International Conference on Space Optics—ICSO 2018

Chania, Greece

9–12 October 2018

Edited by Zoran Sodnik, Nikos Karafolas, and Bruno Cugny

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A. Slemer

E. Simioni

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International Conference on Space Optics — ICSO 2018, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 11180, 111807R · © 2018 ESA and CNES · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2536198

SIMBIO-SYS STC ready for the first light: the radiometric calibration

A. Slemer[a]*, E. Simioni[b], V. Da Deppo[a,b], C. Re[b], M. Dami[c], D. Borrelli[c], I. Ficai Veltroni[c], G. Aroldi[c], L. Tommasi[c], M. T. Capria[d], G. Naletto[e,a], R. Mugnolo[f], M. Amoroso[f], G. Cremonese[b]

[a]CNR-IFN, Via Trasea 7, 35131 Padova, Italy; [b]INAF-OAPD, Vicolo dell'Osservatorio 5, 35122 Padova, Italy; [c]Leonardo S.p.A., Via delle Officine Galileo 1, 50013 Campi di Bisenzio, Firenze, Italy; [d]INAF-IAPS, Via del Fosso del Cavaliere 100, 00133 Roma, Italy; [e]University of Padova, Department of Physics and Astronomy, Via Marzolo 8, 35131 Padova, Italy; [f]ASI, Via del Politecnico, 00133 Roma, Italy

ABSTRACT

The Stereo Channel (STC) is a double wide-angle camera developed to be one of the channels of the SIMBIO-SYS instrument onboard of the ESA BepiColombo mission to Mercury. STC main goal is to map in 3D the whole Mercury surface.

The geometric and radiometric responses of the STC Proto Flight model have been characterized on-ground during the calibration campaign. The derived responses will be used to calibrate the STC images that will be acquired in flight. The aim is to derive the functions that link the detected signal in digital number to the radiance of the target surface in physical units.

The result of the radiometric calibration consists in the determination of well-defined quantities: i) the dark current as a function of the integration time and of the detector temperature, nominally fixed at 268 K; ii) the Read Out Noise, which is associated with the noise signal of the read-out electronic; iii) the Fixed Pattern Noise, which is generated by the different response of each pixel; iv) once these quantities are known, the photon response and the Photo Response Non-uniformity, which represent the variation of the photon-responsivity of a pixel in an array, can be derived.

The final result of the radiometric calibration is the relation between the radiance of an accurately known and uniform source, and the digital numbers measured by the detector.

Keywords: BepiColombo, STC, Radiometric calibration, CMOS detector

1. INTRODUCTION

In order to reconstruct the geological history of Mercury, a detailed identification of the planet surface is needed. It includes the crustal differentiation and resurfacing, the volcanism, the tectonics and the surface/atmosphere interaction. To investigate these topics, good spatial resolution data are needed. A crucial role in the analysis of geological and mineralogical features of Mercury surface will be provided by the Spectrometer and Imagers for MPO BepiColombo-Integrated Observatory SYStem (SIMBIO-SYS) instrument suite [1].

SIMBIO-SYS includes two imaging systems with stereo and high spatial resolution capabilities, which are the STereoscopic imaging Channel (STC) and the High Resolution Imaging Channel (HRIC), and a hyperspectral imager in the V-NIR range, named Visible and near Infrared Hyperspectral Imager (VIHI). STC performs 58-120 m spatial resolution global mapping in stereo mode and coloured imaging of selected areas; HRIC is a camera for high resolution imaging (6-12 m/px) in panchromatic and broad-band (BB) filters; VIHI performs imaging spectroscopy in the 400-2000 nm spectral range. A highly integrated concept is adopted to maximize the scientific return and minimize the resource requirements, primarily mass and power.

