The Solar Orbiter METIS Coronagraph data signal processing chain

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ABSTRACT

METIS, the *Multi Element Telescope for Imaging and Spectroscopy*, is one of the instruments selected in 2009 by ESA to be part of the payload of the Solar Orbiter mission. The instrument design has been conceived to perform both multiband imaging and UV spectroscopy of the solar corona. The two sensors of the detecting system will produce images in visible light and in two narrow UV bands, at 121.6 and 30.4 nm. The instrument is constituted by several subunits that have to be properly controlled and synchronized in order to provide the expected performances. Moreover, the large amount of data collected by METIS has to be processed by the on board electronics to reduce the data volume to be delivered to ground by telemetry. These functionalities will be realized by a dedicated electronics, the Main Power and Processing Unit (MPPU). This paper will provide an overview of the METIS data handling system and the expected on board data processing.

Keywords: Solar corona, Coronagraph, On Board Data Handling, Signal Processing.

1. INTRODUCTION

Despite the huge improvements experienced by solar physics in the last decades thanks to the invaluable results of several successful space experiments, our knowledge on the Sun and the influence of its activity on the Earth are still long away to be exhaustive. The results from missions such as Helios, Ulysses, Yohkoh, SOHO [1], TRACE and RHESSI, as well as the recently launched Hinode and STEREO missions [2][3], have formed the foundation of our understanding of the solar corona, the solar wind, and the three-dimensional heliosphere. Anyway, the unpredicted deep solar minimum that our star has just experienced, clearly shows that numerous issues have still to be clarified in heliophysics.

Solar Orbiter is one of the candidate M-missions to be flown as part of the ESA Cosmic Vision 2015-25 program and it was conceived to catch major breakthroughs in our understanding of how the inner solar system works and is driven by solar activity [4].

Solar Orbiter will use a carefully selected combination of in-situ and remote-sensing instrumentation, a unique orbit and mission design, and a well-planned observational strategy to explore systematically the region where the solar wind originates and heliospheric structures are formed.

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The spacecraft will operate much like a planetary encounter mission, with the main scientific activity and planning taking place during the near-Sun encounter part of each orbit. Specifically, observations with the remote-sensing instruments will be organized into three 10-days intervals centered around perihelion and either maximum latitude or maximum co-rotation passages. As a baseline, the in-situ instruments will operate continuously during normal operations.
The main questions that define the scientific objectives of the Solar Orbiter mission are related to the origin and acceleration of the solar wind, to the heliospheric variability, and to the role of the dynamo in the physics of the heliosphere. To answer these questions, it is essential to perform in-situ measurements of the solar wind plasma, fields, waves, and energetic particles close enough to the Sun that their properties are not modified by subsequent transport and propagation processes. This is one of the fundamental drivers for the Solar Orbiter mission, which will approach the Sun to within 0.28 AU. Relating these in-situ measurements back to their source regions and structures on the Sun requires simultaneous, high-resolution imaging and spectroscopic observations of the Sun in and out of the ecliptic plane. The resulting combination of in-situ and remote sensing instruments on the same spacecraft, together with the new, inner-heliospheric perspective, distinguishes Solar Orbiter from all previous and current missions, enabling breakthrough science which can be achieved in no other way.

1.1 METIS: the SOLAR ORBITER coronagraph

METIS, *Multi Element Telescope for Imaging and Spectroscopy*, is an innovative inverted coronagraph that is part of the Solar Orbiter's payload. The instrument design has been conceived by an international team with the intent to perform both multiband imaging and UV spectroscopy of the solar corona [5]. METIS, owing to its multi wavelength capability, can effectively address some of the major open issues in understanding the corona and the solar wind, exploiting the unique opportunities offered by the Solar Orbiter mission profile. METIS observations are crucial for answering some fundamental solar physics questions concerning the origins of the fast and slow wind, the sources of solar energetic particles, and the eruption and early evolution of Coronal Mass Ejections (CME).
The instrument is approaching the end of the definition phase and the overall architecture of the system is mature but the activities concerning the requirements definition and the subsystem design are still ongoing. In particular some internal subsystems are still under study and also the on board data management has to be clearly identified to properly size METIS hardware and software resources.

