OSIRIS

Optical, Spectroscopic, and Infrared Remote Imaging System

Shutter parameters for exposure time calculation

RO-RIS-MPAE-TN-073

Issue: 2

Revision: -

20/12/2021

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Document Change Record

Iss./Rev.	Date	Author	Pages affected	Description
D / -	10/07/2014	Kovacs	all	first draft
D / a	11/05/2015	Kovacs	7	added default shutter correction time and counter rollover
1 / -	29/06/2015	Kovacs	all	first release
1 / a	22/2/2017	Kovacs	Sec. 3 and 4	added
1 / b	18/10/2017	Deller	all	Added a description of ballistic mode, clarified calibration file calculations and changed introduction. Added Sec. 5
1 / c	19/02/2018	Deller	all	Updated description and visualization of shutter profiles used for exposure time correction in WAC ballistic operations. Added time when operations using BALLISTIC, BALLISTIC_STACKED and BALLISTIC_DUAL started. Added keyword value UNCORRECTED_MISSING_DEFAULT_PROFILE Updated version of RD5. Sec 5: Removed report on wrongly calibrated images that have been corrected since. Changed reference document RD4 for clarification
1 / d	29/10/2018	Deller	Sec 3.2 Sec 3.3 Sec. 4	Shutter Errors in any ballistic mode can be discarded Added details about the execution time for BALLISTIC_STACKED images, and the correction applied to the START_TIME keyword Increased to WAC_FM_EXP_20160405_V03.TXT
2 / -	20/12/2021	Deller	Sec. 3.3 Sec. 6 Sec. 5	Changed the description of BALLISTIC_STACKED images following new implementation correlating the activations using the camera H/K data stream. Removed Section on validation of ballistic stacking Added Section on backtravel opening

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1 General aspects

1.1 Scope

This document describes the OSIRIS shutter operation modes used during the course of the mission as well as the method and parameters used for calculating the effective exposure time as described in RD5.

1.2 Reference Documents

Documents with version number V?? refer to the latest delivered version of that document.

no.	document name	document number, Iss./Rev.
RD1	OSIRIS user manual	RO-RIS-MPAE-UM-004, D/s
RD2	Transfer function between the encoder measurement and the blades position of the FM WAC SHM	RO-RIS-UPD-TN-W333-219
RD3	Transfer function between the encoder measurement and the blades position of the FM NAC SHM	RO-RIS-UPD-TN-N333-213
RD4	Shutter Interface Drawing	RO-RIS-UPD-DI-NW331 250/2c
RD5	OSIRIS calibration pipeline OsiCalliope	RO-RIS-MPAE-MA-007, 1/d [OSIRIS_CAL_PIPELINE_V??.PDF]
RD6	Operation of the OSIRIS Shutter	RO-RIS-MPAE-TN-082, D/-
RD7	OSIRIS EAICD	RO-RIS-MPAE-ID-015 [OSIRIS_EAICD_V??.PDF]

1.3 Introduction

The OSIRIS WAC and NAC utilize a mechanical shutter for exposure control. The shutters have two parallel moving blades which move in front of the CCD, allowing illumination (exposure) times from a few milliseconds up to several minutes on the detector, limited in principle only by the amounting noise generated by cosmic rays impacting on the CCD. The shutter blades are moved by precisely controlled motors, and their actual position is detected by optical encoders coupled to the motor shafts [RD1]. The shutter drive electronics provide a flexible method to generate arbitrary speed-position profiles for the shutter motion.

The OSIRIS shutter has been operated in various modes that need different exposure time correction to calibrate the resulting images. The operation mode is stored in the keyword SHUTTER_OPERATION_MODE of the image header, and the following modes have been used during the Rosetta mission:

- NORMAL
- BALLISTIC
- BALLISTIC_STACKED
- BALLISTIC_DUAL

To calibrate the images, the exact exposure time of each pixel is essential. The exposure time correction is described in RD5, and the corresponding keyword in the HISTORY section of the header, EXPOSURE_CORRECTION_TYPE, can have one of the following values:

- NORMAL_PULSES
- NORMAL_NOPULSES
- BALLISTIC_PULSES
- BALLISTIC_NOPULSES
- BALLISTIC_STACKED_NOPULSES.

In case of errors, when the images cannot be exposure time corrected, the keyword EXPOSURE_CORRECTION_TYPE will begin with UNCORRECTED, followed by the reason for failure:

- UNCORRECTED_UNKNOWN
- UNCORRECTED_SHUTTER_ERROR_A
- UNCORRECTED_SHUTTER_ERROR_C
- UNCORRECTED_SHUTTER_ERROR_D
- UNCORRECTED_ERROR_PULSES
- UNCORRECTED_MISSING_DEFAULT_PROFILE.

Each shutter blade is driven by a dedicated motor. A position encoding device is mounted to the motor axis on the back side of the motor, creating tick marks by the rotation of the encoder disk to a new angular position. The tick marks are used to form time ticks by a clocked timer on the CCD Readout Board, and subsequently transferred to the DPU for addition to the image data. These shutter time profiles allow a reconstruction of the shutter blade's leading edge position, and are stored together with the images.

The exact time each line of the CCD has been exposed to the light and the effective exposure time can be determined exactly in case the shutter profiles have been acquired and stored together with the image. In this document, the parameters needed for this calculation are described in Section 2.1 and 2.2. If no shutter profiles have been acquired or the shutter pulses cannot be used, either a constant correction value is used as given in Table 1 for exposure time correction, or reference profiles that are described in Section 4.

2 Operation of the shutter mechanism

While the basic operation of both the WAC and the NAC shutter is described in RD6, a short wrap-up of the shutter operation is given here.

The schematic in Figure 1 shows the principal parts of the shutter mechanics. When both blades are in the home position, the CCD is covered by the first blade. When the shutter is activated, the first blade is moved to the side by the motor. Acceleration and therefore the resulting velocity of the blade are controlled by a preloaded shutter driver profile that describes the acceleration curve in a vector of 512 values.

