In-flight radiometric calibration of Metis using stars

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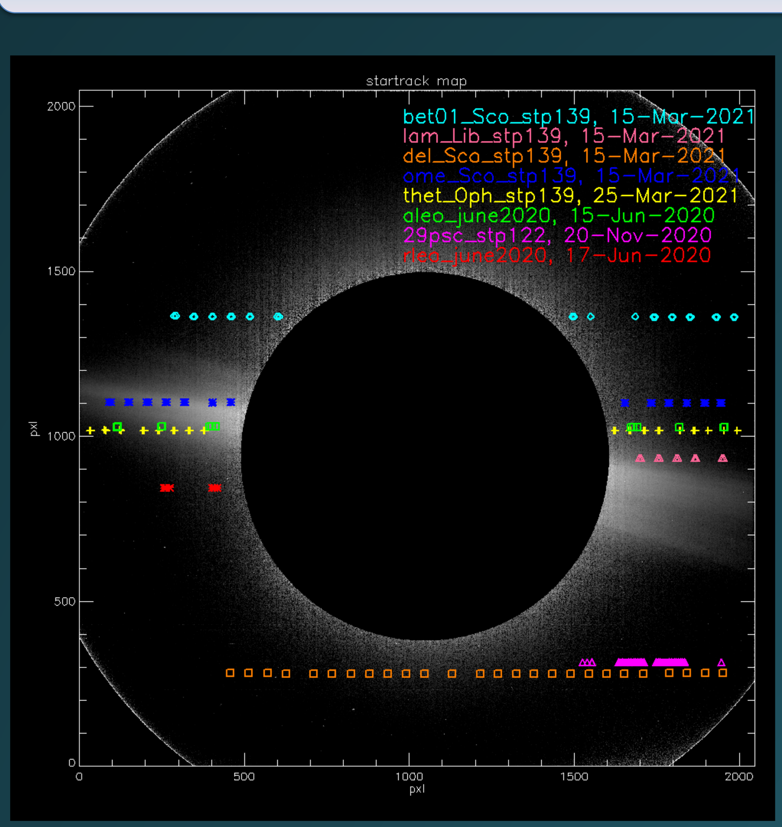
Metis is the coronagraph on-board Solar Orbiter, an ESA/NASA solar mission with two important characteristics of uniqueness: it will observe the Sun and its atmosphere with an orbit inclined on the plane of the Ecliptic, up to a maximum of about 33°, and it will approach our star up to a perihelion of 0.28 AU (Astronomical Units).
The launch of the probe happened successfully in February 2020 and now SolO has also completed the *commissioning phase* and it is in the *cruise phase.* Metis is an externally occulted imaging coronagraph that provides imaging of the extended corona in ultraviolet and visible light, and during these first phases, has performed extensively observational campaigns in order to characterize the response of the two channels.
Amongst the different calibration and characterization activities already performed and planned for the future, an important role is played by stellar observations. Stars with know, stable fluxes are extremely useful to verify the radiometric response of the instrument over the field of view and monitor is evolution over time. Stars, being point sources, are also ideal to verify the spatial resolution of the instrument by gaining information on its PSF.
In this work we describe the first results obtained from the stellar calibration campaigns performed until April 2021.

VL channel radiometric calibration



This maps shows the tracks of the stars analysed up to now, in the Field of View (FoV) of the Metis VL channel. While the stellar target opportunity is very rich for the VL channel, it is important to consider that the available targets for the UV channel are relevantly less and this constraint was fundamental in the planning of the stellar observations, as they prioritized the few available targets falling within the Metis FoV.

Fig. 1 : Map of the observed position of the analysed stars in the FoV of the VL channel (2048 pxl x 2048 pxl frames).

The following plots show the signal of α Leonis (left panel) and ω Scorpii (right panel) along the FoV of the VL channel, star countrates are represented in green, a comparison with the values of the vignetting function (VF) in the same position of the stars is provided in black.
From this first step of the data reduction it is possible to see that the star signal is following the VF trend: the VL channel response is as expected.

