# MESSI, the METIS instrument Software Simulator

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## ABSTRACT

Instrument software simulators are becoming essential both for supporting the instrument design and for planning the future operations. In this paper we present the Software Simulator developed for the METIS coronagraph, an instrument of the Solar Orbiter ESA mission. We describe its architecture and the modules it is composed of, and how they interchange data to simulate the whole acquisition chain from the photons entering the front window to the stream of telemetry? data received and analysed on ground.

Each software module simulates an instrument subsystem by combining theoretical models and measured subsystem properties. A web-based application handles the remote user interfaces of the Institutions of the METIS Consortium, allowing users from various sites to overview and interact with the data flow, making possible for instance input and output at intermediate nodes.

Description of the modes of use of the simulator, both present and future, are given with examples of results. These include not only design-aid tasks, as the evaluation and the tuning of the image compression algorithms, but also those tasks aimed to plan the in-flight observing sequences, based on the capability of the simulator of performing end to end simulations of science cases.

**Keywords**: Solar Corona, Coronagraph, Solar Orbiter, METIS, Space Instrument, Simulator

## 1. INTRODUCTION

### 1.1 The METIS experiment

Solar Orbiter [1] is the first medium-class mission of the ESA Cosmic Vision program, conceived to perform a close-up study of the Sun and inner heliosphere, the extended atmosphere of our star, in order to better understand and predict the behavior of the star and the environment on which our lives and activities depend.

Solar Orbiter will be launched from the Kennedy Space Center on January 2017 (nominal launch date) and after a cruise phase lasting approximately three years will be able to reach periodically, every six months, at least for the 7.5 years of the nominal mission- a perihelion ranging from 0.28 to 0.37AU.Thus the spacecraft (S/C) will be closer to the Sun than any previous spacecraft and in a privileged position suitable to perform unprecedented scientific observations thanks to a powerful combination of in-situ and remote sensing instrumentation.

Equipped with a suite of complementary remote sensing instruments, Solar Orbiter will also be the first satellite to provide detailed and exhaustive observations of the Sun's polar regions from an out-of-ecliptic vantage point at latitudes higher than 30 degrees (up to 34° close to the end of the mission). Solar Orbiter will be almost co-rotating with the Sun providing for the first time the capability of observing solar storms and coronal eruptions building up and development over an extended period from almost the same viewpoint relative to the Sun. It will also deliver data of the side of the Sun not visible from the Earth.

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The Solar Orbiter mission is conceived to address the central issue of heliophysics synthetized by one of the key questions of the ESA's Cosmic Vision 2015-2025 program: *How does the solar system work and how does the Sun to create and control the heliosphere?* The payload's scientific instrumentation is in fact specifically designed to identify the origins and causes of the solar wind, the solar energetic particles, the transient interplanetary disturbances, and the solar and heliospheric magnetic field.

Much of the crucial physics in the formation and activity of the heliosphere takes place close to the Sun. By the time magnetic structures, shocks, energetic particles and solar wind pass near our planet they have already evolved and in many cases mixed so as to blur or even cancel the signatures of their origin.

For these reasons Solar Orbiter will perform in-situ measurements of the solar wind plasma, fields, waves, and energetic particles that are still relatively unaltered and have not had their properties modified by dynamical evolution during their propagation. The main goal of the Solar Orbiter mission will be to connect the plasma measured in situ back to its th source region on the Sun through simultaneous, high-resolution imaging and spectroscopic observations both in and out of the ecliptic plane by means of the remote-sensing instrumentation.

Among these remote-sensing instruments, METIS, the Multi Element Telescope for Imaging and Spectroscopy, is an innovative coronagraph for the study and overall characterization of the solar corona in polarized visible light, UV and EUV light[2].

In the following paragraphs of this paper we will describe the METIS Software Simulator an "easy-to-use" tool in support to the METIS instrument design verification, to the observing sequences definition and planning.

### 1.2 METIS design

METIS is conceived to perform off-limb, near-Sun (FOV from 1.5 to 3degrees) observations in the region where the solar wind is accelerated and where the CME early propagation is observable. The METIS coronagraph design exploits the multi-wavelength capabilities of multi-layers coated mirrors, reflective both in the visible-light band and in the UV and extremely ultraviolet light (EUV).

