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# Evaluation of a liquid crystal based polarization modulator for a space mission thermal environment

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ABSTRACT

The Multi Element Telescope for Imaging and Spectroscopy (METIS) is one of the remote sensing instruments to be onboard the future NASA/ESA Solar Orbiter mission. The science nominal mission orbit will take the spacecraft from 0.28 to 0.95 astronomical units from the Sun, setting challenging and variable thermal conditions to its payload. METIS is an inverted-occultation coronagraph that will image the solar corona in the visible and UV wavelength range. In the visible light path a Polarization Modulation Package (PMP) performs a polarimetric analysis of the incoming solar light. This PMP is based on liquid crystal variable retarders (LCVR) and works under a temporal modulation scheme. The LCVRs behavior has a dependence on temperature and, as a consequence, it is critical to guarantee the PMP performance in the mission thermal environment. Key system specifications are the optical quality and the optical retardance homogeneity. Moreover, the thermally induced elastic deformations of the mechanical mounts and the LCVRs shall not produce any performance degradation. A suitable thermal control is hence required to maintain the system within its allowed limits at any time. The PMP shall also be able to reach specific set-points with the power budget allocated. Consequently, and in order to verify the PMP thermal design, we have experimentally reproduced the expected thermal flight environment. Specifically, a thermal-vacuum cycle test campaign is run at the different mission operational conditions. The purpose is both to check the stability of the thermal conditions and to study the optical quality evolution/degradation. Within this test transmitted wavefront measurements and functional verification tests have been carried out. To do that we adapted an optical interrogation scheme, based on a phase shifting interferometric technique, that allows for inspection of the PMP optical aperture. Finally, measurements obtained at non-operational temperature conditions are also shown. These results demonstrate that the device meets the specifications required to perform its operational role in the space mission environment.



## 1. Introduction

The future Solar Orbiter (SolO) ESA/NASA mission is intended to perform measurements of the inner heliosphere, nascent solar wind, and close observations of the polar regions of the Sun [1]. The spacecraft (S/C) is a Sun-pointed, 3-axis stabilized platform, with a dedicated heat shield to provide protection from the high levels of solar flux near perihelion. Its payload suite combines remote sensing with in situ analysis instrumentation. Suitable fields-of-view to the Sun are provided for the remote-sensing instruments by means of feedthroughs in the heat shield.

The challenging orbit of the mission imposes harsh thermal environments on all on board subsystems. During the science mission the S/C distance to the Sun will oscillate between 0.28 and 0.95 astronomical units (AU) in about 3 months time, thus exposing the platform to very different irradiation conditions. As a consequence, and for a suitable optical performance, a careful thermal modeling and a thorough experimental validation of the instruments in their thermal flight environment is required.

One of the remote sensing instruments on board SolO is the Multi Element Telescope for Imaging and Spectroscopy (METIS) [2]. METIS is an externally occulted coronagraph. This instrument uses a polarimeter to analyse the visible components of the coronal light.

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A section of this polarimeter is a Polarization Modulator Package (PMP) designed to perform temporal modulation of the incoming light [3].

The PMP is based on Liquid Crystal Variable Retarders (LCVRs). Our team have performed an extensive validation campaign of LCVRs for aerospace applications [4,5]. Among other tests, we have evaluated the impact of vacuum, temperature and radiation on the optical performance, such as optical retardance or response time. Our work led to the development of the successful IMaX instrument, a LCVR based spectro-polarimeter, on board the stratospheric Sunrise I and II missions [6,7]. These were projects within the NASA Long Duration Balloon Program. As a consequence of this work LCVRs will be used not only in the METIS PMP, but also in other two modulators within the Polarimetric and Helioseismic Imager, another remote sensing instrument on board SolO [8,9].

Moreover, although LCVRs is a well-known technology for ground applications in astronomy [10,11], this is, to our knowledge, the first time it will be used in a space instrument. LCVRs become a powerful alternative to the traditional rotating polarizing optics since they require less mass, volume and do not need to use any form of mechanisms [12]. The LCVRs response times are in the range of tens of milliseconds or better, adequate for a space spectro-polarimeter. They are also easy to synchronize with the detector readout, due to their electro-optical nature, thus simplifying instrument control. These are significant advantages for an instrument on board a spacecraft, where the resources are very limited and the risk of a mechanical failure must be minimized.

In the first sections of this paper the METIS PMP and its main thermal-related requirements are described. A key constraint for the PMP design is the thermal stability required during the polarimetric measurements. As a consequence, specific temperature set-points are defined within its operational temperature range. These set-points can be selected as a function of the flight environment. Then, an experimental arrangement to set this environment is presented and a thermal analysis verifies the suitability of this arrangement.