Nominally, the first blade is locked by a latch in the open position. After exposing the CCD the desired time, the second blade is fired and moved, covering the CCD again. When the second blade arrives at the end position, it opens the latch releasing the first blade. Both blades then travel together into the home position without additionally exposing the CCD, driven by pivot elements in the bearings of the four-bar mechanism. As the back travel is not further controlled, it is called a 'ballistic' travel into home position.

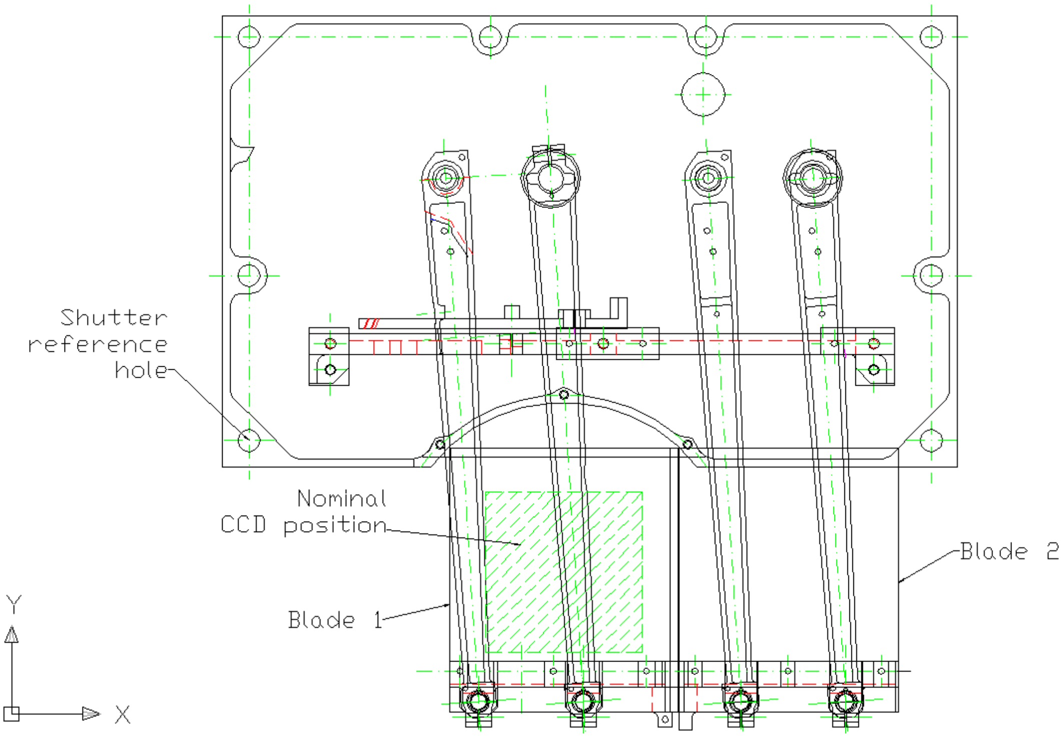


Figure 1 Shutter mechanism

2.1 Shutter parameters

The shutter parameters are used to calculate the blades' cutting edge positions, as a function of the encoder values. They are derived from the mechanical dimensions, measured during system integration [RD2, RD3] and operational tests.

The shutter transfer function is:

$$x = L \cdot [\sin(\Theta_0) + \sin(n \cdot 0.05° + \Theta_z - \Theta_0)] - x_0$$

Where:

- x : cutting edge position of the blade, relative to the CCD edge
- L : shutter arm length
- θ_0 : rotation angle of the shutter arm in nominal (home) position
- n : number of encoder pulses
- θ_Z : rotation angle of the shutter arm from nominal (home) positions, to the zero encoder pulse position
- x_0 : distance between the blade cutting edge and the CCD edge in the nominal (home) position

Table 1 Shutter parameters

Parameter	NAC FM		WAC FM		Source
	Blade 1	Blade 2	Blade 1	Blade 2	
L [mm]	100.00	100.00	100.00	100.00	RD2, RD3
θ_0 [°]	3.56	3.77	4.95	4.16	RD2, RD3
θ_Z[°]	1.025	1.95	1.9	1.2	Calculations*
x_0	8.796	6.956	9.136	7.146	RD2, RD3, RD4
Counter rollover	0	1	1	0	This work*
Default exposure time correction [s]	-0.0027		-0.0025		This work*
*Calculations are based on matching full shutter data of images acquired with ZEROPULSE_FLAG = FALSE and with ZEROPULSE_FLAG = TRUE: - WAC_2008-03-19T21.48.40.651Z_ID10_0000000150_F12.IMG - NAC_2008-02-13T23.05.57.436Z_ID10_0000000200_F21.IMG					

2.2 Exposure time calculation method

The motion of the shutter blades is controlled by the driver electronics, based on a preprogrammed speed profile. Since the velocity is not constant across the CCD surfaces, and the acceleration profiles of the two blades are different, the actual illumination time can only be calculated from the shutter position function. In order to obtain the position-time function, the shutter system uses encoders on the motor shafts. For the precise time base, the electronics utilize a 2.1 MHz clock signal and two separate 14 bit counters, one for each blade. These counters are sampled each time the encoder sends a pulse.

The first counter resets at the exposure start signal when the first blade motor is activated. The second counter resets at the end of the commanded exposure time, when the second blade is activated. In this way the counters deliver a relative time value for each encoder position. Based on the shutter transfer functions (see Section 2.1), the actual positions of the shutter cutting edges are calculated. The time difference between the two shutter functions at the same location over the CCD is used when calculating the value for the line wise exposure time correction factor Δt as described in RD5.

