In-flight calibration and performance verification for space instruments

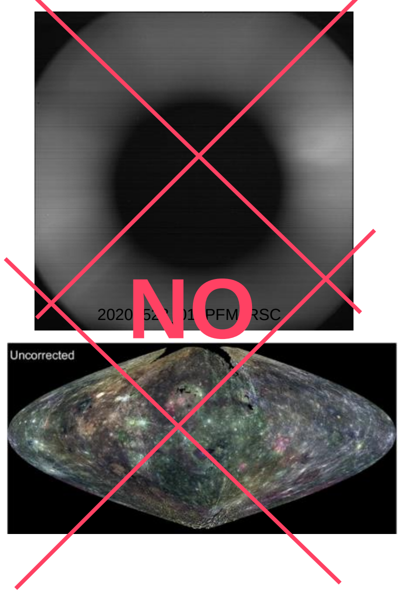
Chiara Casini - 36th Cycle

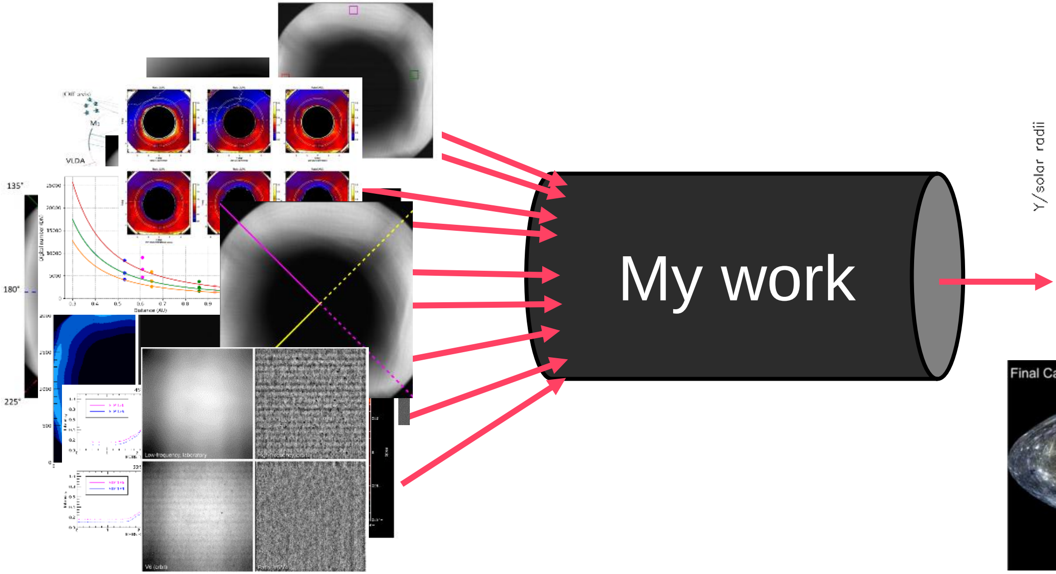
MEETING FOR THE ADMISSION TO THE FINAL EXAM

13-14/09/2023

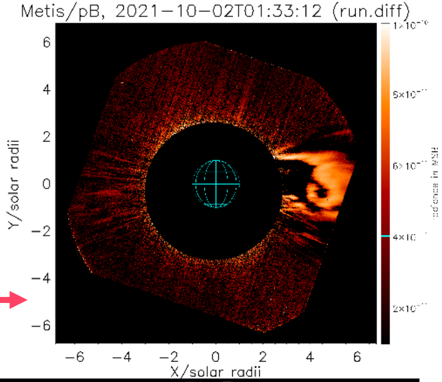
Scientific Images Calibrations

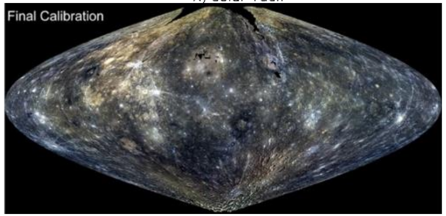
SCIENCE???





SCIENCE???





YES

My PhD activity serves to acquire a deep and detailed knowledge of the Metis and STC instruments in one of the most critical and important phase of a space mission: it's essential to obtain scientific useful images.

https://www.researchgate.net/publication/321358296_Calibration_Projection_and_Final_Image_Products_of_MESSENGER's_Mercury_Dual_Imaging_System/figures

Courtesy of Y. De Leo

Calibration

- Problematics of in-flight calibration
- Two instruments: Metis and STC

Simulation

- Stellar mapping
- Raytracing simulations

Verification

- validation of the simulations
- validation of the calibration through validated simulations
- validation of the instrumental performances
  - comparison between simulation and acquisitions
  - data processing and analysis

Perform simulations

Processing and comparing

Verifying performances

Define the procedures and analyze the data to complete the characterization tests

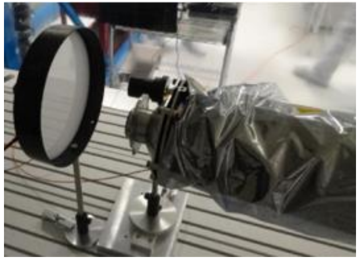
Importance of calibration

Why the calibration is crucial for space instruments

On-ground and in-flight calibrations are important to:

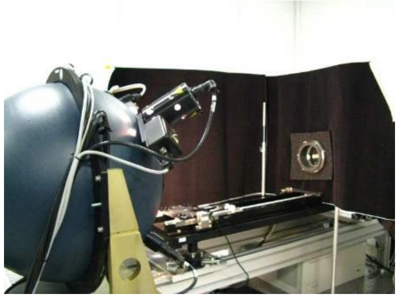
- validate the instrument design
- mitigate systematic errors
- ensure data consistency

On-ground calibration: uniform illumination source



flat field panel

integrating sphere



In-flight calibration: **no** direct access to a uniform source.

How do we handle this issue ? By using Stars

Importance of Stellar Calibration

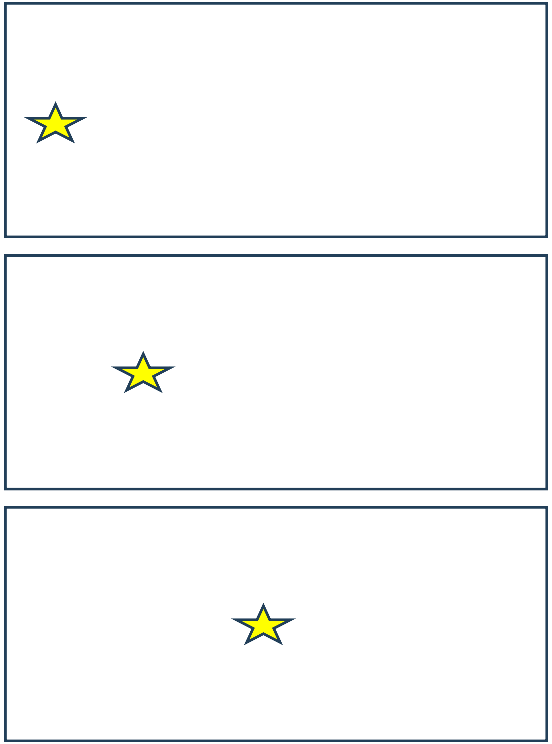
In-flight stellar calibration consists in acquiring images of a star: preferably acquiring sequence of images while the star is moving across the detector, in order to test and check different points in the FoV of the instrument with the same input source.

