OSIRIS

Optical, Spectroscopic, and Infrared Remote Imaging System

OSIRIS calibration pipeline OsiCalliope

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1/a	22/2/2017, Tubiana	All	Added Sect. 4 Corrected flat fielding section Moved references to calibration files to Sect. 4
1/b	22/08/2017, Kovacs	All	Added algorithm flowcharts Added sect.3.9 on solar stray light Added section 3.12 on radiance factors Added Sections Methods, Parameters, Header
1/c	16/10/2017, Tubiana		Sect. 2: Added details about missing higher level images Sect. 4: Added note about file version used. Sect. 1.2: Updated SIS Sect. 3.10: Corrected EXPOSURE_CORRECTION_TYPE
1/d	13/02/2018, Tubiana		Updated Sect. 1.4.1 Updated Figure 1 Updated Sect. 1.4.2 Updated all figures in Sect. 2: replaced Fig. 4-9 with new Figure 3. Updated Sect. 3.9. Added Sect. 3.10. Updated Table 2. Added WAC_FM_EXP_20160823_V??.TXT to Table 2. Updated Sect. 3.11.1.2 and 3.11.1.3 adding EXPOSURE_CORRECTION_TYPE = UNCORRECTED_MISSING_DEFAULT_PROFILE
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1/f	25/4/2018, Tubiana		Clarified OSIRIS/CODMAC levels Corrected typos Added sentence in Sect. 4 concerning the delivered files
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1/h	3/6/2019, Tubiana		Added correction method to Sect. 3.8. Updated Sect. 2. Updated Figure 3. Updated Sect. 3.10.
1/i	30 Sep 2019, Tubiana	All	Corrected use of Stray-light/stray light. Sect. 3.17: Updated description of quality map generation.
1/j	5 Nov 2019, Tubiana	Sect. 3.14.1	Updated geometric distortion correction section to include the case of filter shift and enlarged frames.
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2/-	15 Dec 2021, Güttler	all	- sigma map to include more individual errors (Sect. 3.15) - updated flat field (high and low to lab and spectral) - corrected error in flat field description (images are divided) - document filter scaling factor used in solar stray light - updated Figure 3 - harmonized equations and symbols
2/a	10 May 2022, Güttler		- handling of 2E in Figure 3 - corrected typo in Sect. 2 (radiance to reflectance; RID-JL-02)

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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 v2.39 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 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 OSIRIS_SIS_V??.PDF
AD2	Rosetta-OSIRIS to Planetary Science Archive Interface Control Document	RO-RIS-MPAE-ID-015 OSIRIS_EAICD_V??.PDF

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 EXPOSURETIME_COR_V??.PDF
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 LINEARITY_SATUR_V??.PDF
RD10	OSIRIS camera bad pixel list	RO-RIS-MPAE-TN-080 BAD_PIXELS_V??.PDF
RD11	OSIRIS camera bias levels	RO-RIS-MPAE-TN-079 BIAS_V??.PDF
RD12	Acquisition and processing of flat field images for OSIRIS calibration	RO-RIS-MPAE-TN-075 FLATFIELDING_V??.PDF

no.	document name	document no, Issue./Rev.
RD13	Determination of the absolute calibration coefficients to radiometrically calibrate OSIRIS images	RO-RIS-MPAE-TN-074 RADIOMETRIC_CALIB_V??.PDF
RD14	OSIRIS camera distortion and boresight correction	RO-RIS-MPAE-TN-081 GEOMETRIC_DIST_COR_V??.PDF
RD15	OSIRIS camera tandem ADC offset correction parameter	RO-RIS-MPAE-TN-088 ADC_CORRECTION_V??.PDF
RD16	OSIRIS Camera Solar Stray light	RO-RIS-MPAE-TN-087 SOLAR_STRAYLIGHT_V??.PDF
RD17	Keller et al.: OSIRIS -- The Scientific Camera System Onboard Rosetta, Space Science Reviews, 2007, 128, 433-506.	KELLER_ET_AL_2007_V01.PDF
RD18	In-field stray-light determination and correction	RO-RIS-MPAE-TN-093 IN-FIELD-STRLIGHT_V??.PDF
RD19	OSIRIS Georeferenced Data Products	RO-RIS-MPAE-TN-089 GEO_PRODUCTS_V??.PDF

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 (OSIRIS Level 0[1]; CODMAC L1)
- Generating raw images, with calibrated hardware parameters, and spacecraft position and pointing (OSIRIS Level 1; CODMAC L2)
- Creating calibrated images for scientific analysis (OSIRIS Level 2 and higher; CODMAC L3 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.

1.4.1 Processing levels of the images

OSIRIS images are stored in different data levels, which correspond to the different levels of processing, as summarized in Figure 1. Each image is composed of *header* and *image*. OSIRIS Level 0 (CODMAC L1) and OSIRIS Level 1 (CODMAC L2) have a 16 bit unsigned integer image, while OSIRIS Level 2 (CODMAC L3) and higher have a 32 bit float image.

[1] Note that OSIRIS levels and CODMAC levels are shifted by one [AD2]. OSIRIS levels are used internally and converted to CODMAC levels for public data delivery to PSA.

