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Simulations for in-flight stellar calibration aimed at monitoring space instruments optical performance

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Abstract. Stellar in-flight calibrations have a relevant impact on the ability of space optical instruments, such as telescopes or cameras, to provide reliable scientific products, i.e. accurate calibrated data. Indeed, by using the in-flight star images, the instrument optical performance can be checked and compared with the on-ground measurements. The results of the analysis of star images, throughout the whole instrument lifetime in space, will allow tracking the changes in instrument performance and sensitivity due to optical components degradation or misalignment. In this paper we present the concept, the necessary input and the available outputs of the simulations performed to predict the stars visible in the FoV of a specific space instrument. As an example of the method, its application to two specific cases, i.e, Metis coronagraph on-board Solar Orbiter and the stereo camera STC on-board BepiColombo, will be given. Indeed, due to their operation in proximity to the Sun, and also to Mercury for STC, both instruments operate in a hostile environment, are subjected to high temperatures and experience high temperature variations. Performance optical monitoring is thus extremely important.

Introduction

The proper calibration of a space instrument allows its optimal performance throughout the entire mission duration.

Space is a hostile environment: e.g. a mission going near the Sun experience hot temperatures, likely to induce component degradation, even if the mission is carefully planned and built.

The instrument response to a well-known source, e.g. star acquisition, is a valuable mean for monitoring the optical performance of space instrument and, if necessary, to update and correct the image calibration.

In this paper, a description of the possible in-flight stellar calibrations, and their related simulations, are given and then applied to two space instruments: on board of Solar Orbiter [1] on board of Solar Orbiter; and of SIMBIO-SYS have an original optical design [2] on board of BepiColombo. Both instrument have an original optical design and are working in very hostile environments, near the Sun, and at distances rarely reached so far by other space missions. Comparing on-ground calibration with simulations and in-flight calibration is a key element for assuring the correct performance of these space instruments.

In the next sections the emphasis will be put on: the importance of the calibration, a brief description of the instrumentation where the simulations are applied, how the simulations have been performed and the results obtained are then presented.

Calibrations

Calibration is a key and fundamental step in achieving accurate and reliable scientific measurements from space instruments. To this end, on-ground calibration is crucial. Both are important to validate instrument design, mitigate systematic errors, ensures data consistency. For the in-flight calibration, by comparing the instrument response to known stellar characteristics, any deviations or discrepancies in the optical performance can be detected and corrected. This process enhances the quality and reliability of the acquired scientific data, making calibration an essential component of space missions.

In-flight calibration basically consists in following a star moving across the detector during several minutes. Repeated stellar observations, at different times during the lifetime of the instrument, are important to track the changes in instrument sensitivity due to optical elements or detector degradation and other causes. Systematic observations of several stars will track sensitivity changes, and comparison between the in-flight and on-ground results can give important information on the status and performance of the instrument.

Following such stars requires achieving high accuracy acquisitions over high dynamic range, which is a fundamental challenge. Yet, it is necessary to determine an accurate absolute calibration for astronomical photometry. Direct comparisons of stellar outputs with calibrated flux sources can generally only be made for very bright stars.

Concretely, our goal is to find the stars on a Metis, and on a STC image. Our approach is based on-defining an upper limit on a grayscale image in intensity (mean value +3σ): every pixel with a higher intensity corresponds to a star. Then around the maximum value we define a box, usually is 10 pixels x 10 pixels, and we plot a 2D gaussian, from which we extrapolate information like PSF. Knowing the PSF all over the detector gives us the information on some defocus, vignetting and so on.

Besides, every detector has a linearity curve. On ground we can measure this curve with a uniform light source like an integration sphere, it can give very useful information about the efficiency of each pixel. In flight our light source is the light from the stars. We can use them as calibration sources, acquiring the light of the same star for different Integration Times (IT), and analyzing the response of the detector pixels.

And finally, through the passage of stars all over the detector we can identify defects such as shadows and bad pixels. It is important to know if such defects are stable over time or are changing, which would have an impact on imaging (the Sun or Mercury in our context). To do so we have to analyze the stars in any parts of the detector to know if it responds differently.