2.3 Shutter activation in test mode

The configuration of the shutter electronics during activation is controlled by setting the shutter control byte mask as described in RD6. This allows the setting of a ‘test’ mode. This mode has two effects: (1) The limitation of the shutter profile to 440 data points is revoked, and (2) all pulses received are stored. Furthermore, the hall senor detecting the locking of blade 1 is disabled, preventing the triggering of TYPE_A errors.

Both effects are needed when operating the WAC shutter in the special ballistic operations modes (see Section 3.2), therefore the majority of images taken in a SHUTTER_OPERATION_MODE that is not NORMAL have been acquired in test mode, while for the majority of images in NORMAL mode the test mode was disabled. If the test mode is enabled, the TESTMODE_FLAG is set to TRUE, otherwise it is set to FALSE. The flag is stored in the SR_SHUTTER_CONFIG group in the image header.

2.4 Acquisition and analysis of the shutter pulses

The shutter pulses are generated and stored only when the position encoders are enabled and the image acquisition configuration includes the storage of the profiles.

In some cases, even if the shutter pulses are stored together with the images, analysis of the shutter pulse data shows that either the pulses cannot be used for calibration of the images, or that the shutter did not work as expected and the image cannot be calibrated altogether.

2.4.1 Shutter pulses not usable for exposure time correction

During the analysis of the shutter pulse data, the position and velocity of the shutter blade edge is calculated. If the shutter pulse data contains less than 400 points, the pulses are not further analyzed, and the image is calibrated using a _NOPULSES type for EXPOSURE_CORRECTION_TYPE.

For successful shutter operation, the blade speed must be higher than 1 m/s when reaching the CCD area (0.0 mm position). If this is not achieved, the exposure time correction mode is set to EXPOSURE_CORRECTION_TYPE = UNCORRECTED_ERROR_PULSES and the image will not be exposure time corrected.

The turning point is determined by the first position where the blade speed falls below 0.1 m/s. For ballistic modes the turning point must be before the locking position (30.0 mm position), otherwise the exposure time correction mode is set to EXPOSURE_CORRECTION_TYPE = UNCORRECTED_ERROR_PULSES and the image will not be exposure time corrected. For the EXPOSURE_CORRECTION_TYPE equal to BALLISTIC_PULSES, the turning point is critical to determine the exposure time per CCD line, as it is calculated as the time difference between the shooting and the returning of the first shutter blade.

The return (home) position is determined by finding the first position during the return phase where the velocity is less than half of the previous two positions velocity.

2.4.2 Counter rollover

Each counter holds the number of clock pulses since its reset. Considering that these units are 14 bit counters, the number will roll over after 16384 pulses. This rollover is partially handled by the on-board software. Partially means, that the spacecraft software examines the sampled values of the counter, and supposing a continuously increasing time, if the value is smaller than the previous one, the rollover number n is incremented and the pulse count is calculated by increasing its value by $n \cdot 16384$. This method should be corrected when the sampling time interval is larger than 16384/2.1 MHz.

2.4.3 The "ZEROPULSE_FLAG"

To ensure a stable reference point for the blades, the encoders provide an additional signal, a "zero pulse" to the electronics. This is a reference point of the encoder, thus not affected by the mechanical elasticity, or wear out. The position of this pulse is not coincident with the shutter nominal (home) position. During the image acquisition the "ZEROPULSE_FLAG" determines the first sampling position of the pulse count:

- ZEROPULSE_FLAG = FALSE: the first sample in the pulse array is the time count at the first encoder pulse (practically the start of the blade motion). In principle this should be corresponding to the rest position, where the blade is physically touching the catch mechanism. Analysis shows that in some cases, the blade actually starts one encoder tick away from the rest position, resulting in one less encoder tick to reach the zero pulse position.

- ZEROPULSE_FLAG = TRUE: the first sample in the pulse array is the time count at the zero pulse position. This gives a more accurate positioning; however the counter rollover during the first time slot must be handled separately.

The keyword ZEROPULSE_FLAG is stored in the image header in the SR_SHUTTER_CONFIG group.