The optical scheme is based on a Gregorian configuration. Light enters through the inverted external occulter, a circular aperture located at the level of the outside panel of the spacecraft heat shield facing the Sun[3], [4]. An Internal Door Mechanisms (IDM),positioned at the end of the boom of the coronagraph is used mainly to preserve the instrument's cleanliness and the detectors safety; it will also be used for calibration purposes.

The instrument is able to select three different wavelength bands by a Filter Insertion Mechanism (FIM): visible light, collected by a visible light detector after being processed by a polarizer, or either ultraviolet or extreme ultraviolet lines collected by the UV-EUV detector. Visible and UV light are detected simultaneously.

Thus the instrument, thanks to its innovative characteristics, will be able to perform for the first time near-Sun simultaneous imaging of the full corona in polarized visible-light (590-650 nm) and narrow-band ultraviolet HI Ly-α, monochromatic imaging of the full corona in the extreme ultraviolet HeII Ly-α and spectroscopic observations in the same spectral lines in a sector 32 deg wide of the solar corona centred on the equatorial plane on the West limb.

Data analysis and image reduction will allow a complete characterization of the three most important plasma components of the corona and the solar wind (electrons, protons and helium ions), by means of detailed diagnostics and coronal phenomena interpretations by advanced modeling.

METIS consists of an Optical Unit (MOU) plus an external electronics box, the METIS Processing and Power Unit (MPPU), located near the MOU (Fig. 1) and connected to it and to the spacecraft On Board Computer (OBC) by suitable harnesses. The optical unit is composed by the coronagraph optics, detectors assemblies, mechanisms subsystems, electrical interfaces for power supply and telecommand/telemetry links, and thermal regulating hardware. A Service Unit is foreseen next to the EUV detector assembly in order to perform some ancillary tasks needed for the proper detector functioning.

The METIS Processing and Power Unit (MPPU) [5], [6] acts as the unique electrical interface towards the S/C. It manages the TM/TC data flows from/to the S/C OBC via two (N+R) SpW links, controlling and powering the two detectors assemblies, the Service Unit and the mechanisms. It is composed by several sections, each one dedicated a specific electronic function. These functions are logically distributed on six electronics boards: 2 power supply boards, 2 mechanisms driver boards, 1 housekeeping collection and mass memory board and 1 Processing and Control (CPU) board. These boards are mounted and interconnected together by means of a motherboard.

The CPU board is based on the LEON2 processor (ATMEL AT697F) and a service logic implemented in a rad-hard FPGA, the RTAX2000S model from ACTEL. The processor will run the Real Time Operating System (VxWorks 6.3) and the METIS Application SW, being thus able to manage the Operative Modes of the instrument and to perform the overall scientific tasks.

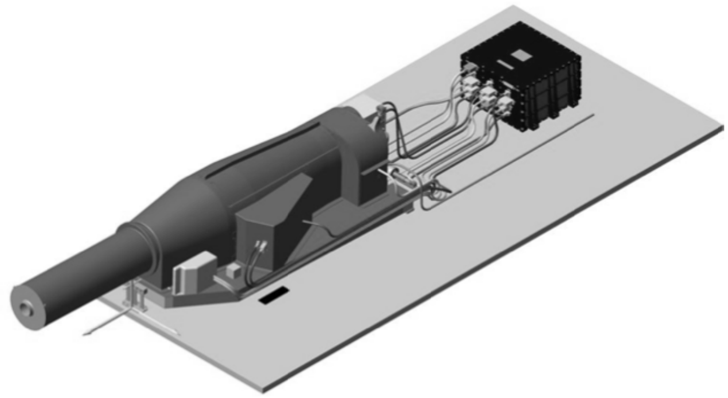

Figure 1. METIS Optical Unit (MOU) and MPPU accommodation on Solar Obiter panel

## 2. MESSI GOAL AND OVERVIEW

The preliminary concept of the METIS Software Simulator was first developed to test different data compression schemes, necessary for the limited telemetry available. A simple "data pipeline", fed by synthetic corona images, was established. These images were compressed and decompressed and the result compared with the original one. The present goal of the simulator is that to include as many subsystems as possible, present in the scientific acquisition chain and to increase the accuracy in simulating the function of each subsystem.

The present structure of the simulator is sketched in Fig.2. The flow of the simulation steps is linear and each block output is the input of the following one. Although METIS is a three band instrument able to perform multiband), the simulator provides the simulation of a channel at time, thus it is acting as a set of three independent simulators.

