FreeForm Gratings for Imaging Spectrometers

V. Moreau¹
A.Z. Marchi²
B. Borguet¹

Dispersing element for astronomy: New trends and Possibilities
Milano, October 9-11, 2017

¹ AMOS, Liege Science Park, Rue des Chasseurs Ardennais, 4031 Angleur, Belgium, vincent.moreau@amos.be
² ESA/ESTEC, Keplerlaan 1, 2201 AG Noordwijk, The Netherlands,
Turn-key Telescopes

PanStarrs Survey Telescope

OAJ: Javalambre Observatory

Devastal Optical Telescope

1.8 m Telescope
IfA - Hawaii

2.5 m Telescope
Javalambre

3.6 m Telescope
ARIES Nainital
Large opto-mechanical sub-systems

- Auxillary Telescopes System for VLTi (ESO)
- Adapter/Rotator for VLT (ESO)
- M3 unit for GTC
- Interferometric Telescopes for MRO
- Primary Mirror Cell for DKIST
- Sub-systems studies for E-ELT
Astronomy Optics

- Polishing capabilities for complex large optics up to 3 meters
These equipments are flying on board satellites, probes or the Space Shuttle. They are mainly instruments, mirrors, mounts, telescopes, structures or mechanisms.

- Ceramic Mirrors
  DM3 Satellite (for SSTL)

- Aluminium Mirrors
  Tropomi (Sentinel 5 precursor)

- Silicon Carbide Mirrors
  GAIA
Free Form Optics

“Freeform Optics is not just an Evolution, It’s a Revolution”

J. Rolland, Director of Center for Freeform Optics, Rochester NY

Freeform Optics = surfaces without rotational symmetry

**Conical**
- Coaxial design
  - On-axis
  - Obscuration
  - Narrow Field-of-view

**Aspherical**
- Coaxial design
  - Off-axis
  - No Obscuration
  - Large Field-of-view

**Freeform**
- Free orientation of optics
- Free position of image
- No obscuration
- Large Field-of-view
- 3D-configurations possible
- Much more compact
Imaging spectrometers

Original question (ESA 2013)

**Is it possible to improve Hyperspectral Imager with a freeform grating?**

subsidary issue

**Is it possible to manufacture it?**

“The technology of ruling a grating on a convex freeform surface has not yet been demonstrated to our knowledge, but is an active research area”.

Freeform Grating Spectrometer

Original Offner Spectrometer

- Slit
- Convex Spherical Grating
- Concave Spherical mirror
- Sensor

ELOIS
(Enhanced Light Offner Imaging Spectrometer)

- Freeform design

- 2->1 demagnification
- Larger Slit = 30 µm x 60 mm
- Compatible with 15 µm pix detector
- F# = 2.5 at focal plane -> high SNR
- Factor 4 reduction in volume
- Really Compact design : A5 format

Factor 4 reduction in volume
Free Form Grating = Significant improvement of performances

<table>
<thead>
<tr>
<th>Optical performance</th>
<th>ELOIS spectrometer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Image F#</td>
<td>2.5</td>
</tr>
<tr>
<td>Entrance slit</td>
<td>60 mm x 30 µm</td>
</tr>
<tr>
<td>Image</td>
<td>30 mm (spatial) x 2.7 mm (spectral)</td>
</tr>
<tr>
<td>Grating frequency</td>
<td>104 lp/mm</td>
</tr>
<tr>
<td>Spectral range</td>
<td>400-1000 nm</td>
</tr>
<tr>
<td>Spectral sampling</td>
<td>2.5 nm</td>
</tr>
<tr>
<td>Keystone</td>
<td>1.1 µm</td>
</tr>
<tr>
<td>Smile</td>
<td>1.9 µm</td>
</tr>
<tr>
<td>Global size</td>
<td>116 x 145 x 130 mm (with folding)</td>
</tr>
</tbody>
</table>
Free Form Grating Manufacturing

Machined on NiP-plated Aluminum blank with a 5 axis ultra-precision lathe using a sharp edge diamond tool. Blaze angle is following the normal to the surface (-6° -> 6°)

Nominal Shape

Mirror turning : 50 nm rms SFE

Grating ruling: 57 nm rms SFE
Diffraction efficiency

- Maximum diffraction efficiency of 85% is measured at 633 nm
Grating Roughness

- First trials were...disappointing
Identification of Ghost origin

- Analysis of groove to groove spacing on a microscope image of the grating
- Evidence of a periodic error in groove spacing
Grating Roughness

- First trials were...disappointing

- But perseverance finally paid...