Systematic observations of several stars will track:

- sensitivity changes (degradation of the optical elements or detector).
- check the evolution of vignetting phenomenon or defects (shadows and/or bad pixels).
- detector linearity curve: acquiring the light of the same star for different Integration Times (IT) and analyzing the response of the detector pixels.

There is a need to know the stars crossing the FoV

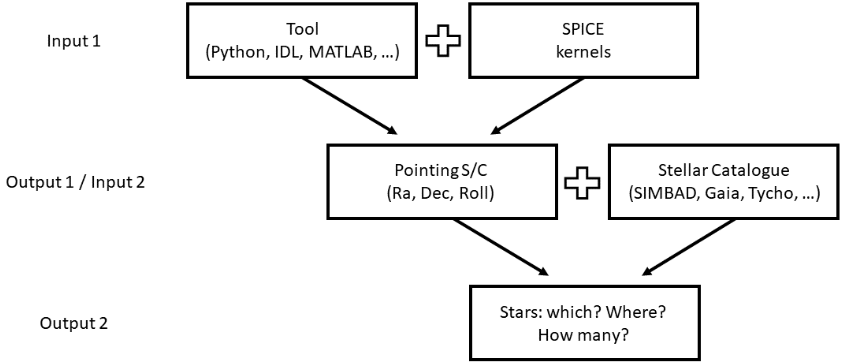
⇒ We need simulations



Simulation Methodology

Keystones of these simulations:

- ✓ Python
- ✓ SPICE kernel (Spacecraft, Planet, Instrument, Camera pointing, and Events).
  - ✓ Gives the information on the location of the spacecraft at a given point in time, the boresight of each specific channel and the Field of View (FoV).
- ✓ SIMBAD catalogue to determine the position of the stars, till a determine maximum apparent magnitude, that are visible in the instrument FoV.

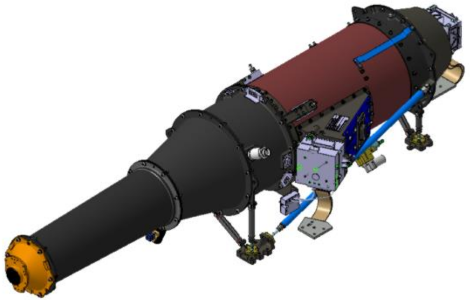


Compilation of stars that can be observed through the channel employed by Metis or STC.

https://naif.jpl.nasa.gov/pub/naif/toolkit_docs/C/info/intrdctn.html#:~:text=SPICE%20Kernels,API%20(%22furnsh%22)

http://simbad.cds.unistra.fr/guide/simbad.htx

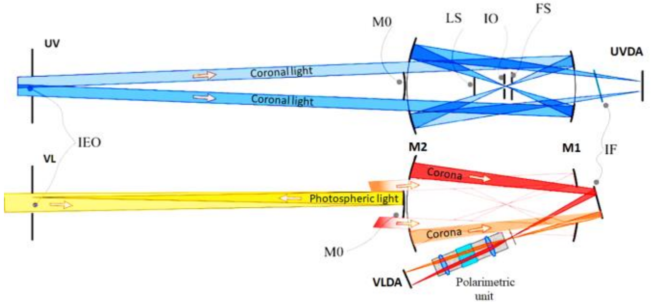
Components of Calibration - Metis



Metis is a coronagraph that makes linearly polarized acquisitions of the solar corona

Acquires simultaneously images in the:
- UV Ly-α neutral hydrogen line 121.6 nm
- VL spectral range

Observes the Sun as close as 0.28 AU: it is designed to reduce the extremely high thermal load: an Inverted Externally Occulted configuration is used to block the light of the solar disk.



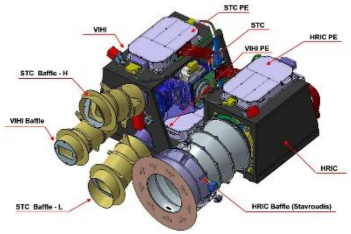
Optical Path:

- the light of the photosphere enters in Metis through the Inverted External Occulter (IEO) and is then rejected towards the entrance aperture by the mirror M_0
- The coronal light is reflected by the mirror M_1 towards mirror M_2.
- Internal Occulter (IO) and a Lyot Stop (LS) block the diffused light generated by IEO and M_0.
- The coronal light reflected by mirror M_2 goes towards the dichroic beam-splitter, the Interferential Filter (IF).
- The IF is optimized for narrowband spectral transmission in the ultraviolet. The visible light reflected by IF enters in a polarimetric unit and arrives on the visible detector.
- **Both channels have a CMOS sensor, a 1024 x 1024 pixel matrix for the UV, and a 2048 x 2048 pixel matrix for the VL:**

http://metis.oato.inaf.it/instrument_ita.html

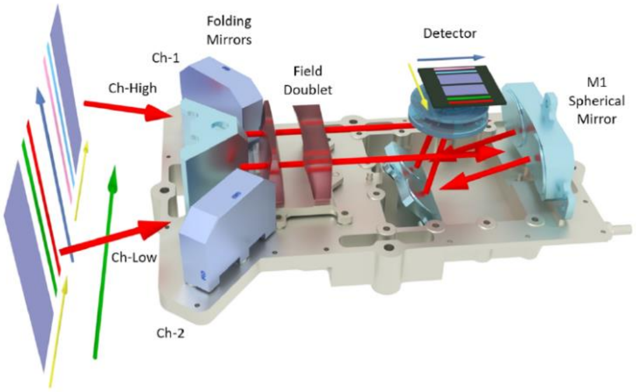
http://www.zam.fme.vutbr.cz/~druck/eclipse/Ecl2008m/Tse2008_1000_mo1/0-info.htm

Components of Calibration - STC



Double wide-angle camera whose main scientific aim is the mapping of the entire surface of Mercury in 3D

STC camera consists of two sub-channels: High (H) and Low (L) with respect to the mounting interface on the spacecraft.



