# FreeForm Gratings for Imaging Spectrometers


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


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# Turn-key Telescopes

## PanStarrs Survey Telescope

1,8 m Telescope
IfA - Hawaii

## OAJ: Javalambre Observatory

2,5 m Telescope
Javalambre

## Devastal Optical Telescope

3,6 m Telescope
ARIES Nainital

# Large opto-mechanical sub-systems

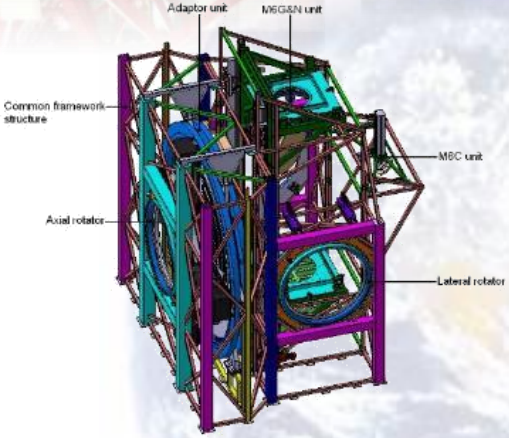
Auxillary Telescopes System for VLTi (ESO)

Adapter/Rotator for VLT (ESO)

M3 unit for GTC

Interferometric Telescopes for MRO

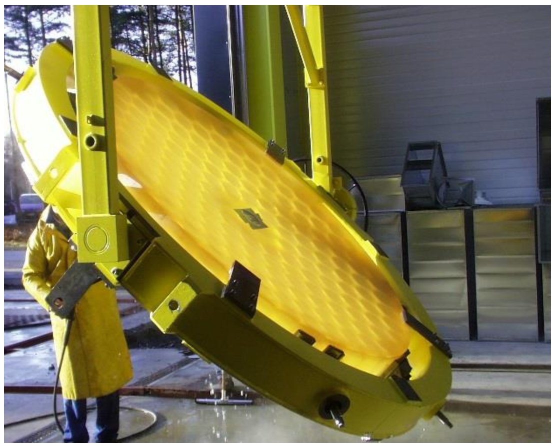
Primary Mirror Cell for DKIST

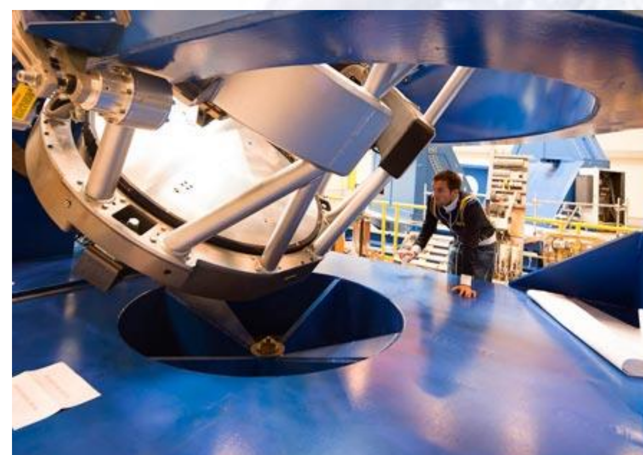



Sub-systems studies for E-ELT

# Astronomy Optics

- Polishing capabilities for complex large optics up to 3 meters



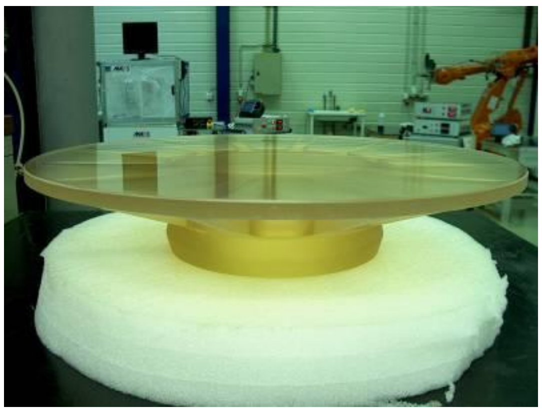


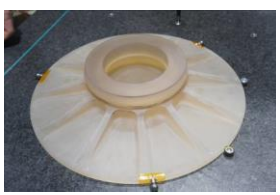
# Space Optics

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)