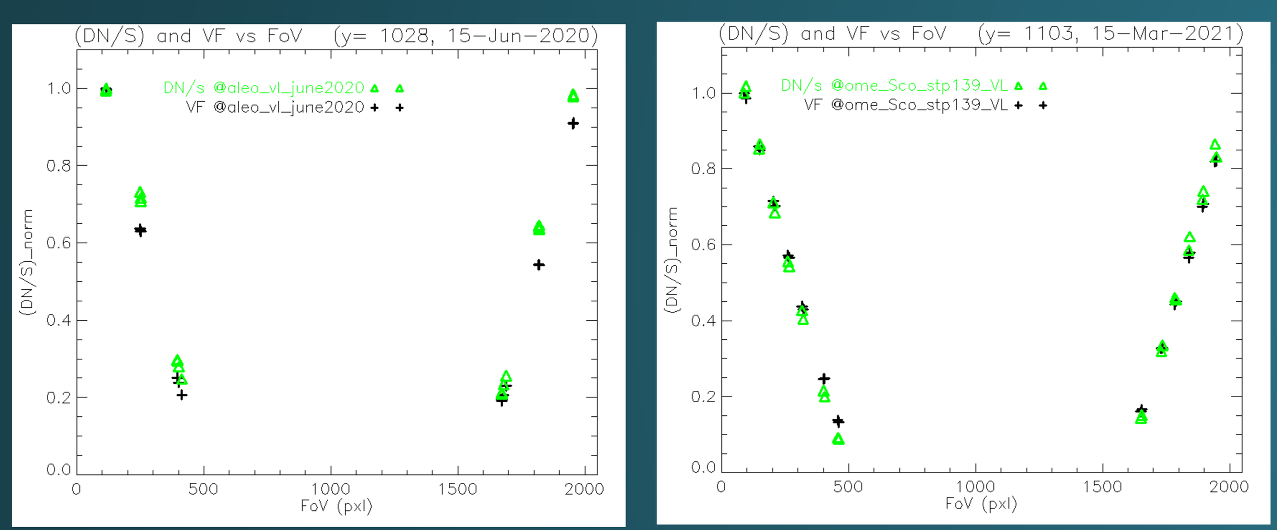
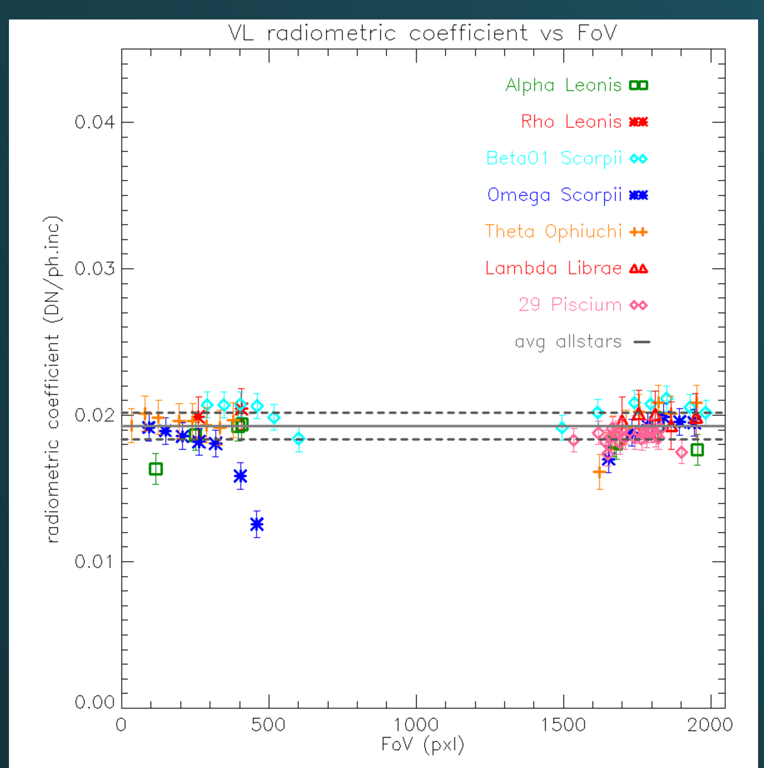


Fig. 2 – Left panel: α Leonis countrate (green triangles) and the VF trend (black crosses) vs FoV. The track of the star is almost horizontal (y=1028), in the central region of the detector. Right panel: the same plot for the star ω Scorpii (y=1103).