Optical path:

The light scattered by Mercury passes through the external baffle

- It is reflected inside a rhomboid prism, passes through a correcting doublet, the aperture stop (AS), and arrives on the spherical mirror M_1
- M_1 reflects the light on the secondary plane mirror of the telescope which in turn reflects into a two-lens field corrector and, finally, arrives on the focal plane assembly (FPA).
- The STC detector can read a maximum of **six** specific **windows**: two panchromatic (PAN H and PAN L) with FoV 5.3°×2.4° and four coloured filters with FoV 5.3°×0.4°: f750, f420, f920 and f550, for a total spectral range: 410 nm-930 nm

Cremonese et al., *Space Sci Rev* 216 (2020)

https://www.cosmos.esa.int/web/bepicolombo/simbio-sys

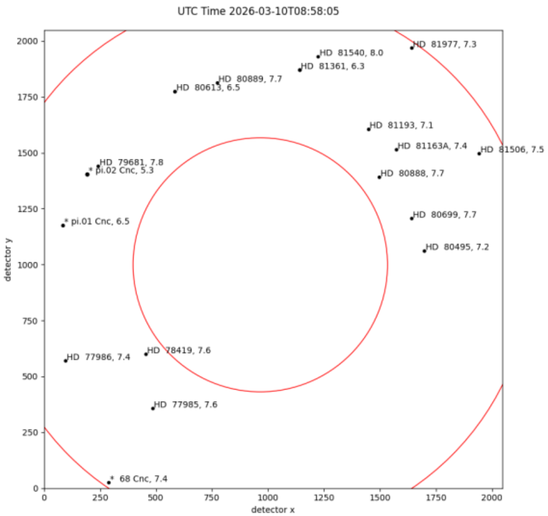
https://www.esa.int/kids/en/learn/Our_Universe/Planets_and_moons/Mercury

Star Crossing Simulations - Metis

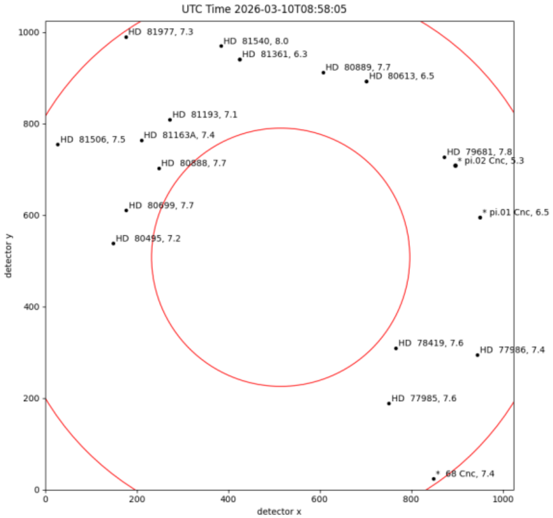
Simulations have been performed at the same date and hour: **10-03-2026 at 8:58:05**, for both instruments.

- Both the channels are looking at the same field in the sky, so the observable objects are the same.
- Inside the Field of View there are 18 stars.

Visible channel (VIS)



Ultraviolet channel (UV)

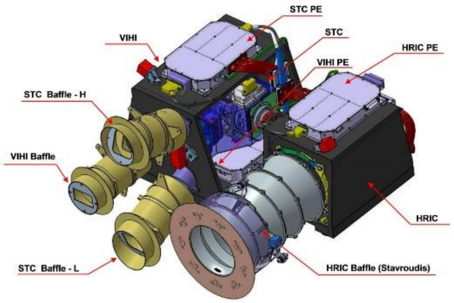


The results appear mirrored because of the different reflection inside the elements of the coronagraph for the two channels.

C. Casini, P. Chioetto, A. Comisso, A. Corso, F. Frassetto, P. Zuppella, V. Da Deppo, "Simulations for in-flight stellar calibration aimed at monitoring space instruments optical performance", submitted AIDAA

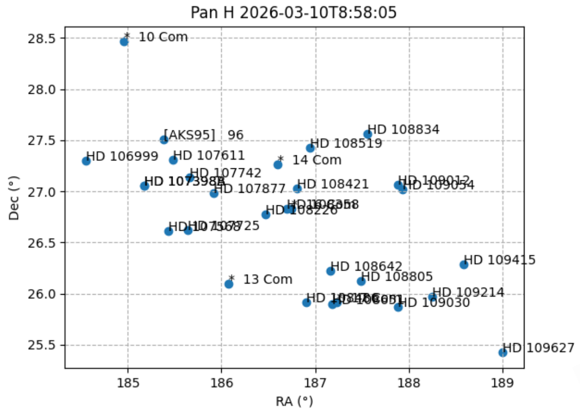
Università degli Studi di Padova

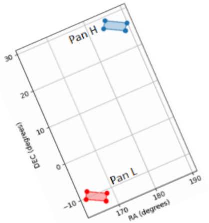
Star Crossing Simulations - STC

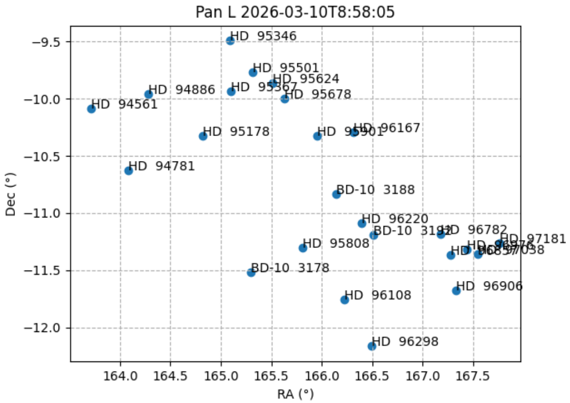


For STC, the two STC sub-channels H and L are looking at -/+20° with respect to the Nadir direction.

- So the stars imaged by the PAN H and PAN L filters are completely different.
- The stars visible by the Pan H and Pan L filters are respectively, 29 and 24 stars.

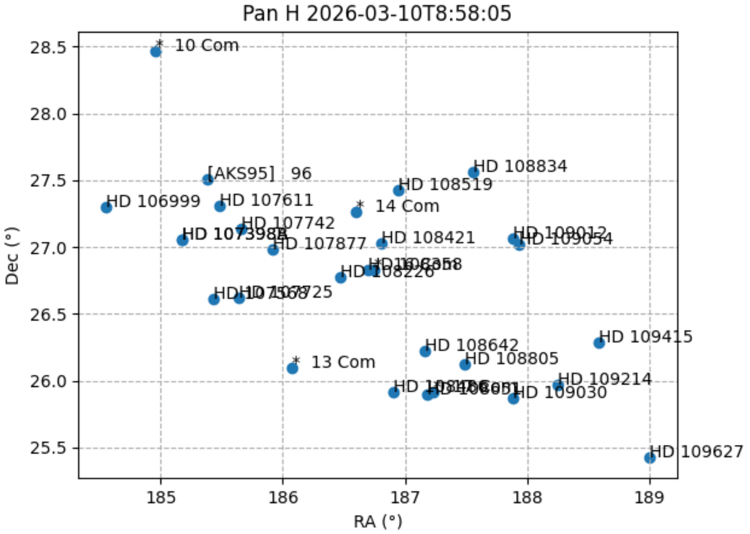


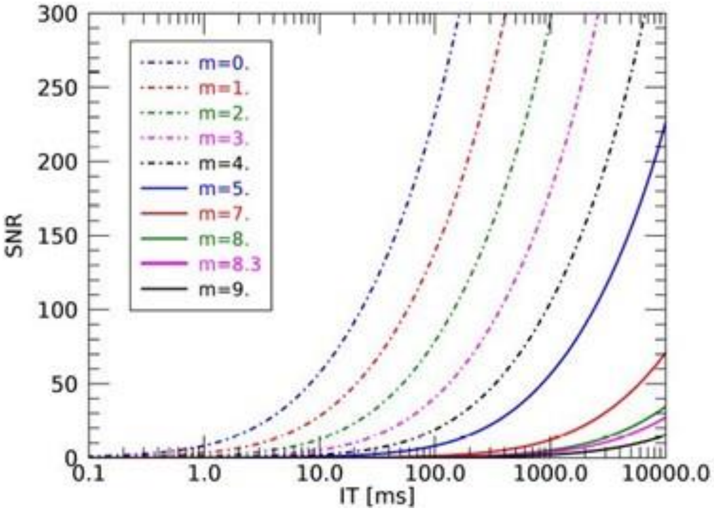




Star-crossing Simulations

For STC, on the basis of the SNR analysis, it is useful that the bright stars are marked to allow, if needed, avoiding them.