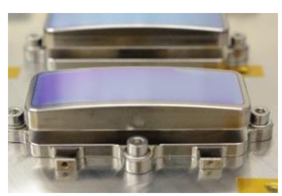




SURREY SATELLITE TECHNOLOGY LTD

## Aluminium Mirrors

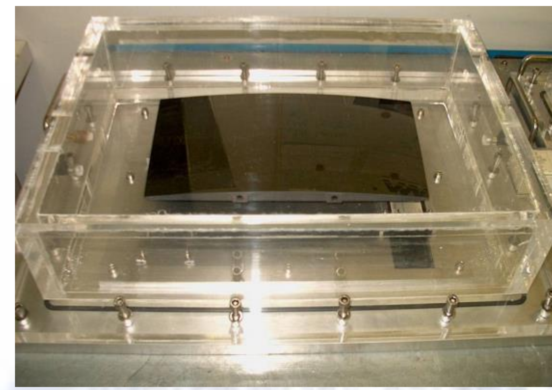
### Tropomi (Sentinel 5 precursor)

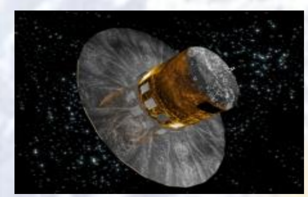


Dutch Space an EADS Astrium company

## Silicon Carbide Mirrors

### GAIA





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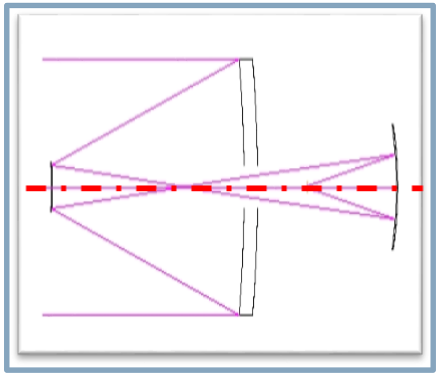
# Free Form Optics

" Freeform Optics is not just an Evolution, It's a Revolution"

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

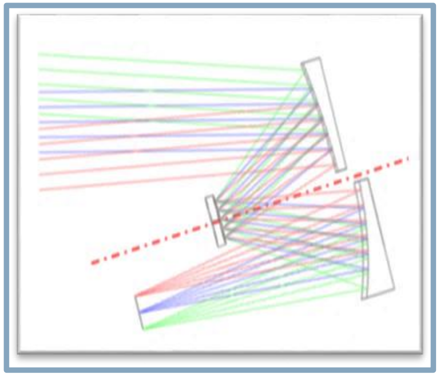
## Freeform Optics = surfaces without rotational symmetry

### Conical



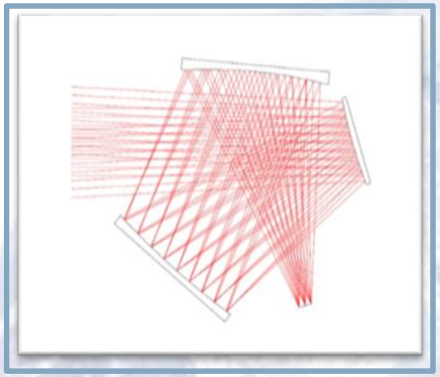
Coaxial design
- On-axis
- Obscuration
- Narrow Field-of-view

