Metis Coronagraph
Ground Calibration

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On behalf of the Metis Team

VI Metis Workshop – Gottingen, D, 21 November 2018
Outline

• Solar Orbiter/Metis
  – General introduction
  – Instrument description
• Calibration facility and setup
• Instrument Calibrations
   Vignetting function (Flat-Field)
   VLDA Photon Transfer Curve
   VL & UV Imaging & Radiometric Performance
   VL Polarimeter Performance
   Stray-light Suppression Performance and internal occulter centering
• Conclusions
In short

It works!
Metis Coronagraph

- Polarized VL imaging @ 580 - 640 nm
- UV HI Ly α imaging @ 121.6 ± 10 nm
- FoV (1.5° · 2.9° annular, 1.6 – 3.0 R☉ @ 0.28 AU)
- Spatial sampling element ≤ 4000 km (20″) @ 0.28 AU
- Time resolution ≥ 1 sec
- Simultaneous VL and UV imaging

Units:
MOU  METIS Optical Unit (boom and telescope)
MPPU  METIS Power Processing Unit
HVU   High Voltage Unit
CPC   Camera Power Converter
Metis Opto-mech Layout

- Inverted external occulter
- Baffle SEA
- Mirror M0
- Mirror M2
- Lyot stop
- Internal occulter
- Field stop
- Mirror M1
- Interference filter
- UV detector
- Polarimeter
- Alignment reference surface
- Visible detector

Session 11b Thursday 15:00

Marta Casti

Posters

P62 F. Frassetto: Optical performance

P71 V. Da Deppo: Alignment procedure

Session 8b Wednesday 14:40

Federico Landini

Metis Stray-lighty

Metis Optomech Layout

Layout
• AIT/AIV and calibrations were performed at the OPSys (Optical Payload System) facility, an INAF laboratory hosted by ALTEC S.p.A. in Torino.

• OPSys: three communicating clean rooms which host the SPOCC (Space Optics Calibration Chamber)

• SPOCC is a solar divergence simulator that can operate in air and in vacuum.
Metis in the Space Optics Calibration Chamber (SPOCC)
Metis in the Space Optics Calibration Chamber (SPOCC)
Ground Calibrations

- Vignetting function (VL Flat-Field)
- VLDA Photon Transfer Curve
- VL & UV Imaging & Radiometric Performance
- VL Polarimeter Performance
- Stray-light Suppression Performance
- Internal occulter centering
Vignetting Function & VL Flat Field
Vignetting Function & Flat Field

Metis Internal Occulter $\varnothing = 5.0$ mm
Consistent with calibrations at MSP

Average

Gain [ADU/e⁻] 0.119
## VL Measured Efficiency

<table>
<thead>
<tr>
<th>Component</th>
<th>Efficiency</th>
<th>Error</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.9</td>
<td>0.02</td>
<td>METIS-ANT-NCR-018 Appendix 1</td>
</tr>
<tr>
<td>M2</td>
<td>0.9</td>
<td>0.02</td>
<td>INF 28/07/2016</td>
</tr>
<tr>
<td>IFA</td>
<td>0.886</td>
<td>0.001</td>
<td>INAF Fineschi et al. 22/092016</td>
</tr>
<tr>
<td>Polarimeter</td>
<td>0.33</td>
<td>0.05</td>
<td>METIS- ATI-TNO-011 (estim.: 0.27) 0.33 Measured on the EBB with Muller SpectroPolarimeter</td>
</tr>
<tr>
<td>QE</td>
<td>0.5</td>
<td>0.05</td>
<td>METIS-MPS-AT-03b-PFM-RP0005 Issue 1 rev 1. Sect 6.10, Figure 6.29</td>
</tr>
<tr>
<td>Total efficiency</td>
<td>0.118</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Estim. Tot. Eff.</td>
<td>0.096</td>
<td></td>
<td>METIS- ATI-TNO-011 (Tab.14-1 )</td>
</tr>
</tbody>
</table>
Vignetting Normalization

Metis IO $\varnothing = 5$ mm

Vignetting =

= Meas. Throughput [phot. detect./phot. in] / Efficiency

(Efficiency = 0.10±0.01 from components measurements)
Off-axis Metis in SPOCC

Metis set-up for VL and UV Measurements

Pinhole(s)

VL or UV Source

45° Folding-mirror

2-m focal-length collimating mirror

Collimated beam axis

Metis optical axis

2.2°
VL Imaging Performance

Target:
200-μm pinhole × 4
SPOCC collimator f.l. = 2030 mm
VL effective f.l. = 200 mm
Demagnification = 0.098

simulating 4 “artificial stars”
with 20-μm FWHM on VLDA
VL Imaging Performance vs Field-of-View