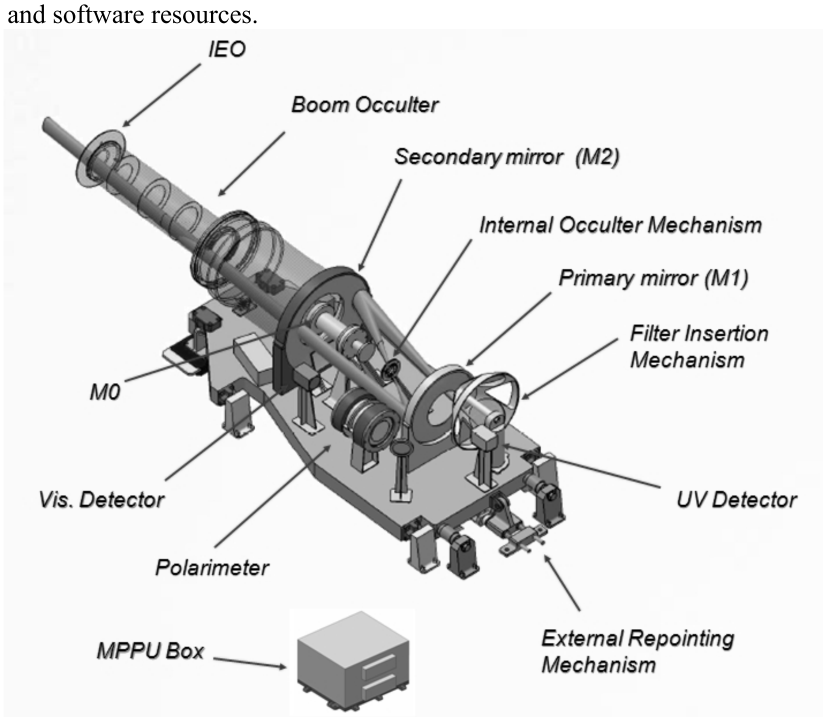

Figure 1: Overview of the METIS coronagraph.

2. METIS INSTRUMENT DESIGN

The METIS coronagraph performs imaging of the close solar corona (1.5 - 3 solar radii) in the visible, ultraviolet (UV) and extreme ultraviolet (EUV) band and spectroscopy of an equatorial portion of the corona in the UV/EUV, by means of an integrated instrument located on a single optical bench. METIS is conceived with a novel design for externally occulted solar coronagraphs, based on an *inverted external occulter* (IEO) [6] [7]. The IEO is a small circular aperture which replaces the classical annular aperture of the standard externally occulted solar coronagraph design (see Figure 1). The Sun disk light entering the IEO is rejected back by a spherical mirror (M0). Then an on-axis annular-shape Gregorian telescope acting as imaging system, focuses the solar corona on the focal plane assembly (FPA). For a general description of the telescope see reference [5].

In order to realize the foreseen multiband imaging and spectroscopy, just before the FPA, a mechanism exchanges filters along the optical path creating two distinct channels: visible and UV/EUV channel. Two detectors are present: one dedicated to UV/EUV coronal imaging; the other dedicated to visible light imaging, which images the broadband polarized visible light corona after a polarimetric system.
In order to improve the scientific return of this instrument, a spectroscopic channel has also been included in the METIS optical path. Essentially, in the prime focus of the Gregorian telescope, a three slits system is located in correspondence of an equatorial region of the solar corona; this slit system inhibits the possibility of doing imaging in this portion of the corona, so the actual coronal images of METIS will have a small sector missing as shown in the simulated image of Figure 2 (A. Bemporad courtesy [8]). Light passing through the slits is collected by a diffraction grating located in a section in front of the Gregorian telescope secondary mirror. UV light is then dispersed and focused on the centre of the same UV/EUV detector used for imaging. The METIS spectroscopic capability is essential for assessing the degree of, and thus to correct for, the blending with height of the He II 30.38 nm line and the Si XI 30.33 line, when imaging the helium corona.

