OSIRIS

Optical, Spectroscopic, and Infrared Remote Imaging System

OSIRIS calibration pipeline OsiCalliope

RO-RIS-MPAE-MA-007

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1/-	29/06/2015	Kovacs	All	first release
1/a	22/2/2017	Tubiana	All	Added Sec. 4 Corrected flat fielding section Moved references to calibration files to Sec. 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		Sec. 2: Added details about missing higher level images Sec. 4: Added note about file version used. Sec. 1.2: Updated SIS Sec. 3.10: Corrected EXPOSURE_CORRECTION_TYPE
1/d	13/02/2018	Tubiana		Updated Sec. 1.5 Updated Figure 1 Updated Sec. 1.6 Updated all figures in Sec. 2: replaced Fig. 4-9 with new Figure 3. Updated Sec. 3.9 Added Sec. 3.10 Updated Table 1. Added WAC_FM_EXP_20160823_V??.TXT to Table 1. Updated Sec. 2) and 3) adding EXPOSURE_CORRECTION_TYPE = UNCORRECTED_MISSING_DEFAULT_PROFILE
1/e	1/3/2018	Tubiana		Added line with "conversion to radiance factor unit" in Table 1. Updated Sec. 3.12.2. Sec. 3.7.2: corrected area_type = (x,y,w,h) and generalized section, removing specific examples. Added L4 section (Sec. 3.16) Sec. 3.2: changed ADC_SW_DN to 2^{14}-1 to be consistent with RD15.
1/f	25/4/2018	Tubiana		Clarified OSIRIS/CODMAC levels Corrected typos Added sentence in Sec. 4 concerning the delivered files

1/g	11/10/2018	Tubiana		Sec. 3.15.2: Added SHUTTER and READOUT to Quality Map. Removed the description of the flags that are not present anymore in the Quality Map. Updated Bad Pixels section (Sec. 3.7). Added PSA compliant filenames to Sec. 1.2 and 1.3.
1/h	3/6/2019	Tubiana		Added correction method to Sec. 3.7. Updated Sec. 2. Updated Figure 3. Updated Sec. 3.10.
1/i	30 Sep 2019	Tubiana	All	Corrected use of Stray-light/stray light. Sec. 3.16: Updated description of quality map generation.

Table of contents

List of Figures

List of Tables

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 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

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 correction parameters	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. (2017): 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 for NAC and WAC	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+; 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.

1.5 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 16 bit unsigned integer image, while OSIRIS Level 2 (CODMAC L3) and higher have 32 bit float image.

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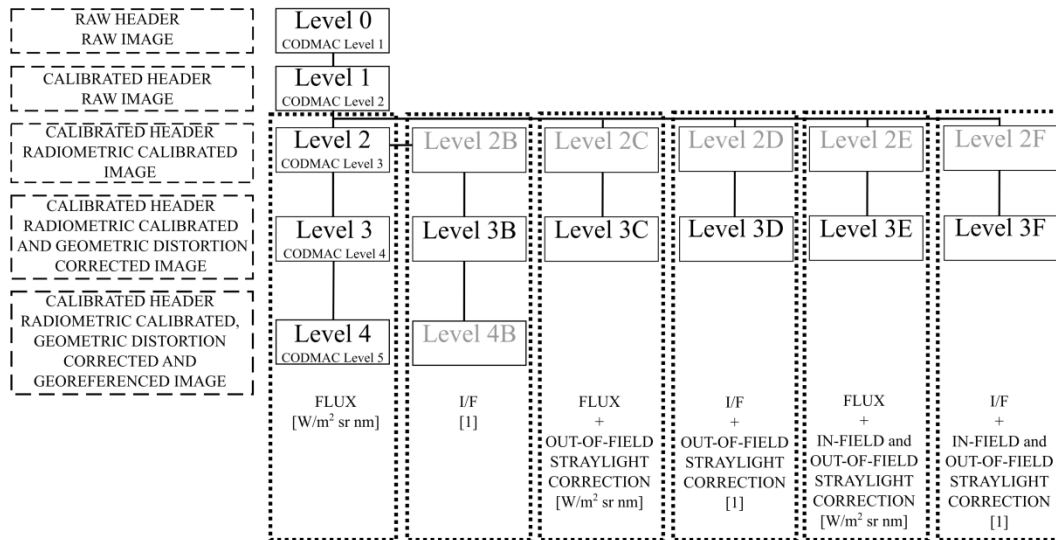
Figure 1 OSIRIS data levels. The grey levels are optional outputs.