- Inner Field-of-View ⇒ Diffraction from IEO vignetting
- Outer Field-of-View ⇒ Optical aberrations
VL Imaging Performance vs Field-of-View

VL Imaging Performance \( \downarrow \)
well within requirements
Metis off-pointed at 2.2° sees an "artificial Sun" at 1 AU

VL Radiometric Response =

\[
\text{VLDA signal (DN/s/pxl)/Input Radiance (W/cm}^2\text{/sr)}
\]

\[\text{VL Throughput @ FOV 2.2°} = (1.9 \pm 0.2) \times 10^{-2}\]

(estimate based on component-level: 2.3 \times 10^{-2})
UV-analog Imaging Performance vs FoV

- UV-analog Imaging Performance vs FoV
- 1.8°, 2.2°, 2.7°
The UV imaging performances, when the UVDA is operated in analog mode, are limited in spatial resolution to: 3-4 pixel $\Rightarrow$ 80-100 arcsec

Cfr.
P62 F. Frassetto: Optical performance
P71 V. Da Deppo: Alignment procedure
## UV (121.6 nm)

<table>
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<tr>
<th>Component</th>
<th>Efficiency</th>
<th>Error</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>0.54</td>
<td>0.12</td>
<td>Bear 02/10/2016 (T=0.77) &amp;</td>
</tr>
<tr>
<td>M2</td>
<td>0.54</td>
<td>0.12</td>
<td>IFN 29/09/2016 (T=0.77); IFN 09/09/2017 (T=0.59); IFN 10/01/2017 (T=0.54)</td>
</tr>
<tr>
<td>IFA</td>
<td>0.24</td>
<td>0.04</td>
<td>INAF Fineschi et al. note 22/09 2016 Selected FM=0.24 (email by E. Antonucci Tue, 27 Sep 2016)</td>
</tr>
<tr>
<td>MgF2 window</td>
<td>0.18</td>
<td></td>
<td>MPS private communication</td>
</tr>
<tr>
<td>QE</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Total efficiency  | 0.013      | 0.004  |                                                                |
| Efficiency w/o QE| 0.07       | 0.02   | 0.36                                                           |
| Estim. Eff. w/o QE| 0.16       |        |                                                                |

| Eff. Estim./Meas. | 2.27       |        |
Response Efficiency [DN/phot.In] = \((6.6 \pm 0.1)e-1\) [DN/s/pxl/phot.In]
UV Throughput Measured during Defocus Test

UV Throughput at 2.2° w/o Gain

[Incid. phot./Detect. phot.]

Defocus [mm]
Response Efficiency = (6.6 ± 0.1)e-1 [DN/s/pixel/phot.In] =

\[
\frac{\text{Response Throughput [DN/s/pixel/phot.In] (measured @ FoV = 1.8°, 2.2 °, 2.7 °)}}{\text{Vignetting @ FoV = 1.8°, 2.2 °, 2.7 ° (derived from VL radiometric calibration)}}
\]
VL Polarimeter Calibration
Frames of Reference
Polarimetry Data Analysis & Results

Model:
\[\delta(V) = a \cdot e^{b \cdot V} + c \cdot e^{d \cdot V}\]
Demodulation Tensor Measurement

The demodulation matrix must be measured, and the accuracy to which it is known will determine the accuracy of the measured Stokes parameters.

The incoming light Stokes parameters are obtained by inversion:

\[ m = X \cdot S \]

\[ S = X^{-1} \cdot m \]

Method:

Moore-Penrose pseudoinverse → matrix that can act as a partial replacement for the matrix inverse in cases where it does not exist. This matrix is frequently used to solve a system of linear equations when the system does not have a unique solution or has many solutions.
### Demodulation Tensor