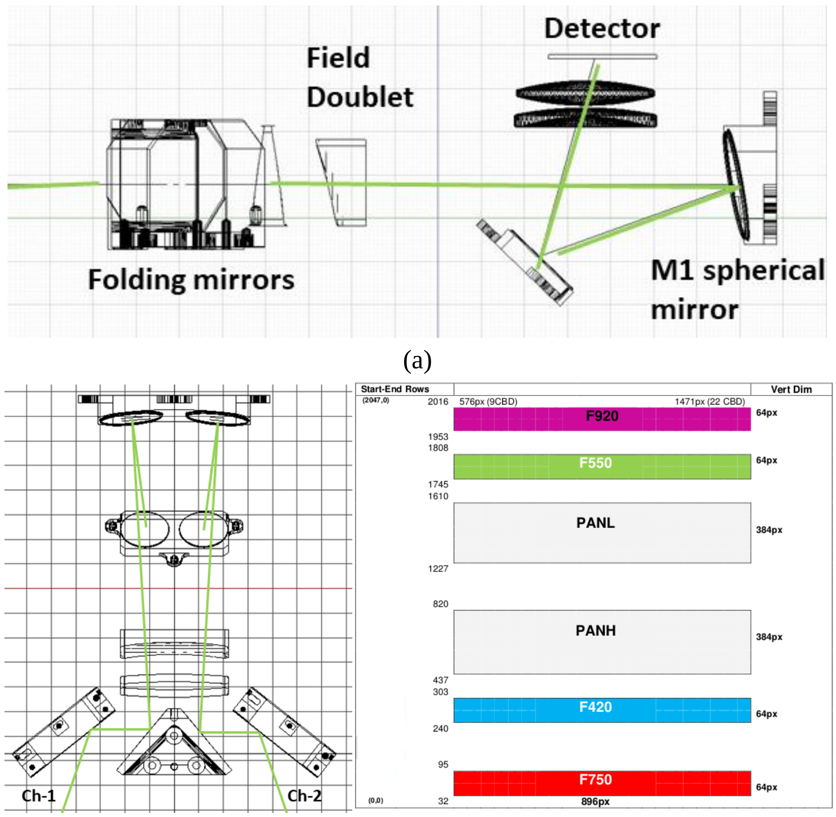
The main scientific goal of SIMBIO-SYS is to map the Mercury surface in different wavelengths and with different spatial resolutions to investigate the morphology and chemical composition of the planet surface.

*alessandra.slemer@pd.ifn.cnr.it;

The paper is structured as follows. In section 2 a brief description of the STC optical concepts is reported; section 3 is dedicated to the description of the on-ground calibration setup and to the definition of the radiometric calibration pipeline; section 4 reports the preliminary results and some corollary considerations.

2. THE STEREO IMAGING CHANNEL

The STC channel is a stereo-camera that consists in two sub-channels which deflect the light, coming from two different directions, on one common detector [2] (see Figure 1). The two STC sub-channels are named H (High) and L (Low) following their position with respect to the mounting interface on the S/C. For each sub-channel, STC can acquire simultaneously three quasi-contiguous areas of the Mercury surface in different colors, one panchromatic and two BB [3]. The central ray of the panchromatic filter of each sub-channel forms an angle of ±20° with respect to the nadir direction.



(b) (c)

Figure 1: STC optical scheme (panels *a* and *b*), and detector configuration (panel *c*).

The characteristics of the STC optical design and the scientific requirements have been summarized in Table 1. STC is different from conventional on-axis reflecting and catadioptric telescopes, such as Schmidt and Maksutov. It has an off-axis configuration with no central obstruction in its light path and no spiders, or other support structures, which could impact on the MTF and PSF of the system.

The pair of folding mirrors, located at the entrance of each optical sub-channel, guides the incoming light to a common Schmidt modified telescope. The telescope has a focal length of 95.2 mm.

The camera is equipped with four BB filters, each one having 20 nm bandwidth (centered at 420 nm, 750 nm, 550 nm and 920 nm), and two panchromatic (PAN) filters, whose bandwidth is 200 nm, centered at 700 nm. The filters are mounted on the detector, following the configuration shown in panel (c) of Figure 1.

Table 1: Optical characteristics and scientific requirements of STC [4].

Optical characteristics	
Optical concept	Catadrioptic: off-axis portion of a modified Schmidt telescope with folding mirror fore-optics
Stereo solution	Two optical channels with detector and most of the optical elements in common
Focal length	95.2 mm
Pupil size	15 mm (diameter)
IFOV	105 μrad/px
Focal ratio	f/6.3
Distortion	<1.6%
FoV(cross track)	5.38°
FoV(along track)	2.4° for panchromatic/0.38° for color filters

The nominal FoV of each sub-channel is 5.38° × 4.8°, which includes gaps, while the scientific useful FoV is 5.38° × 3.07°. The latter FoV is divided in three portions that correspond to the filters of the considered sub-channel: 5.38° × 2.31° for the PAN filter, and 5.38° × 0.38° for each color filter. STC will perform 58-120 m spatial resolution global mapping in stereo mode and colored images of selected areas in color mode.

