Number	43
Publication Year	2020
Acceptance in OA@INAF	2020-10-24T14:55:07Z
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Handle	http://hdl.handle.net/20.500.12386/27976; http://dx.doi.org/10.20371/INAF/TechRep/43

A database of synthetic images in WL and UV filters to test diagnostic and modeling techniques to be applied on the future Metis data

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Abstract

In this report we describe how Metis synthetic images have been created to develop, test and optimize diagnostic tools for the inversion of combined WL and UV future images, and the determination of 2D maps of electron density and solar wind. We used FORWARD package and a coronal 3D model in order to create a baseline of WL and UV coronagraphic images representative of future Metis data acquired at different s/c distances and periods of solar activity cycle.

1 Introduction

Metis will be the first solar coronagraph, mounted on the Solar Orbiter ESA-NASA observatory, capable of acquiring simultaneous imaging of the off-limb solar corona in white light (WL) and in UltraViolet light (UV). The unprecedented temporal coverage and spatial resolution of Metis will allow to perform a diagnostic of structures and dynamics of the full corona.

The Solar Orbiter mission profile will allow to observe the solar corona from a close vantage point (0.28 AU, at the closest perihelion), achieving increasing out-of-ecliptic views with the increase of the orbit inclination over time. Moreover, observations near perihelion, during the phase of lower rotational velocity of the solar surface relative to the spacecraft (s/c), will allow longer-term studies of the off-limb coronal features.

Metis will acquire images the solar corona simultaneously in the WL band in wavelength range of 580 and 640 nm (including a broad-band polarimeter to observe the linearly polarized component of the K-corona), and in the UV H I Lyman-α line at 121.6 nm. The Metis measurements, obtained from different helio-latitudes, will allow to characterize in a better way the main physical parameters and dynamics of the electron and neutral hydrogen/proton plasma components of the corona in the region where the solar wind undergoes the acceleration process and where the onset and initial propagation of coronal mass ejections (CMEs) take place. Metis can offer the possibility to take a step forward about the origin and heating/acceleration of the fast and slow solar wind streams; the origin, acceleration, and transport of the solar energetic particles (SEPs); the transient CMEs and their evolution in the inner heliosphere, improving our understanding of the region connecting the Sun to the heliosphere (Antonucci *et al.* 2019).

2 A database of synthetic images in WL and UV filters

Nowadays, a lot of data from existing magnetometers and EUV imagers on-board previous and current space missions (e.g. SOHO, STEREO, SDO) are available as a baseline for the development of data analysis tools that will be applied to data products provided in the next future by Solar

Orbiter. Unfortunately, the same baseline of data exists only for the Metis WL channel (e.g. LASCO and COR1-COR2 coronagraphs), while only sparse observations (limited to the field of view of the UVCS instrument on-board SOHO) are available for the Metis UV Lyman-α channel. It is important to make available a data archive to develop, test and optimize diagnostic tools for the inversion of combined WL and UV future images in order to obtain 2D maps of electron density and solar wind (protons) speed (radial speed), see fig. 1.

To overcome this limitations, in previous works colleagues in the Metis team employed the sparse UVCS observations to reconstruct (via interpolation and extrapolation) full 2D images of the coronal UV Lyman-α emission (Bemporad 2017; Dolei *et al.* 2018; Dolei *et al.* 2019). These images have been thus analized, in combination with WL images, to test future diagnostics (based on the Doppler dimming effects; Noci, Kohl, and Withbroe 1987) for Metis data, as well as possible uncertainties related with physical parameters to be assumed for the data inversion technique. Nevertheless, this method can be applied only for a limited amount of data acquired by UVCS.

A possible alternative solution is to use FORWARD package to create a baseline of WL and UV coronagraphic images representative of future Metis data acquired at different s/c distances and periods of solar activity cycle to test data analysis tools. The advantage of this approach is that to build the synthetic 2D images it is necessary to assume a 3D model of the solar corona, hence for the 3D distribution of coronal densities and outflow speed. This means that, by applying the data inversion tools to the synthetic images, it will be possible to perform a direct comparison between the input 3D distribution of plasma physical quantities, and the output 2D distribution of the same quantities as derived with data inversion. Hence, this will allow a very important test for the optimization of diagnostic tools for Metis images.

