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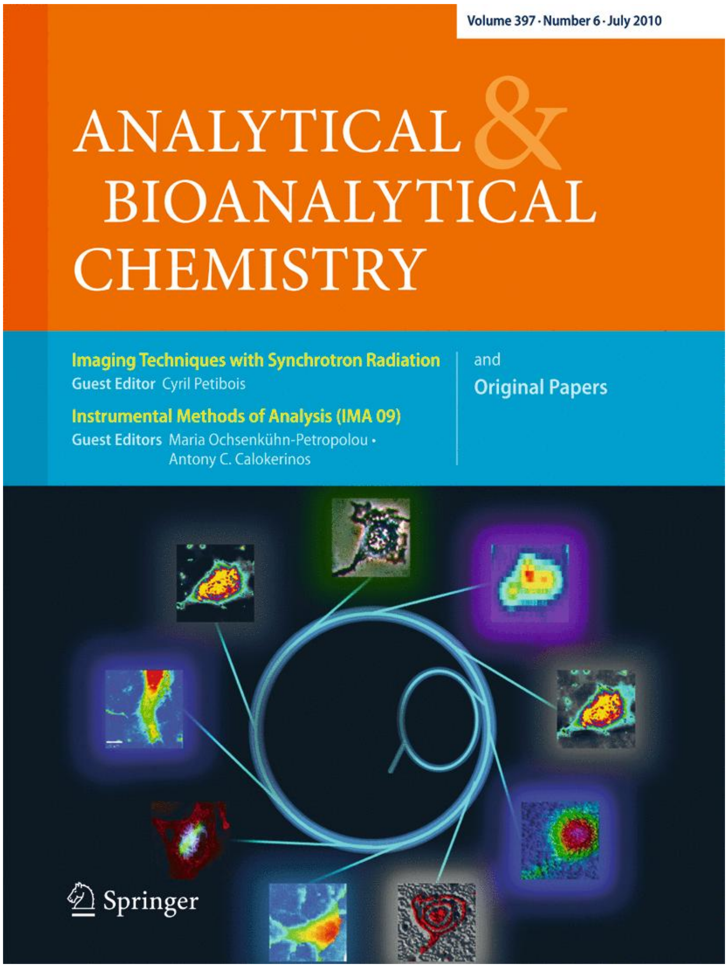

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TRENDS

HERSCHEL/SCORE, imaging the solar corona in visible and EUV light: CCD camera characterization

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Abstract The HERSCHEL (helium resonant scattering in the corona and heliosphere) experiment is a rocket mission that was successfully launched last September from White Sands Missile Range, New Mexico, USA. HERSCHEL was conceived to investigate the solar corona in the extreme UV (EUV) and in the visible broadband polarized brightness and provided, for the first time, a global map of helium in the solar environment. The HERSCHEL payload consisted of a telescope, HERSCHEL EUV Imaging Telescope (HEIT), and two coronagraphs, HECOR (helium coronagraph) and SCORE (sounding coronagraph experiment). The SCORE instrument was designed and developed mainly by Italian research institutes and it is an imaging coronagraph to observe the solar corona from 1.4 to 4 solar radii. SCORE has two detectors for the EUV lines at 121.6 nm (HI) and 30.4 nm (HeII) and the visible broadband polarized brightness. The SCORE UV detector is an intensified CCD with a microchannel plate coupled to a CCD through a fiber-optic bundle. The SCORE visible light detector is a frame-transfer CCD coupled to a polarimeter based on a liquid crystal variable retarder plate. The SCORE coronagraph is described together with the performances of the cameras for imaging the solar corona.

Keywords UV/vis detectors · Imaging · Coronagraph · Solar corona · CCD cameras

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Introduction

The Sun is the closest star to the Earth and its proximity is fundamental not only for the development of life on our planet, but also for astronomical purposes. In fact, the Sun is a unique laboratory for astronomers and physicists to study matter in a highly ionized state (plasma). Moreover, the Sun is the only star we can study in great detail and it represents a comparison model for all other stars. Finally, the Earth and its star are strongly related: understanding the behavior of the Sun, and in particular monitoring its activity, is necessary for our lives.