Starting from the star signal N_* (counts per second), it is necessary to invert the data in order to find the channel efficiency ε_{ch}:

- $$\varepsilon_{ch} = \frac{N_*(FoV)}{\bar{f}_* \cdot A_{pup} \cdot VF(FoV)}$$

where A_{pup} is the entrance pupil of the instrument, VF is the vignetting function that depends on the position in the FoV and $\bar{f}_*$ is the average star flux in the Metis VL bandpass (580-640 nm).



In this plot the first results of the data inversion:
the value of the radiometric coefficient (in DN per incident photon on the instrument aperture) vs the FoV position for different stars.
The values are consistent between the several stars. This analysis provides the radiometric coefficient to pass from L0 data (in digital units) to L2 data (in physical units).

Fig. 3 : VL radiometric coefficient vs FoV from 7 different stars observations.

The Metis VL channel peculiar photometric system

Considering its bandpass, the VL channel is comparable to a non-standard red filter so it is necessary to adapt the calibration of a non-standard photometric system to a standard one. In order to find the photon flux $\bar{f}_{Metis}$ related to a certain value of red magnitude m_R we introduce the R coefficient:

$$R = \frac{\bar{f}_{Metis}}{\bar{f}_R}$$ where

$$\bar{f}_{Metis} = \frac{\int F_\lambda T_{Metis} d\lambda}{\int T_{Metis} d\lambda}$$ and $$\bar{f}_R = \frac{\int F_\lambda T_R d\lambda}{\int T_R d\lambda}$$

and from the magnitude relation

$$m_R - m_{R0} = -2.5 \log \frac{\bar{f}_R}{f_{R0}}$$ with

$f_{R0} = 2190 \cdot 10^{-12}$ erg/cm²/s/Å *(zero point flux)*

m_{R0}=0.07

we can obtain the flux that the instrument receives:

$$\bar{f}_{Metis} = R \cdot \bar{f}_R = R \cdot f_{R0} \cdot 10^{-\frac{m_R - m_{R0}}{2.5}}$$

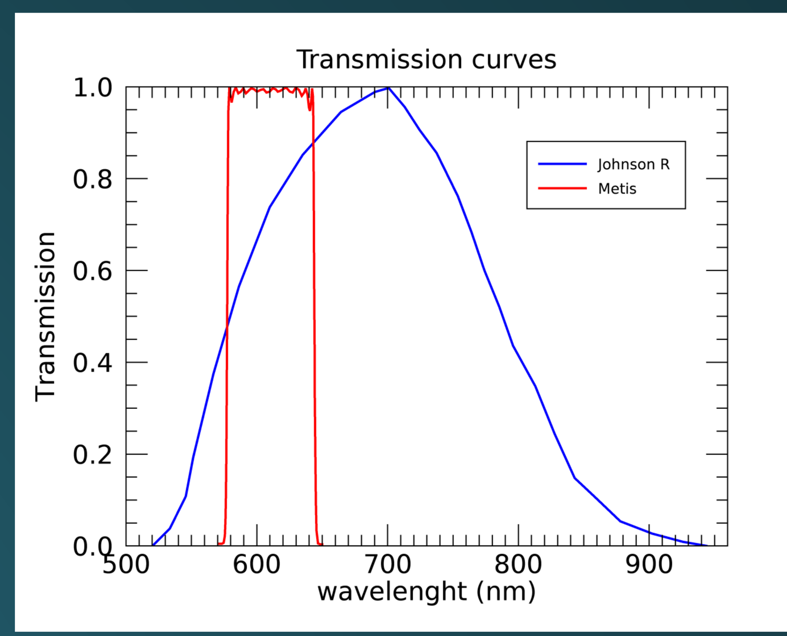


Fig. 4: Comparison between the transmission curves of the Metis VL filter and Johnson standard red filter.