1.6 OSIRIS cameras

NAC and WAC use a 2k x 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, do not represent illuminated pixels of the CCD and contain valuable information for readout noise and bias analysis. Pre-pixels are typically binned 8x8 (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.
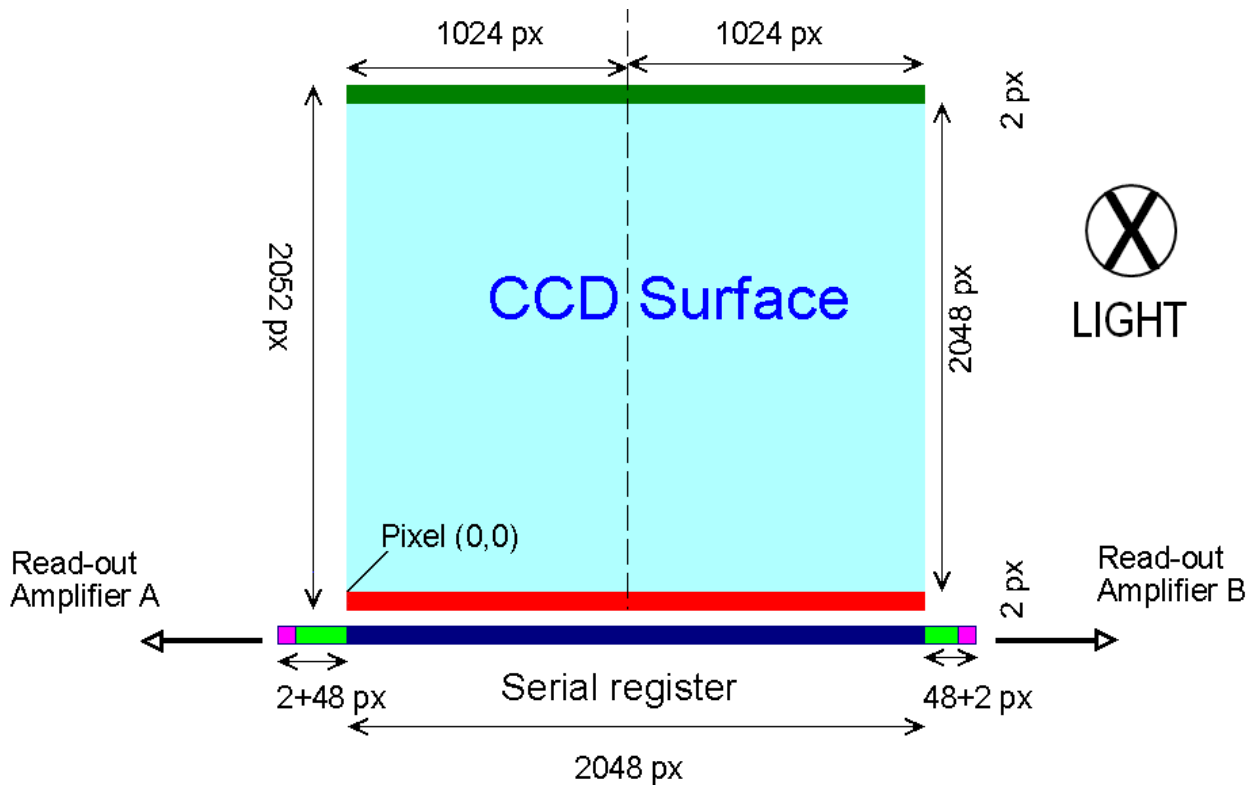
Figure 2 Structure of the OSIRIS CCDs

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 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.