The STC detector is a 2048 × 2048 hybrid Si-PIN based on CMOS technology, back-illuminated, 10 μm of pixel size and a dynamic range of 14 bit. The Integrated Then Read (ITR) technology allows to avoid a mechanical shutter. The choice of this detector has been driven by three reasons: (i) to acquire images with the lowest possible integration time (IT), (ii) to reach the fill-factor of 100%, and (iii) to avoid the detector degradation due to radiations. Using this detector, it is easy to obtain millisecond exposure times that are needed to reduce the possible image smearing, due to the motion of the S/C with respect to the Mercury surface.

3. ON GROUND RADIOMETRIC CALIBRATION PIPELINE

The geometric and radiometric responses of the STC Proto Flight Model (PFM) have been characterized on-ground during the calibration campaigns. The derived responses will be used as starting point for the calculation of the calibration key data parameters that will be refined with the in-flight calibration.

The calibration pipeline to convert the raw data images into images whose pixel value is expressed in physical units includes dark removal, radiometric conversion and geometric distortion correction. In this section we briefly describe the experimental set-up used for the instrument calibration and the procedure developed to derive the calibrated images.

3.1 Calibration set-up

The Optical Ground Support Equipment (OGSE) used for the STC calibration was developed by Leonardo S.p.A. The OGSE is composed of different elements: 1) the Thermal Vacuum Chamber (TVC), where the STC PFM is mounted; 2) the TVC control system, which is represented in the left panel of Figure 2; 3) different optical elements mounted on the Optical Bench (OB) used to provide the optical stimulus. The light beam passes through an optical window on the TVC before reaching each of the STC sub-channels [5]. The experimental set-up is schematized in Figure 2.

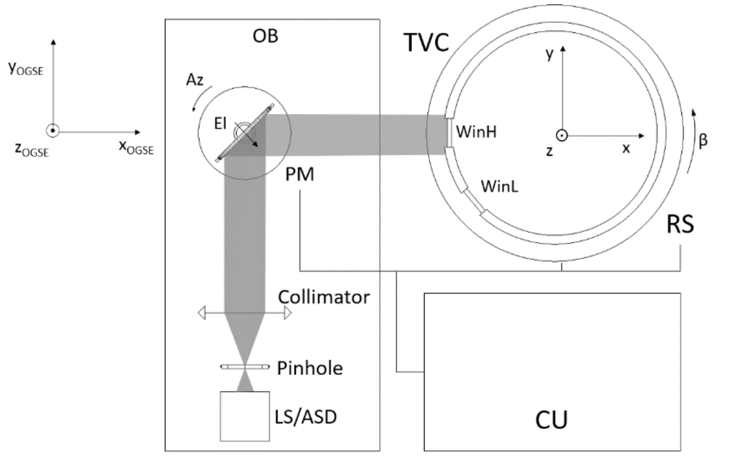


Figure 2. Schematic representation of the OGSE [4].

During the on-ground calibration, the dark current of the detector has been measured at different temperature values to determine its temperature dependence. The TVC guarantees the control of the temperature of the mechanical structure while an active Thermo Electric Cooler (TEC) mounted on the back of the detector controls the temperature of the FPA [5]. The radiometric calibration has been performed to derive the instrument response and characterize the spatial and temporal noise.

3.2 Performed measurements

The radiometric calibration is related to the determination of well-defined quantities. The first one is the detector dark current (DC), and its behavior as function of the IT and of the detector temperature. The nominal operating temperature of the detector is 268 K [6]. Figure 3 shows the detector mean DC curve as function of IT for the temperature interval between 263 and 273 K. The DC of STC channel detector is characterized by two different trends. For ITs lower than 1 ms the DC increase is almost exponential, while for ITs longer than 1 s (foreseen for stellar acquisitions) it is linear.