Notable reduction of Ghost (<10^{-3}) and grass (<10^{-5})
Low Scattering (<10^{-7}) -> correspond to Rq=3.5 nm rms
ELOIS: Breadboard Performances

BREADBOARD

TEST SETUP

Monochromator
Integrating sphere
Target Object
Optical Relay

Light source: Xenon lamp or Laser source
Camera
Amos breadboard
Slit
Polarizer

FFG
Primary mirror
Tertiary mirror
Test Camera
First results from breadboard tests

Initial results: Test of the Breadboard in front of a Xenon arc Lamp

Theoretical spectrum

Image from ELOIS

The resolution of the spectrometer is well achieved!
Hyperspectral Image acquisition: Vegetation Samples

1: Honeysuckle (Lonicera periclymenum)
2: Bunchgrass (Brachypodium sp)
3: Blackberry (Rubus fruticosus)
New perspectives: CHIMA - High Spectral resolution instrument

- Holographic FreeForm Grating Spectro-Imager
  - Demagnification factor of 3
  - All Reflective design – Full aluminum - Athermal
  - Spectral Resolution R~4000 (0.16 nm)
  - Spectral Bandwidth 0.5 nm
  - Long slit (60 mm)
  - Excellent imaging prop. (MTF > 0.5)
  - High SNR (> 1000)
  - Compactness (20x20x40 cm³)

1000 lp/mm Freeform replicated grating

HORIBA
JOBIN YVON
New perspectives: Multi-blazed Gratings

- Measured profile
- Typical roughness: ~4nm RMS
- Typical grating SFE: ~30nm RMS

<table>
<thead>
<tr>
<th>Optical performance</th>
<th>Chandrayaan II gratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grating frequency</td>
<td>20 lp/mm</td>
</tr>
<tr>
<td>Spectral range</td>
<td>700-5000 nm</td>
</tr>
<tr>
<td>Shape</td>
<td>Spherical convex</td>
</tr>
<tr>
<td>Multi-blazed</td>
<td>9 blaze angles</td>
</tr>
</tbody>
</table>

- Measurement results:
- Analysis parameters:
- Contour plot

[Image of measurement data and graphs]
New Perspectives: ELOIS VNIR/SWIR

- Multi-Blazed Freeform grating for combined VNIR/SWIR Spectrometer with Splitted-orders

VNIR+SWIR Order 1

VNIR Order 2

SWIR Order 1

Diffraction efficiency

SNR
<table>
<thead>
<tr>
<th>Requirement</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral range</td>
<td>400-2450 nm</td>
</tr>
<tr>
<td>Ground sampling distance (@650 km)</td>
<td>35 m</td>
</tr>
<tr>
<td>Swath width</td>
<td>70 km</td>
</tr>
<tr>
<td>Mass</td>
<td>40 kg</td>
</tr>
<tr>
<td>Volume</td>
<td>550 x 650 x 450 mm³</td>
</tr>
<tr>
<td>Number of bands</td>
<td>210</td>
</tr>
<tr>
<td>Spectral FWHM</td>
<td>&lt;12 nm (uniform over range)</td>
</tr>
<tr>
<td>MTF</td>
<td>&gt;0.3</td>
</tr>
<tr>
<td>SNR at 0.3 albedo</td>
<td></td>
</tr>
<tr>
<td>VIS</td>
<td>&gt; 400</td>
</tr>
<tr>
<td>NIR</td>
<td>&gt; 250</td>
</tr>
<tr>
<td>SWIR</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Radiance accuracy</td>
<td>&gt; 95%</td>
</tr>
<tr>
<td>Polarisation sensitivity</td>
<td>&lt;3% absolute, 2% between bands</td>
</tr>
<tr>
<td>Out of band rejection</td>
<td>&lt;1%</td>
</tr>
</tbody>
</table>
Conclusions

- Innovative non-symmetrical Offner Imaging spectrometer with large demagnification have been successfully designed by introducing Freeform Grating.
  - Improved SNR
  - Compact design
  - Longer Slit (=FoV/Sampling ratio)
  - Smaller detector pixels

- Ultra-accurate single point diamond machining is a key technology for manufacturing FFO systems:
  - For low resolutions grating (<150 lp/mm), it offers new degrees of freedom:
    Complex shapes, Multi-blazed, variable period...

- Through the tests of a functional breadboard, we demonstrate the perfect control of the complete process chain for freeform grating and instrument, from design to manufacturing & calibration.
Thank You!

Acknowledgments:

Coralie De Clercq (AMOS)
Arnaud Cotel (Horiba-Jobin-Yvon)
Luca Maresi (ESA)
Atul Deep (ESA)
Michael François (ESA)
Yvan Stockman (CSL)