Simulation gives us the opportunity to select the best target star field.
Simulations for both instruments need first to be validated by being compared to real acquisitions!

A.Slemer et al., Setting the parameters for the stellar calibration of the SIMBIO-SYS STC camera on-board the ESA BepiColombo Mission. Proc. of SPIE Vol. 11443 1144374-1 doi: 10.1117/12.2560648

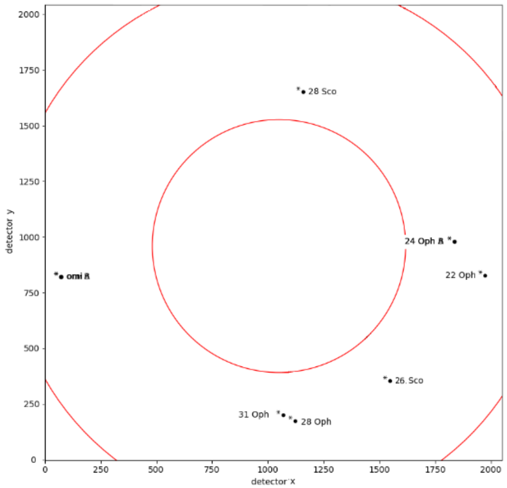
Validation of Simulations

As an example of the validation of the simulation, the stellar fields (simulated and acquired) during the transit of the **comet Leonard (16-12-2021** at 01:13:27) have been considered.

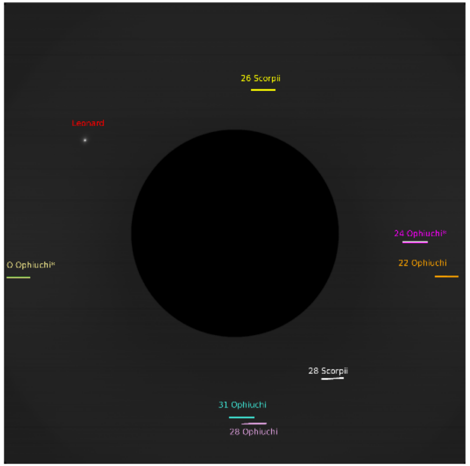
Python:

- simulation of stars
- signal (+3σ) + SIMBAD catalogue

Simulation



Acquisition + Simulation



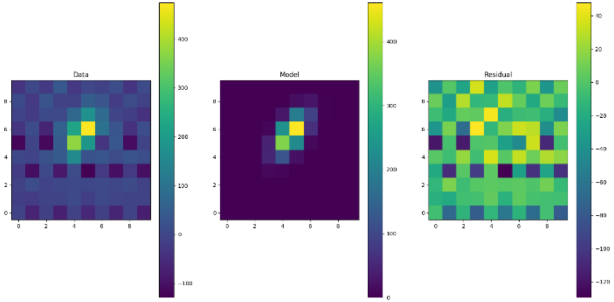
The simulations are in good agreement with the acquisitions!

Stars for PSF calibration

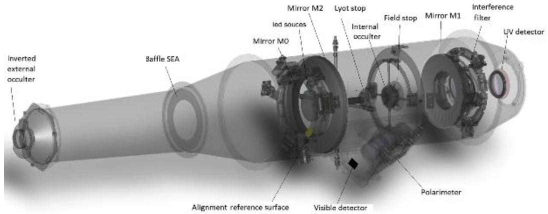
3 simulations are performed using:

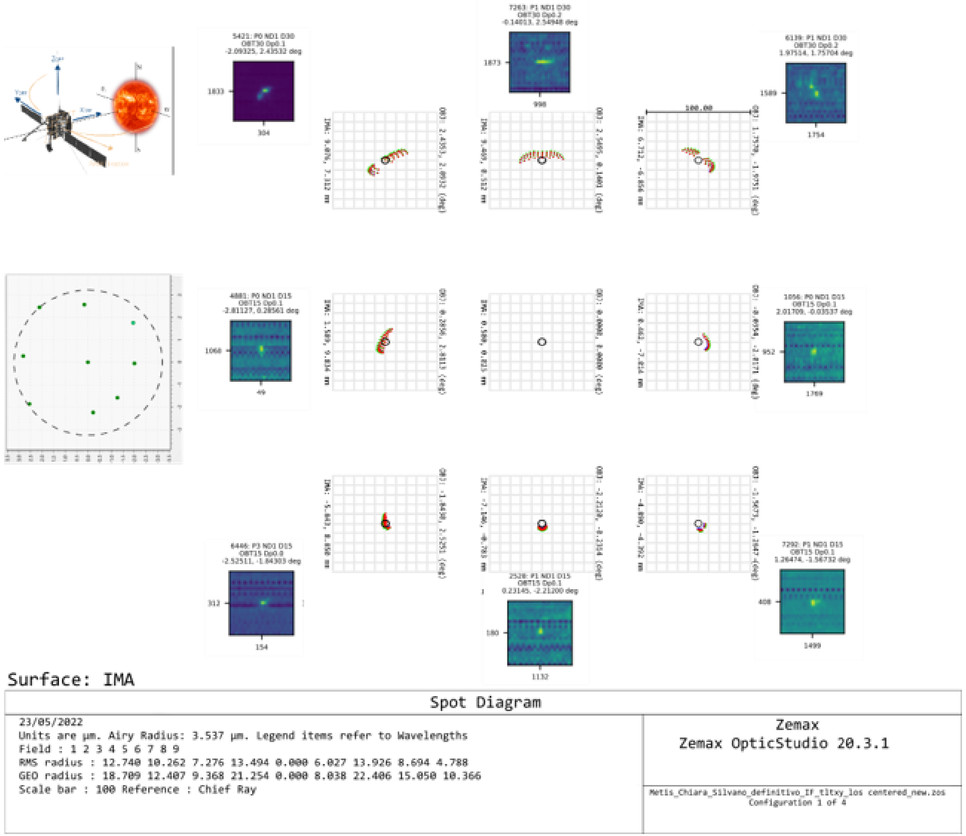
Python:

- where the star is (location)
- 2D gaussian fit of the target star.



Zemax: software of ray tracing.