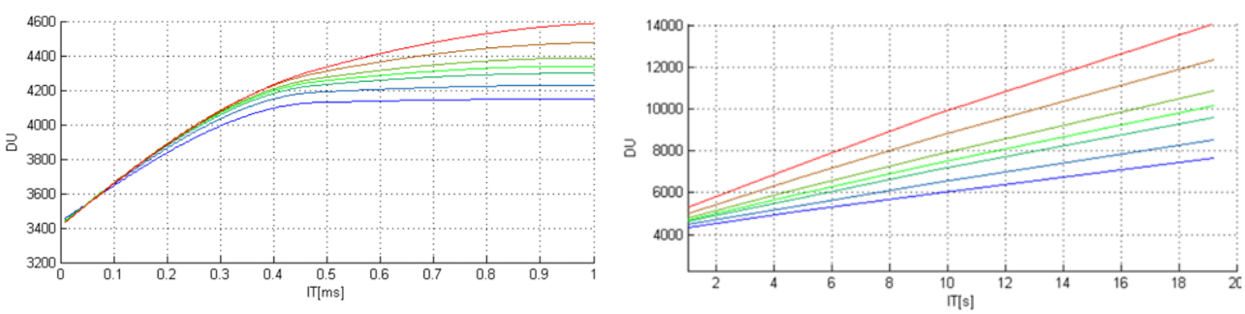


Figure 3: Mean detector dark current as function of IT and measured in the range 263-273 K with temperature intervals of 2 K. Left panel shows the DC for ITs from 400 ns to 0.96 ms, while the right panel from 9.6 ms to 19.6 s.

The Read Out Noise (RON) is the noise associated with the read-out process, related to the amplification and conversion of the photoelectrons in a voltage level. For CMOS technology, each individual pixel has its own read-out structure and so its own specific read-out noise. At the nominal operating temperature, the mean RON is limited to 70 e^- for lower ITs, which corresponds to almost 10 digital numbers (DN) given the detector conversion chain, and 170 e^- (25 DN) for the highest one.

The CMOS detector is also characterized by a Fixed Pattern Noise (FPN), which is the spatial noise generated by the different response of each pixel. The FPN is 135 DN RMS for the dark images acquired with IT < 10 ms, independently of the temperature. For higher IT the FPN reaches 400 DN RMS (on a dynamic of 14 bits).

For the radiometric calibration, in order to fully cover the expected radiance range, an Integrating Sphere (IS) with variable flux has been used. The IS used for the STC calibration is a Labsphere ISS-2000-C, provided with four halogen lamps, one of which is equipped with a shutter. Each lamp can be powered on and off independently of the others. The technical characteristics of the integrating sphere are shown in Table 2.

Table 2: Technical characteristics of the integrating sphere.

IS Specifications	
Inner diameter	20" (50 cm)
Aperture diameter	8" (20 cm)
Inner wall coating&reflectance	Spectraflect® / 98%
Lamp configuration (number and rated power)	three 35 W lamps, one 100 W lamp
Lamp type	Tungsten halogen
Color temperature	3000 K
Lamp power supply current stability (35 W /100 W)	3.07 A ± 0.1% / 8.33 A ± 0.1%
Peak radiance (at 900 nm)	550 W/m^2/sr/µm
Luminance uniformity (at maximum radiance level)	98%
Internal monitor detector	Silicon detector

3.3 Calibration pipeline

The procedure used for the radiometric calibration is outlined in Figure 4, which describes the data reduction for one acquisition session. The raw data have been read to obtain the raw images and the relative ITs. Two sets of images have been acquired for same values of ITs: either in dark condition, or illuminated by the IS. For each set, the images taken with the same IT have been averaged in order to remove the RON. The dark removal has been done by subtracting the DN value of the images taken without the illumination source at the correspondent IT. The dark has been subtracted using a window with dimension 64×128 pixels (called Window-X) taken in a non-illuminated part of the detector [7]. The result of the dark and window X reduction is the Photo Response Not Uniformity (PRNU), that has been derived for each filter.

Finally, using the known radiance of the IS light source, the relation between the flux in physical units and the DN detected has been derived.