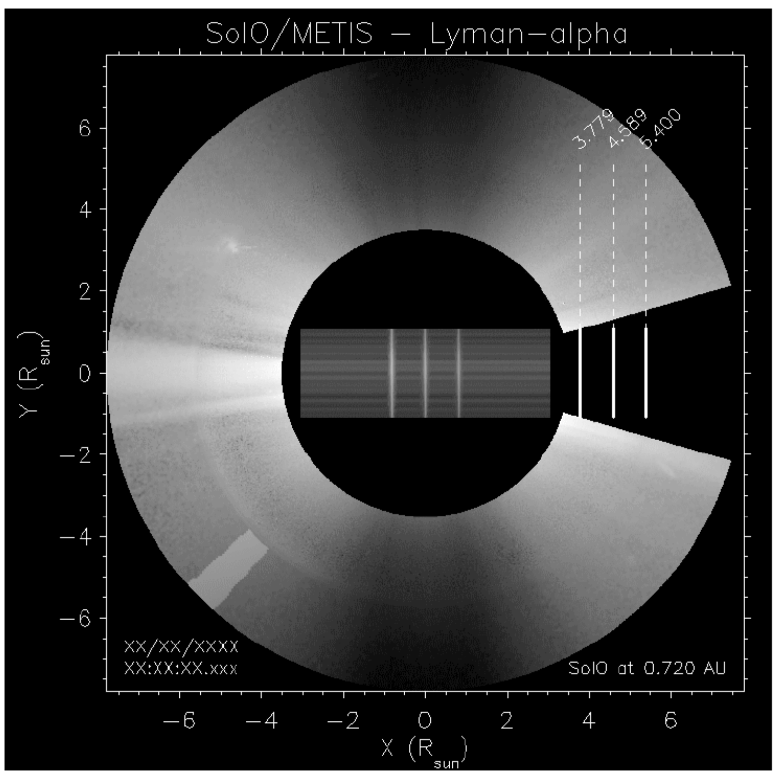

Figure 2: METIS simulated solar corona annular image of EUV/UV detector (HI line), courtesy of A. Bemporad. The rectangular field in the centre of the black disc of the coronagraph occulter is the image produced by the spectroscopic channel. The position of the three slits are superimposed in the image to show which are the observed heights in the corona.

2.1 METIS Detectors

METIS is designed to effectively obtain the highest scientific return while minimizing the overall resource allocation. The proposed architecture takes advantage of the commonality between the different elements that constitute the suite, by sharing the great majority of the system optical components to pursue different scientific investigations. The instrument design enables the simultaneous operation of both detectors, in UV (HI Lyα) and visible range, whereas when the EUV channel is selected, only the UV/EUV detector can be used.

The METIS visible detector will be a 2048x2048 CMOS Active Pixel Sensor (APS), the HyVISI (H2RG) from Teledyne, controlled by the Teledyne SIDECAR ASIC, which implement the FEE [9][10], with 36 analog input channels and 16-bit ADCs. The converted frame will be transferred to the MPPU throughout the proprietary Teledyne serial link interface to be processed, packetized and then delivered to the spacecraft (S/C).

The need to observe in the EUV requires a windowless EUV/UV detector. Moreover, the low expected count rates [11] advocate for a device operating in photon-counting mode. These characteristics are fulfilled by an imaging device coupled with a micro-channel plate (MCP) intensifier. Radiation hardness and read-out flexibility calls for a CMOS active pixel sensor (APS) as the visible light device.

The baseline for the UV detector architecture is a photon counting Intensified Active Pixel Sensor (IAPS) with a 2k × 2k format, with the capability of working also in integration mode, with a reduced resolution resulting in a 1Kx1K format, under high flux. An IAPS consists of a microchannel plate (MCP) intensifier with phosphor screen output, optically coupled via fiber optic taper to an APS sensor. A photocathode deposited on the entrance MCP face converts the incoming photons in primary photoelectrons, which are then multiplied by the MCP plate and finally converted into optical photons by the phosphor screen. At the end of the process, the APS detects these optical photons. MCP intensifiers can be operated both in analogue and in photon counting mode by changing their operating voltage: when the voltage across the channels of the MCP is below a given threshold, the MCP works at low gain and the number of electrons at the output is proportional to the number of electrons at the input; as the voltage increases, saturation effects dominate and the electronic clouds at the output tend to have similar charge; under these conditions, the pulse height distribution is quasi-gaussian and this enables the discrimination of the single photon signal from the exponentially decaying background distribution [12].

