Polarimeters with Liquid Cristal Variable Retarders for PHI & METIS

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Introduction

Liquid Crystal Variable Retarders is a well-know technology for ground applications and currently in use by many instruments.

During last 10 years have undergone an important development driven mainly by the fast expansion of the LCDs.

**Polarimetric applications:**
- Study of the human eye *(J.-M. Bueno et al. 1999)*
- Hyperspectral imaging polarimeter for the observation of ice clouds *(C. Beeler et al. 2000)*
- Target detection *(F. Goudail et al 2004)*
- Glucose sensor *(Y.-L. Lo 2006)*
- Polarimeter in the IR range *(E. Garcia-Caurel 2004, J. Ladstein et al 2008, L.M. S. Aas et al 2010)*
- Cancer diagnosis *(T. Novikova et al 2012)*
Introduction

• Astrophysics and Solar Physics:
  - Full Stokes polarimeter (L.J. Novemeber et al 1995)
  - La Palma Stokes Polarimeter (LPSP) and Tenerife Infrared Polarimeter (TIP) (V. Martinez Pillet et al 1998)
  - Liquid imaging Stokes polarimeters for the Gregory Coudé telescope (T. Horn et al 1999)
  - SOLIS vector-magnetograph (C. U. Keller et al 2001)
  - HAO/NSO diffraction limited Spectro-Polarimeter
  - P1c du Midi Turret Dome magnetograph (J.-M. Malherbe et al 2004-2007)
  - Solar Flare telescope polarimeter (Y. Hanaoka 2005)
  - Yunnan solar tower polarimeter (F. Snik et al 2006)
**Introduction**

- **Space applications**
  - Alternative to the traditional rotary polarizing optics
  - **Mass reduction**
  - **Volume reduction**
  - To avoid the utilization of mechanism

- Resources are very limited
- The risk of a mechanical failure should be minimized

**First attempt**  
Flare Genesis mission (P.N. Bernasconi et al 2000)

LCVRs + Etalon LiNbO$_3$

IMaX of the SUNRISE mission *(V. Martinez-Pillet et al 2011)*

KPol for the SCORE coronagraph *(S. Fineschi et al 2011)*
Introduction

The SUNRISE mission

The SUNRISE mission consisted of a stratospheric balloon, with a solar telescope of 1 m aperture onboard. It was successfully launched on June 8th 2009 in the Arctic, within the NASA Long Duration Balloon Program.

The flight duration was 5 days and 17 hours.

The main scientific objective of SUNRISE is the study of the solar magnetic fields with high spatial resolution (100km in the solar surface).

Post-focal instruments

- SUFI: SUNRISE Filter Imager
- IMaX: Imaging Magnetograph eXperiment
- CWS: Correlation Tracker and Wavefront Sensor

Quality data and observation time never achieved before

2nd flight: 2012-13
**Introduction**

**IMaX is a solar magnetograph**

The spectral line is sensitive to the solar magnetic fields due to the Zeeman effect

- High sensitive polarimeter (<10^{-3})
- High resolution spectrometer (<70mÅ)
- Diffraction limited Imager(<0.14 arcsec)

R.L. Heredero et al 2007

LCVRs

LiNbO3 etalon

SO/PHI precursor
SO/PHI and METIS Polarisation Modulation Packages

**SO/PHI PMP**

Two anti-parallel nematic (APAN) LCVRs oriented with their fast axes at 45° with respect to each other followed by a linear polarizer aligned with the fast axis of the first LCVR.

**METIS PMP**

Two anti-parallel nematic (APAN) LCVRs oriented with their fast axes parallel with respect to each other but opposite molecular tilt angle followed by a linear polarizer at 45° with the fast axes of the LCVRs.
SO/PHI and METIS Polarisation Modulation Packages

METIS LCVRs will be identical to the PHI ones to reduce costs during design, procurement and qualification activities.
SO/PHI and METIS Polarisation Modulation Packages

Molecular tilt

![Diagram of molecular tilt and wavelength profile](image-url)
## Polarization Modulation

### SO/PHI PMP

<table>
<thead>
<tr>
<th>deg</th>
<th>PM₁</th>
<th>PM₂</th>
<th>PM₃</th>
<th>PM₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCVR₁</td>
<td>225.00</td>
<td>225.00</td>
<td>315.00</td>
<td>315.00</td>
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<tr>
<td>LCVR₂</td>
<td>234.74</td>
<td>125.26</td>
<td>54.74</td>
<td>305.26</td>
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</table>