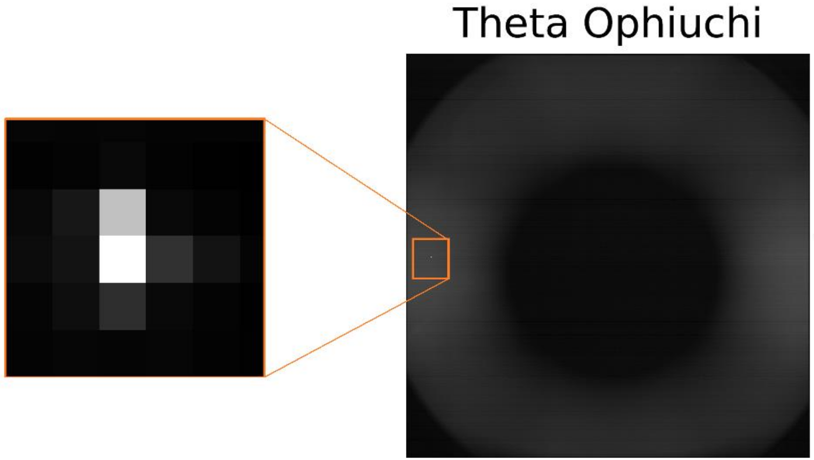


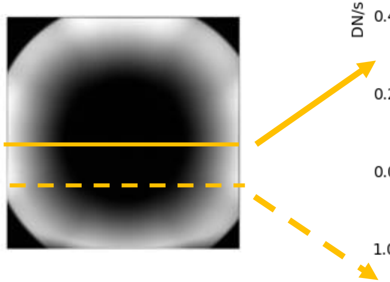


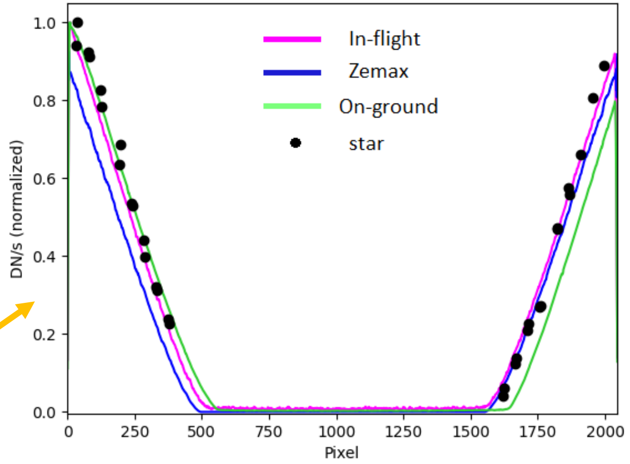
Processed and Compared - Metis

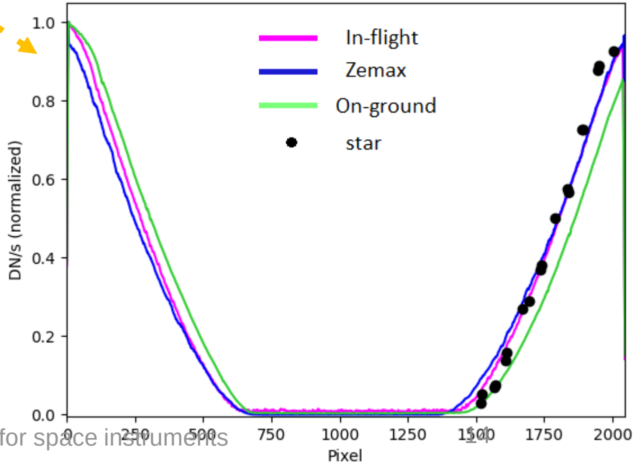
Theta Ophiuchi passed twice in front of Metis:

- STP 140 March 2021 (0,72 AU) - *row 1017*
- STP 182 December 2021 (1,01 AU) - *row 615*







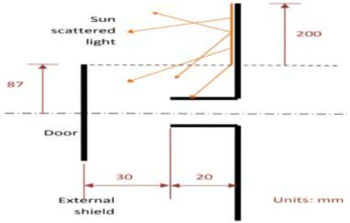


The agreement between stars vignetting and in-flight vignetting is >85%

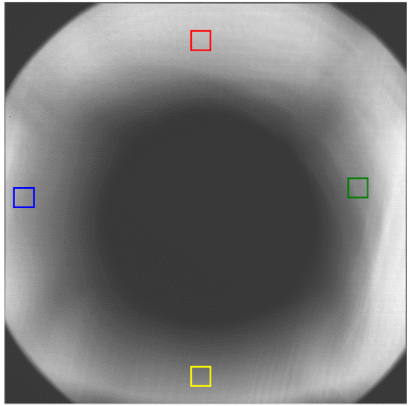
C. Casini, P. Chioetto, Y. De Leo, Da Deppo, V.. P. Zuppella,F. Frassetto, M. Romoli, F. Landini et al., "Theoretical, on-ground and in-flight study of the Metis coronagraph vignetting", Proc. of SPIE

Verified Performances - METIS

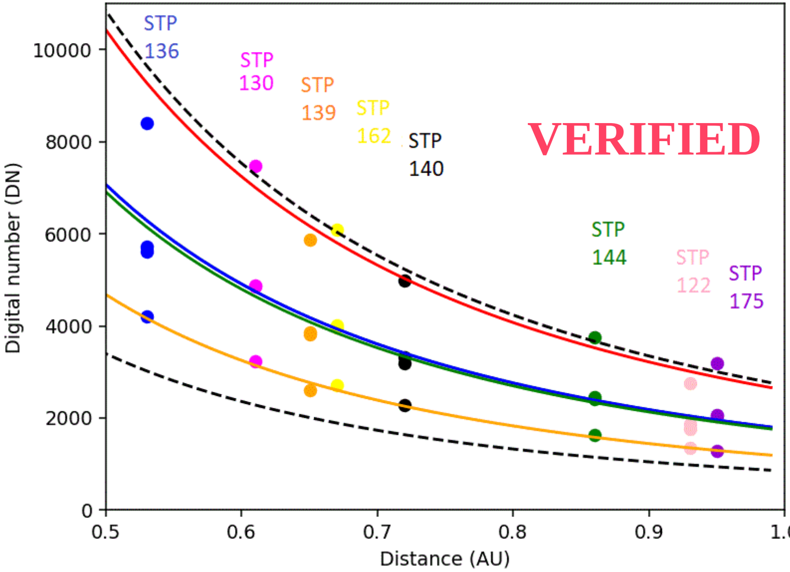
Verification of non degradation: 8 images at 8 different Astronomical distances



The light of the sun is reflected by the shield and, a portion is reflected towards the door.



Boxes of 100 x 100 pixels in the visible channel 4 fitting curves.



α $1/r^2$

- ➢ we can use the retro-reflection of the door to estimate the optical elements possible degradation
- ➢ we can predict the effects of the possible degradation on the door images via ray tracing simulations.