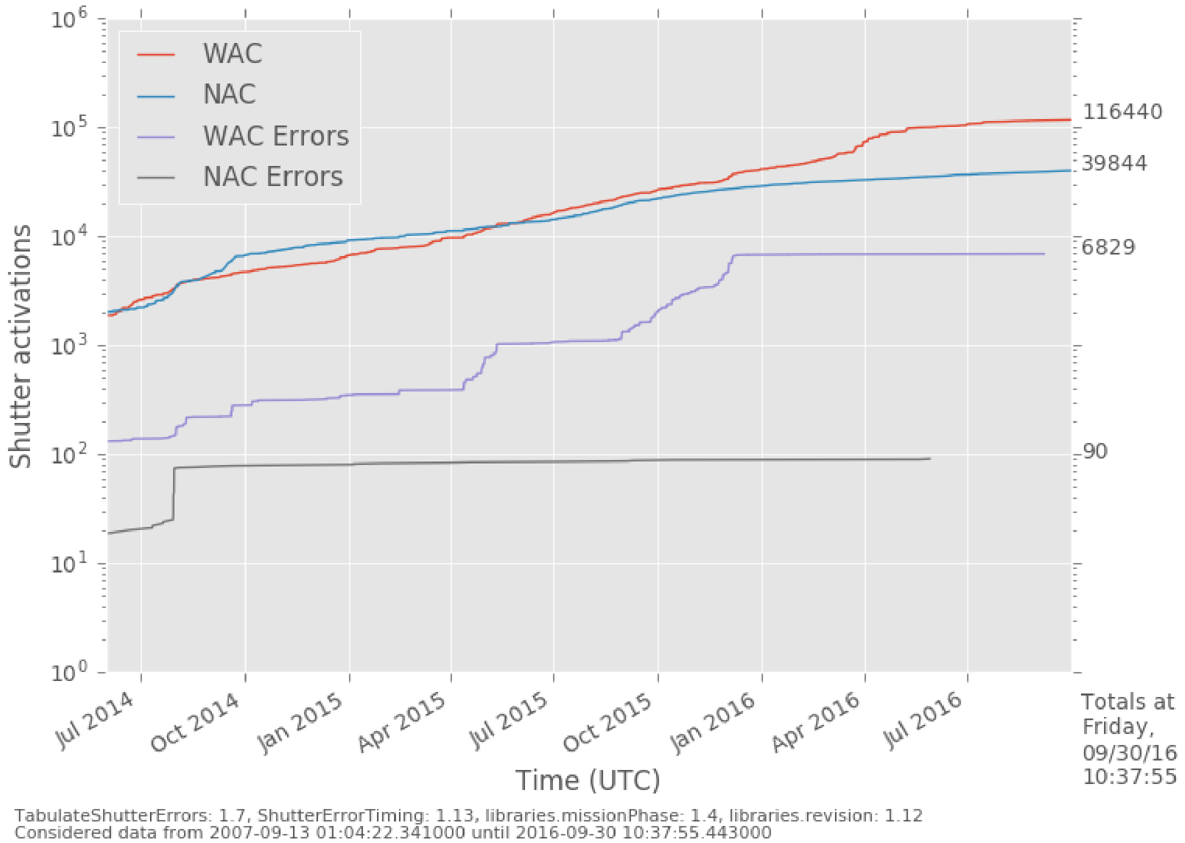


Figure 2 Cumulative number of shutter activations and shutter errors in the course of the mission

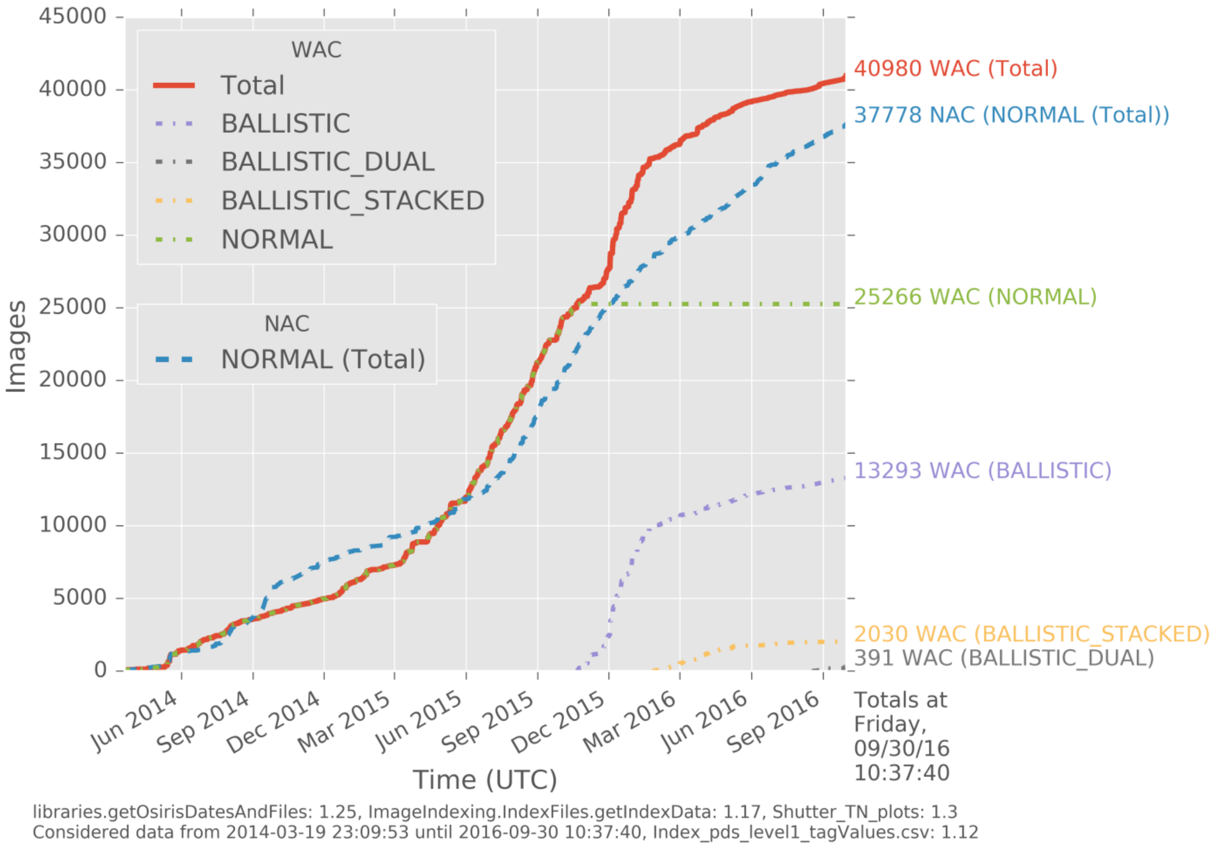
3 Shutter operation modes

The shutter operations manual RD6 describes the nominal operations of the shutter. After the failure of the latching mechanism in the WAC, preceded by a steep increase in shutter errors that can be seen in Figure 2, the nominal operations mode could not be used any more to acquire images, and a series of 'ballistic' modes has been developed to cope with the non-locking of the first blade. These modes require special treatment during the exposure time correction of the calibration pipeline.

The shutter operation mode used to acquire an image is not directly stored in the level 0[1] image file header on board of the spacecraft, but added on ground into the level 1 image header using the

[1] In this document, OSIRIS image levels are used. For the correspondence between OSIRIS and CODMAC levels see Table 1 in the OSIRIS EAICD [RD7].

keyword SHUTTER_OPERATION_MODE that is stored in the SR_SHUTTER_CONFIG group. The number of images acquired in each mode can be seen in Figure 3.