Solar photons are not the only particles hitting the Earth; charged particles are continuously released from the Sun's surface and spread all over the surrounding space. This flux is known as the solar wind and our planet is wrapped by this breeze of particles. The interaction of ionized particles with the Earth's atmosphere usually just causes the beautiful northern lights. Sometimes stronger fluxes of particles or particular solar eruptive events (coronal mass ejection) can produce problems for satellites and communication systems or damage and disruption to ground power distribution networks. To prevent these (and other) kinds of problems and try to forecast the solar storms, we have to continuously monitor the Sun and its activity (this is the aim of a new branch of science called "space weather"), trying to understand the processes that generate and drive the solar wind. This last issue is one of the major challenges for modern solar physics.

Although the subject of this paper is an experiment that does not use synchrotron radiation, the radiation it deals with is extreme UV (EUV) light and falls within the range of synchrotron capabilities. This work was intended to present an application of EUV imaging in a different research field sharing common instrumental techniques with synchrotron imaging.

HERSCHEL: studying the solar corona

In recent decades, through observations carried out by space-based telescopes, many open issues about the Sun were clarified but many other unexpected ones arose. Concerning the solar wind, the observations of the *Ulysses* and *Solar and Heliospheric Observatory* (*SOHO*) satellites [1, 2] clearly showed the existence of two components that have different speed, charge state composition, and elemental abundance. The fast solar wind seems to originate from large stable polar coronal holes; in contrast, the slow solar wind seems to be associated with the low-latitude streamers that are observed in coronagraph images. In both cases the exact source of the wind is presently unclear.

Since helium is the largest contributor to the density of coronal plasma after hydrogen and is four times heavier than hydrogen, it is very important for the dynamics and mass flux of the solar wind [3, 4]. Despite its crucial role, a global solar map of helium abundance has never been accomplished; it could help to understand the mechanisms responsible for the solar wind acceleration and provide hints about the origin of the solar wind. In particular, there is a lack of helium observations at coronal altitudes where the solar wind acceleration takes place, and actual knowledge is essentially based on theoretical studies. A targeted helium observation of the solar corona appears to be a useful investigating tool also to explain the presently misunderstood process of coronal heating.

These are the main goals of the HERSCHEL (helium resonant scattering in the corona and heliosphere) mission. HERSCHEL is a suborbital mission selected within the NASA “Living With a Star” program NRA 02-OSS-01-SHP. It is a collaboration among the Naval Research Laboratory (NRL; Washington, DC, USA); the universities of Florence, Padua, and Pavia; the Istituto Nazionale di Astrofisica (INAF) Astronomical Observatory of Turin in Italy; and the Institut d’Astrophysique Spatiale of Paris in France. The experiment aims to obtain the first global image of the Sun (disk and corona) in the HeII 30.4 nm line, provide the first helium observation in the extended corona, and provide the first map of helium abundance.

HERSCHEL observes the solar corona and the Sun’s disk in the visible light (VL) and in the EUV bands through three instruments: the HERSCHEL EUV Imaging Telescope (HEIT) and two coronagraphs, HECOR (helium coronagraph) and SCORE (sounding coronagraph experiment). HEIT is an EUV sun disk imager telescope and it is a copy of the Extreme-Ultraviolet Imaging Telescope (EIT) that is operating on *SOHO* [5]. HECOR is a coronagraph designed to observe the solar corona at the HeII 30.4-nm line between 1.2 and 4 solar radii [6]. The SCORE coronagraph enables observation of the corona from 1.4 to 4 solar radii and it is able to image the singly ionized helium Lyman α 30.4-nm line, the neutral hydrogen Lyman α 121.6-nm line, and to measure the polarized brightness of the visible K corona. The helium observation of the solar corona represents the major achievement of this experiment. Therefore, two coronagraphs were designed with slightly different fields of view and different observing approaches. The SCORE coronagraph is a test bench for the Solar Orbiter coronagraph, whereas HECOR uses a less conservative approach to stray-light rejection at EUV wavelengths.