C. Casini, V Da Deppo, P. Zuppella, P. Chioetto, F. Frassetto, M. Romoli, F. Landini, M. Pancrazzi, et al., "In-flight Metis radiometric performance verification using the light retro-reflected from its door", Proc. SPIE Vol. 12180, 121803E,27 August 2022, DOI: 10.1117/12.2631515

Verified Performances - STC

STC detector composed by:

- 2 Panchromatic filters (PanL and PanH)
- 4 colored filters (f750, f420, f920 and f550)

Dark current acquisitions campaign:

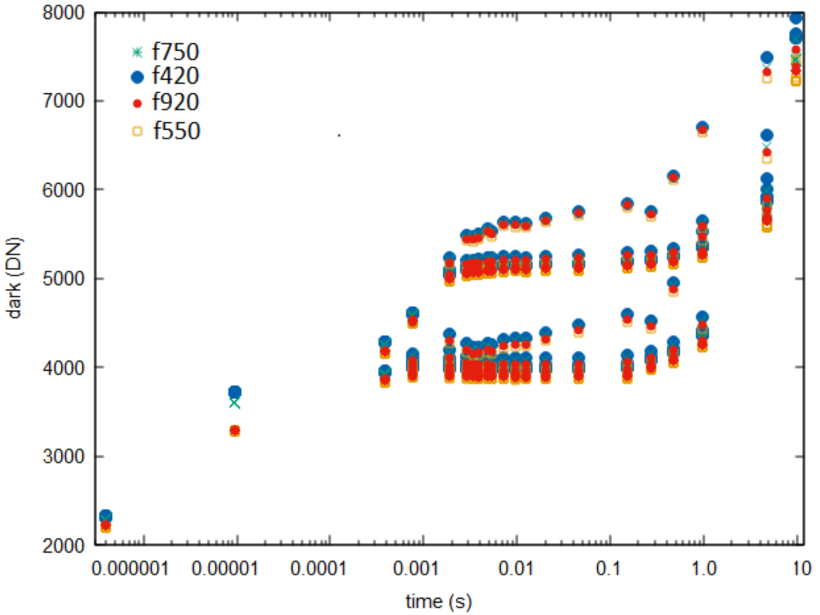
- the acquisition of a set of 10 dark-current images
- for a specific Integration Time (IT)
- with a specific Repetition Time (RT)

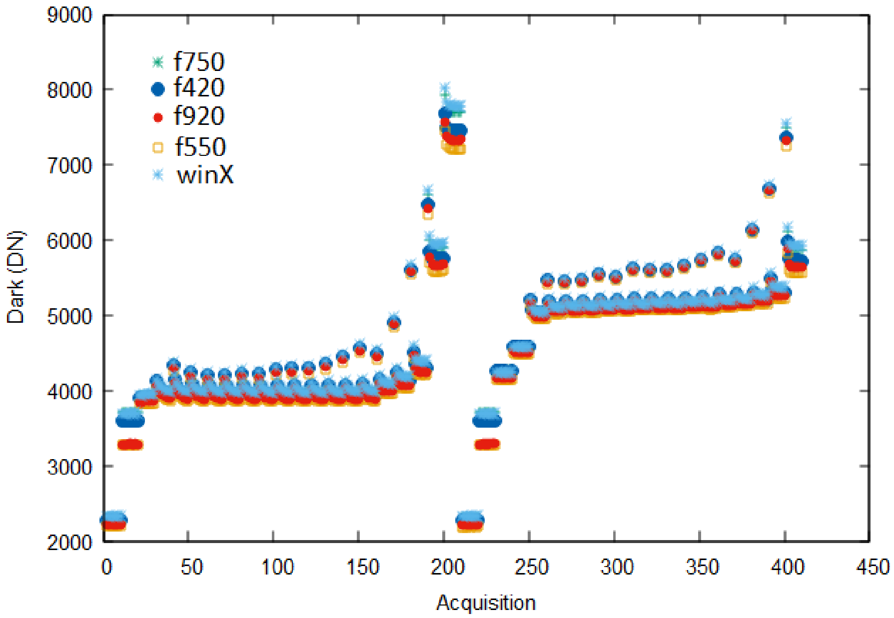
Start-End Rows		Vert Dim
2016	576px (strip 9) 1471px (strip 22)	
	F920	64px
1953 1808		
	F550	64px
1745 1610		
	PANL	384px
1227 820		
	PANH	384px
437 303		
192:319 (strips 3,4)	F420	64px
163 240 WinX 100 95		
	F750	64px
(0,0) 32	896px	

SIMBIO-SYS: Scientific Cameras and Spectrometer for the BepiColombo Mission, G. Cremones Space Sci Rev (2020) 216:75 https://doi.org/10.1007/s11214-020-00704-8e

Verified Performances - STC

Mean value of the dark signal intensities acquired through the filter f750, f420, f920 and f550 at different exposure time.