### METIS PMP

<table>
<thead>
<tr>
<th>deg</th>
<th>PM₁</th>
<th>PM₂</th>
<th>PM₃</th>
<th>PM₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>LCVR₁</td>
<td>(\delta_0)</td>
<td>(\delta_0 +90)</td>
<td>(\delta_0 +180)</td>
<td>(\delta_0 +270)</td>
</tr>
<tr>
<td>LCVR₂</td>
<td>(\delta_0)</td>
<td>(\delta_0 +90)</td>
<td>(\delta_0 +180)</td>
<td>(\delta_0 +270)</td>
</tr>
</tbody>
</table>

Selected to optimize the modulation efficiencies

\[
\xi_i = \left( \frac{\sum_{j=1}^{n} D_{ij}^2}{n} \right)^{-1/2} \Rightarrow \xi_{\text{max,1}} = 1 \quad \text{and} \quad \sum_{i=2}^{4} \frac{\xi_{\text{max},i}^2}{4} = 1
\]
SO/PHI and METIS Polarisation Modulation Packages

Important Issues to be taken into account:

**as PMP**

1. Angle of incidence dependence of retardance
2. Temperature dependence of retardance
3. Homogeneity of retardance across clear aperture
4. Response times
5. Chromatism

**as IMAGER**

1. Wavefront error
2. Alignment quality

- Operational temperature
- High birefringence LC
- Achromatic LCVRs
- $\lambda$ range and voltage selection
- Manufacturing quality
- Instrument optical design
- Double cells
- Instr. optical design
- Thermal control (±0.5º)
- Manufacturing quality
- instr. optical design
- Pixel per pixel calibration

Achromatic LCVRs
- range and voltage selection
SO/PHI PMPs

High Resolution Telescope (HRT)

Full Disk Telescope (FDT)

Correlation Tracker (CT)

Filtergraph (FG)

Focal Plane Optics (FPO)
SO/PHI PMPs
SO/PHI PMPs
Validation of LCVRs for Solar Orbiter

ESA contract No.22334/09/NL/SfE

**GOAL:** “this activity aims at increasing the relevant technology readiness level in Europe from TRL4 “Component Validation in Laboratory Environment” to TRL5 “Component Validation in Relevant Environment” by providing a significant step towards full space qualification of high-performance LCVRs for the Solar Orbiter mission.”

<table>
<thead>
<tr>
<th></th>
<th>Types</th>
<th>Cells</th>
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</thead>
<tbody>
<tr>
<td>APAN</td>
<td>4</td>
<td>40</td>
</tr>
<tr>
<td>HAN Hybrid Aligned Nematic</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Wide Acceptance Angle</td>
<td>1</td>
<td>20</td>
</tr>
<tr>
<td>Achromatic LCVRs</td>
<td>1</td>
<td>20</td>
</tr>
</tbody>
</table>