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\level1" and ".\geo" 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.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 OSIRIS Level 1 (CODMAC L2).
2. TARGET_TYPE = STAR / NEBULA: non-reflecting objects. No conversion to radiance 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 radiance 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):
   a. in-field stray-light corrected images (OSIRIS Level 3E / F, CODMAC L4, INFLDSTR / INF-REFL) are generated and stored, if ghost images (RD18) are available.
   b. georeferenced images (OSIRIS Level 4, CODMCA L5) are generated and stored if 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.
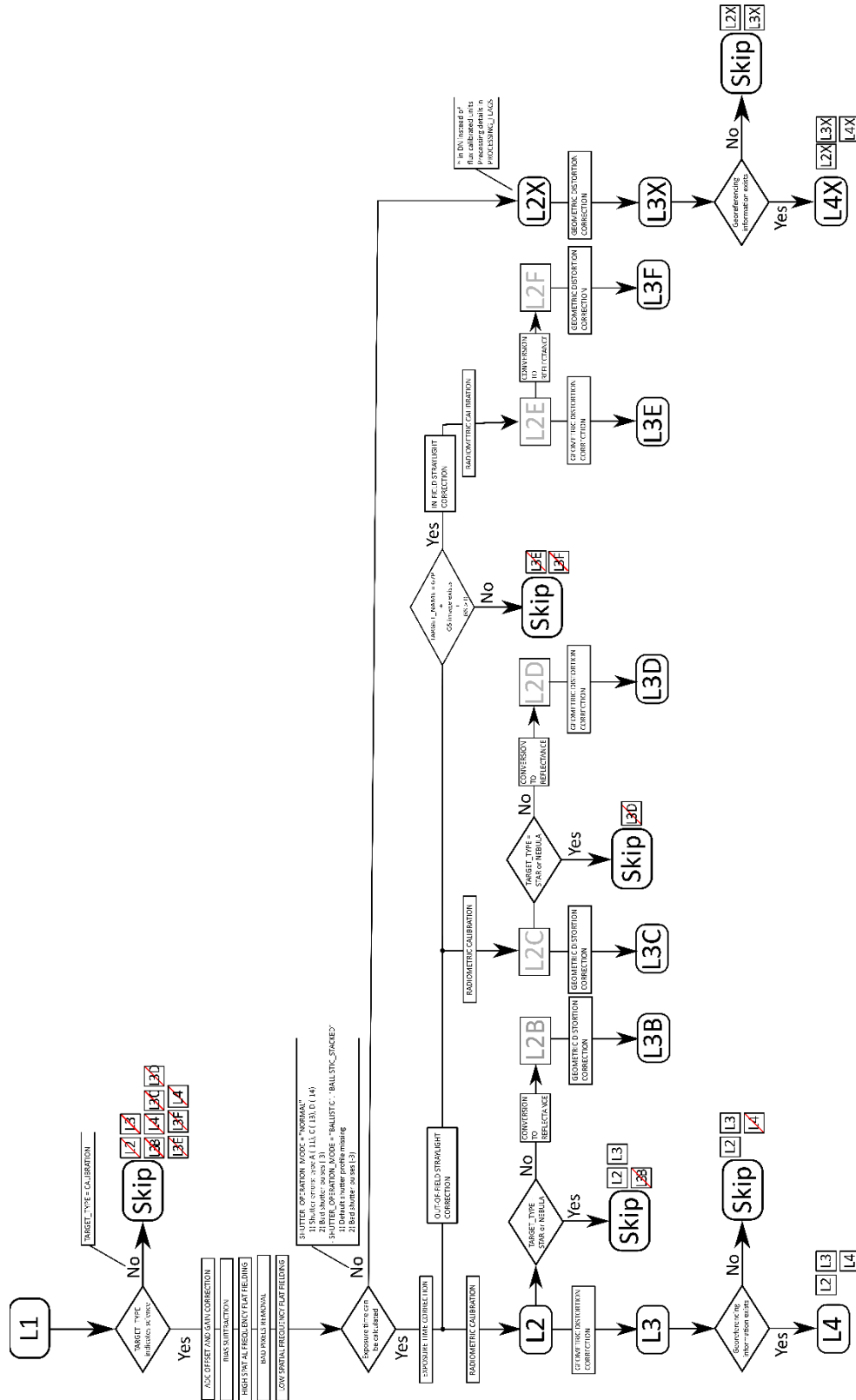
Figure 3 Overview of the OsiCalliope calibration algorithm and image level generation. Please note that the image levels are OSIRIS levels.