### 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)*

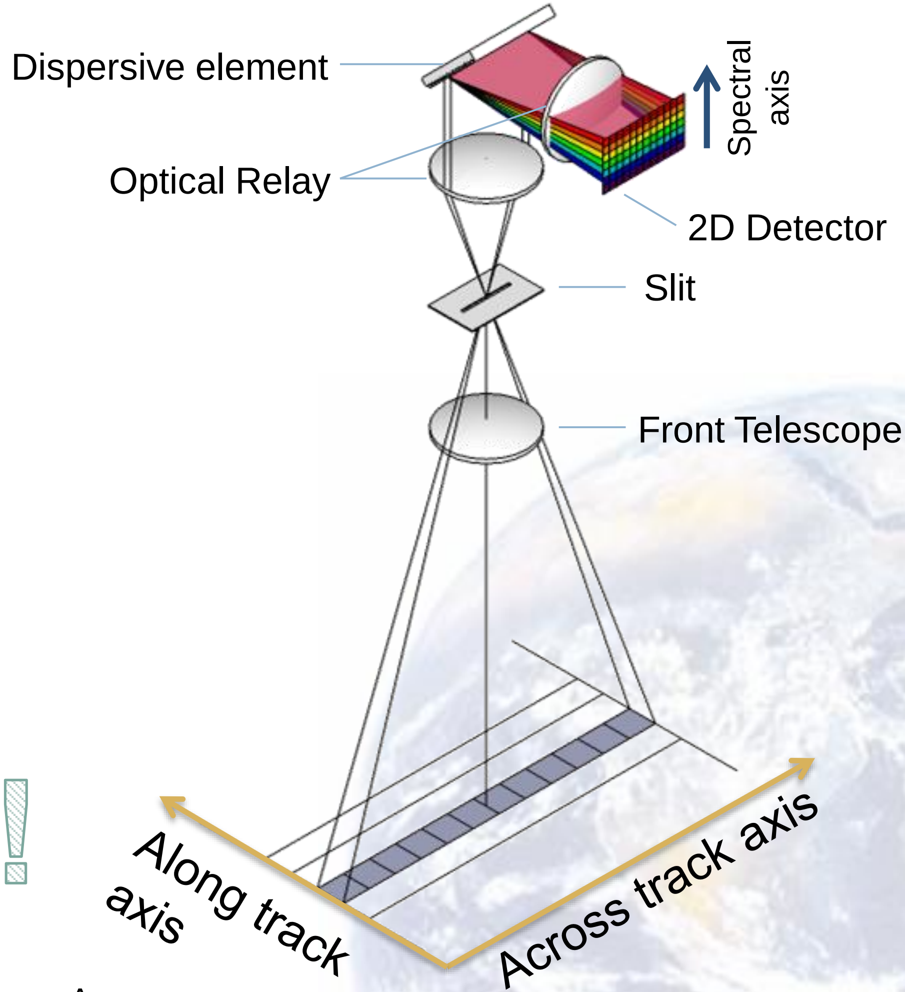
*Is it possible to improve Hyperspectral Imager with a freeform grating?*

*subsidiary issue*

*Is it possible to manufacture it?*

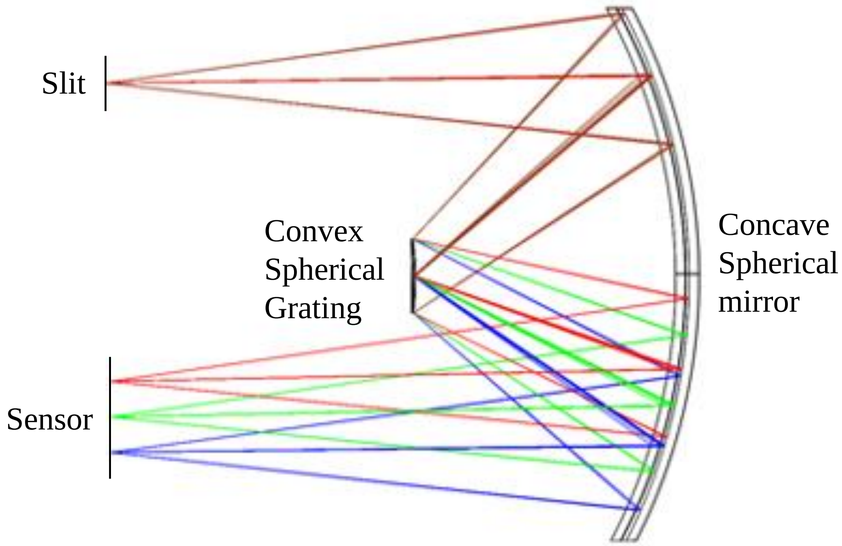
*"The technology of ruling a grating on a convex freeform surface has not yet been demonstrated to our knowledge, but is an active research area".* ?!