Each single functional block can be defined as a convolution operator and its transfer function is defined by a mix of theoretical models and measured subsystem properties. At the present the simulator is still without a GUI.A web-based application is under development. This will allows remote users to interact with the data flow, making possible for instance to feed input and get output at intermediate nodes.

As a common description, each block receives from either the previous block or the operator an input stimulus (either a matrix or a data cube), some context data (scalar or vectors) and its configuration parameters (scalar or vectors). According to what the block is simulating, it produces an output stream (again a matrix or a data cube) with its set of context data ready to be downloaded or passed to next block in the functional flow. The standard format used to encapsulate and exchange data is FITS (with the exception of the compressed stream) and the context data are stored in the FITS file header.

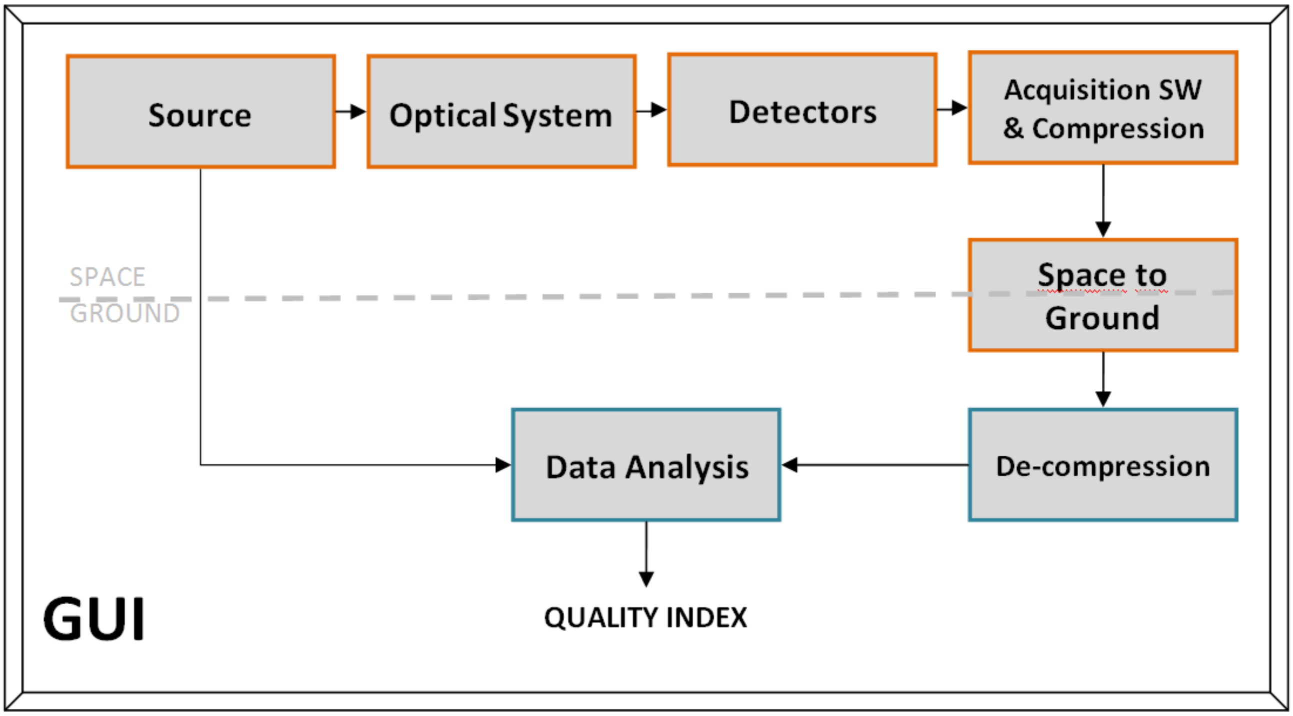


Figure 2. MESSI functional scheme

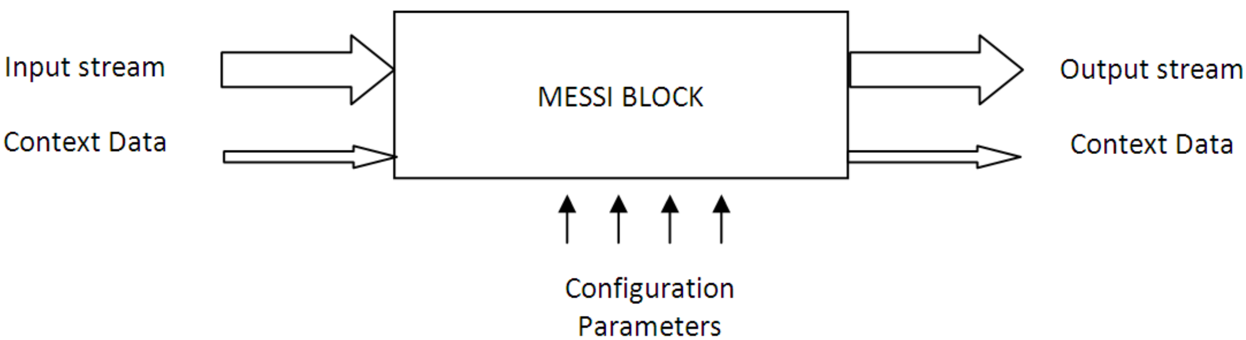


Figure 3. MESSI Block general concept scheme

## 3. MESSI FUNCTIONAL BLOCKS DESCRIPTION

### 3.1 The Source

The first block is the astronomical source, that provides a synthetic image of the Sun disk (featureless because the direct disk light is occulted) and of the corona having realistic fluxes. In this image, the physical observable quantities (like solar wind outflow speed, electron density and so on) deducible with the data reduction techniques, well defined and known at-priori. The