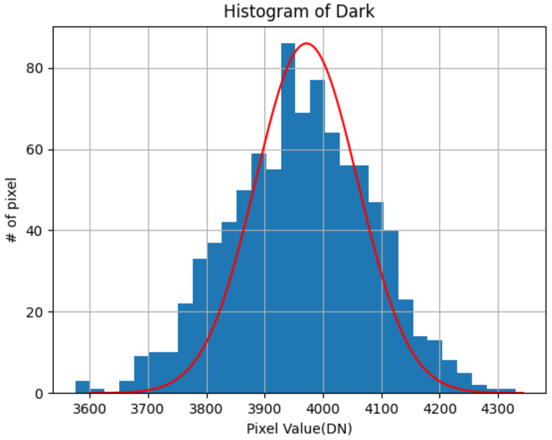


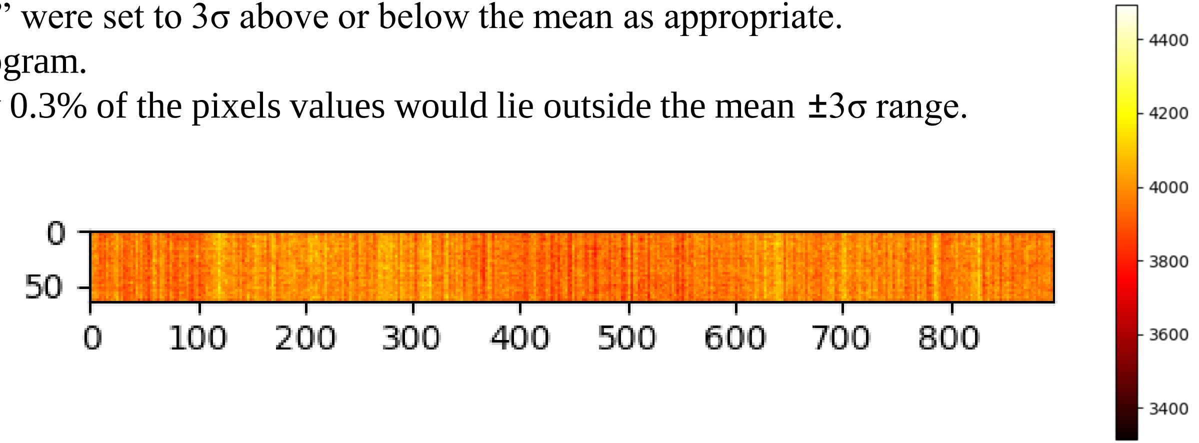


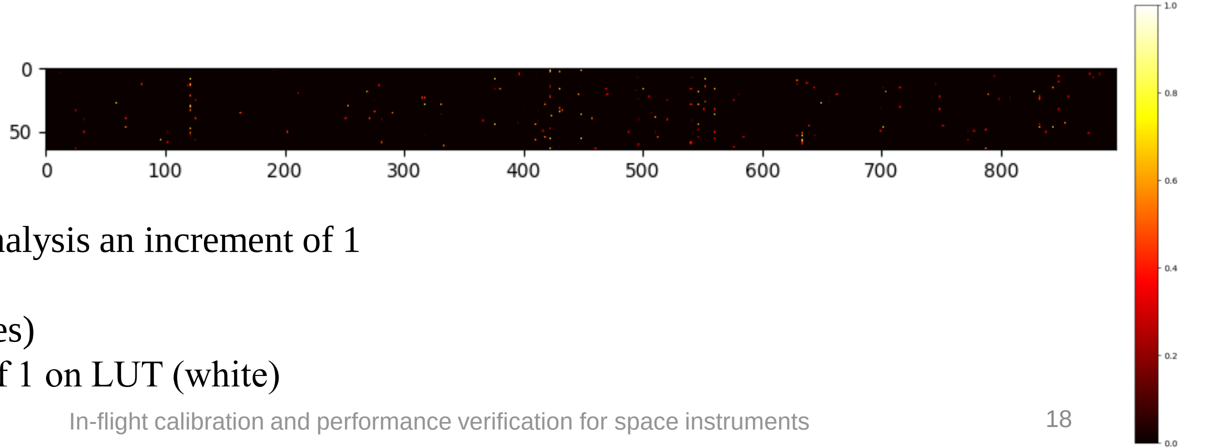
One possible solution is considering a small window named windows-x (WINX). It is an out-of-filter window, which is a region on the detector of dimension 64x128px sitting in the unilluminated part of the detector

Verified Performances - STC

The thresholds for designating a pixel as "bad" were set to 3σ above or below the mean as appropriate.
Therefore, I calculate for every image its histogram.
For Normally (Gaussian) distributed data only 0.3% of the pixels values would lie outside the mean ±3σ range.







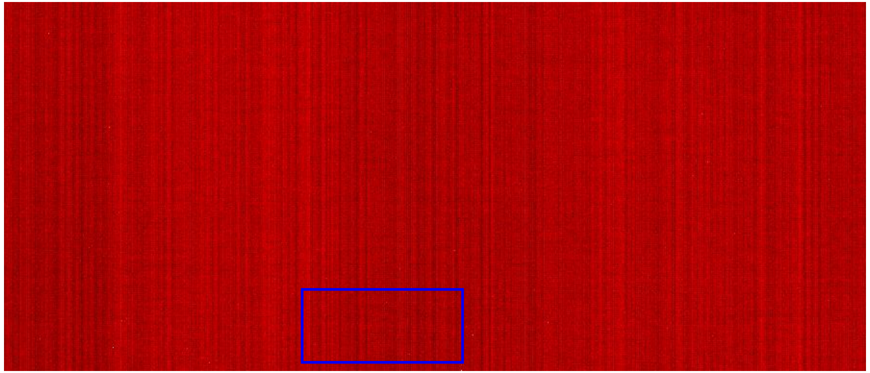
Take all value beyond **mean ± 3σ**

- Lookup table (LUT): on each image analysis an increment of 1 on bad pixel coordinates
- Divide for the 10 (number of the images)

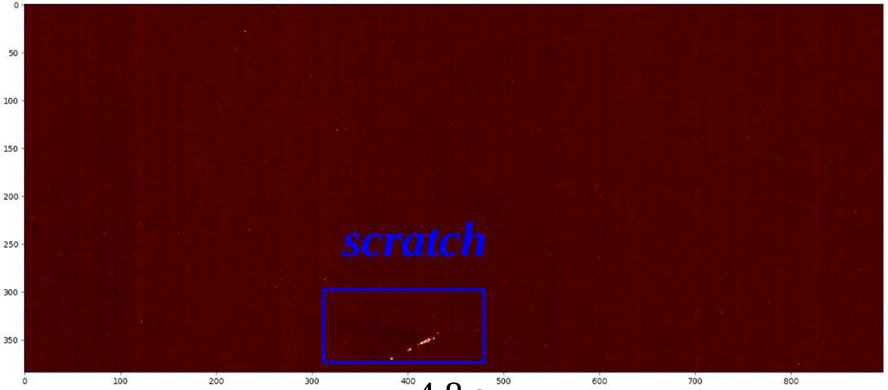
→ bad pixel on all images has the value of 1 on LUT (white)

Data analysis for characterization

Pan L

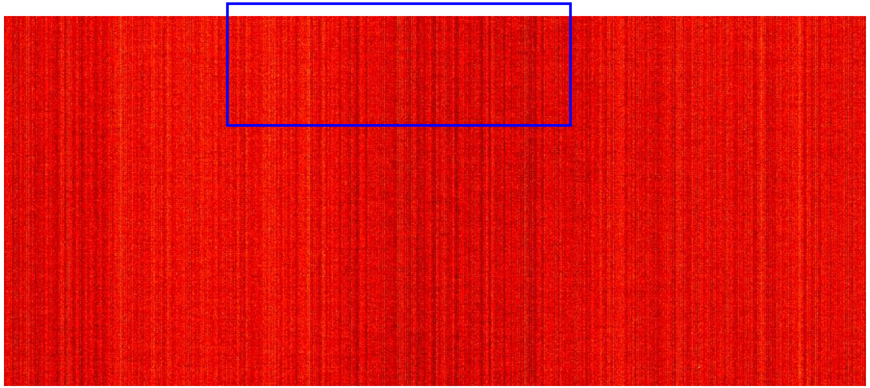


400 ns

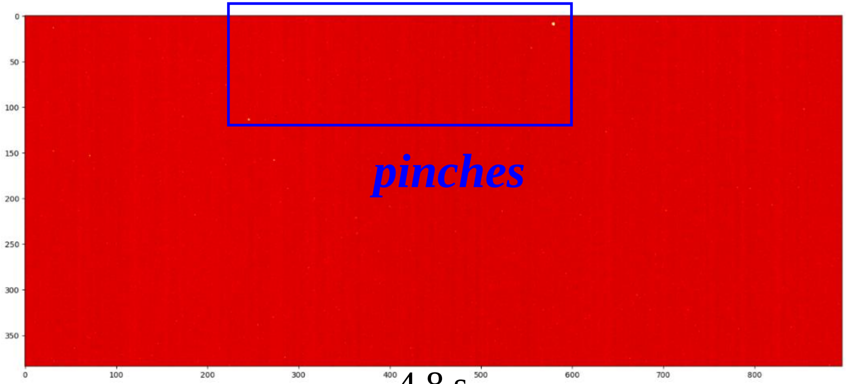


4,8 s

Pan H



400 ns

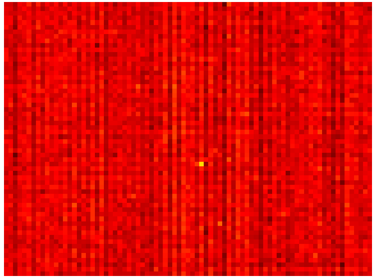


4,8 s

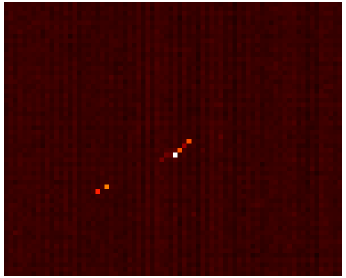
Data analysis for characterization

Pan L (scratch)