Instrumentations: Metis and STC

The Metis coronagraph and STC have innovative optical design due to their respective missions. Metis makes linearly polarized measurements of the solar corona in the visible spectral range, and simultaneously acquires images in the ultraviolet Ly-α neutral hydrogen line 121.6 nm, with an annular field of view from 1.5° to 2.9° and with an unprecedented temporal resolution among other space coronagraphs (10s). Metis will observe the Sun as close as 0.28 AU, so it is important to reduce the extremely high thermal load, therefore an Inverted Externally Occulted configuration is used to block the light of the solar disk. Indeed, to reduce the thermal load, the light of the photosphere enters in Metis through the Inverted External Occulter (IEO) and is then rejected towards the entrance aperture by the mirror M_0 that is acting as an occulter as shown in ***Figure 1*** (a). Coronal light is reflected by mirror M_1 towards mirror M_2, which also induces diffused light

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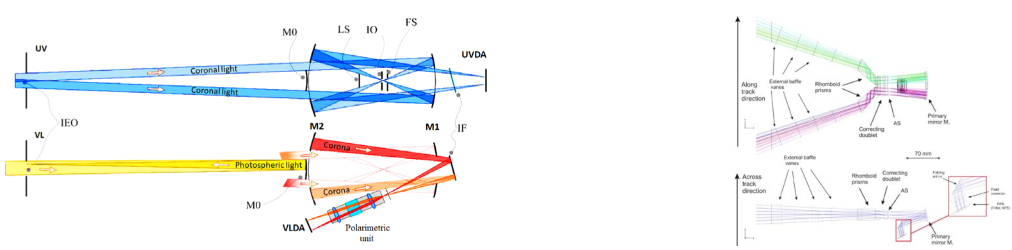
from real images of the edges of the IEO and the M_0 mirror. Therefore, an internal occulter (IO) and a Lyot Stop (LS) are respectively introduced, the rest of the diffused light being blocked by a Field Stop (FS). Then, the coronal light is reflected by mirror M_2 in the direction of the dichroic beam-splitter, the Interferential Filter (IF). The IF is optimized for narrowband spectral transmission in the ultraviolet (UV, 121.6 nm, H I Lyman-α), and broadband spectral reflection in the visible (VL, 580–640 nm). The visible light reflected by IF enters in a polarimetric unit and arrives on the detector. Both channels have a CMOS sensor, a 1024 x 1024 pixel matrix for the ultraviolet, and a 2048 x 2048 pixel matrix for the visible [1].

STC is a double wide-angle camera which main scientific aim is the mapping of the entire surface of Mercury in 3D. As shown in *Figure **1*** (b), the STC camera consists of two sub-channels named High (H) and Low (L) with respect to the mounting interface on the spacecraft. There are also two different fore optics for each sub-channel plus a common modified Schmidt telescope. The light scattered by Mercury passes through the external baffle, is reflected inside a rhomboid prism, passes through a correcting doublet, the aperture stop (AS), and arrives on the spherical mirror M_1. It reflects on a telescope mirror, positioned off axis, which in turn reflects into a two-lens field corrector and arrives on the focal plane assembly (FPA). The STC detector can read a maximum of six specific windows. Nominally, these windows correspond to the areas of the 6 filter: two panchromatic (PAN) with FoV 5,3°×2,4° and four colored filter with FoV 5,3°×0,4° [2]. The tridimensional modeling of the instrument is available on [5].

Knowing the accurate location of the spacecraft and the optical path going through the instruments enables to perform simulations on what may be acquired by the instruments. This is of major importance to enhance *in fine* the performances of the in-flight calibrations.

Simulations

Simulations have emerged as powerful tools for addressing the challenges associated with in-flight stellar calibration. They enable scientists to create virtual environments that accurately mimic the behaviour of space instruments and their interaction with celestial objects. These virtual experiments allow for the optimization of calibration strategies, evaluation of instrument design choices, and testing of data analysis techniques. Simulations offer a cost-effective and efficient means of exploring a wide range of scenarios that may not be feasible in real-world settings.



(a) (b)

Figure 1 Optical path inside the Metis coronagraph (a), and STC (b) [4].

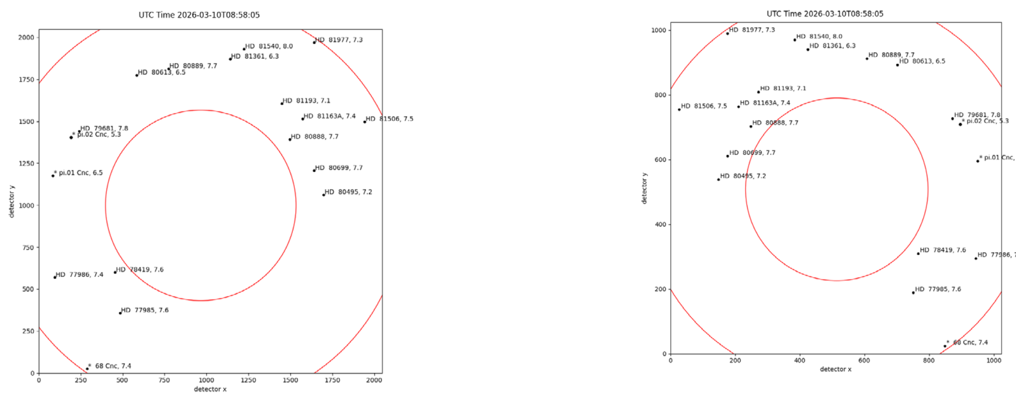
The keystone of these simulations, performed in Python, is the SPICE kernel (Spacecraft, Planet, Instrument, Camera pointing, and Events). For each space instrument, the SPICE kernel gives, among other things, the information of the location of the spacecraft in the past and in the future, the boresight of each specific channel and the Field of View (FoV).