TOTAL: 7 types, 90 cells

2 years of work SUCCESSFULLY FINISHED on May 2011

Results presented in SPIE2011, San Diego
## LCVRs under study

<table>
<thead>
<tr>
<th>LC Type</th>
<th>Symbol</th>
<th>Comment</th>
<th>Alignment</th>
<th>Glass</th>
<th>Manufacturer</th>
<th>LC mixture</th>
<th>$\Delta n$</th>
<th>$\Delta n_{20^\circ C/589nm}$</th>
<th>T-Range $^\circ C$</th>
</tr>
</thead>
<tbody>
<tr>
<td>APAN</td>
<td>1.Aα</td>
<td>anti-parallel nematic</td>
<td>Poly PI2545</td>
<td>fused silica</td>
<td>Arcoptix</td>
<td>ZLI-3700-000</td>
<td>medium</td>
<td>0.101</td>
<td>[-30, +105]</td>
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<tr>
<td>APAN</td>
<td>1.Bα</td>
<td>anti-parallel nematic</td>
<td>Poly PIA2000</td>
<td>fused silica</td>
<td>Visual Display</td>
<td>BL006</td>
<td>high</td>
<td>0.285</td>
<td>[-20, +118.5]</td>
</tr>
<tr>
<td>APAN</td>
<td>1.Aβ</td>
<td>anti-parallel nematic</td>
<td>Poly PI2545</td>
<td>fused silica</td>
<td>Arcoptix</td>
<td>MLC-6025-000</td>
<td>low</td>
<td>0.084</td>
<td>[-40, +103]</td>
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<tr>
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<td>1.C</td>
<td>anti-parallel nematic</td>
<td>Poly PIA2000</td>
<td>SF57</td>
<td>Visual Display</td>
<td>BL006</td>
<td>high</td>
<td>0.285</td>
<td>[-20, +118.5]</td>
</tr>
<tr>
<td>HAN</td>
<td>4.A</td>
<td>hybrid aligned nematic</td>
<td>Poly PI2545</td>
<td>fused silica</td>
<td>Arcoptix</td>
<td>MLC-6610</td>
<td>negative</td>
<td>0.0996</td>
<td>[-30, +79.5]</td>
</tr>
<tr>
<td>Dual APAN</td>
<td>5.A</td>
<td>dual anti-parallel</td>
<td>Poly PI2545</td>
<td>fused silica</td>
<td>Arcoptix</td>
<td>MDA-98-1602</td>
<td>high</td>
<td>0.267</td>
<td>[-20, +109]</td>
</tr>
<tr>
<td>ALCVR</td>
<td>6.A</td>
<td>achromatic</td>
<td>Poly PI2545</td>
<td>fused silica</td>
<td>Arcoptix</td>
<td>BL006 + MLC-6025-000</td>
<td>high+low</td>
<td>0.285/0.084</td>
<td>[-20, +118.5] + [-40, +103]</td>
</tr>
</tbody>
</table>

ALCVRs: Patent pending INTA-INAF

*M-MOD1 Analysis, LCVRs-INTA-RP-115, Issue 1, Revision 0 (2011)*
Test campaign

**Ionizing radiation tolerance (Gamma)**
>75krads (100krads)

**Protons radiation tolerance**
fluence (60 MeV) > 1.39 $10^{11}$ p+/cm$^2$ (2.78$x10^{11}$ p+/cm$^2$)
fluence (80 MeV) > 1.08 $10^{11}$ p+/cm$^2$ (2.16 $10^{11}$ p+/cm$^2$)

**UV radiation tolerance**
1.50 ESH 200-400 nm
1.00 ESH 160-200nm

**Vibration/Dynamic test**
Random vibration
Sine vibration
Shock (>3000g)

**Outgassing test**
TML < 1%, CVCM < 0.1%

**Thermal-Vacuum test**
Operational Temperatures [-20°, +60°]
Non-operational Temperatures [-40°, 70°]
Optical measurements

Variable Angle Spectroscopic Ellipsometry

Null ellipsometer
Optical measurements

Mach-Zehnder interferometer

Transmittance
Chromatism

**T1A\(\alpha\)5 AOl=0°**

![Graph showing Chromatism relationship between voltage and optical retardance for different wavelengths.](image)

**T1A\(\alpha\)5 Spectral Response**

![Graph showing Chromatism relationship between wavelength and optical retardance for different wavelengths.](image)
Chromatism

**T1Bα9 AOI=0°**

- wvl=500nm
- wvl=575nm
- wvl=650nm

**T1Bα9 Spectral Response**

- Optical Retardance [deg]
- Wavelength [nm]
Wide acceptance angles

Nominal retardante for MDA-98-1602 LCVR and WF-LCVR is 1.3782 waves and for MLC-6025-000 1.3921 waves
Other tests performed

- High Temperature tests
- Reversibility clearing point
Other tests performed

- Repeatability of cells with high birefringence LC mixtures

![Graph showing optical retardance vs voltage for different cell samples.](image)
Next actions

• Breadboards: (4 cells) mechanical manufacturing in progress. Cells received
• Selection of final LC mixture (decision to be taken in the next days)
• UV irradiation tests (10 cells). Additional test requested by ESA during TDA, manufacturing in progress
• Life test: 2013 (50 cells)
• Qualification: 2013 (50-60 cells)
General conclusions

1. LCVRs is a promising technology for imaging polarimeters on-board space platforms. In order to validate the technology for the Solar Orbiter mission, an exhaustive investigation was carried out.

2. PHI and METIS successfully passed PDR with PMPs based on LCVRs as baseline (no RIDs).

3. The detail design is well advanced as well as the remaining tests before the life tests and qualifications tests foreseen for 2013. This last LCVRs batch will include the flight cells for both instruments.