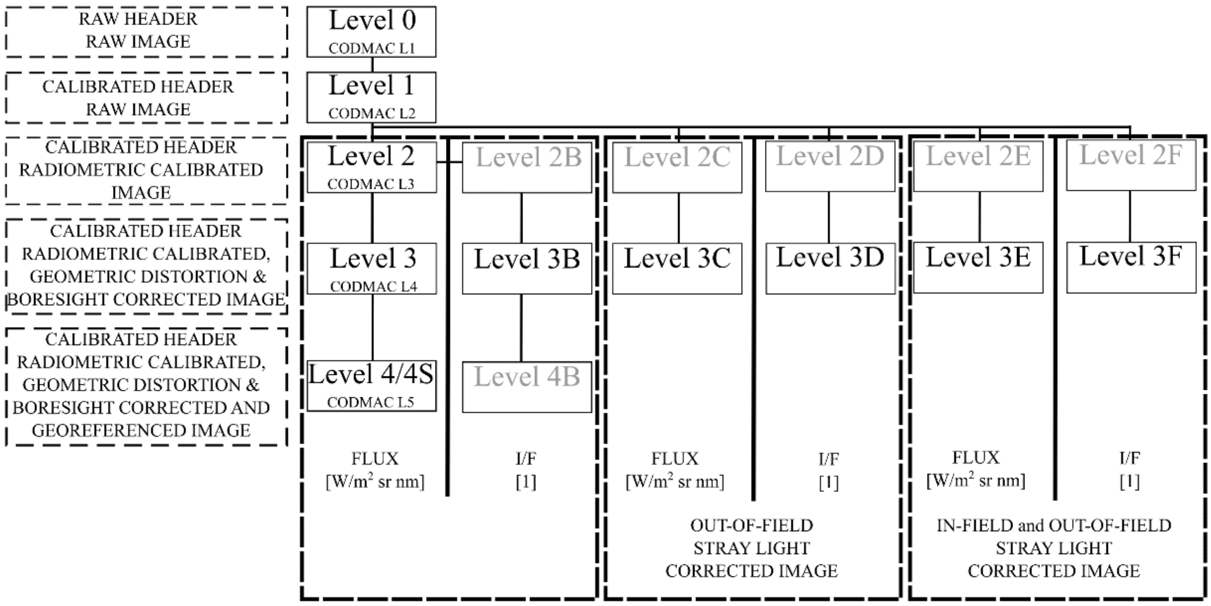

Figure 1 OSIRIS data levels. The grey levels are optional outputs.

1.4.2 OSIRIS cameras

NAC and WAC use a 2k × 2k pixel backside illuminated full frame CCD with a UV optimized anti-reflection coating [RD1]. The CCDs comprise 2048 samples and 2052 lines (see Figure 2). The image area is 2048 x 2048 pixels. The two lines at the bottom of the CCD (red in Figure 2) are discarded from the image. The two lines at the top of the CCD (green in Figure 2), which are read out after the image data, are called overclocking lines and can be used for charge transfer efficiency calculation. The readout serial register has 50 + 2048 + 50 pixels. The first 2 pixels (pink in Figure 2) are needed for electronic stabilization of the readout and they cannot be used for science. The following 48 pixels (green in Figure 2) are used as pre-pixels. They do not represent illuminated pixels of the CCD but contain valuable information for readout noise and bias analysis. Pre-pixels are typically binned 8 × 8 (using average) by the onboard software.

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.

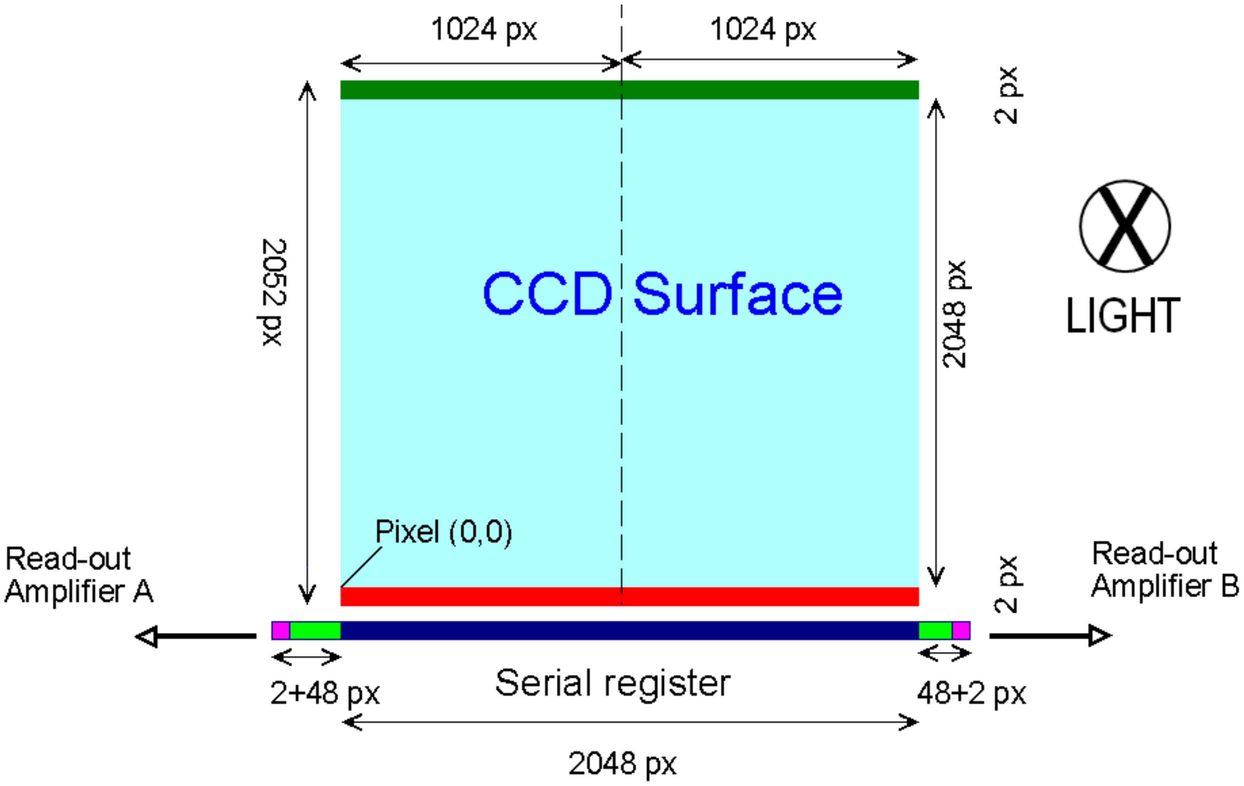

Figure 2 Structure of the OSIRIS CCDs

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, 1×1, 2×2, 4×4 and 8×8 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.