Since the atmosphere of our planet is opaque to the UV band, it is impossible to accomplish these observations from the ground. For these reasons, the payload is fitted into a rocket (Fig. 1) and the observation of the Sun takes place when the missile is above 250-km altitude, enabling the observation of the coronal radiation in the EUV spectral

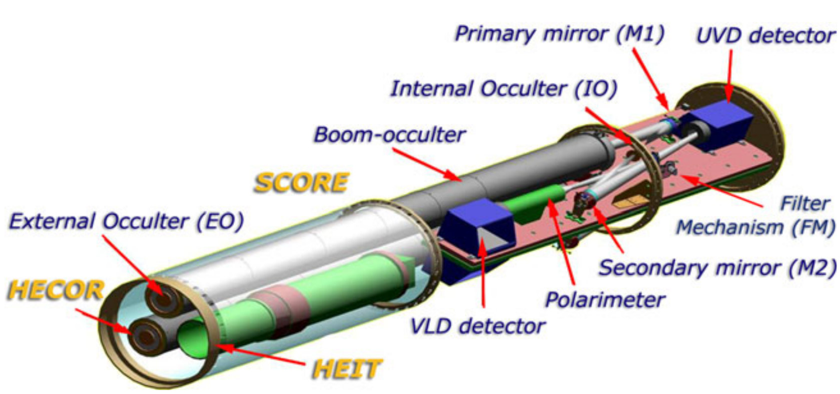

Fig. 1 The HERSCHEL payload accommodation. The SCORE coronagraph is shown in detail. The *blue boxes* on the bench are the visible light detector and UV detector cameras

band for approximately 300 s. HERSCHEL instruments are capable of observing different solar regions at several wavelength bands simultaneously. This feature allows all the required measurements to be obtained within a short observing time. It also allows matching the structures observed in the solar corona to those seen on the solar disk and to investigate their correlations.

The Italian team is responsible for the SCORE instrument. This paper describes this coronagraph and the performance of its two cameras.

The SCORE instrument

SCORE is an instrument with an innovative design that aims at demonstrating that a single coronagraph can be used to image both VL and EUV light. A UV instrument requires specific optimization; so it is usually developed just for the UV wavelength range selected. Through the use of multilayer optics, SCORE is aimed at testing the possibility of simultaneous EUV/VL observations through a single optic (Fig. 2). Moreover, SCORE includes a VL polarimeter based on a liquid crystal variable retarder (LCVR) plate to select the polarization plane. The application of this polarimeter to space experiments is innovative.

For many reasons, SCORE represents both a scientific and a technological challenge. The coronagraph is an external occulted off-axis Gregorian telescope with multilayer coated optics, capable of acquiring images in the VL and EUV narrowband. The telescope section of the coronagraph is mounted on the optical bench, as shown in Fig. 1, and images the solar corona after the solar disk radiation has been rejected by the external occulter (EO). The major issue in designing coronagraphs is the stray-light reduction. The optical design of SCORE was optimized to minimize the geometric stray light [7]: the boom is devoted to stray-light reduction and Sun disk light rejection. It consists of a baffled black tube that ends with the EO on the Sun side, and with a black light-shield, M0, on the telescope side. M0 has a centered hole, H, shadowed from the disk light by the EO central disk. H is the aperture stop of the telescope. The internal occulter removes the light diffracted by EO edges and reflected by the primary mirror, M1. For stray-light rejection purposes, the secondary mirror, M2, is placed on the conjugate plane of M0 imaged by M1. The coronal light is imaged by the off-axis Gregorian telescope onto the detector systems after a filter has separated EUV radiation from visible radiation. A two-position filter mechanism selects the observation mode of the coronagraph: an aluminum filter enables the HeII observation, whereas a MgF_2 filter images the hydrogen Lyman α line onto the UV detector (UVD). In the latter case, the MgF_2 filter enables the simultaneous observation of the Sun corona in VL, reflecting the visible radiation, through the polarimeter, to the VL detector. During the flight an onboard computer executes a predefined observational schedule, managing the filter mechanism positioning and the acquisition by the detectors. The schedule foresees the execution of a strict cadence of activities that ensure the acquisition of all data produced by the SCORE instrument.