This kernel is used alongside the SIMBAD catalogue, which exhaustive for our purposes because it provides extensive stellar data. The Metis team and Slemer et al. for STC [3] performed the analysis for determining the maximum apparent magnitude of a star detectable by the instruments. Combining the SPICE kernel with the SIMBAD catalogue allowed us to obtain the results described in the next paragraph.

Results

The simulations reported for both instruments have been performed on the same day: 10-03-2026 at the 8:58:05, in order to highlight the fact that they are looking at different places. For this reason, the results of the stars seen by each channel is different.

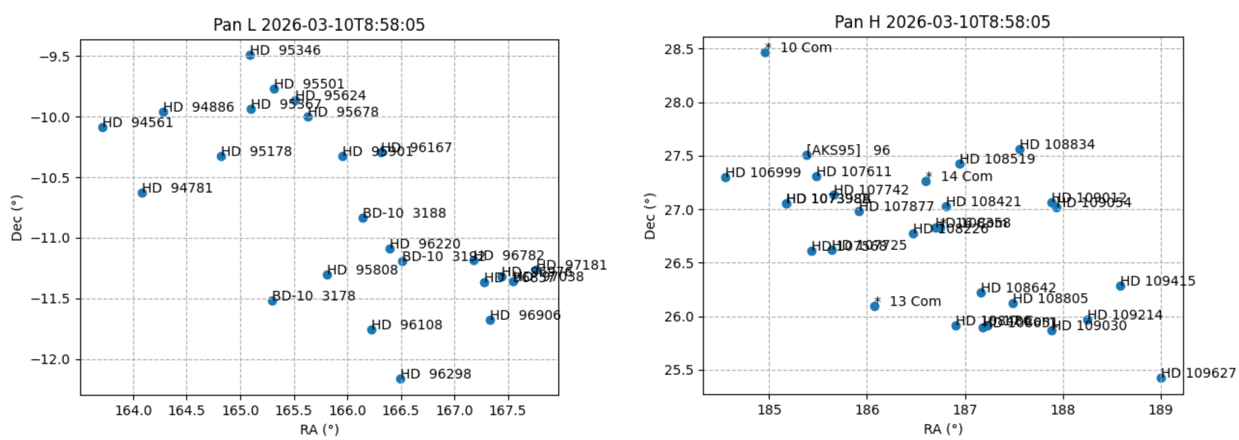
The stars seen by the Metis coronagraph are presented in the *Figure 2*, respectively for the Visible channel (VL, (a)) and for the Ultraviolet channel (UV, (b)). Inside the Field of View there are 18 stars. Metis acquires in two channels but is looking at the same objects. The results appear mirrored because of the reflection inside the elements of the coronagraph.



(a) (b)

Figure 2 Simulations of the stars seen by the Metis the day 10-03-2026 at the 8:58:05 in the visible (a) and UV (b).

For STC, in the FoV of the two panchromatic on March 10th 2026 at 8:58:05 are shown in *Figure 3* (a) and (b). The stars seen by the Pan L and Pan H are respectively, 24 and 29 stars. Because they are looking at 20° of difference respect to the Nadir.



(a) (b)

Figure 3 Simulations of the stars seen by the panchromatic L (a) and H (b) the day 10-03-2026 at the 8:58:05.

The difference between the imaged simulated for Metis and STC are the display of the results. Knowing the stars can be seen from the instruments give us the opportunity to select the best target for the in-flight calibration.

Conclusion

In this paper, the problematics of stellar in-flight calibration have been presented, in particular the importance of the calibrations (on-ground and in-flight), and the crucial role of the stars as in-flight calibration light sources have been highlighted. We report the simulations to determine the stars observable by two instruments: the Metis coronagraph on board of Solar Orbiter, and STC on board of BepiColombo. This simulation activity is part of an on-going work, associated with on-ground and in-flight, acquired and simulated images.

Fundings
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