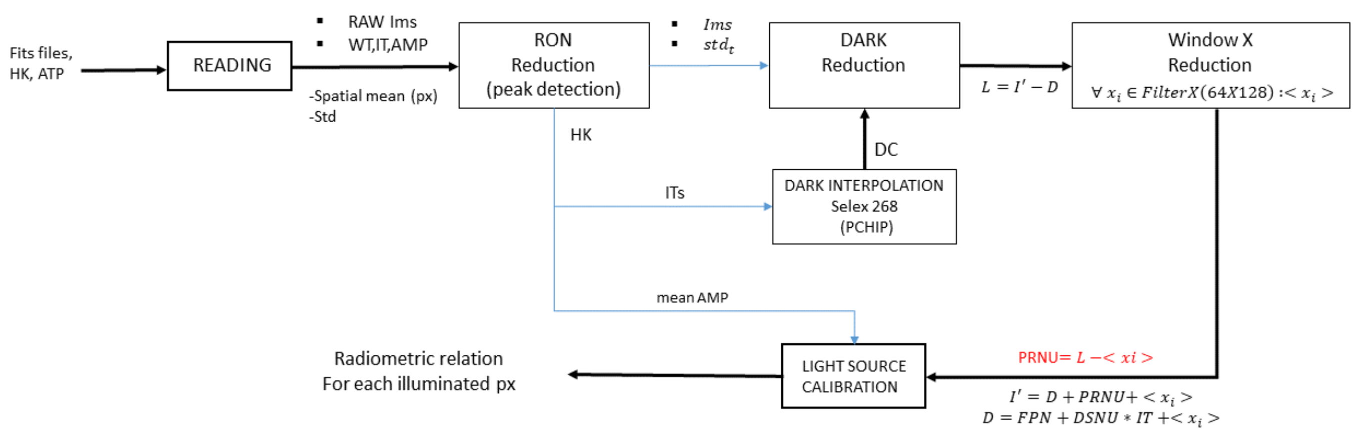


Figure 4. Flow chart of the radiometric calibration pipeline.

4. PRELIMINARY RESULTS

Once DC and FPN are known, the Photo Response (PR) and the Photo Response Non-Uniformity (PRNU) can be derived. For an imaging detector, the PR measures the ability to convert optical incident power (i.e. the number of impinging photons for a given exposure time) into an electrical signal. The PRNU represents the RMS variation of the photo-responsivity of the pixels in the array under the same illumination condition. The final result of the radiometric calibration consists in the determination of the relation between the signal expressed in DN and the signal expressed in physical units. Namely, the absolute radiometric calibration is the relation between the detected signal and the radiance value of an accurately known source illuminating the instrument.

This relation has been derived for each pixel of the illuminated region of the detector, in order to obtain a map that will be used to calibrate the raw images. Figure 5 shows the mean values of the slopes in the linearity range, for each filter of the detector.

The result depicted represents a starting point for some interesting considerations. First of all, by looking at the PAN filters, the values of the slopes in the right hand side of the detector are lower than those in the left side. This behavior can be due to different causes: either a real varying detector/instrument sensitivity (i.e. a flat field effect), or spurious effects such as straylight inside the TVC.

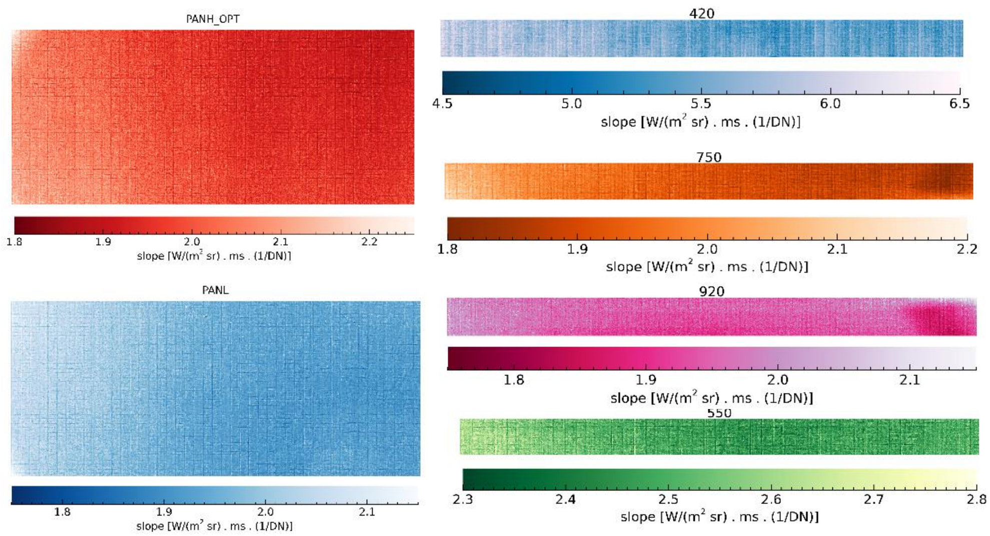


Figure 5. Mean values of radiometric function in the linearity range, for each filter of the STC detector.