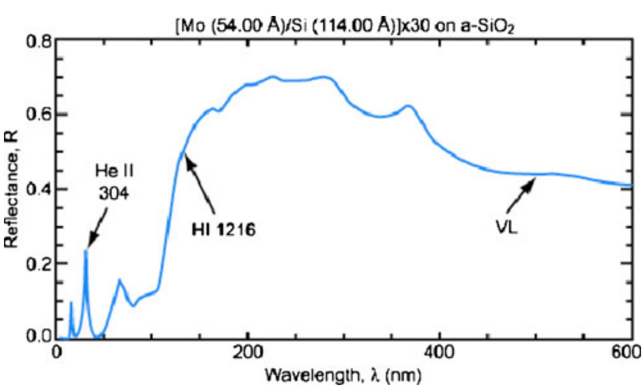

Fig. 2 Reflectivity in extreme UV (EUV)/UV and visible wavelength range for the Mo/Si multilayer. Owing to multilayer optics, SCORE can use a single optic for the three wavelengths and can accomplish simultaneous visible light (*VL*)/EUV observations. The key element in the SCORE instrument concept is that the mirrors with coatings optimized for 30.4 nm still have good reflectivity at 121.6 nm and in the visible. In the case of the HI 121.6-nm line, the off-band rejection of the VL is provided by an Al/MgF_2 interference filter such as the commercially available Acton 120-nm filter

SCORE detectors

SCORE has two detectors, one for the visible and one for the EUV channel. The SCORE VL detector (VLD) is based on a frame-transfer CCD and it is coupled to the LCVR polarimeter. The VLD and the polarimeter controller were provided by the XUVLab of the Department of Physics and Astronomy of the University of Florence.

The SCORE VLD enables the observation of the polarized brightness of the solar corona. During the flight, the VLD and the LCVR polarimeter provide sequences of four images, each one taken with a different orientation of the polarimeter axis. The camera has custom electronics which provides the required control signals for the detector (bias voltages, clocks), manages the acquisition sequence, and controls the liquid crystal variable retardation [8]. One of the constraints in the VLD design was the short observing time available during the mission; we optimized the camera operations to reduce all overhead time due to functional procedures not concerning the observation (image readout, download, camera-on-board computer handshaking, etc.). To avoid time losses due to the CCD readout, we used a frame-transfer CCD, E2V CCD47-20, having a frame format of 1,024×2,048 pixels. Half the frame is sensitive to light, whereas half is the light-shielded storage area. On completion of image acquisition, the charge packets collected under each pixel are transferred very rapidly (roughly 10 ms) to the storage area. The image in the storage area is read out while the imaging area is exposed again; so, no time losses occur between two exposures. The detector is operated in 2×2 binning mode, it has a 16-bit dynamic range, and produces 4 Mb images. The pixel rate is 300,000 pixels per second and the image is stored into an internal FIFO memory, where it is ready for downloading to the onboard computer. To prevent overwork of the onboard computer, the VLD camera reduces the computer control and keeps the downlink busy time as short as possible. For these reasons the camera has a high level of automation and it is able to recognize errors and recover from them.

The UVD has to acquire images in HI and HeII bands. Owing to the expected low count rate for the HeII Lyman α line [9], the SCORE UVD is an intensified CCD with a microchannel plate (MCP) coupled to a CCD through a fiber-optic bundle. The MCP converts EUV photons into visible ones, improving the UV quantum efficiency of the CCD detector. Moreover, the MCP is solar-blind, i.e., it is not sensitive to light at optical wavelengths. This is an important feature for an EUV coronagraph, where the spurious visible stray light could be comparable to the signal to be measured. The MCP was provided by Sensors Scientific and it has a 25-mm circular anode with an alkali halide (KBr) photocathode and an output fiber optic. The CCD is a 47-10 E2V (AIMO), 1 k×1 k, full frame, and provided with a fiber-optic faceplate. The MCP output and the CCD input are coupled through a fiber-optic taper to match the different sizes and shapes of the sensors. The integration of the two detectors was performed at the XUVLab. The driving electronics for the UVD was provided by NRL and it was a copy of the electronics used for the SECCHI instruments of the two *STEREO* satellites. The CCD collects the visible photons produced by the MCP and is read out at a frequency of 1 MHz. The output signal is then converted into a 14-bit digital number and data are immediately sent to the rocket computer to store them (onboard storage is not possible).

Both cameras adopt the Spacewire communication protocol [10] that ensures a high data rate (up to 200 Mb/s), minimizing the download time and providing reliability, low power consumption, and space compliance. Owing to the use of embedded reprogrammable devices, the design of the cameras is quite versatile. All procedures and functionalities they offer are produced by means of software procedures enabling custom performance for different applications.