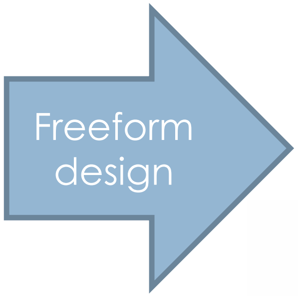
In Light: Science & Applications (July 2017) "Freeform spectrometer enabling increased compactness", J. Reimers, A. Bauer, K. P. Thompson and J. P. Rolland.



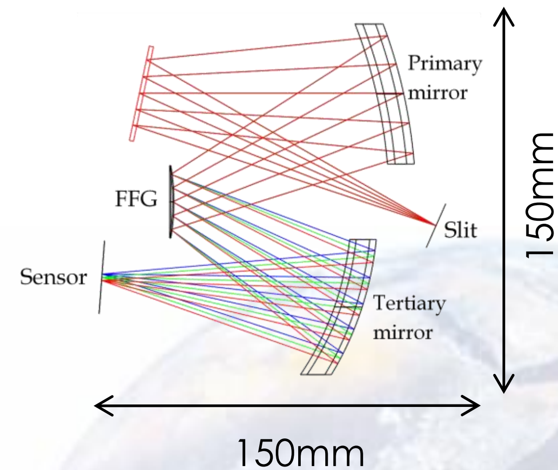
# Freeform Grating Spectrometer

## Original Offner Spectrometer



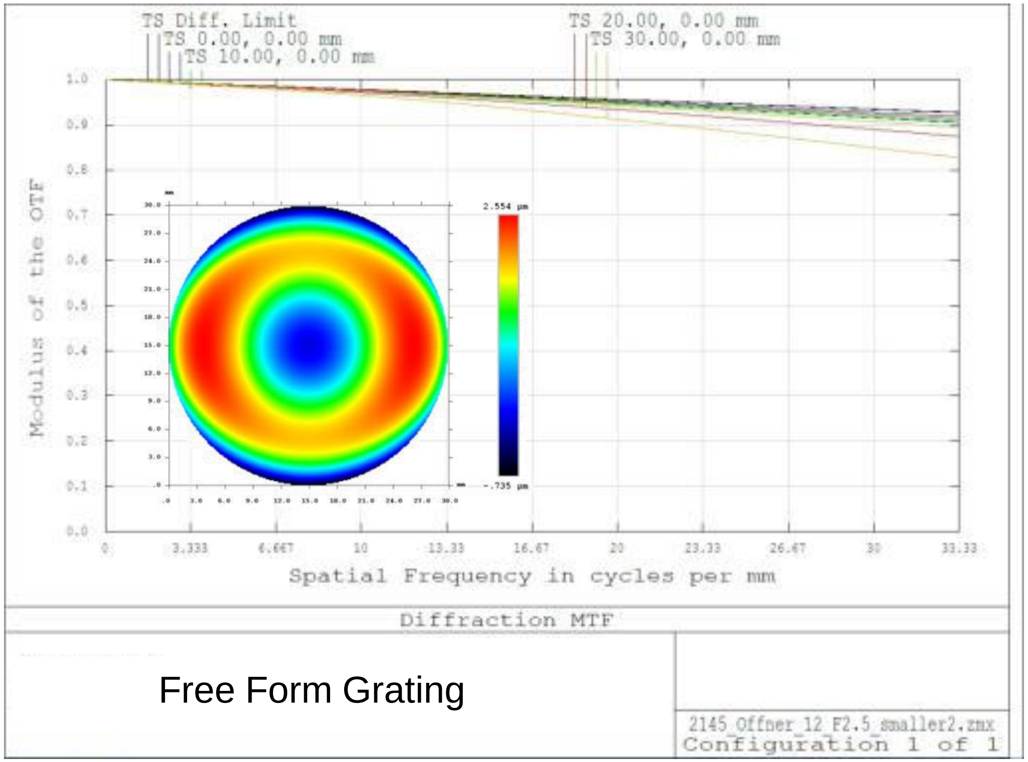




## ELOIS
(Enhanced Light Offner Imaging Spectrometer)




- 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

# Free Form Grating = Significant improvement of performances



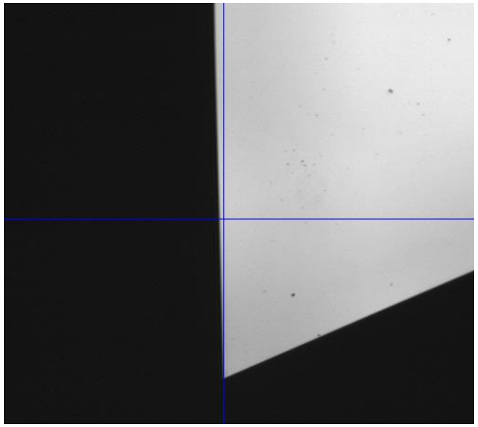

Free Form Grating

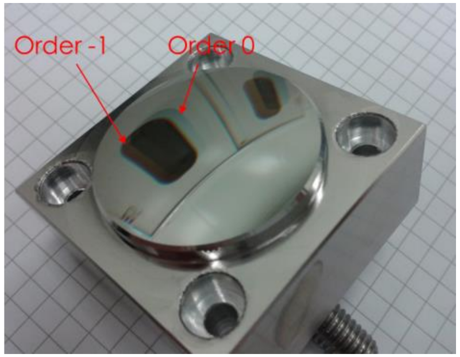
| Optical performance | **ELOIS spectrometer** |
|---|---|
| Image F# | 2.5 |