EVALUATED ON THE WHOLE IMAGE

<table>
<thead>
<tr>
<th>Demodulation Matrix Element</th>
<th>Theoretical value</th>
<th>Mean of the computed value</th>
<th>Std of the computed values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{11}^*$</td>
<td>0.5</td>
<td>0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>$x_{12}^*$</td>
<td>0.5</td>
<td>0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>$x_{13}^*$</td>
<td>0.5</td>
<td>0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>$x_{14}^*$</td>
<td>0.5</td>
<td>0.50</td>
<td>0.00</td>
</tr>
<tr>
<td>$x_{21}^*$</td>
<td>1</td>
<td>1.12</td>
<td>0.15</td>
</tr>
<tr>
<td>$x_{22}^*$</td>
<td>0</td>
<td>0.47</td>
<td>0.38</td>
</tr>
<tr>
<td>$x_{23}^*$</td>
<td>-1</td>
<td>-1.39</td>
<td>0.25</td>
</tr>
<tr>
<td>$x_{24}^*$</td>
<td>0</td>
<td>-0.19</td>
<td>0.24</td>
</tr>
<tr>
<td>$x_{31}^*$</td>
<td>0</td>
<td>-0.29</td>
<td>0.20</td>
</tr>
<tr>
<td>$x_{32}^*$</td>
<td>1</td>
<td>1.35</td>
<td>0.34</td>
</tr>
<tr>
<td>$x_{33}^*$</td>
<td>0</td>
<td>0.06</td>
<td>0.33</td>
</tr>
<tr>
<td>$x_{34}^*$</td>
<td>-1</td>
<td>-1.16</td>
<td>0.31</td>
</tr>
</tbody>
</table>

Cfr. VL channel calibration
Session 11b Thursday 15:00
Marta Casti
Demodulation Tensor

\[ x^* = \frac{1}{2} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 2 & 0 & -2 & 0 \\ 0 & 2 & 0 & -2 \end{pmatrix} \]
Demodulation Matrix
(parameters variability across the focal plane)

\[ x^* = \frac{1}{2} \begin{pmatrix} 1 & 1 & 1 & 1 \\ 2 & 0 & -2 & 0 \\ 0 & 2 & 0 & -2 \end{pmatrix} \]
Polarimetry of an Extended Source
Demodulation Matrix Verification
Demodulation Matrix Verification

![Graphs showing demodulation results for different angles](image)

- **p 90deg**
- **p 135deg**
- **theta 90deg**
- **theta 135deg**
Demodulation Matrix Verification

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
<td>1,04</td>
<td>0,02</td>
<td>45</td>
<td>43,29</td>
<td>0,42 (~ 0,01 rad)</td>
</tr>
<tr>
<td>45</td>
<td>1</td>
<td>0,94</td>
<td>0,02</td>
<td>0</td>
<td>-1,04</td>
<td>0,36 (~ 0,01 rad)</td>
</tr>
<tr>
<td>90</td>
<td>1</td>
<td>0,99</td>
<td>0,01</td>
<td>-45</td>
<td>-44,01</td>
<td>0,39 (~ 0,01 rad)</td>
</tr>
<tr>
<td>135</td>
<td>1</td>
<td>1,00</td>
<td>0,02</td>
<td>90</td>
<td>89,68</td>
<td>0,27 (~ 0,01 rad)</td>
</tr>
</tbody>
</table>

\[
\sigma_{th}(p) = \frac{1}{SNR} = \sqrt{\frac{G}{DN}} \\
\sigma_{th}(\theta) = \frac{\sigma_{th}(p)}{p}
\]
OAC\textsuperscript{t} OAC OATs

SPOCC Set-up for Stray-Light Measurements

Collimated beam axis
Metis optical axis = 0°

Light-trap ("dark corona")

Solar Source & 45° Folding-mirror

2-m focal-length collimating mirror

Metis

Collimated beam axis
Metis optical axis = 0°
Required level of suppression of the stray-light: $B_{\text{stray}} / B_{\text{Sun}} \leq 1.e^{-9}$
• The bright halo was mainly due to a back reflection of one of the first baffle in the pipeline blackened only by Aeroglaze.

After Acktar application
Stray light at 0.5 AU before IO position fine tuning

Acquired image

Zemax simulation with off-centered IO
Stray light at 0.5 AU

Level of suppression of the stray-light from the Sun at 0.5 A.U. ("dark corona"): 

\[ \frac{B_{\text{stray}}}{B_{\text{Sun}}} \leq 5. \times 10^{-10} \]  

(Req.: \( \frac{B_{\text{stray}}}{B_{\text{Sun}}} \leq 1. \times 10^{-9} \))
Conclusions

- Vignetting function (Flat-Field) ✓ according to ray-trace
- VLDA Photon Transfer Curve ✓ matching component-level calibration
- VL Imaging & Radiometric Performance ✓ within specs
- UV Imaging ✓ PSF > × 3 wrt ray-trace (VL-UV alignment balancing)
- UV Radiometric Performance ✓ less then a factor 2.3 wrt estimated (due to mirror coating: 54% vs expected 80%)
- VL Polarimeter Performance ✓ within specs
- Stray-light Suppression Performance ✓ within specs
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