The NAC uses an off axis three mirror optical design. The off axis design was selected in order to minimize the stray light reaching the CCD (the NAC has a proven stray-light attenuation of better than 10^{-9}). The optical beam is reflected by the three mirrors (M1, M2 and M3) before passing through a double filter wheel, a mechanical shutter mechanism and an anti-radiation plate (ARP) before reaching the CCD.

The WAC uses an off axis two mirror optical design. The off axis design was selected in order to minimize the stray light reaching the CCD (the WAC has a proven stray-light attenuation of better than 10^{-8}). The optical beam is reflected by the two mirrors (M1 & M2) before passing through a double filter wheel, a mechanical shutter mechanism, and an anti-radiation plate (ARP) before reaching the CCD.

More detailed information about the design of the cameras, the filter wheels, the mechanical shutter mechanism and the CCD can be found in RD17.

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” and “.\level0” folders on the internal OSIRIS server) as a parameter. The software generates higher-level images from the OSIRIS Level 1 (CODMAC L2) data.

The pipeline software loads the OSIRIS Level 1 (CODMAC L2) 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 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 Sect. 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 OSIRIS Level 1 (CODMAC L2).
2. TARGET_TYPE = STAR / NEBULA: non-reflecting objects. No conversion to reflectance units can be performed. OSIRIS Levels 2 (CODMAC L3), 3A (CODMAC L4) and 3C (CODMAC L4, STRLIGHT) are generated and stored.
3. TARGET_TYPE = PLANET / ASTEROID / SATELLITES / COMET: reflecting objects. Conversion to reflectance units can be performed. OSIRIS Levels 2, 3A, 3B, 3C, and 3D (CODMAC L3, L4, L4 REFLECT, L4 STRLIGHT, L4 STR-REFL) are generated and stored.
4. For images of 67P/Churyumov-Gerasimenko (TARGET_NAME = 67P/Churyumov-Gerasimenko 1) georeferenced images (OSIRIS Level 4 and Level 4S, CODMAC L5) are generated and stored if the comet nucleus is in the FOV and georeferencing information [RD19] exists.

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 OSIRIS Level 1 (CODMAC L2).

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 OSIRIS Level 2X and OSIRIS Level 3X. Please note that the shutter error types are described in the shutter description document [RD2].

The overview of the OsiCalliope calibration algorithm and image level generation is shown in Figure 3.

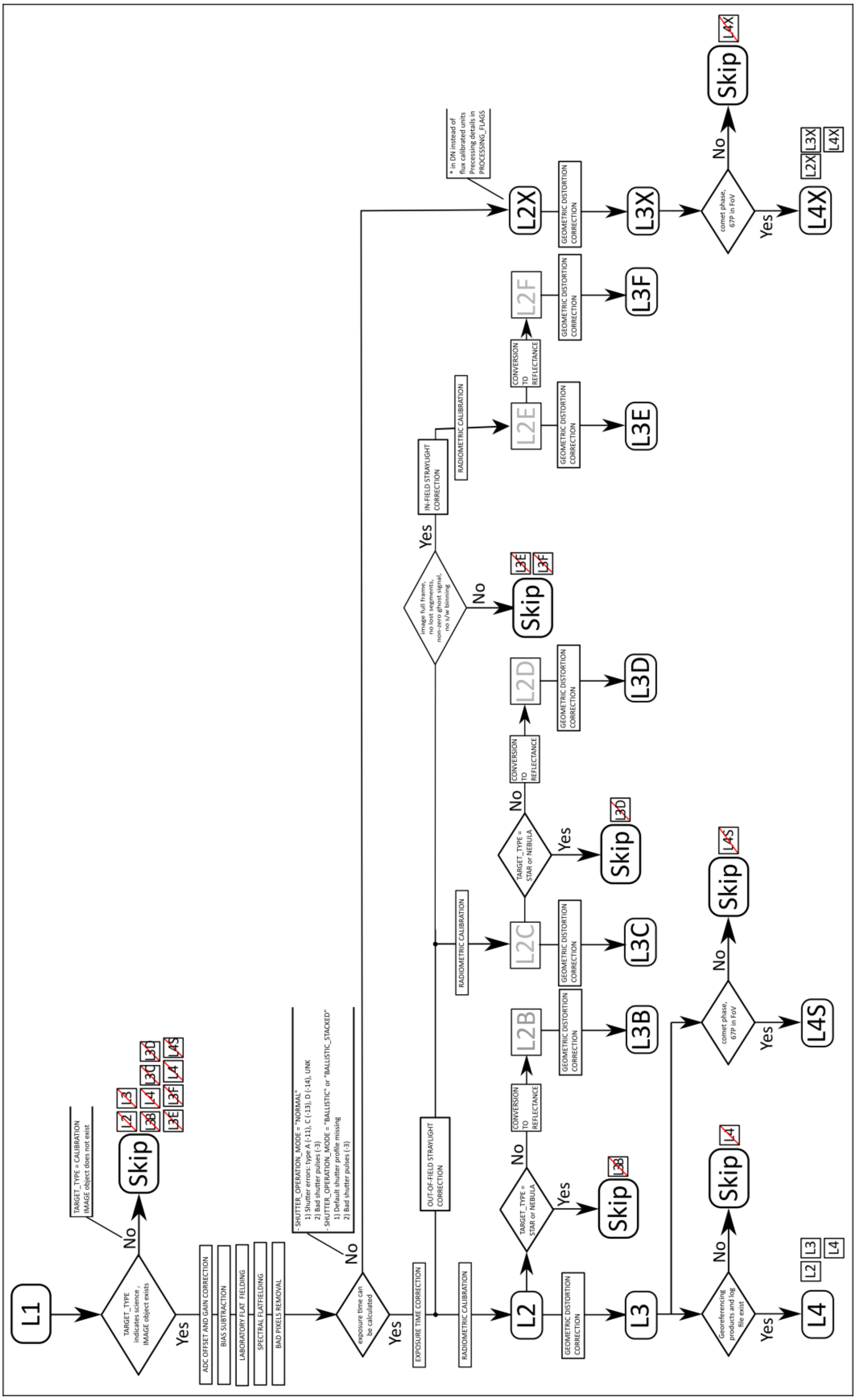

Figure 3 Overview of the OsiCalliope calibration algorithm and image level generation. Please note that the image levels are OSIRIS levels.