In the following, the characteristics of the shutter operation modes are explained. The details of the exposure time correction methods are described in the next section.

Figure 3 Cumulative number of images per SHUTTER_OPERATION_MODE during comet phase

3.1 NORMAL operation mode

In the NORMAL operation mode the image is acquired according to the description in the shutter manual RD6. The camera is normally configured with test mode disabled. If configured, the 440 data points of the shutter profiles for each blade are attached to the image file and can be used for the exposure time correction. All error conditions can occur. This is the only mode used for all NAC image acquisitions.

In the NORMAL mode of operations, the uniformity of the CCD illumination is better than 1/500. Using calibration data, the deviation of the achieved exposure time to the commanded exposure time was measured, and is given in Table 1.

3.2 The WAC shutter in BALLISTIC operation mode

During summer 2015, the WAC shutter showed an ever increasing number of locking errors (see Figure 2), and eventually failed to lock entirely. To recover science operations, a new operations mode had been implemented, called the “ballistic” mode. This is not described in the shutter operations document [RD6].

In this mode, only the first blade is used (the second blade is disabled). For an exposure, the first blade is fired and moves over the CCD to expose the CCD. The blade is decelerated to reach zero velocity slightly before contacting the latch. The blade then falls back into home position in quasi-ballistic motion driven by spring forces only. This operation mode allows only a fixed exposure time that is different for each line of the CCD, ranging from about 20 ms in the last CCD line to 160 ms in the first CCD line.

The shutter has a sensors that is used to detect whether blade 1 is locked at the beginning of the exposure and unlocked (by blade 2) at the end of the exposure. If those conditions are not met, the hall sensor generates an error (LOCKING_ERROR_A or UNLOCKING_ERROR_C).

In the BALLISTIC operation mode blade 1 never locks, thus for each exposure the hall sensor triggers an error.

To enable the storage of more than 440 data points in the shutter profiles, needed to determine the exposure time per line, the WAC shutter was configured with test mode enabled. This configuration also disables the hall sensor, preventing the shutter to generate errors.

Due to the non-nominal operation of the shutter in ballistic mode the error reporting (due to the hall sensor) is not representative of the quality of the image. Therefore, all ballistic images with SHUTTER_FOUND_IN_ERROR_FLAG = TRUE (acquired with test mode disabled) are as well suited for scientific analysis as images with SHUTTER_FOUND_IN_ERROR_FLAG = FALSE (acquired with test mode enabled).

Science operations using the WAC in BALLISTIC mode started on 2015-11-15T00:00:00, the first image acquired in this mode is WAC_2015-11-15T11.11.44.411Z_ID10_\ 1397549300_F18.IMG, acquired on 2015-11-15T11:13:04.990 for activity STP082_ONIT_082. The first science image using this mode is WAC_2015-11-18T10.56.36.611Z_ID??_\ 1397549000_F13.IMG, acquired on 2015-11-18T10:57:57 during activity STP083_DUST_JET_001. The validity of the average correction file (see below) starts at 2015-11-20T09:00:00.

3.2.1 Tweaking of shutter parameters for the WAC ballistic operation mode.

During the introduction of this mode, the shutter profile parameters where slightly tweaked to enhance performance and repeatability. After extensive testing during October and November 2015, an initial configuration for the ballistic mode was found. The only parameter to improve was the CCD travel distance that describes the distance after which the blade is supposed to decelerate to stop and turn to 'fall' back to the home position. If this parameter is set too large, the blade might make contact to the latch and bounce back, leading to unpredictable behavior and therefore a large spread in flight profiles at the last CCD lines. On the other hand, if the parameter is chosen too short, a part of the CCD is not well illuminated and lost for scientific imaging. Figure 4 shows the value of this parameter from the first test images in ballistic mode.

The average profiles of a number of test shots for each of these parameter sets can be seen in Figure 5. These profiles are used to during calibration for the exposure time correction if there are no profiles attached to the image files. The validity epochs of these data as well as the value of the CCD travel distance used and the sequences containing the test data are listed in Table 2 and visualized in Figure 4.

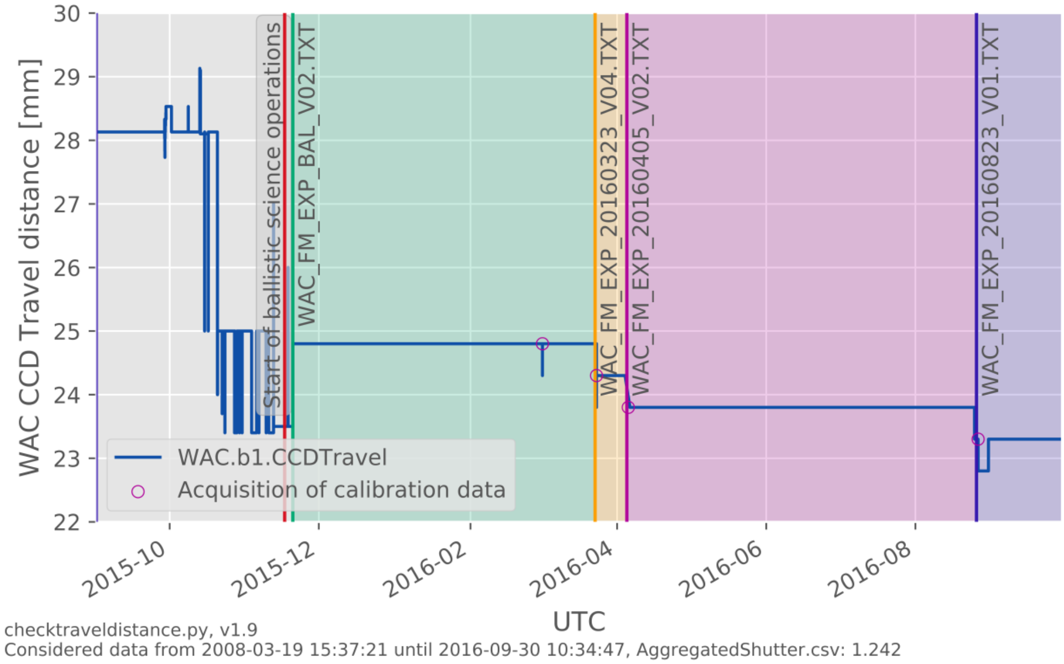


Figure 4 Value of the WAC CCD travel distance. Indicated is also the validity periods of the average shutter profile files used for exposure time correction in the ballistic operation mode.