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 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]:

$0 \leq DN \leq ADC\_SW\_DN$ ==> ADC-LOW is used

$ADC\_SW\_DN < DN < 2^{16}$ ==> ADC-HIGH is used.

Where:

ADC_SW_DN: switch-over value, set to $16383 = 2^{14} - 1$

DN: analog digital converter (ADC) output value

The two ADCs are adjusted to cover a continuous range linearly but, there is a few DNs 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: corrected pixel intensity

PX_O: original pixel intensity

ADC_{offset}: 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	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 = (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:

$$PX_C = PX_O - BIAS_{OM\_T0} + (T_{ADC}-T_0) \times C_T.$$

Where:

PX_C:	corrected pixel value
PX_O:	original pixel value
$BIAS_{OM\_T0}$:	bias constant for the specific operational mode, at T_0 temperature of the AD converter
T_0:	bias constant reference temperature
T_{ADC}:	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 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 nominal temperature of the bias calibration constants (T_0) 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   = "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 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"   (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 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.

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, the correction method and the type of issue that the pixels experience in the following form:

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

For *single pixels*:

PIXEL = (x, y, method, type)

where x and y are the column 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 Sec. 3.15.2.

For *columns*:

COLUMN = (x, y, method, type)

where x is the column number 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 is an improved version of the previous correction. It used a more complex method for correcting those columns, which takes into account that the two columns display a different behavior for low ($\leq$ 250 DN) and high (> 250 DN) illumination. 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.

$$DN_{SHIFTED} = DN_{ORIGINAL} + \Delta$$

$\Delta = OFFSET$ if $DN_{ORIGINAL} \leq 250$ DN

$\Delta = OFFSET + (DN_{ORIGINAL} - 250) \cdot C$ if $DN_{ORIGINAL} > 250$ DN

$OFFSET = AVG_{L2} - AVG_{L}$

$C = (AVG_{1} - AVG) / (AVG - 250)$.

Where:

$DN_{SHIFTED}$	is the pixel value of the column after the correction is applied
$DN_{ORIGINAL}$	is the original pixel value of the column
AVG	is the median of the pixels belonging to the column to correct (994 or 996)
AVG_{1}	is the median of the pixels of the next left or right column (993 or 997)
AVG_{L}	is the median of the pixels with value below 250 DN of the column to correct (994 or 996)
AVG_{L2}	is the median of the pixels with value below 250 DN of the second left or right column (992 or 998

- NO_CORR: no correction is applied, pixels are marked in the quality map according to their *type*, using the values specified in Sec. 3.15.2.

For *rectangular areas*:

$$AREA\_R = (x, y, w, h, method, type)$$

where x and y are the starting column 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 Sec. 3.15.2.