The APS detector and the readout system are provided by the Max Plank Institute of Lindau, Germany, whereas the photon counting digital front end electronics will be developed at Istituto di Astrofisica Spaziale e Fisica cosmica (IASF) in Milan. The present baseline is to use the photon counting mode for HeII observation and the integration mode for HI line. Whereas in integration mode the detector is read out once at the end of the exposure time, in photon counting regime the APS is operated continuously at a frame rate high enough not to have overlapping of the spots generated by each primary photon; then each frame is inspected in order to detect these spots and determine the (x,y) coordinates of their centers at half pixel (physical APS pixel) resolution. However, an integration mode will be also implemented for use in high flux conditions. In this case, a lower HV voltage will be applied to the MCP, in order to have the MCP working in linear mode, and single photon footprints are no longer distinguishable in the frame, instead the signal in each pixel will be the results of secondary photons generated by multiple primary photons and linearly proportional to their number.

Due to the spectral range of the coronagraph, the UV/EUV detector will be in open configuration because there is no transparent material to realize a window to work with a sealed detector. The intensifier will be then hosted in a vacuum housing with a single-shot door to be opened once in orbit and when in operation during the laboratory characterization and calibration phases (EDWM, see next section). The intensifier housing will be connected to a GSE ion pump to maintain the operating pressure level ($< 10^{-3}$ Pa) continuously during ground operations.

A prototyping activity on the photon counting digital processing electronics is starting at IASF in Milan. This electronics will also implement a 'bright protection' function, by checking the count rate in the field of view and shutting down the MCP High Voltages (HV) when the photon flux is higher than a selected safety threshold. Still to preserve the detector, in case of S/C off-pointing with the Sun disk light entering the optical path, it is foreseen the possibility of shutting down the voltage when the internal Sun Sensor will flag a S/C off-pointing. The same electronics will also implement the Spacewire standard interface to manage the internal communication with the MPPU unit.

2.2 METIS Subsystems

METIS is aimed at providing a very simple interface to the spacecraft (S/C), by internally handling the needs of the various subsystems. Besides the two detectors and their proximity electronics, the instrument has 6 mechanisms and a Sun Sensor, for safety and re-pointing, that enables to optimize the telescope's performances and safely and properly operate the coronagraph. The mechanisms required by METIS, in addition to the telescope aperture door mechanism which is S/C provided, are the following:

1. The External Re-pointing Mechanism (ERM); it shall move the instrument to correctly point METIS to the Sun center in case of S/C off-pointing, exploiting the feedback info provided by the Sun Sensor.
2. Internal Occulter alignment Mechanism (IOM): this mechanism is designed to adjust the position of the internal occulter and compensate for possible post-launch external occulter misalignments.
3. Filter Insertion Mechanism (FIM): this is a precision three positions mechanism that accommodates two filters providing multiband observation capability and a safety mirror or a neutral density filter to protect the detectors from S/C failure and off-pointing.
4. EUV Detector Window Mechanism (EDWM): this is the two position mechanism required to open the vacuum tight window of the EUV detector. This mechanism will be operated manually on ground for testing and will be definitive opened once in orbit.
5. Liquid Crystal Variable Retarder (LCVR): it constitutes the visible polarimetric system. LCVR plates replace the classical mechanically rotating retarders with electro-optical devices. The nematic liquid crystal constituting the LCVR, are able in fact to change their birefringency features by applying a 2 kHz balanced (i.e with mean equal to 0 V) square wave changing the voltage amplitude of the wave.
6. Internal Door Mechanism (IDM); this mechanism is a neutral density filter door that internally closes the METIS entrance aperture to preserve the instrument cleanliness, to use for calibrations purposes and to protect in case of a large Sun center misalignment. It will be use, during Assembly, Integration and Test activities (AIT) on ground to avoid external contaminants from entering the instrument thus degrading the METIS optics.