This effect is confirmed by Figure 6 and **Błąd! Nie można odnaleźć źródła odwołania.**, which represent the statistics of the slope distribution shown for each filter separately. The histograms relative to PANH and PANL show a double-Gaussian profile, which is related to the left-right different behavior shown in Figure 5.

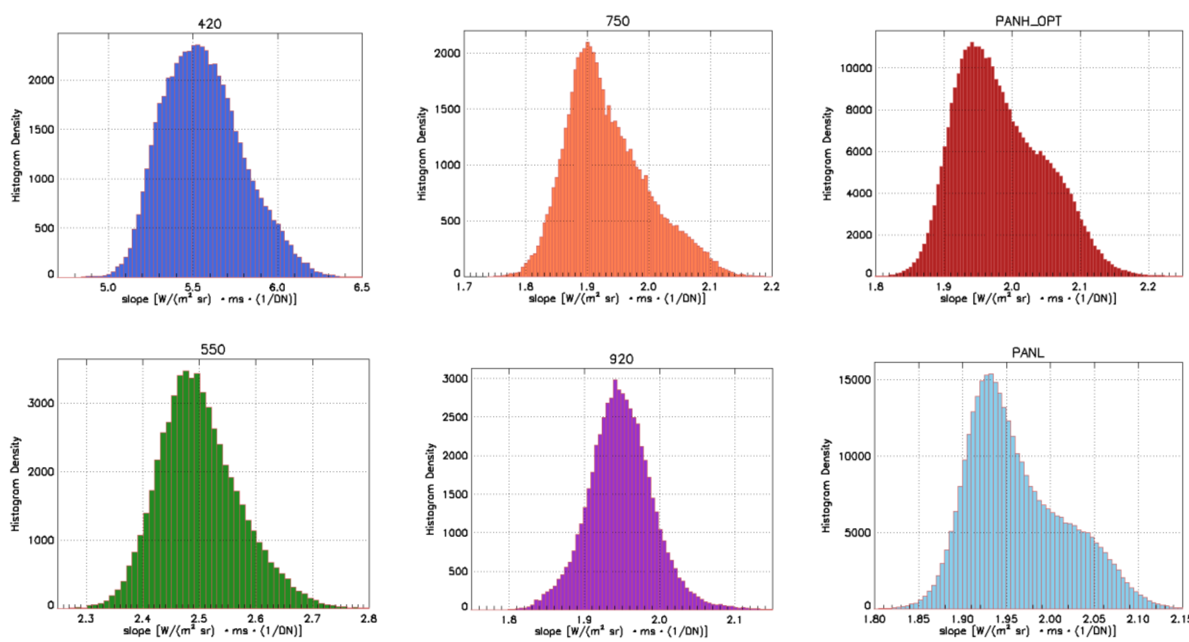


Figure 6: Statistics of the slope of the radiometric curve for the PAN and BB filters of STC detector.

Table 3. Mean value and standard deviation of the radiometric function for each filter.

Filter name	Mean [W/(m^2 sr) ms (1/DN)]	Standard deviation
920	1.95	0.05
550	2.50	0.07
PANL	1.96	0.21
PANH	1.98	0.07
420	5.56	0.02
750	1.93	0.07

The plots relative to BB filters show that the left-right difference in sensitivity is slightly observed. The effect is less evident only for filter 920, for whose statistics is more regular.

This consideration, together with the fact that the panchromatic optical path has no particular characteristics which could introduce a flat fielding effect, confirms the hypothesis that this cross track trend should be due to the calibration set-up.

5. CONCLUSIONS

The goal of this work is to show the preliminary results of the STC on-ground radiometric calibration, describing also the method used to derive them. The first step has been the definition of the detector noises and the radiometric response for each pixel of the detector, with the associated statistics. Then, once the photo-response is known, the relation between the input flux in physical units and the DN detected by the CMOS has been derived. These preliminary results have been obtained without taking into account the related statistical errors.

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