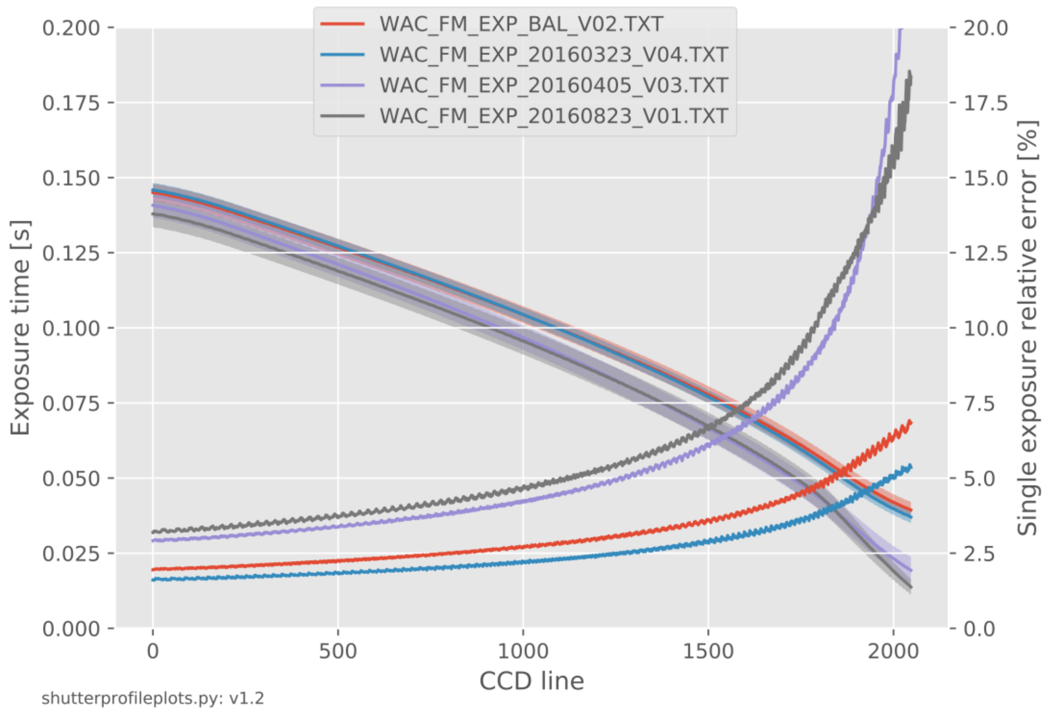


Figure 5 Average exposure time (left axis) and relative error of the average exposure time for a single shutter activation (right axis) per CCD line as derived from the datasets in Table 2 in the ballistic mode in 4 different configurations. See Table 2 for a definition of the sequences.

3.3 The WAC shutter in BALLISTIC_STACKED operation mode

Because of the fixed (and very short) exposure time in ballistic mode, the amount of light collected during one exposure was not sufficient to allow the usage of all but the brightest filter combinations. A single BALLISTIC mode exposure was fine to image the comet nucleus, but not deep enough for the surrounding coma. To enable the detection of the faint structure in the dust and gas coma the BALLISTIC_STACKED mode was implemented.

In this mode, the CCD is exposed during multiple activations of the shutter in ballistic mode, without being read out in between, therefore accumulating the charge in the CCD.

The BALLISTIC_STACKED mode had to be commanded in the bulb mode, using a series of TCAcquireImage and TCMonitorObservation commands, significantly increasing the number of telecommands used by OSIRIS.

The number of repeated shutter activations and the timing of the repeats define the duration of a sequence. The commanding implementation was optimized during the first weeks of execution.

The shutter activations in a stacked exposure are not equidistantly distributed over the total duration, but follow, in most cases, the scheme below. For a stack of n exposures:

- First shutter activation starts at the corrected start time ($START\_TIME_{cor}$)
- 2 seconds delay
- $n - 2$ shutter activations executed as fast as possible: The shutter mechanism is activated after all capacitors are recharged. Due to command buffer limitations, the maximum number of shutter activations in a single command is 50. If $n > 50$, the shutter activations were split in separate commands.
- Last shutter activation finishes at the corrected stop time ($STOP\_TIME_{cor}$).

After the completion of the n shutter activations, the CCD is read out by ending the bulb mode and the image header is generated. This command tries to activate the inhibited second blade, and as the Hall sensor subsequently does not detect a blade reaching the end of the CCD, a Shutter Error D event is reported.

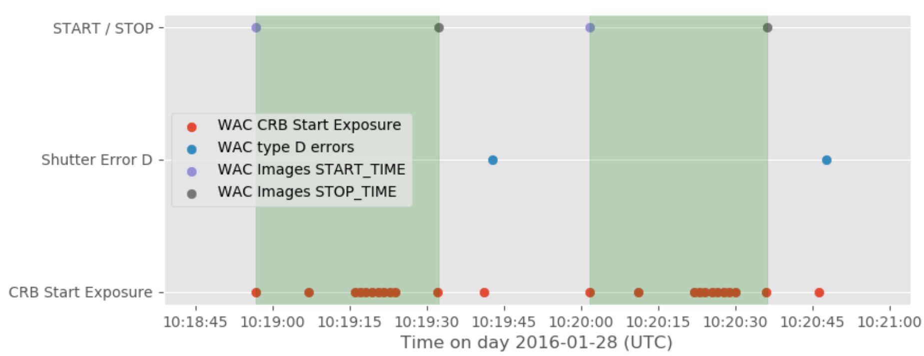


Figure 6 START_TIME, STOP_TIME of images WAC_2016-01-28T10.18.18.649Z_ID??_1397549211_F17.IMG and WAC_2016-01-28T10.19.23.675Z_ID10_1397549711_F18.IMG, and the time of “Shutter Error D” and “CRB Start Exposure” events in the H/K data stream.