The control and management of the different instrument's subsystems is handled by the METIS Power and Processing Unit, MPPU; the MPPU realizes the main operative functionalities of the instrument, providing power, decision-making and data handling capabilities to METIS. A scheme of the general architecture of METIS is shown in Figure 3.

3. METIS POWER & PROCESSING UNIT

METIS is a complex instrument constituted by several subunits, mainly two detectors, six moving mechanisms and a Sun Sensor. The MPPU is the control unit of METIS that is in charge of managing the different subsystems constituting the instrument and realizing the overall observational procedures of the coronagraph. This unit manages the communication with the S/C, dispatches commands to the instrument subsystems, gathers and sends the payload telemetry (science and housekeeping) to the S/C.

3.1 MPPU Hardware

The MPPU electronics will be accommodated in a box, externally to the METIS optical bench (see Figure 1) and will distribute its duties on six electronics boards:

- A control & processing board
- A housekeeping (HK) and Mass Memory (MM) board
- Two driver Mechanisms boards
- Two secondary low voltage Power Supply boards

An additional board will connect the six boards acting as motherboard.
The processing board is based on a RISC LEON2 Processor [13] and it will implement 3 Spacewire interfaces, a custom serial link (for the VL detector) and High and Low Level commands interfaces. The processor will run an Operating System as well higher level software applications in order to manage the METIS subunits. High processing capabilities will be addressed by this radiation hard CPU, able to ensure a multi-tasking control and numeric computational power.

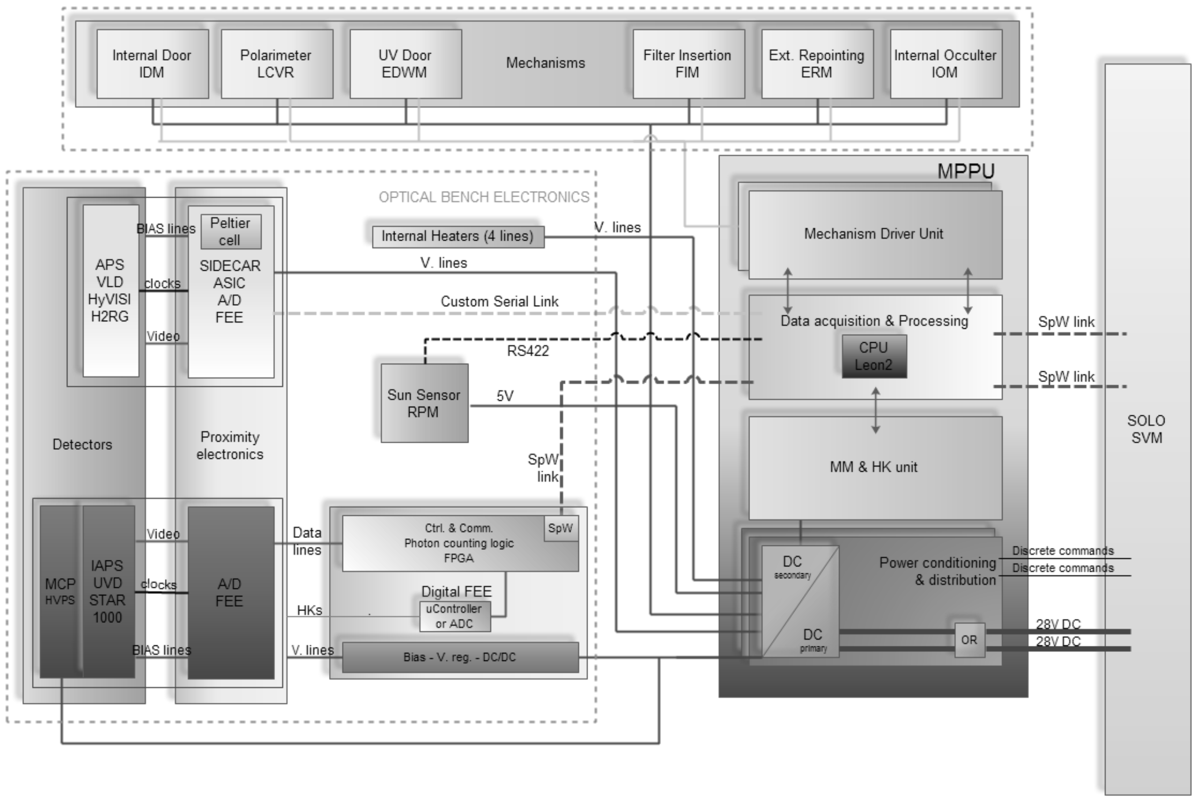

Figure 3: The METIS overall block diagram showing the instrument subunits and their main interfaces.