configuration parameters, allow to select one of the three optical bands, and to vary the field of view as a function of the S/C distance from the Sun. The output data cube for the visible light channel may supply up to four images, carrying thus the polarized light information. The standard output image size is 2048x2048 simulating the input flux at the entrance pupil integrated over the bandwidth expressed in photons $cm^{-2}$ $s^{-1}$ $sr^{-1}$. The bandwidth integration is a simplification justified by the narrow spectral bands where METIS is sensitive.

### 3.2 The Optical System

As convolution matrix, the optical system block uses the transfer function of the optical system itself obtained by running the geometrical image analysis  simulation with the numerical ray-trace software. In the optical model, are present not only the optical components but also most of the structural components along the optical path; the latter effect is clearly noticeable in the West (right) coronal sector obscured by the components of the spectroscopic path. Therefore, the used convolution matrix includes the real vignetting function information over the whole field of view.
The output image represents the photon flux incident on the focal plane, integrated over the bandwidth, sampled with a 2048x2048 elements grid and expressed in photons·pxl$^{-1}$·s$^{-1}$. The element (pixel) size is 18μm for the visible light channel and 15 μm for the UV channel (because they same field of view, about 10 arcsec, on the sky).
In the present model of this block the optical response given by the spectroscopic path is not simulated.