UV channel radiometric calibration

As for the VL channel, the plots show a comparison between the star signal and the VF trend (α Leonis on the left panel and ω Scorpii on the right panel), along the field of view of the UV channel. In this case there is an evident discrepancy between the two trends on the west side of the FoV (S/C still substantially on the Ecliptic plane).

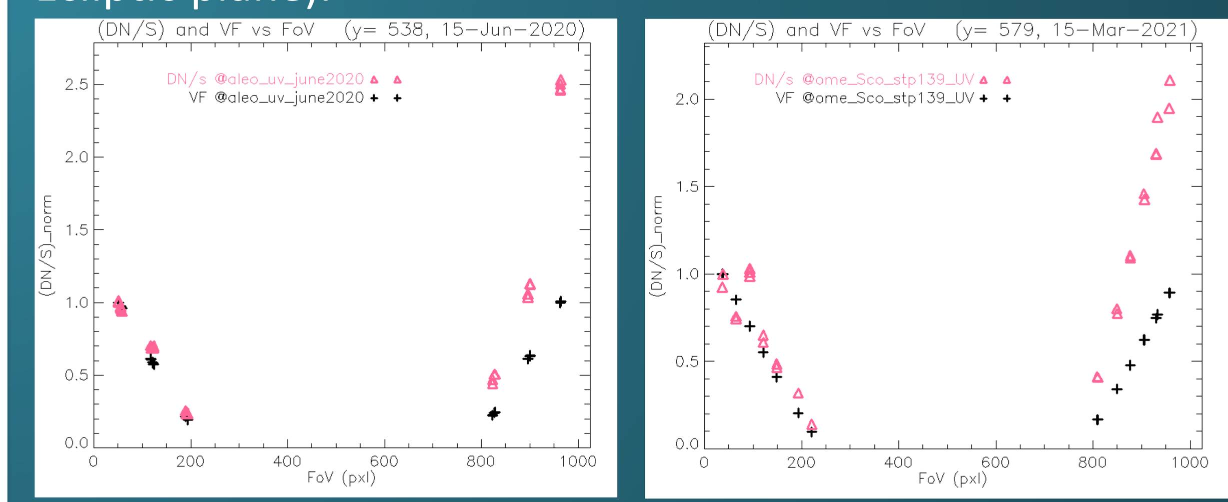


Fig. 5 – Left panel: α Leonis countrate (magenta triangles) and the VF trend (black crosses) VS the FoV (1024 pxl x 1024 pxl). Right panel: the same plot for the star ω Scorpii. The data of the 2nd star present a "jump" in the signal that is under investigation.

With the aim of reducing the explained discrepancy we used the back-illumination door frames, as a set of independent data. We created "UV2VL ratio" maps (Fig.6).
These maps have brightness gradients.

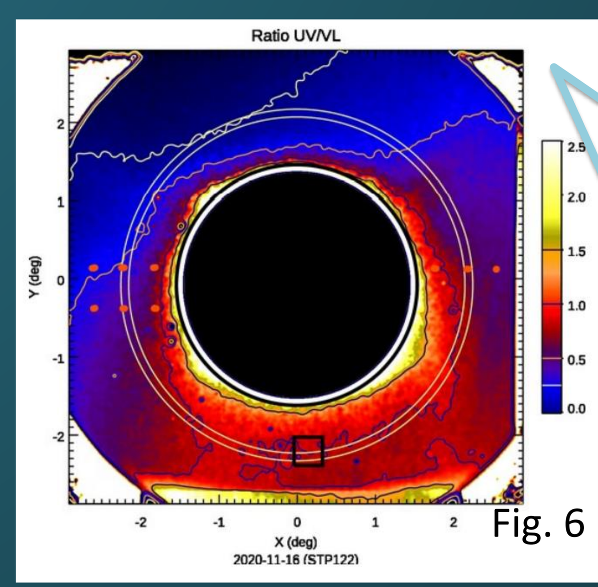


Fig. 6

Working hypothesis:
Assuming that at each point of the door the reflectance ratio for the 2 channels is the same, we can try to use UV2VL ratio to correct the data.