The START_TIME and STOP_TIME coming from this last command have to be corrected to set START_TIME to the time of the start of the first shutter activation, and STOP_TIME to the time when the last shutter activation was finished.

Each activation of any shutter blade is reported as "CRB Start Exposure" Event to the camera H/K data stream. These events can be correlated to a ballistic stacked exposure as the final command to read out the CCD activates the inhibited second blade, producing a "Shutter Error D" event (see Figure 6). Knowing the number of stacked images, the START_TIME of the image is set to the time of the first "CRB Start Exposure" event, and the STOP_TIME to the last event of a shutter blade 1 activation with the average time of a ballistic shutter activation of 150 ms added.

The time of each shutter blade 1 activation relative to START_TIME is stored in the keyword ROSETTA:STACKING_ACTIVATIONS.

As example, for the image WAC_2016-01-28T10.18.18.649Z_ID**??** _1397549211_F17.IMG the following is reported:

START_TIME = 2016-01-28T10:18:56.828

END_TIME = 2016-01-28T10:19:32.276

ROSETTA:STACKING_ACTIVATIONS = (0.000 19.300 20.340 21.357 22.458 23.711 24.799 26.034 27.082 35.298)

Please note that the duration START_TIME to STOP_TIME of the total image stacking sequence is much longer than the actual summed exposure time given by the number of stacked exposures (n) times the average exposure duration of a single exposure in ballistic mode.

No blade 1 shutter profiles can be stored for stacked images. Therefore these images have to be calibrated using the average profiles described in Table 2 and Figure 5. In this case, the relative error of the exposure time correction scales down with $1/\sqrt{n}$ for an image with n shutter activations.

Images with up to 100 shutter activations have been commanded. Operations using the mode started on 2016-01-27T00:00:00, the first science image using this mode is WAC_2016-01-27T07.05.45.471Z_ID??_1397549550_F17.IMG, acquired on 2016-01-27T07:07:08.082.

An error is associated with all BALLISTIC_STACKED images: SHE_RESET_ERROR_D. This error is generated any time none of the shutter blades move and therefore the camera does not receive shutter pulses. This error is generated by the last stacking command, which reads out the CCD without any blade movement, since in ballistic mode blade 2 is disabled.

As for the ballistic non-stacked images, the error reporting is not representative of the quality of the image: all BALLISTIC_STACKED images with SHUTTER_FOUND_IN_ERROR_FLAG = TRUE are suited for scientific analysis.

3.4 The WAC shutter in BALLISTIC_DUAL operation mode

In the planning of the final descent sequence during the end of mission it was recognized that the surface brightness of the comet at the distance and phase angle planned would saturate the CCD when operating in BALLISTIC mode. Therefore the definition of a new mode of operation was necessary.

In the BALLISTIC_DUAL operation mode, both blades of the WAC shutter where used again.

The first blade is fired, and using a power profile similar to the one used in BALLISTIC mode slowed down before reaching the position of the latch. The second blade is fired 15 ms after the first blade, with a similar power profile. The second blade is slowed down as well, and both blades travel together back into the home position driven by the bearing spring with a small current in the motor of the first blade to try to prevent reopening of the slit between both blades.

In this mode, the lower part of the CCD is exposed evenly with 15 ms exposure time. Only the last lines of the CCD are affected by a slightly more uneven exposure. Therefore the exposure time correction is equivalent to images taken in NORMAL shutter operation mode. Because during the final descent in an effort to minimize data volume no shutter profiles where acquired, all BALLISTIC_DUAL images are corrected with EXPOSURE_CORRECTION_TYPE = NORMAL_NOPULSES.

Start of the science operations with BALLISTIC_DUAL was 2016-09-27. The first scientific image using WAC shutter operation mode BALLISTIC_DUAL is WAC_2016-09-27T22.28.36.427Z_ID??_1397549000_F12.IMG, acquired at 2016-09-27T22:30:05.895 during activity STP129_APPROACH_REHEARSAL.

During the final descent of the spacecraft, 114 images including the very last one have been taken in BALLISTIC_DUAL operation mode.

4 Error of exposure time determination

There are two main contributors to errors in the determination of the exposure time: The determination of the time between activation of the first and the second blade, and the variation in blade velocity during the shot.

For images in NORMAL exposure mode, the line-wise correction that is the relative time between the first and second blade at a CCD line position has a negligible error compared to the timing of the shutter activations. The timing error of the effective exposure time t_{exp} per line l has been estimated to a value of

$$\sigma_{t_{\text{exp}}}(l) = 0.1\ \text{ms}\ .$$

For images in BALLISTIC exposure modes, only the first blade is activated and the only error source is in the line-wise exposure time. In case the shutter profile is supplied with the image, e.g. EXPOSURE_CORRECTION_TYPE = BALLISTIC_PULSES, the line-wise exposure time is estimated to have an accuracy of

$$\sigma_{t_{\text{exp}}}(l) = 1.0\ \text{ms} + 0.01 \cdot t_{\text{exp}}(l)\ .$$

