2 and higher images.

The quality estimate values stored in the quality map are generated by setting a given bit to value 1 for specific effects. If more than one effect is present in the data several different bits can be set. The following values are possible:

	Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0
Value	128	64	32	16	8	4	2	1
Effect	BAD	SAT	DIM	WARM	LOSSY	NLIN	-	VALID

BAD: Pixel is marked as bad

SAT: Pixel was saturated during the exposure [RD9]

DIM: Pixel is marked as dim (low sensitivity)

WARM: Pixel is marked as warm (increased or varying sensitivity) use with caution

LOSSY: Lossy image compression applied on pixel

NLIN: Pixel was exposed into the nonlinear DN range of the CCD

VALID: Pixel is valid. Invalid or non-existing (0) due to packet loss, or distortion correction.

Some flags have been removed from quality map (they are valid for the full image area):

CONV: (bit 1) Pixel has seen gauss convolution filtering as part of the image compression

SQRT: (bit 0) Pixel has seen sqrt filtering as part of the image compression



4 Calibration files used by OsiCalliope

The calibration files used by OsiCalliope to calibrate OSIRIS images are listed in Table 1. Please note that if more than one version of the same file is available, the one with the highest version number is used.

Calibration step	Calibration File	Reference Document
ADC offset removal	OSICALLIOPE_??_TXT	RD15
Bias subtraction	NAC_FM_BIAS_V??_TXT WAC_FM_BIAS_V??_TXT	RD11
High spatial-frequency flat fielding	NAC_FM_FLATHI_00_V??_IMG WAC_FM_FLATHI_00_V??_IMG	RD12
Bad pixels correction	NAC_FM_BAD_PIXEL_V??_TXT WAC_FM_BAD_PIXEL_V??_TXT	RD10
Low spatial-frequency flat fielding	NAC_FM_FLAT_??_V??_IMG WAC_FM_FLAT_??_V??_IMG	RD12
Exposure time normalization	For ballistic mode: NAC_FM_EXP_BAL_V??_TXT WAC_FM_EXP_BAL_V??_TXT WAC_FM_EXP_20160323_V??_TXT WAC_FM_EXP_20160405_V??_TXT	RD2
Radiometric calibration	NAC_FM_ABSCAL_V??_TXT WAC_FM_ABSCAL_V??_TXT	RD13
Geometric distortion correction	NAC_FM_DISTORTION_V??_TXT WAC_FM_DISTORTION_V??_TXT	RD14
Solar stray-light removal	OSICALLIOPE_??_TXT NAC_FM_SOL_STL_??_V??_IMG	RD16

Table 1 Calibration files used by OsiCalliope to calibrate OSIRIS images and reference document where the files are described.