3 Pipeline procedures and algorithms

3.1 OSIRIS Level 1 (CODMAC L2) image pre-processing

The first step of the OsiCalliope calibration pipeline is reading the OSIRIS Level 1 (CODMAC L2) 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 OSIRIS Level 1 (CODMAC L2) 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 bit ADCs for each readout channel (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]:

$0 \leq n_0 \leq n_{\mathrm{ADC}}$ ==> ADC-LOW is used
$n_{\mathrm{ADC}} < n_0 < 2^{16}$ ==> ADC-HIGH is used.

Where:

n_{ADC}: switch-over value, set to $n_{\mathrm{ADC}} = 16383 = 2^{14} - 1$
n_0: analog digital converter (ADC) output value

The two ADCs are adjusted to cover a continuous range linearly but there is a few DN 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 value n_0 of $n_0 > n_{\mathrm{ADC}}$:

$$n_{\mathrm{corr}} = n_0 - \Delta_{\mathrm{ADC}}$$

Where:

n_{corr}: corrected pixel intensity
n_0: original pixel intensity
Δ_{ADC}: offset value of the matching amplifier (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	Key
A (single channel)	ADC_ OFFSET_A
B (single channel)	ADC_ OFFSET_B
A (dual channel)	ADC_ OFFSET_DA
B (dual channel)	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 = (36 <DN>, 36 <DN>)              (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:

$$n_{\mathrm{corr}} = n_0 - B(\xi) + C_{\mathrm{T}}(\xi) \cdot (T_{\mathrm{ADC}} - T_0)$$

Where:

n_{corr}:	corrected pixel value
n_0:	pixel value before this calibration step
$B(\xi)$:	bias constant for the specific operational mode ξ, at temperature $T_{\mathrm{ADC}} = T_0$ of the AD converter
ξ:	operational mode of the camera (see below)
T_0:	reference temperature
T_{ADC}:	current temperature calculated as the average of the two ADC temperature sensors on the CCD readout board
$C_{\mathrm{T}}(\xi)$:	bias temperature dependency factor for the specific operational mode ξ

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

$B(\xi)$ 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 synchronization modes for the respective binning

3.3.2 Parameters

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

The correction constants $B(\xi)$ are determined during inflight calibration campaigns, and stored with the following key schemes:

BIAS_Wn_Bn_An_Snn for singe 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 reference temperature T_0 of the bias calibration constants is stored in Kelvin, the temperature coefficient C_{T} in 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        = "NAC_FM_BIAS_V01.TXT"                (example)
BIAS_BASE_VALUES = (235.160 <DN>, 235.160 <DN>)
BIAS_TEMP        = (279.8 <K>, 280.3 <K>)
BIAS_TEMP_DELTA  = (-3.132 <DN>, -3.132 <DN>)
```

3.4 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 in MTP003:

STP003_CALIB_BIAS_001 and 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

No coherent noise removal procedure is implemented in the pipeline.

3.4.2 Parameters

Coherent noise standard deviation:

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 Dark current

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

3.5.1 Methods

Dark frames with exposure times between 1 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 300 s), 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 Laboratory flat fielding

3.6.1 Methods

Laboratory 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 laboratory flat fielding is applied by dividing the original image with the "FLAT_LAB_FILE" image. For all pixels, the applied correction is:

$$n_{\mathrm{corr}} = \frac{n_0}{F_{\mathrm{lab}}}$$

Where:

n_{corr}:	corrected pixel value
n_0:	pixel value before this calibration step
F_{lab}:	value of laboratory flat field image at same pixel location

3.6.2 Parameters

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

3.6.3 Header records

In the PDS header and HISTORY:

```
ROSETTA:FLATFIELD_LAB_CORRECTION_FLAG = TRUE
```

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

```
FLAT_LAB_FILE = "WAC_FM_FLAT_18_V02.IMG"            (example)
```

3.7 Spectral flat fielding

3.7.1 Methods

Laboratory flat field files were acquired with a halogen or xenon lamp spectrum. The variation of the filter band pass with the incidence angle on the filter and the difference of these spectra with respect to the solar spectrum require a spectral correction, which is described in further detail in RD12. The spectral flat fielding is applied by dividing the original image with the "FLAT_SPECTRAL_FILE" image. For all pixels, the applied correction is:

$$n_{\mathrm{corr}} = \frac{n_0}{F_{\mathrm{spec}}}$$

Where:

n_{corr}:	corrected pixel value
n_0:	pixel value before this calibration step
F_{spec}:	value of spectral flat field image at same pixel location

3.7.2 Parameters

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

3.7.3 Header records

In the PDS header and HISTORY:

```
ROSETTA:FLATFIELD_SPECTRAL_CORRECTION_FLAG = TRUE
```

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

```
FLAT_SPECTRAL_FILE = "WAC_FM_SPEC_18_V01.IMG"     (example)
```

3.8 Removal of bad pixels

3.8.1 Methods

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

Bad pixels are areas of the CCD surface that show a non-nominal behavior. 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.

All bad pixels, independent of whether or not a correction is applied, are marked in the quality map.

3.8.2 Parameters

The bad pixel lists [RD10] for the NAC and WAC used by OsiCalliope are listed in Sect. 4. The list indicates the position of the bad pixels, the correction method and the type of issue that the pixels experience in the following form:

```
area_type = (x, y, [w, h,] method, type)
```

3.8.2.1 Single pixels

The method is described as

```
PIXEL = (x, y, method, type)
```

where x and y are the sample and line coordinates, respectively. The correction methods are:

- MEDIAN_CORR: replaces each pixel with the median of the neighboring 8 pixels
- AVERAGE_CORR: replaces each pixel with the average of the neighboring 8 pixels
- NO_CORR: no correction is applied, pixels are marked in the quality map according to their *type*, using the values specified in Sect. 3.16.

3.8.2.2 Columns

The method is described as

```
COLUMN = (x, y, method, type)
```

where x is the column number (sample) and y is the starting line. If y > 0, this parameters specifies the length of the corrected cluster, starting from line y and counting up.

The correction methods are:

- 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 **L**eft or **R**ight neighbors.
- SHIFT2_L_CORR or SHIFT2_R_CORR: corrects column 994 and 996, neighboring column of the bad column 995. It used a method for correcting those columns, which takes into account that the two columns display a different behavior for different illumination and saturation levels. The correction uses a two-parameter algorithm: a constant offset (calculated using the second next columns, to reduce the ADC noise in the low DN range) and a pixel dependent linear component. It should be noted that the correction is skipped in case one of the two parameters is negative. Additionally, the correction is not applied to binned images.

$$n_{\mathrm{shifted}} = n_0 + \Delta$$

$$\Delta = \begin{cases} N_{\mathrm{offset}} & : \text{ if } n_0 \le N_{\mathrm{back}} \\ N_{\mathrm{offset}} + (n_0 - 250) \cdot C & : \text{ if } n_0 > N_{\mathrm{back}} \end{cases}$$

$$N_{\mathrm{offset}} = N_{\mathrm{L2}} - N_{\mathrm{L}}$$

$$C = \frac{N_1 - N_0}{N_0 - N_{\mathrm{back}}}$$

Where:

n_{shifted}	pixel value of the column after the correction is applied
n_0	original pixel value of the column
N_0	mean of the pixels belonging to the column to correct (994 or 996)
N_1	mean of the pixels of the next left or right column (993 or 997)
N_{L}	mean of the pixels with value below BKG_LEVEL of the column to correct (994 or 996)
N_{L2}	mean of the pixels with value below BKG_LEVEL of the second left or right column (992 or 998)
N_{back}	background level, which depends on the number of (unbinned) saturated pixels in the row under correction:

  - 250 if the number of saturates pixels is ≤ 102
  - 500 if the number of saturates pixels is > 102 and ≤ 204
  - 1000: if the number of saturates pixels is > 204

- NO_CORR: no correction is applied, pixels are marked in the quality map according to their *type*, using the values specified in Sect. 3.16.

3.8.2.3 Rectangular areas

The method is described as

```
AREA_R = (x, y, w, h, method, type)
```

where x and y are the starting sample and line, respectively, of the area to be corrected and w and h are the width and the height of the rectangular region to be corrected.

The correction methods are:

- NO_CORR: no correction is applied, pixels are marked in the quality map according to their *type*, using the values specified in Sect. 3.16.

3.8.3 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 = "NAC_FM_BAD_PIXEL_V04.TXT"        (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 time and 1 AU solar distance. In case of filter combinations not having a dedicated stray-light calibration sequence, intensity scaling with a factor s 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 pixel of the image:

$$n_{\mathrm{corr}} = n_0 - \frac{n_{\mathrm{sol}}(\epsilon) \cdot s \cdot t_{\mathrm{exp}}}{d^2}$$

Where:

n_{corr}:	corrected pixel value
n_0:	pixel value before this calibration step
$n_{\mathrm{sol}}(\epsilon)$:	pixel value of solar stray-light image, interpolated for the actual solar elongation ϵ of the camera
s:	intensity scaling factor of solar flux with respect to reference image
t_{exp}:	exposure time in seconds
d:	heliocentric distance in AU

3.9.2 Parameters

The method for generating the solar stray-light reference images is described in RD16. Files used by OsiCalliope are listed in Sect. 4.

3.9.3 Header records

In the PDS header and HISTORY:

```
ROSETTA:OUTFIELD_STRAYLIGHT_CORRECTION_FLAG = TRUE
```

Note that no actual correction is performed by OsiCalliope if the solar elongation is above 90°, since the image is free of solar stray light. In this case the processing flag is set to FALSE.

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

```
SOL_STL_IMAGE = ("NAC_FM_SOL_STL_22_V01.IMG", 1.000000)
                                                (example)
```

The two values correspond to the filename of the reference image and the scaling factor of solar flux s.

3.10 Correction of in-field stray light

3.10.1 Methods

OsiCalliope subtracts the ghost image (see Sect. 3.10.2) from the original image, generating an in-field stray-light (or ghost) corrected image. The prerequisite is that the ghost image is available and that its maximum value is > 0. If those conditions are not met, the generation of the in-field stray-light corrected image is skipped.

3.10.2 Parameters

For each full frame image (with the exception of images with TARGET_TYPE = CALIBRATION), GhostCrawler[2] generates the ghost image, which contains only the in-field stray-light (or ghost) contribution. The filename of the ghost image is the same as the original image (Sect. 6 in AD1), but "ID" is replaced with "GS". A detailed description of the ghost image generation can be found in RD18.

3.10.3 Header records

In the PDS header and HISTORY:

```
ROSETTA:INFIELD_STRAYLIGHT_CORRECTION_FLAG = TRUE
```

In the HISTORY section, the filename of the ghost image and the group GROUP = GHOST_IMAGE_GENERATION are added. This group is copied from the ghost image and contains all the information provided by GhostCrawler about the generation of the ghost image.

3.11 Normalization of the exposure time

3.11.1 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[3].

---

[2] GhostCrawler is a stand-alone application that generates the ghost images. Details can be found in RD18.
[3] The shutter error types are described in the shutter description document [RD2].

3.11.1.1 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:

$$t_{\mathrm{eff}} = t_{\mathrm{comm}} + \Delta t \qquad \text{Eq. 1}$$

Where:

t_{eff}: effective exposure time per line
t_{comm}: commanded exposure time
Δt: 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 line wise effective exposure time t_{eff} 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 t_{eff}

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.

3.11.1.2 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 (2.1 MHz) 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 line wise effective exposure time t_{eff} is calculated using the following equation:

$$t_{\text{eff}} = \Delta t \qquad \text{Eq. 2}$$

  Where:

  t_{eff}: effective exposure time per line
  Δt: actual exposure time per CCD line calculated as the time difference of the shooting and the returning blade

- The average of t_{eff} is the MEAN_EFFECTIVE_EXPOSURETIME
- For the normalization, every image pixels value is divided by the effective exposure time t_{eff}

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[4], depending on the mission time. The correction data and their applicable time periods are given in RD2. If no pre-determined shutter profile can be found, the image is not exposure time corrected and EXPOSURE_CORRECTION_TYPE is set to UNCORRECTED_MISSING_DEFAULT_PROFILE.

3.11.1.3 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. If no pre-determined shutter profile can be

[4] STP095_SHUTTER_PULSE_001, STP101_SHUTTER_TEST, STP102_SHUTTER_TEST

found, the image is not exposure time corrected and EXPOSURE_CORRECTION_TYPE is set to UNCORRECTED_MISSING_DEFAULT_PROFILE.

3.11.1.4 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.

3.11.2 Parameters

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

3.11.3 Header records

In the PDS header and HISTORY:

```
ROSETTA:EXPOSURETIME_CORRECTION_FLAG = TRUE
```

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

```
EXPOSURE_CORRECTION_TYPE    ="NORMAL_PULSES"      (example)
EXPOSURE_CORRECTION_FILE    = "PULSE_DATA"
NUM_OF_EXPOSURES            = 1
MEAN_EFFECTIVE_EXPOSURETIME = 0.3271 <s>
```

3.12 Radiometric calibration

3.12.1 Methods

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

$$n_{\mathrm{rad}} = \frac{n_0}{f_{\mathrm{abs}}}$$

Where:

n_0: pixel value before this calibration step (in DN/s)
n_{rad}: pixel value in radiance units (W/m^2/sr/nm)
f_{abs}: radiometric calibration factor

3.12.2 Parameters

The calibration constants (f_{abs}) 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 Sect. 4.

3.12.3 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"          (example)
ABSCAL_FACTOR  = 4.62665e+08 <(DN/s)/(W/m**2/nm/sr)>
BINNING_FACTOR = 1
```

3.13 Conversion to radiance factor units

3.13.1 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:

$$n_{\mathrm{rf}} = \frac{\pi \cdot d^2 \cdot n_{\mathrm{rad}}}{F_{\mathrm{sol}}}$$

Where:

n_{rf}: pixel value in radiance factor units (unitless)
n_{rad}: original pixel value in radiance units ($W/m^2/sr/nm$)
d: target solar distance in AU (calculated from PDS header Sun and target position)
F_{sol}: solar flux or irradiance at 1 AU at the central wavelength of the filter used ($W/m^2/nm$)

3.13.2 Parameters

The solar flux values (F_{sol}) must be the same that are used in the determination of the absolute calibration coefficients and they are described in the radiometric correction document [RD13]. The correction files [RD13] used by OsiCalliope are listed in Sect. 4.

3.13.3 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/m**2/nm>                (example)
SOLAR_DISTANCE = 1.2582921 <AU>
```

3.14 Correction of geometric distortion and boresight

3.14.1 Methods

Both the NAC and WAC optical layouts are off-axis mirror systems, which provide high transmittance over the UV-VIS-NIR spectral bands and a chromatic aberration free, near diffraction limited performance. However, this asymmetric optical setup has a significant geometrical distortion which must be corrected.

Both cameras are equipped with a set of band-pass filters in the optical path. Material dispersion, manufacturing and mounting tolerances of the filters introduce a boresight shift. Temperature variations of the spacecraft structure and of the camera mounting also introduce a boresight shift.

The image distortion and the boresight shift are corrected by resampling the image following the method described in RD14.

To obtain the distortion corrected and boresight corrected OSIRIS Level 3 (CODMAC L4) images, the OSIRIS Level 2 (CODMAC L3) images are non-linearly stretched (wrapped) according to the distortion removal coefficients.

The correction algorithm stretches the images non-isotropically. Therefore, a certain number of pixels is mapped to positions that are beyond the original image size. In the standard OSIRIS Level 3 (CODMAC L4) images (*ID4n*) the size of the image is identical to the one of the lower processing levels. This implies that the pixels that fall outside the original area are cropped. To retain the full image information, OSIRIS Level 3 (CODMAC L4) images are also stored as enlarged frames (*EF4n*). The size of the enlarged frames is extended compared to the original images by 128/*b* pixels on each side, where *b* is the binning. Enlarged frame images with 1x1 binning have a size of 2304 x 2304 pixels. The correction algorithm uses the same method that is applied to the standard size images, calculating the resampled image coordinates. For consistency, to ensure that all pixels coordinates are positive, all resampled coordinates are shifted by (128/*b*, 128/*b*). Enlarged frame images with 1x1 binning have the image center at (1152, 1152). This position corresponds to the camera boresight location, which is (1024, 1024) in the standard frames. The enlarged frames differ from the standard ones only in terms of size and image center coordinates. All the other photometric properties are identical.

3.14.2 Parameters

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

3.14.3 Header records

In the PDS header and HISTORY:

```
ROSETTA:GEOMETRIC_DISTORTION_CORRECTION_FLAG = TRUE
```

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

```
GEOMETRIC_CORRECTION_FILE     = "WAC_FM_DISTORTION_V02.TXT"
GEOMETRIC_CORRECTION_METHOD   = (POLY4_2D_LUT,POLY4_2D_LUT)
GEOMETRIC_CORRECTION_AVERAGE  = 0.00
FILTER_SHIFT                  = (-0.41, -0.07)
BORESIGHT_TEMP_SHIFT          = -0.36, 1.01)       (example)
```

3.15 Sigma map

In addition to the calibrated frame, the pipeline also creates for each image a map with error estimates (SIGMA_MAP_IMAGE). In OSIRIS Level 3 (CODMAC L4) geometric distortion corrected images, the sigma map is distortion corrected, applying the same resampling method that is used for the IMAGE object.

The sigma map is a float image with the same dimension and unit as the image itself. It is calculated in several steps. It is initialized after image bias subtraction and updated during laboratory flat fielding, spectral flat fielding, exposure normalization, and absolute radiometric calibration. Depending on the processing level it is also updated during conversion to radiance units, and stray-light correction (out-of-field and/or in-field).

The initialization of the sigma map is described in Sect. 3.15.1, the update in Sect. 3.15.2.

3.15.1 Initialization

The error Σ associated to each pixel is initialized from contributions of the Poisson error of the same pixel $\sigma_{\mathrm{Poisson}}$, the constant readout noise error (coherent noise and analog channel noise) $\sigma_{\mathrm{readout}}$, as well as the residual error remaining from the bias subtraction $\sigma_{\mathrm{bias\ model}}$:

$$\Sigma_{\mathrm{init}} = \sqrt{\sigma^2_{\mathrm{Poisson}} + \sigma^2_{\mathrm{readout}} + \sigma^2_{\mathrm{bias\ model}}} \quad .$$

The Poisson statistics are done using the intensity in number of electrons $n_{\mathrm{e-}}$, thus the image intensity n_{DN} has to be converted from DN to number of electrons as

$$n_{\mathrm{e^-}} = n_{\mathrm{DN}} \cdot G \quad ,$$

where the gain G is the number of electrons per DN (same for both cameras, 3.1 $\mathrm{e^-/DN}$ in HIGH gain and 15.5 $\mathrm{e^-/DN}$ in gain LOW mode).

The Poisson error in number of electrons is

$$\sigma_{\mathrm{e-}} = \sqrt{n_{\mathrm{e-}}} = \sqrt{n_{\mathrm{DN}} \cdot G} \quad ,$$

thus the Poisson error converted into DN follows as

$$\sigma_{\mathrm{Poisson}} = \frac{\sigma_{\mathrm{e-}}}{G} = \frac{\sqrt{n_{\mathrm{DN}} \cdot \mathrm{G}}}{\mathrm{G}} = \sqrt{\frac{n_{\mathrm{DN}}}{\mathrm{G}}} \quad . \qquad \text{Eq. 3}$$

The total readout noise error $\sigma_{\mathrm{readout}}$ is determined as the standard deviation of the bias frame as described in Sect. 3.4.

The error remaining from the bias subtraction $\sigma_{\mathrm{bias\ model}}$ was computed from the average of bias subtracted bias frames. Deriving this for all OSIRIS bias frames, the mean is at 0 DN and the standard deviation is 0.68 DN for NAC and for WAC, which we use for $\sigma_{\mathrm{bias\ model}}$.

Values $\sigma_{\mathrm{readout}}$ and $\sigma_{\mathrm{bias\ model}}$ are stored in the OSICALLIOPE _V??.TXT configuration file as tags COHERENT_NOISE and BIAS_TEMP_ERROR. They are reported in the HISTORY of the image headers as READOUT_ERROR_ABS and BIAS_TEMP_ERROR_ABS, respectively.

3.15.2 Update of Sigma Map

Whenever the image is updated in a calibration step, the sigma map is updated accordingly. We define n_{old} and n_{new} as an image pixel value before and after a correction step. Accordingly, the values of the sigma map are Σ_{old} and Σ_{new}, where we know Σ_{old} and want to determine Σ_{new}.

The algorithm discriminates between calibration steps that are

- Multiplication or division in the form of $n_{\mathrm{new}} = n_{\mathrm{old}} \cdot c$ or $n_{\mathrm{new}} = n_{\mathrm{old}} \,/\, c$
- Addition or subtraction in the form of $n_{\mathrm{new}} = n_{\mathrm{old}} \pm c$

The parameter c with its error σ_c is a constant used for calibration, e.g., a flat field pixel value, the absolute calibration factor, etc. Subtraction occurs for the correction of out-of-field and in-field stray light. All other steps are multiplication or division.

For multiplication or division steps, the sigma map is updated as

$$\Sigma_{\text{new}} = |n_{\text{new}}| \cdot \sqrt{\left(\frac{\Sigma_{\text{old}}}{n_{\text{old}}}\right)^2 + \left(\frac{\sigma_c}{c}\right)^2} \quad , \qquad \text{Eq. 4}$$

for addition or subtraction as

$$\Sigma_{\text{new}} = \sqrt{{\Sigma_{\text{old}}}^2 + {\sigma_c}^2} \quad . \qquad \text{Eq. 5}$$

Values and references for absolute errors σ_c or relative errors σ_c/c are provided in Table 1 and implemented in the database files listed in the respective documents and Table 2. These values are also reported in the HISTORY section of the image header (see Sect. 3.15.4).

Table 1 Error components used to update and initialize sigma map.

Calibration Step	**Error description**	**Ref.**
Poisson noise	as of Eq. 3	Sect. 3.15.1
Readout noise	$\sigma_c = 7.6$ DN for NAC, $\sigma_c = 7.1$ DN for WAC	Sect. 3.4
Bias model	constant same for both cameras ($\sigma_c = 0.68$ DN)	RD11
Laboratory flat field	1% flatness of integrating sphere ($\sigma_c = 0.01$)	RD12
Spectral flat field	no error associated ($\sigma_c = 0$)	n/a
Exposure normalisation	depends on shutter mode, see reference	RD2
Radiometric calibration	σ_c from aperture photometry error propagation	RD13
Reflectance conversion	relative error of solar spectrum σ_c/c	RD13
Out-of-field stray light	assume 10% of the corrected signal ($\sigma_c = 0.1 \cdot c$)	n/a
In-field stray light	assume 10% of the corrected signal ($\sigma_c = 0.1 \cdot c$)	n/a

3.15.3 Usage of Sigma Map

The error provided in the sigma map covers all known error sources as described above, which is a mix of statistical pixel-to-pixel variations and systematic errors for a group of images acquired with the same filter and camera. For transparency, all factors used to compute the sigma map are provided with each image in the header HISTORY section. For certain applications, it may be necessary to modify the error map, i.e., add or remove error components. This is possible by applying Eqs. 4 or 5. As an example, to remove multiplicative error components, the equation has to be solved for Σ_{old}, where $n_{\text{old}} = n_{\text{new}}/c$. All necessary information is provided to perform these calculations (in the header and in the calibration database, Sect. 4), which works precisely for all steps except the exposure time normalization where it works as an average over the image.

3.15.4 Header records

The applied error values are listed in the HISTORY. The tag name discriminates between absolute errors (corresponding to σ_c) and relative errors (corresponding to σ_c/c):