If no shutter profile is available, e.g. for EXPOSURE_CORRECTION_TYPE = BALLISTIC_[…]_NOPULSES, in principle the error is given by the repeatability of the shutter profile. This can be estimated from the line-wise standard deviation in the average exposure time profiles seen in Figure 5 and ranges between 2.5% for the first lines and up to 19% for the last CCD lines. However, the NOPULSES exposure correction types are mostly used in ballistic stacked images, where the total error of the exposure time is reduced by the number N of repeated shutter activation, $\sigma_{\text{ballistic}} = \sigma_{\text{single}}/\sqrt{N}$. For typical images of $N = 20$ this gives a standard error for the first line $\sigma_{\text{ballistic}}(l = 1)$ of 0.55% corresponding to $0.8\ \text{ms}$ and for the last line $\sigma_{\text{ballistic}}(l = 2048)$ of 4% or $1.0\ \text{ms}$. The equation to calculate $\sigma_{\text{t}_{\text{exp}}}$ used for EXPOSURE_CORRECTION_TYPE = BALLISTIC_PULSES is even more conservative than these values. Therefor it was decided to apply the same equation for the error estimate in all ballistic exposure types.

5 Backtravel opening

In the time frame of January and February 2015 (planning phase MTP012 and MTP013), about 70 NAC images were affected by a shutter mechanism malfunction. After the end of exposure, when both blades traveled back to the home position, there was a small gap between the blades and extra light could reach the CCD during readout. This *backtravel opening* shows as vertical stripes on the images, resembling a curtain. Details on the shutter operation can be found in [RD4]. This additional flux cannot be corrected from affected images but the affected areas are flagged in the QUALITY_MAP_IMAGE (bit 1, see [RD5]) and the 4th entry in DATA_QUALITY_ID is set to 1.

The following is implemented in the database to mark the affected area for these images:

> *AREA_R = (0, 0, 2048, 2048, NO_CORR, 2)*
> *Note: This is only applied for images that are affected by the NAC backtravel opening, which is flagged in the DATA_QUALITY_ID in the image header.*

During the end of the Rosetta mission, the WAC mechanical shutter was operated in the so called BALLISTIC_DUAL mode (details in in [RD4]). Due to an imperfect blade travel, this resulted in an opening of the two blades in the upper part of the full frame image (in Rosetta standard orientation), thus extra light. This additional flux cannot be corrected from affected images but the affected areas are flagged in the QUALITY_MAP_IMAGE (bit 1, see [RD5]) and the 5th entry in DATA_QUALITY_ID is set to 1.

The following is implemented in the database to mark the affected area for these images:

> *AREA_R = (0, 1536, 2048, 512, NO_CORR, 2)*
> *Note: This is only applied for images that are affected by the WAC backtravel opening, which is flagged in the DATA_QUALITY_ID in the image header.*

6 Calibration files used by OsiCalliope

For EXPOSURE_CORRECTION_TYPE equal to NORMAL_NOPULSES, the exposure time correction is constant for all lines of the CCD and given in Table 1 of this document.

When no shutter profile information is available for images taken by the WAC in the shutter operation mode of either BALLISTIC or BALLISTIC_STACKED, OsiCalliope uses average shutter profile data for calibrating the exposure time using EXPOSURE_CORRECTION_TYPE equal to BALLISTIC_NOPULSES or BALLISTIC_STACKED_NOPULSES.

Due to changes in the shutter configuration, these profiles had to be updated. The sequences used to acquire the data and the validity epochs are listed in Table 2. Each sequence contains 50 to 200 shutter activations acquiring the shutter profiles for each image. For each image, the line wise exposure time is calculated using the algorithm described for correction type NORMAL_PULSES in RD5:

- The shutter pulse array contains the number of clock pulses (2.1 MHz) 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 [RD2, RD3].
- The blade position – time function is calculated.
- The difference of the above functions for the two blades at a certain CCD position gives the actual exposure time, for a given pixel. The average of these values is the MEAN_EFFECTIVE_EXPOSURETIME
- The exposure time is calculated as the difference of the above functions for the two blades at each CCD line position.

The profiles listed in Table 2 are calculated as the line-wise average of exposure times for all files in the sequence and shown in Figure 5. Because the shutter profiles are varying, the flux error caused by varying exposure times can be significant. In Figure 5 it can be seen that the relative error is greater than 5% for the lower half of the CCD (after line ~1080) and reaches 10% from line 1770 for the profile WAC_FM_EXP_20160405_V03.TXT used from April 2016 on (See Table 2). For stacked images, this relative error scales down with $1/\sqrt{n}$ for an image with n shutter activations.

Table 2 Acquisition sequences for shutter profiles used in ballistic mode. The file version is given as the lowest version where the ACTIVITY_NAME is valid.

Filename	CCD travel distance [mm]	ACTIVITY_NAME	Acquisition date	Validity epoch
WAC_FM_EXP_BAL_V02.TXT	24.8	STP097_SHUTTER_PROFILE*	2016-03-01	2015-11-20T09:00:00 to 2016-03-22T23:59:59
WAC_FM_EXP_20160323_V04.TXT	24.3	STP101_SHUTTER_TEST*	2016-03-23	2016-03-23T00:00:00 to 2016-04-05T12:00:00
WAC_FM_EXP_20160405_V03.TXT	23.8	STP102_SHUTTER_TEST	2016-04-05	2016-04-05T12:00:00 to 2016-08-26T17:01:29
WAC_FM_EXP_20160823_V01.TXT	23.3	STP123_SHUTTER_TEST§	2016-08-26	2016-08-26T17:01:30 to 2016-09-30T23:00:00
*last 100 images in activity §Images in activity with sequence number 36 to 85				

When no shutter profile information is available for images taken by the WAC in the shutter operation mode of either BALLISTIC or BALLISTIC_STACKED and no valid average correction profile can be found (e.g. for some images in STP083_ONIT_083 taken 2015-11-18), the image is no exposure time corrected and EXPOSURE_CORRECTION_TYPE is set to "UNCORRECTED_MISSING_DEFAULT_PROFILE".