Using the UV2VL ratio maps was helpful for the purpose, as the following set of plots is showing.

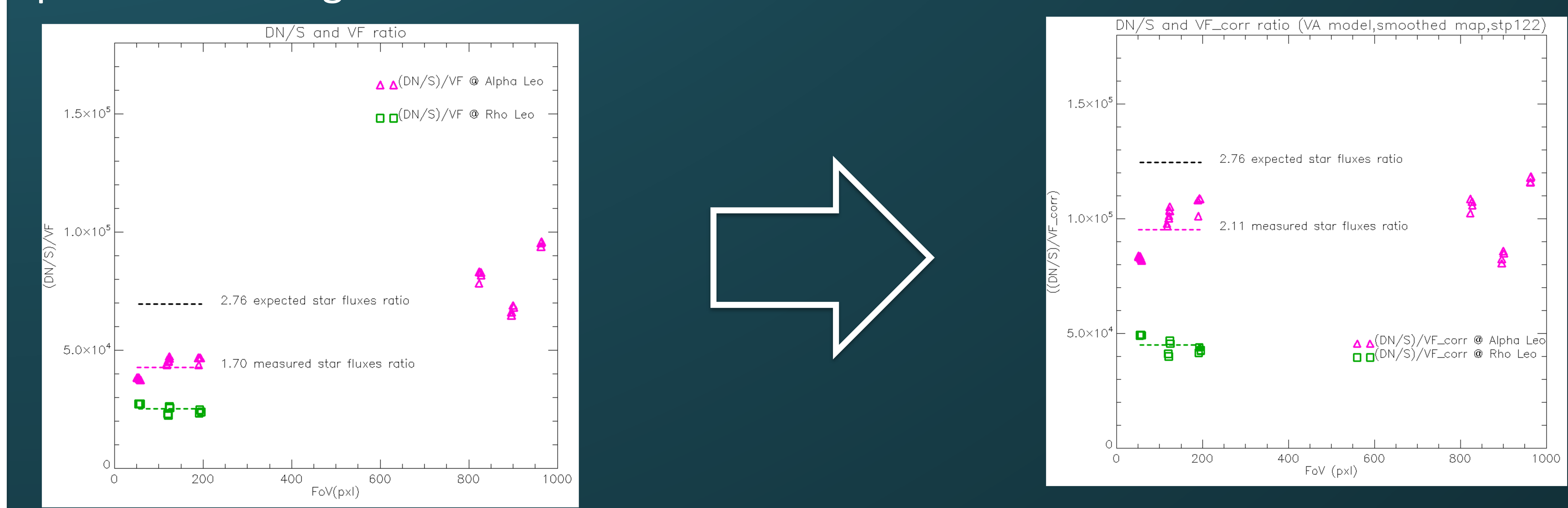


Fig. 7 – Left panel: Counts per second divided by the VF along the FoV, for α and ρ Leonis. Right panel: Same ratio of the left panel "corrected" with the UV2VL ratio map.

Conclusions

- The study of the stars transits, since the beginning of the *commissioning phase*, has proven to be very useful in order to optimize the radiometric calibration of the channels of the instrument.
- This preliminary analysis shows that the VL channel response is substantially as expected.
- For the UV channel we noticed a discrepancy between star data and the VF measured on ground, and this requires more work in order to fix the response of this channel.

References

Antonucci E. et al., (2020), "Metis: the Solar Orbiter visible light and ultraviolet coronal imager", A&A, 642, A10.

Acknowledgments

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