All bad pixels, independent of whether or not a correction is applied, are marked 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 = "NAC_FM_BAD_PIXEL_V01.TXT"   (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"   (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 pixel of the image:

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

Where:

PX_C: corrected pixel value

PX_O: original pixel value

PX_{iSolSL}: solar stray-light image, interpolated for the actual solar elongation of the camera

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 Sec. 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_IMG = "WAC_FM_SOL_STL_12_V01.IMG"   (example)

3.10 Correction of in-field stray light

3.10.1 Methods

OsiCalliope subtracts the ghost image (see Sec. 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 TARGET_NAME = 67P/Churyumov-Gerasimenko 1, 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 (Sec. 6 in AD1),

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[2] GhostCrawler is a stand-alone application that generates the ghost images. Details can be found in RD18.

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].

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:

$$exp\_time_{effective} = exp\_time_{commanded} + \Delta t \qquad (1)$$

Where:

$exp\_time_{effective}$:   effective exposure time per line

$exp\_time_{commanded}$:   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:

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[3] The shutter error types are described in the shutter description document [RD2].

- 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 $exp\_time_{effective}$ 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 $exp\_time_{effective}$.

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 $exp\_time_{effective}$ is calculated using the following equation:

$$exp\_time_{effective} = \Delta t \qquad\qquad (2)$$

Where:

$exp\_time_{effective}$: 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 $exp\_time_{effective}$ is the MEAN_EFFECTIVE_EXPOSURETIME.

- For the normalization, every image pixels value is divided by the effective exposure time exp_time$_{effective}$.

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

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 Sec. 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   = "BALLISTIC_PULSES"   (example)

    EXPOSURE_CORRECTION_FILE   = "WAC_FM_EXP_20160405_V01.TXT"

    MEAN_EFFECTIVE_EXPOSURETIME = 0.0933 <s>

3.12 Radiometric calibration

3.12.1 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: original pixel value (in DN/s)

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

3.12.2 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.

3.12.3 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.

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

Where:

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

PX_{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)

SFX: 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 (SFX) 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 Sec. 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

3.14.1 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:

$$X_u = \sum_{i,j} kx_{i,j} \cdot X_0^i \cdot Y_0^j$$

$$Y_u = \sum_{i,j} ky_{i,j} \cdot X_0^i \cdot Y_0^j$$

Where the undistorted coordinates (X_u, Y_u) 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 OSIRIS Level 3 (CODMAC L4) images, the OSIRIS Level 2 (CODMAC L3) images are wrapped according to the tabulated kx and ky distortion removal coefficients.

3.14.2 Parameters

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

3.14.3 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"

    GEOMETRIC_CORRECTION_METHOD   = (POLY3_2D, POLY3_2D)

    GEOMETRIC_CORRECTION_AVERAGE   = 5.02

3.15 Generate sigma map and quality map

In addition to the calibrated frame, the pipeline also creates for each image a map with error estimates (SIGMA_MAP_IMAGE) and quality estimates (QUALITY_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. For the quality map, 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.

3.15.1 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:

$$error_{ij} = \sqrt{E_P^2 + E_C^2}, \text{ with } E_P = \frac{\sqrt{N_{ij}}}{N_{ij}}$$

where N_{ij} 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).

NB: $N_{ij} = I_{e_{ij}^-}$, $\sum_{ij} N_{ij} = I_{e^-}$

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

3.15.2 Quality map

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+ (CODMAC L3+) 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 are not valid).

For example, a pixel is valid:

0000 0001b = 1d

And if the same pixel is also saturated:

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

3.16 OSIRIS Level 4 (CODMAC L5) image generation

3.16.1 Methods

OSIRIS Level 4 (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).

3.16.2 Header records

The used shape model and the generation time of the georeferencing layers are listed in the HISTORY:

        GEO_CREATION_TIME   = "2017-12-13T19:21:57"   (example)

        GEO_SHAPE_MODEL   = "cg-dlr_spg-shap7-v1.0_4Mfacets-spc-v2.0.ver"

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.

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

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 *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 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[4]	WAC_FM_GHOST_??_V??.TXT	
Conversion to radiance factor unit	NAC_FM_ABSCAL_V??.TXT WAC_FM_ABSCAL_V??.TXT	RD13

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

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