The CPU shall be equipped with basic SW features providing bootstrap capability, low level SW drivers, including on-board memory management SW and application SW loading capability. The boot SW will reside in a PROM located on the motherboard. The HK and MM board will have a control and communication logic (FPGA) to manage the on board mass memory (9 Gb EDAC protected of SDRAM or FLASH memory) and to perform auxiliary tasks. The connection between CPU, the control and communication logic and memories (SRAM, PROM and EEPROM) will be achieved with a dedicated memory bus on the motherboard. Actually, a more detailed study on the needed resources is ongoing to evaluate the possibility of gathering the functionalities of the control & processing and HK & MM boards in a single board.

The mechanism driver boards shall be in charge of driving, monitoring and controlling the METIS mechanisms thanks to the high level commands sent by the processor. The HK collection function is also hosted in these boards.

The two DC/DC converter boards shall provide and distribute LV (Low Voltage) electric power through the motherboard to the other internal boards and supply the mechanisms units and detectors' Front End Electronics (FEE). It will host DC/DC regulators as well as linear regulators in order to provide the voltage levels required by the electronic devices. This board will host standard DC/DC fly-back converters with short circuit, reverse polarity and in-rush current protections. The LV power supply shall be designed to supply main digital and analog electronics, providing all the necessary voltage levels. These voltage levels shall be collected and sent to the processing board for HK monitoring purposes.

3.2 On Board Software

The MPPU control & processing board represents the 'brain' of the METIS coronagraph. The overall procedure to operate the telescope is controlled and managed by the MPPU Application Software (ASW) running in the CPU.

Through the ASW, the unit manages the TM & TC tasks with the On Board Computer (OBC) to implement both the autonomous in-flight operations and the execution of possible commands sent by the ground segment. Every commands received by the S/C has to be validated by the on board software before being executed.
Once a valid acquisition command is sent by the OBC, the ASW on the MPPU manages the configuration of the HW systems operating the mechanisms and dispatching the "start" command to the METIS FEEs. The HK and scientific data produced by the instrument are then gathered by the MPPU, processed, packetized and delivered to the S/C.
The on board SW will monitor the "health status" of the overall system and will execute the FDIR (Fault Detection Isolation and Recovery) function. Herein are summarized the main functionalities the application software shall provide:

- Instrument control (FDIR, Time distribution)
- Management of instrument operational modes
- METIS subsystem management (Mechanisms, TEC)
- Collection of science and HK data produced by the METIS FEEs
- Collection of HK and ancillary data from instrument subsystems (Mechanisms, TEC, power)
- Provision of data processing and temporary storage (TBC) capabilities
- Data compression
- Managing the communication with the S/C
    - Reception, validation and dispatch of TCs
    - Transmission of TM packet (science and HK data).

Moreover specific features for the METIS on-board SW have to be developed to cope with the case of S/C offset from Sun center: a critical off-pointing angle threshold, variable as a function of perihelion distance will be defined. In case of scheduled off-center pointing above the critical threshold, the instrument will be re-pointed to the Sun center by using the ERM. If the S/C off-pointing was too large to be corrected using the ERM (i.e. for a S/C failure) the MPPU will close the IDM for safety and enter in safe mode.
This task will be managed by the METIS ASW in response to the Sun Sensor signal. To increase the detector MCP lifetime, a further internal watchdog routine checks the incoming radiation is below a specific threshold. Passing the threshold limit will put the UV detector in safe mode.
At the moment it is under study the possibility to implement a SW algorithm in the MPPU able to point out particular incoming events like CMEs, flares etc. In case one of these eruptive events occurred, the instrument could increment the data acquisition cadence maximizing the temporal resolution and therefore improving the science return.