Calibration of the SCORE cameras

Detector calibration allows the conversion of the digital output signal *S*(DN), where DN is the digital number, into physical units (electrons or photons). The CCD signal is related to the photoelectrons collected through the camera

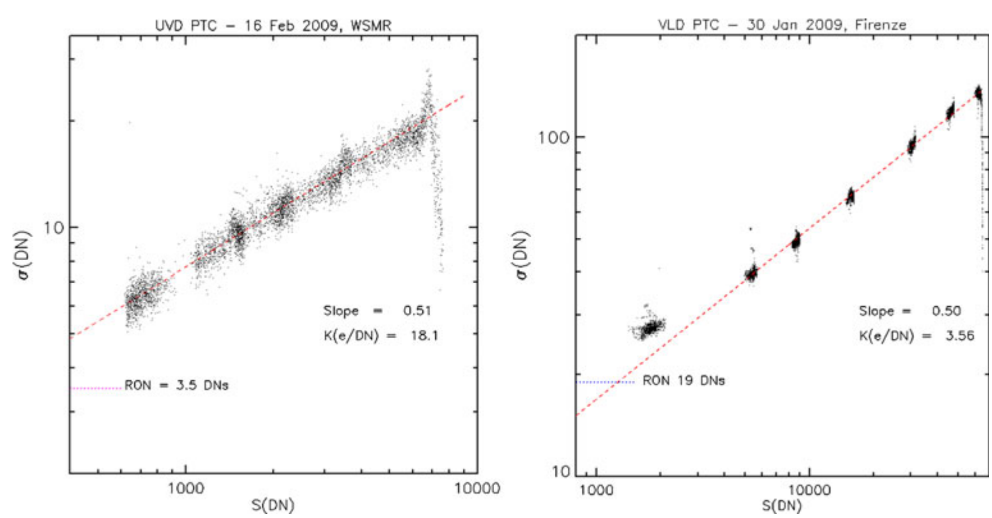

Fig. 3 The photon transfer curve (*PTC*) obtained with the SCORE detectors, VL detector (*VLD*) on the *left* and UV detector (*UVD*) on the right. Both CCDs were operated at room temperature. The detectors were illuminated by a uniform visible source through a shutter with selectable exposure time from 0 s (dark) to the saturation. For each exposure time selected, we took a couple of images to remove the fixed pattern noise. We used an IDL code to analyze the images and to extract the data. The readout noise was evaluated by considering the overclocked region of the frame, and it is shown on the graph as a *dotted line*. The *dashed line* is the linear fit computed on the data to extrapolate the conversion constant from the PTC. The noise at high *S*(DN) values drops off owing to the camera analog to digital converter saturation

conversion constant $K(e^-/\mathrm{DN})$, providing the number of digital signal units (DN) generated by the system per photoelectrons collected (Φ_c):

$$K(e^-/\mathrm{DN}) = \frac{\Phi_c}{S(\mathrm{DN})}, \qquad (1)$$

where $\Phi_c = N_\Phi \eta$ is the number of electrons produced by each interacting photon N_Φ and η is the quantum yield. So, we need to evaluate the conversion constant $K(e^-/\mathrm{DN})$ for both cameras to go back to photons collected by each CCD during the observation of the solar corona.

Both SCORE CCDs were calibrated through a procedure called photon transfer curve (PTC). The PTC is one of the most powerful tools to characterize and optimize the detector–camera system [11]. In addition to the conversion constant K, the PTC also provides the sensor full well, the noise floor of the camera, and the dynamic range of the entire system. A correct PTC can provide information about how the camera is operating and is a strong diagnostic tool for discovering potential problems. To obtain this curve, we acquire images with the CCD uniformly illuminated at different light levels (ideally from zero to the saturation level) and plot, on a log–log scale, the standard deviation of pixel values, $\sigma(\mathrm{DN})$, as a function of the average signal, $S(\mathrm{DN})$. In an ideal system, where the readout electronics does not introduce measurement errors, $\sigma(\mathrm{DN})$ should be due just to the Poissonian statistics of incoming photons [shot noise $\sigma_{\mathrm{SHOT}}(\mathrm{DN})$]; therefore, the evaluated curve should show a typical slope of 0.5. In the real case, every system adds an unavoidable uncertainty, the readout noise $\sigma_{\mathrm{RON}}(\mathrm{DN})$, which dominates at low-level signals [$\sigma_{\mathrm{SHOT}}(\mathrm{DN}) < \sigma_{\mathrm{RON}}(\mathrm{DN})$] and reduces the detector dynamic range. $\sigma_{\mathrm{RON}}(\mathrm{DN})$ can be evaluated directly through the PTC or by considering the overclocked regions on the CCD frame. The overclocked regions are pixel regions where there is no CCD signal. They are intentionally created, reading more pixels than the detector really has, because these fake pixels provide just the signal generated by the readout electronics. This allows the evaluation of the camera readout noise, as the distribution of the overclocked pixels of a single frame.