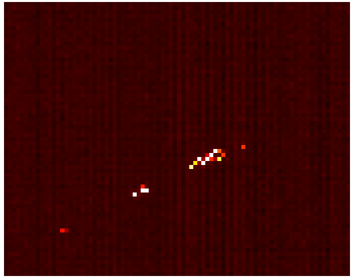
57 ns



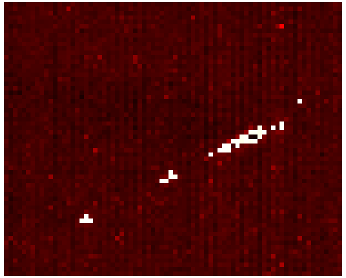
2,4 ms



9,6 ms

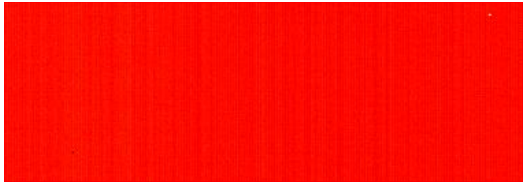


4,8 s



Pan H (pinches)

2,4 ms



0,03 s

0,27 s

4,8 s

Acquisitions are now taken with the same intervals and times to understand if they are replicable and therefore correctable!

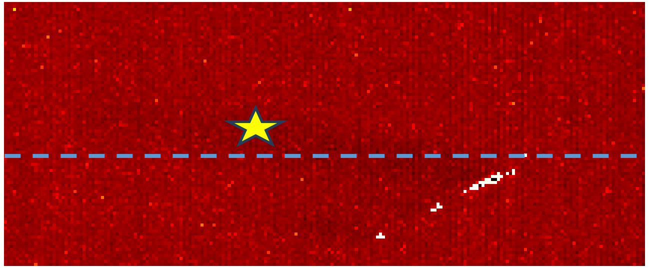
C. Casini, V. Da Deppo, E. Simioni, C. Re, “STC bad pixels analysis: instrument check-out 1 images”, CNR-IFN-PD-SIMBIO-STC-IR-001, Issue 1.0, approved 22/06/2023.

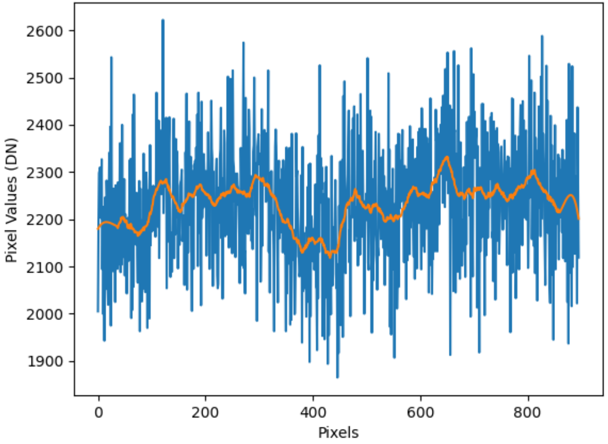
A practical case mixing simulation, calibration and verification.

Through the passage of stars all over the detector we can know if there are modification of the defects, as shadows and bad pixels, found during the on-ground calibration.

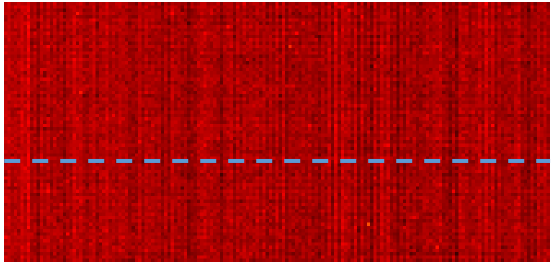
It is important to know if this defect changing over time has an impact on the image of Mercury.

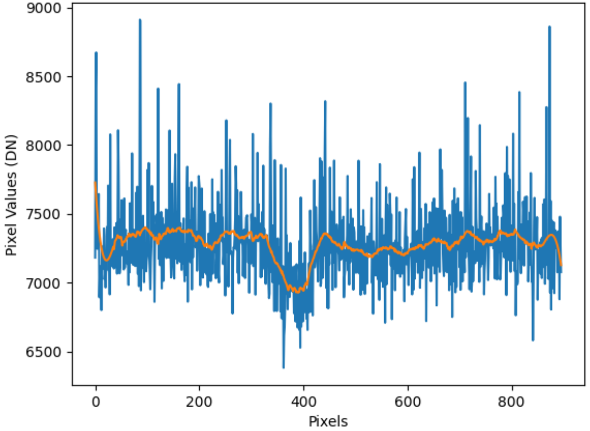
9,6 s





400 ns





Analyse the stars in any parts of the detector to know if it responds differently!

Conclusion

I conducted simulations using Python to determine at any desired epoch the number of stars visible by Metis and STC.

- ✓ The stars are used to measure the Point Spread Function (PSF) in-flight calibration results.
- ✓ Star theta Ophiuchi on the FoV of Metis:
  - ✓ assess the evolution of the vignetting function during the in-flight mission lifetime.

Metis

- ✓ $1/r^2$ law for door illumination → provided insights into the potential degradation of optical elements and allowed us to perform ray tracing simulations to predict the impact on door images.

STC

- ✓ Creation maps of bad pixels for all windows.
- ✓ Extrapolate the behaviour of each filter
- ✓ Evolution of “scratch” and some “pinches” for Pan L and Pan H.

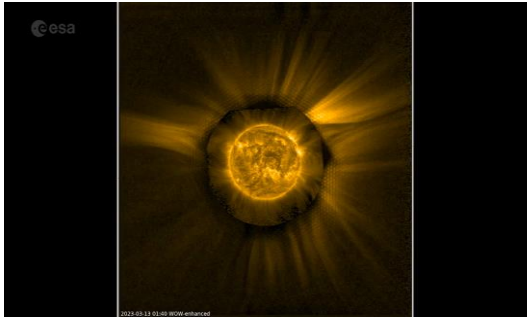
Perspective

Metis

- Investigation of the Point Spread Function (PSF) to create a model of “double” stars.
- Improving the vignetting image reconstruction

It has been recently (and internally) observed that other instruments aboard the Solar Orbiter have already experienced a **10%** decrease in performance.

2023, Solar Orbiter



https://www.esa.int/Science_Exploration/Space_Science/Solar_Orbiter/Camera_hack_lets_Solar_Orbiter_peer_deeper_into_Sun_s_atmosphere

STC

- Check the evolution of the defects (shadows and/or bad pixels).
- Recreate detector linearity curve.

Thanks for the attention

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