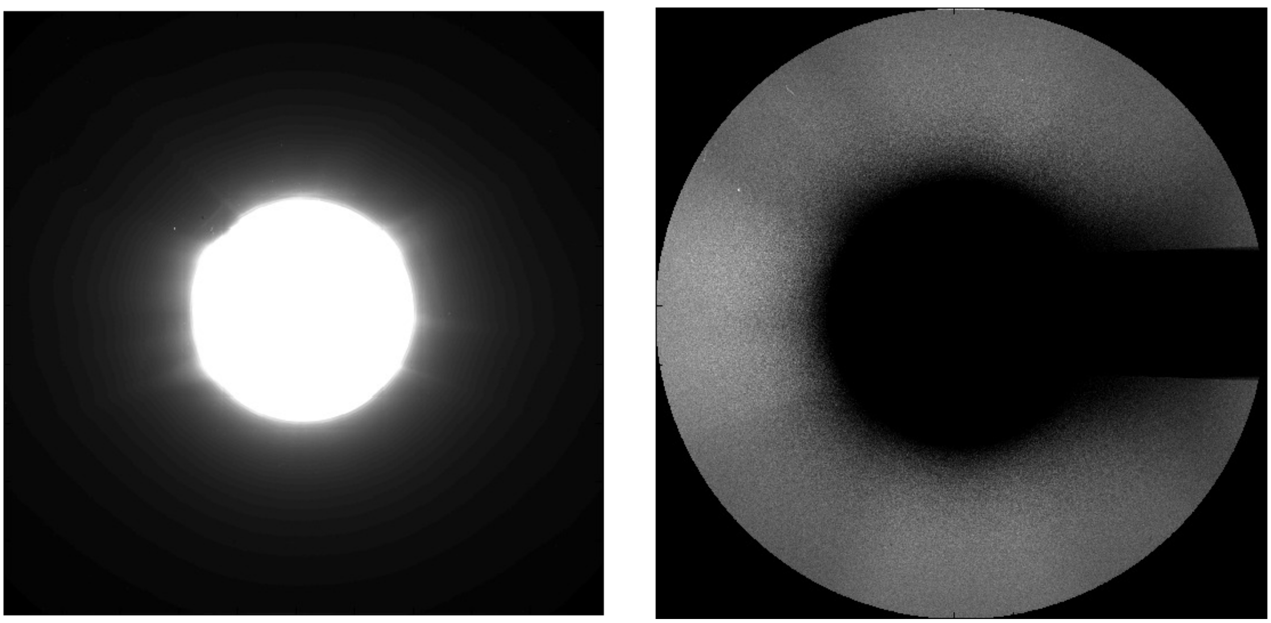

Figure 4 (left): A simulated un-occulted METIS FOV at 0.28 AU in the visible light (K+F) derived from a LASCO-C2 observation; palette threshold have been set to give some visibility to the corona features.
(right): the simulated visible light image as acquired and digitized by the detector.

### 3.3 The Detectors

The Detector Block converts the input focal plane flux in a digitized image on the basis of the characteristics of the two METIS detectors. The simulator has three distinct mode of simulation according to the detector selected, the Visible light or UV/EUV detector, and for the latter the readout technique adopted, chose as a function of the incident flux and the desired dynamic range.
The following configuration are common to all channels: Exposure Time (ET) [s], Detector Integration Time (DIT) [s], the gain [e-/ADU], the ReadOut Noise (RON) [ADU] ,the temperature [°C], the full well capacity [e-] and the mean quantum efficiency over the spectral band.
The following parameters are instead specific to the UV/EUV channels: the readout mode [integration / photon counting], the MCP intensifier voltage [V] and – applicable only when in photon counting mode - the pixel size [15 or 30 μm].

### 3.4 The Acquisition and Compression SW, the Space to Ground and the De-Compression SW

Due to the shape of the features in a typical coronal image, it was necessary to develop a compression algorithm having the option to vary the decoded image quality depending on specific regions of arbitrary shape, from high values of CR, Compression Ratio, up to possibly lossless compression in some critical image portions.

The simulator block runs the same software code which is under development for the project. In the preliminary version it accepts a 2048x2048 “Quality Matrix” where it is possible to set the desired quality or fidelity for that specific pixel or area by assign to the matrix element an integer varying from 0 (lossless) to 10 (not important).The output stream is stored in a vector of length depending to the quality imposed.
The Ground to Space block in the present implementation adds to the context data set only the real data volume to be transmitted to ground taking into account the packetization process and the number of packets transmitted.
The de-compression block performs the opposite transformation from vector to a 2048x2048 matrix and does not have, at the moment, any configuration parameter.

# 4. THE WORK AHEAD

## 4.1 The Data Analysis

At the moment no automated data analysis is foreseen within the simulator because the data reduction and analysis is performed off-line with dedicated tools.
The required functionality for this block is that to able to provide an automated “Quality Index” by comparing the physical observable quantities computed from both the original synthetic image and the image obtained at the end of the simulation. This means to include in this block specific data reduction functionalities tuned accordingly to the input stimuli.

## 4.2 The GUI

The next improvement of the simulator foreseen will be the web based graphical user interface. This will allow a local or remote user to submit his own stimuli to the simulator and retrieve the results. The preliminary layout design is a multiple tab page where each tab is assigned to a dingle block. Here it is possible to set the configuration parameters, upload or read from the previous block the input file and set the optional download of the output.
It is foreseen to have also some “global” instrumental parameters that are passed to multiple blocks (e.g. the temperature).
It is planned to use the jQuery library for the browser management and to rely on python (or php) scripts for running the blocks simulations. These scripts will enwrap the block code written in IDL, C++ or MatLab and will manage the status of each simulation step. In this way it will be possible to monitor and analyze the output with specific developed tools.

## 4.3 Other Blocks improvements

The most relevant functionalities, that are planned to be included in the future versions of the simulator, are

- Introduction of the shot noise in the Source block;

- Temperature dependence of the Liquid Cristal Variable Retarder response in the Optical block;

- Stray-light simulation in the Optical block;

- time tagging of the operations in order to simulate also the timeline of an observing sequence;

- Photo response non uniformity and linearity for the Detectors block;

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