Since both CCDs operate in the visible range (in the intensified CCD, the MCP converts EUV photons into visible ones), we used a broadband visible lamp as a calibration source. The detectors were operated in air, at room temperature, so a thermal contribution to the signal (dark current) has to be considered. However, in the photon transfer technique, it is not important how charge is generated in the detector, as long as the source exhibits Poissonian statistics as photons. This is the case for dark current; therefore, thermal noise does not represent a problem.

The PTC was evaluated by analyzing 1,000 different sets of 40×40 pixel square subimages randomly selected across the image. Each subimage in the frame generates a point in a log–log graph reporting $\sigma(\mathrm{DN})$ as function of $S(\mathrm{DN})$. The PTC was plotted by considering the images acquired with different exposure times. The computed PTC for the VLD and for the UVD CCDs are shown in Fig. 3. The conversion constant $K(\mathrm{DN})$ is related to the noise $\sigma(\mathrm{DN})$ through

$$\mathrm{K} = \frac{S(\mathrm{DN})}{\sigma^2(\mathrm{DN})} = \frac{S(\mathrm{DN})}{\sigma^2_{SHOT}(\mathrm{DN}) + \sigma^2_{RON}(\mathrm{DN})}, \qquad (2)$$

where symbols should be evident. We can estimate K from the PTC graph using Eq. 2. If we compute a linear fit on the shot-noise dominated data (higher signal), we obtain a line showing the 0.5 slope. We can extrapolate K as the intercept

Table 1 SCORE camera main performance summary

		SCORE CCD detectors	
		Visible light detector	UV detector
CCD (E2V)		47-20 BI AIMO	47-10 FI AIMO
Special features		Frame transfer	Fiber-optic window
Detector pixel size (μm)		13	13
No of detector pixels		1,024×2,048	1,024×1,024
Sensitive area dimensions (mm)		13.3×13.3	13.3×13.3
Conversion constant (K) (e^-/DN)		3.6±0.4	18±2
Dark signal (at 293 K) (e^-/pixel/s)		250	100
Peak charge storage (DN/pixel)		65,000	7,000
Readout noise	(DN)	19	3.5
	(e^-)	70	63
Binning (pixels)		2×2	–
Frame dimensions (pixels)		514×536	1,088×1,024

DN digital number

between this line and the x-axis. At this point $K=S$(DN) (σ_{RON} is negligible and $\sigma_{SHOT}=1$). The computed conversion constant K and the readout noise σ_{RON}(DN) are reported in Table 1 together with a summary of the features of the detectors.

Conclusions

HERSCHEL was successfully launched on 14 September 2009 from White Sands Missile Range, New Mexico, USA. The launch and trajectory were nominal; all the instrumentation worked properly and acquired data. The parachute deployed regularly and the payload was recovered in good condition. The scientific data are being analyzed and the first preliminary results will soon be published. As a first result we can confirm the success of the SCORE instrument and its innovative design; both EUV and VL images were positively taken. The LCVR polarimeter worked as expected, representing an important improvement for future space applications addressing polarimetry. The calibration accomplished on the SCORE detectors has enabled us to derive the main features of the cameras. These parameters are intrinsic characteristics of the camera electronics and are independent of the conditions used to measure them. The results are fundamental for correct data interpretation and for the extrapolation of helium abundance, which is one of the main goals of HERSCHEL. A comparison of the results obtained with a postflight calibration will be useful to check the status of the overall SCORE instrument.

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