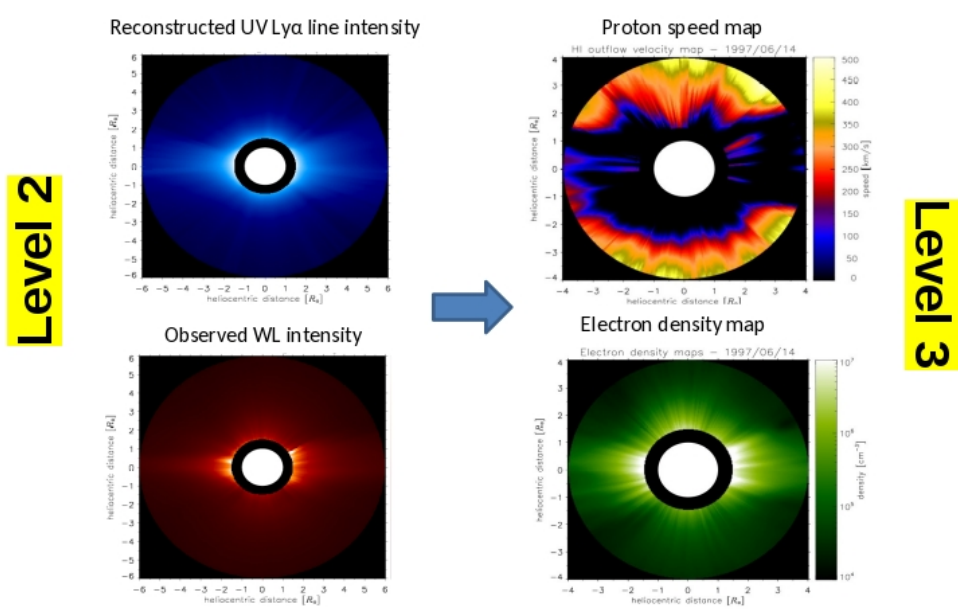

Figure 1. From intensities (level 2) to plasma parameters (level 3).

2.1 FORWARD package

The FORWARD package is a set of codes, developed by HAO, intended to be used for forward modeling of various coronal observables, and for access and comparison with existing data. Given a coronal 3D model, many different synthetic observables may be produced, as well as plots of

model plasma properties (density, magnetic field, etc.). FORWARD enables "forward-fitting" of specific observations, and helps to build intuition into how physical properties of coronal plasma translate to observable properties.

The package works (under IDL environment) with user-inputted numerical simulation datacubes, and automatically interfaces with the Solar Soft routines. FORWARD includes routines to reproduce data from EUV/Xray imagers, UV/EUV spectrometers, white-light coronagraphs, and radio polarimeters. More details can be found in Gibson *et al.* (2016).

Nevertheless, the available version of the FORWARD package is not able also to simulate the coronal Lyman-α emission, taking into account the complex geometry of resonant scattering of chromospheric radiation emitted by the Sun (Noci, Kohl, and Withbroe 1987). Hence, in collaboration with S. Gibson and other colleagues at HAO, the FORWARD package has been modified to also include the computation of the Lyman-α emission, as well as the computation of polarized component in the Lyman-α emission and effects related with the presence of the magnetic field due to the so-called Hanle effect (see Fineschi *et al.* 1993). For the purposes of this work only the total Lyman-α brightness has been considered, because Metis has not a polarizing filter for the UV emission.

2.2 Orbit and time range selection

Assuming the launch date planned on 10th February 2020, we load the kernels files,available on https://issues.cosmos.esa.int/solarorbiterwiki, to be used in SunSPICE package (for handling spacecraft ephemeris and pointing information, with particular emphasis on interplanetary missions) in order to obtain the future space coordinate of Solar Orbiter (heliodistance, latitude, and longitude) in Heliocentric Inertial (HCI) reference system. For our purposes only heliodistance and latitude are important. The entire evolution of these coordinates during the whole mission (cruise phase, nominal phase, and extended mission) are shown in fig. 2:

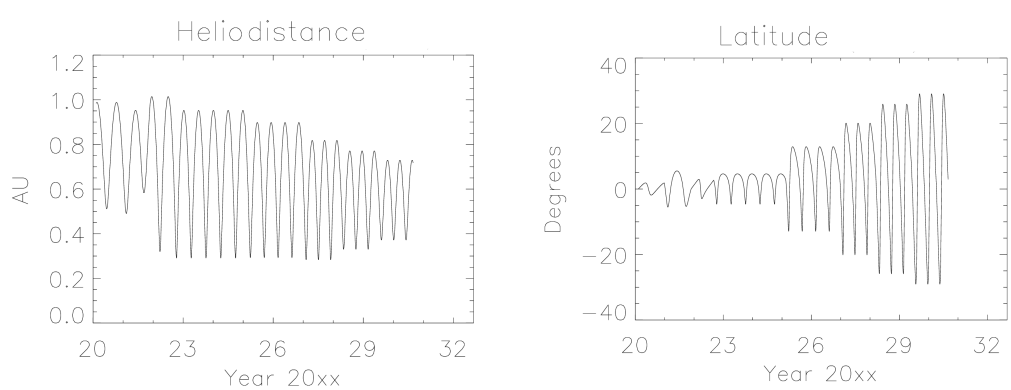

Figure 2. The heliodistance and latitude variation of Solar Orbiter during the entire mission period (2020-2030).

To build synthetic 2D images with FORWARD it is necessary to assume a 3D MHD model of the solar corona, providing the 3D distribution of coronal densities and outflow speeds. Then, by applying the data inversion tools to the 2D synthetic images, it will be possible to perform a direct comparison between the input 3D distribution of plasma physical quantities, and the output 2D distribution of the same quantities as derived with data inversion. This will allow a very important test and optimization of diagnostic tools for Metis images analysis. For each future remote sensing window, the synthetic images have been simulated by importing with FORWARD 3D data cubes relative to the conditions on the Sun 11.7 years before the mission time (nominal + extended). In this way, the synthetic images will capture the expected variations of the coronal appearance

related with the solar cycle during the mission. Numerical MHD simulations were performed by the Predictive Science Group based on Carrington maps of photospheric magnetic fields on the Sun. The 3D data cubes are constructed with the MAS (Magnetohydrodynamic Algorithm outside a Sphere) model. The MAS code (Mikić *et al.* 1999) integrates the time-dependent resistive thermodynamic magnetohydrodynamic (MHD) equations in three-dimentional spherical coordinates and is used extensively in models of coronal structure, coronal dynamics and coronal mass ejections out to the Earth. Other important information, including the links to all papers, are available at https://www.predsci.com/corona/model$_$desc.html

2.3 Synthetic images by FORWARD

To reproduce the solar corona as it will be observed by Solar Orbiter also considering the evolution related with the solar activity cicle, we used data cubes representative of coronal conditions 11.7 years old with respect to time range selected along the orbit, and the following Metis FoV (field of view) parameters:

1. 1.6 deg (the occulter)
2. 2.9 deg FoV outer limit (image borders)
3. 3.4 deg FoV outer limit (image corners)

The projected FoV will depend on the actual heliodistance of the spacecraft.

The synthetic observable produced with FORWARD are:

1. WL (pb) integrated along the LOS ($\pm 2R_{\odot}$) on a 512 x 512 pixels map;
2. EUV (174 Å SWAP synthetic images) on POS on a 512 x 512 pixels map;
3. UV (Ly-α, STOKES parameter I) integrated along the LOS ($\pm 2R_{\odot}$) on a 512 x 512 pixels map;

An example of a synthetic image produced by FORWARD (the inner region represent the EUV disk as it will be seen by EUI at 174 Å and the external part is the WL corona) is shown in fig.3.

A possible limitation on this way to proceed is the requested computational time for synthetic UV/Ly-α images that is 24 hrs, meanwhile for WL is a few seconds.

From the MHD data cube we imported:

- Velocity (radial) map (512 x 512 pixels)
- Density map (512 x 512 pixels)
- Temperature map (512 x 512 pixels)

2.4 Solar rotation rate correction

As Solar Orbiter will orbit in quasi co-rotation with Sun the effect is that the solar angular rotation rate will appear slowed down. To obtain this effect with FORWARD (designed to simulate observations from a distance of 1 AU) we used relative motion equations. In particular, We employed the solar and s/c angular velocities $\omega_{\odot}$ (at the equator) and ω_{sc}, respectively; ω_{sc} was calculated as:

$$\omega_{sc} = \frac{\phi_i - \phi_0}{\Delta t}, \tag{1}$$

where Δt_i is time interval and ϕ_i are the solar longitude obtained by SunSPICE at every time. The sun longitudinal variation as seen from the Earth and s/c ($\Delta\phi_{sc,i}$ and $\Delta\phi_{\odot,i}$, respectively) are:

$$\Delta\phi_{sc,i} = \phi_{i+1} - \phi_i \tag{2}$$

$$\Delta\phi_{\odot,i} = \omega_{\odot} * (\Delta t_i) \tag{3}$$

Then, considering the reference system of the s/c we obtain the time interval Δt_{rel} requested by the spacecraft to see the Sun rotating of the same angle from the Earth:

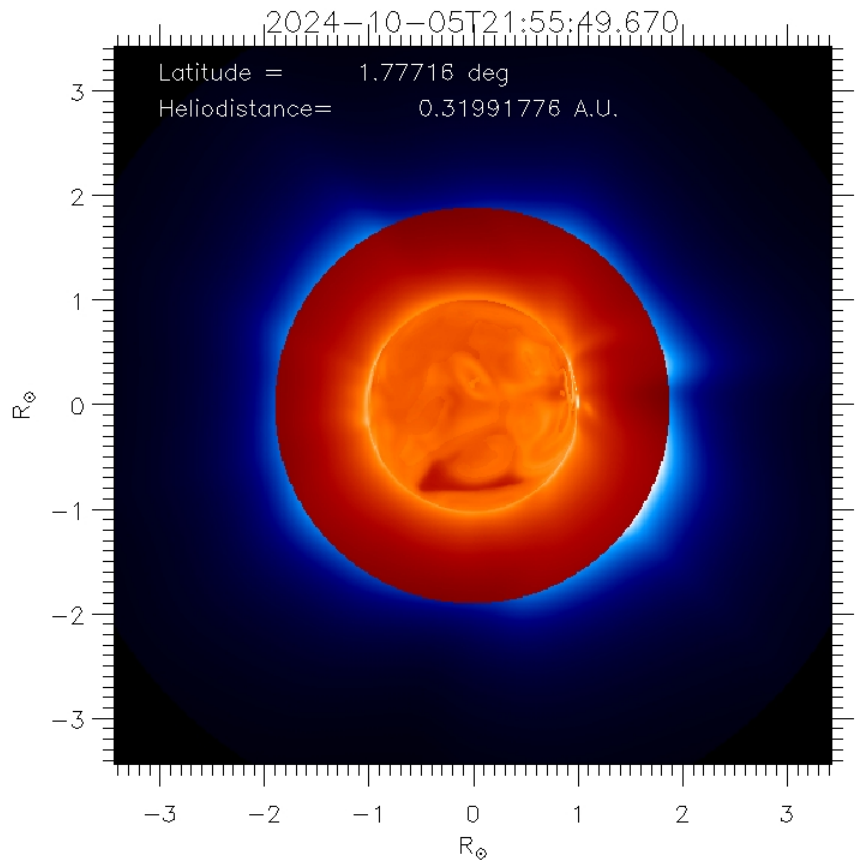

Figure 3. An example of a synthetic image produced by FORWARD: the inner region represent the EUV disk as it will be seen by EUI at 174 Å and the external part is the WL corona.

$$\Delta t_{rel} = \frac{\phi_{rel}}{\omega_{\odot}} \tag{4}$$

The final effect is a time contraction: the sun is seen to rotate slower and so the effect of quasi-corotation is reproduced.

3 Conclusions

In this report, we summarized the methods used to obtain coronal images simulating those will be observed by Metis coronagraph. Using the FORWARD package of Solar SoftWare we built WL and UV images taking into account the field of view and the relative motion of the s/c respect with the Sun. The collection of synthetic images will allow us to test the data analysis tools. In fact, the simulated images derived from 3D data cubes obtained with a numerical MHD simulation: the Magnetohydrodynamic Algorithm outside a Sphere (MAS, by Predictive Science team). This MHD model provide important plasma parameters distributions (density, temperature, magnetic field, etc..) that can be used to perform a direct comparison between the input 3D data distribution and the output 2D distribution of the same quantities as derived with data inversion and so, to test and improve our analysis technique. The current limitation on this method to proceed is the high computational time to build the UV images compared with that request by WL images, however this problem could be solved involving different processors working in parallel.

The final result is the creation of a synthetic data archive for every remote sensing window during the mission and collected them in an online repository (Google Drive). It is possible to start testing the actual analysis technique and develop new ones.

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