The second half of this work deals with the PMP thermo-vacuum test campaign. The device is subjected to the mission operational conditions in a thermal cycle test using the experimental arrangement previously described. The thermal control is programmed to establish the different set-points along these cycles. The main objective here is to verify the PMP thermal control in the expected mission environment. Combined to this test we perform optical quality measurements of the PMP optical aperture in order to check that the thermo-elastic deformation of the components (i.e. LCVRs, mechanical mounts, . . .) do not produce any degradation. This is done by means of a phase shifting interferometric technique, that we have adapted to our set-up. Thus, transmitted wavefront measurements were obtained in order to verify the performance and degradation of the device. In addition, functional verification of the LCVRs was also performed during this thermo-vacuum test.

Finally, a list of other parameters, evaluated at the non-operational temperatures, are given in the last section. However, it is important to mention that the tests described here are just a fraction of the complete acceptance campaign at the subsystem level. These tests are preceded and followed by other tests such as radiation, vibration and more specific tests, such as the characterization of the polarimetric efficiencies, following the method described in the literature [4,13].

## 2. The Multi Element Telescope for Imaging and Spectroscopy

METIS consists of a coronagraph for the study and characterization of the solar corona. METIS is based on a novel design, which introduces the concept of occulter inversion in solar coronagraphy [2]: the coronal light enters through a circular aperture (Ø40 mm) acting as an Inverted External Occulter (IEO) located on the outside panel of the heat shield. The IEO is supported by a suitable truss (boom) which protrudes from the S/C instrument bay through the heat shield. Fig. 1 shows a CAD model of the instrument.

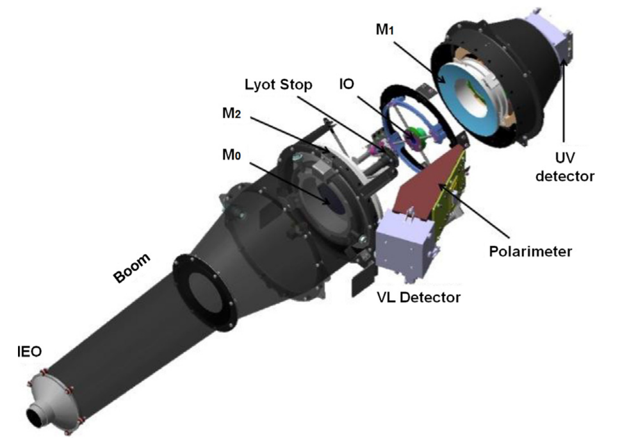


**Fig. 1.** METIS optomechanical layout showing the main telescope elements. The PMP is a section of the polarimeter.

A Ø71 mm spherical mirror ($M_0$) rejects back the disk light through the IEO up to 1.1°, this is 1.17 times the apparent solar radii at a distance of 0.28 AU. The coronal light is collected by an on-axis Gregorian telescope. The suppression of the diffracted light off the edges of the IEO and $M_0$ is achieved by, respectively, an Internal Occulter (IO) and a Lyot trap.

The METIS optical configuration includes visible light (VL) and UV imaging. Moreover, the inverted occultation concept can also accommodate a EUV spectrograph maintaining the same basic optical layout. The design of this coronagraph minimizes the solar flux entering the instrument [14].

The METIS polarimeter arm includes a number of polarization optics in a Senarmont configuration [15]. After diffraction in $M_1$, visible light is transmitted by a bandpass filter (580–640 nm). The optical path travels through a fixed quarter-wave retarder (at 0° with respect to the PMP LCVRs fast axis), the PMP itself, and a linear polarizer (analyzer with transmission axis at 45°) before reaching the VL detector.

Consequently, the METIS polarimetric system will measure the Q and U Stokes parameters corresponding to the linear polarization components of the incoming solar light. The polarization modulation shall be carried out by the PMP, which generates different modulations of the polarization state by controlled changes in the optical retardance.

## 3. The Polarization Modulation Package

A partially exploded view of the PMP is shown in Fig. 2(a). The PMP main structure is manufactured of titanium (Grade 5) in order to have enough mechanical stiffness, withstand high mechanical loads and provide for thermal insulation. It is finished with an Astroblack coating (Metal Estalki S.L.) to fulfill the straylight requirements. The PMP consist of two identical LCVR assemblies. Each assembly allocates one LCVR, its aluminum mounting rings, a heater and a thermal sensor. Fig. 2(b) shows a picture of the PMP flight model.

The driving voltage is applied to the LCVRs through a kapton flexible cable attached to the cells using an electrical conductor glue (Eccobond 56C, Henkel). The kapton cable also includes the signal of the Pt100 temperature sensor (model POTL1102, Rose-