4. ON BOARD DATA HANDLING

4.1 Data flow

The VL and EUV/UV detectors operate simultaneously when the HI filter is inserted, whereas the HeII filter enables only the EUV/UV sensor to be illuminated. In the former operative mode, the detector are operated in integration mode, each one producing a frame at a cadence that depends by the selected observing program. During HeII observations, the UV/EUV detector works in photon counting mode.
In integration mode the data produced by each detector are read out and converted by the dedicated FEEs and then are transferred to the MPPU. The received frames are processed by the MPPU CPU mainly to reduce the data volume, then are packetized in compliance to the ECSS standard [14] and finally stored into the internal MM waiting for the S/C download.
In photon counting mode a dedicated electronics on the FEE detects the photon events generated by the IAPS. The data acquisition and processing system is based on Field Programmable Gate Array technology (FPGA) and is capable of satisfying requirements of real-time operation.
The detector is read out in rolling shutter mode at a rate of 12 frame/s and the output data are serially acquired as to generate a 3x3 pixel^2 event window that sweeps dynamically the APS matrix. Each window is analyzed looking for the presence of events whose charge content lies within proper limits and satisfies a given set of morphological rules, i.e., a single peak charge profile.
The centroid coordinates of identified events are determined with sub-pixel accuracy and subsequently sent to the MPPU as a packet containing coordinate pairs and collected photo-charge information. The MPPU stores the packets in its MM

and then transfer the photon list as single, properly coded, packet at the end of the exposure time. No data compression is applied in this case.

4.2 Compression Algorithms

The METIS instrument has limited available bandwidth towards the ground segments, therefore the MPPU ASW shall implement algorithms capable of performing data reduction. In order to match the available bandwidth, a compression ratio of 10:1 is targeted. Generally, this high level of compression can only be achieved by means of lossy compression. This kind of algorithms removes information from the image, raising the problem of assessing the quality of the decoded images in order to maintain their scientific value.

Compression must be tailored to the specific characteristics of the images generated by the METIS instrument. A typical image is shown in Figure 2. The spectroscopy image is superimposed to the Lyman α image, and the resulting image has to be compressed. This image has particular characteristics that can be exploited for compression. The region of the image outside the solar corona is not of interest, and needs not to be encoded. The parts containing the spectroscopy need to be encoded with very high quality, possibly without information losses. The solar corona itself can be compressed with different degrees of quality. The quality must be higher towards the center of the image, as the samples closer to the sun bear more information (photons) than those towards the boundary of the image. These requirements call for the development of algorithms capable of performing compression with differentiated degrees of quality in different parts of the image, from lossy to lossless compression.

The activity on compression is ongoing, and will investigate the following aspects:

- assessment of the suitability of existing techniques, such as the wavelet-based CCSDS Image Data Compression recommendation, the JPEG 2000 image compression standard (also based on wavelets), and the JPEG-LS standard, which can perform lossless and near-lossless compression with low complexity;
- development of techniques for compression of regions of interest with differentiated quality;
- possible development of an ad-hoc algorithm for METIS, in case existing standards are not flexible enough;
- investigation of the possibility to perform binning after compression;
- quality assessment of the decoded image, in collaboration with the final users of the instrument;
- prototyping of the selected algorithm on a LEON 2 simulator or evaluation board, to verify complexity and performance requirements.

5. CONCLUSIONS

An overview of the METIS coronagraph and its data management system is shown. The instrument is still in the definition phase (the Instrument Preliminary Design Review, IPDR, is planned for the end of 2011) therefore the present design could undergo some changes to optimize performances, mass and power budgets. The detectors for the two channels of METIS have been selected and a preliminary design of the electronic and data handling system has been identified. In the following months a breadboarding activity will start to develop the photon counting digital processing electronics for the EUV/UV detector. Concerning the MPPU, an assessment of the computational power is ongoing to establish if the present architecture is able to satisfy performance requirements. The results of these activities will address the final architecture of the overall METIS data handling system.

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