```
READOUT_ERROR_ABS          = 7.10 <DN>                 (example)
BIAS_TEMP_ERROR_ABS        = 0.68 <DN>
FLAT_LAB_IMAGE_ERROR_ABS   = 0.01
EXPOSURETIME_ERROR_ABS     = 0.0001 <s>
EXPOSURETIME_ERROR_REL     = 0.000
SOLAR_FLUX_ERROR_REL       = 0.025
SOL_STL_IMAGE_ERROR_REL    = 0.100
GHOST_IMAGE_ERROR_REL      = 0.100
ABSCAL_ERROR_ABS           = 323210.00<(DN/s)/(W/m**2/nm/sr)>
```

3.16 Quality Map

In addition to the calibrated frame and the sigma map, the pipeline also creates for each image a map with quality estimates (QUALITY_MAP_IMAGE). In OSIRIS Level 3 (CODMAC L4) geometric distortion corrected images, each pixel is calculated as a binary OR of the quality estimate for each of the original pixels which contribute to the resampled pixel. This means that if a quality flag is set for any of the contributing pixels, it will be set for the resulting pixel.

The QUALITY MAP is an 8-bit image with the same dimensions as the image itself, containing a quality estimate of each pixel. The quality map exists for OSIRIS Level 2 and higher (CODMAC L3 and higher) images, but not for OSIRIS Level 4 (CODMAC L5) images.

The values in the quality map are composed of a series of 8 bits, with each bit representing a specific effect. If more than one effect affects the pixel, multiple bits are set to 1. The bit values are as follows:

	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
Type	BAD	SAT	-	READOUT	LOSSY	NLIN	SHUTTER	VALID

BAD: Bad pixel
SAT: Saturated pixel (details about the saturation levels can be found in RD9)
READOUT: Pixel affected by readout problem
LOSSY: Lossy compressed pixel
NLIN: Pixel exposed into the non-linear DN range [RD9]
SHUTTER: Pixels affected by shutter non-nominal behavior (for details see RD2)
VALID: Valid pixel (due to packets loss and/or distortion correction a number of pixels may not be valid)

For example, a pixel is valid:

0000 0001b = 1d

And if the same pixel is also saturated:

0100 0001b = (64d + 1d) 65d

3.17 OSIRIS Level 4 and Level 4S (CODMAC L5) image generation

3.17.1 Methods

OSIRIS Level 4 and Level 4S (CODMAC L5) images are PDS compliant .IMG files with 9 layers, generated by OsiCalliope using the OSIRIS Level 3 (CODMAC L4) image and its corresponding georeferencing layers. Details about the georeferencing layers and their generation can be found in the "OSIRIS Georeferenced Data Products" [RD19].

3.17.2 Header records

The used shape model and the generation time of the georeferencing layers are listed, among other keywords, in the GEO_GENERATION group of the HISTORY section.

4 Calibration files used by OsiCalliope

The calibration files used by OsiCalliope to calibrate OSIRIS images are listed in Table 2. Please note that if more than one version of the same file is available, the one with the highest version number is used.

The calibration files are included in each public delivery of OSIRIS data to PSA. The location is specified in the OSIRIS EAICD [AD2].

Table 2 Calibration files used by OsiCalliope to calibrate OSIRIS images and reference document where the files are described.

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
Laboratory flat fielding	NAC_FM_FLAT_??_V??.IMG WAC_FM_FLAT_??_V??.IMG	RD12
Spectral flat fielding	WAC_FM_SPEC_??_V??.IMG	RD12
Bad pixels correction	NAC_FM_BAD_PIXEL_V??.TXT WAC_FM_BAD_PIXEL_V??.TXT	RD10
Exposure time normalization	For *normal* mode: OSICALLIOPE_??.TXT 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 WAC_FM_EXP_20160823_V??.TXT	RD2
Radiometric calibration	NAC_FM_ABSCAL_V??.TXT WAC_FM_ABSCAL_V??.TXT	RD13
Geometric distortion and boresight correction	NAC_FM_DISTORTION_V??.TXT WAC_FM_DISTORTION_V??.TXT	RD14
Solar stray-light correction	OSICALLIOPE_??.TXT NAC_FM_SOL_STL_??_V??.IMG WAC_FM_SOL_STL_??_V??.IMG	RD16
In-field stray-light correction[5]	WAC_FM_GHOST_??_V??.TXT	
Conversion to radiance factor unit	NAC_FM_ABSCAL_V??.TXT WAC_FM_ABSCAL_V??.TXT	RD13
Alignment of synthetic data	GEO_SPICE_SHIFT_V??.TXT	RD19

[5] These data files are used by the GhostCrawler to generate the ghost image. For details see Sect. 3.10.