| Entrance slit | 60 mm x 30 µm |
| Image | 30 mm (spatial) x 2.7 mm (spectral) |
| Grating frequency | 104 lp/mm |
| Spectral range | 400-1000 nm |
| Spectral sampling | 2.5 nm |
| Keystone | 1.1 µm |
| Smile | 1.9 µm |
| Global size | 116 x 145 x 130 mm (with folding) |

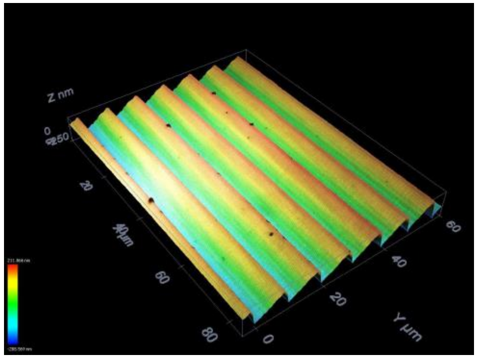
# Free Form Grating Manufacturing

Machined on NiP-plated Aluminum blank with a 5 axis ultra-precision lathe *using a sharp edge diamond tool.*

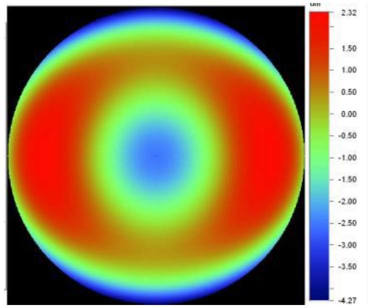
*Blaze angle is following the normal to the surface (-6° -> 6°)*



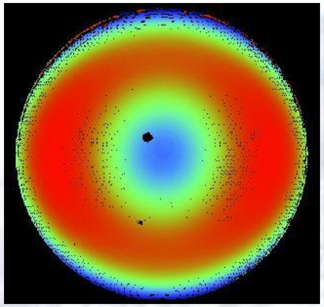


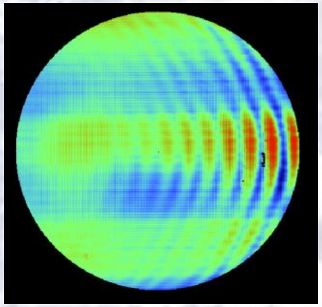

Nominal Shape




Mirror turning : 50 nm rms SFE

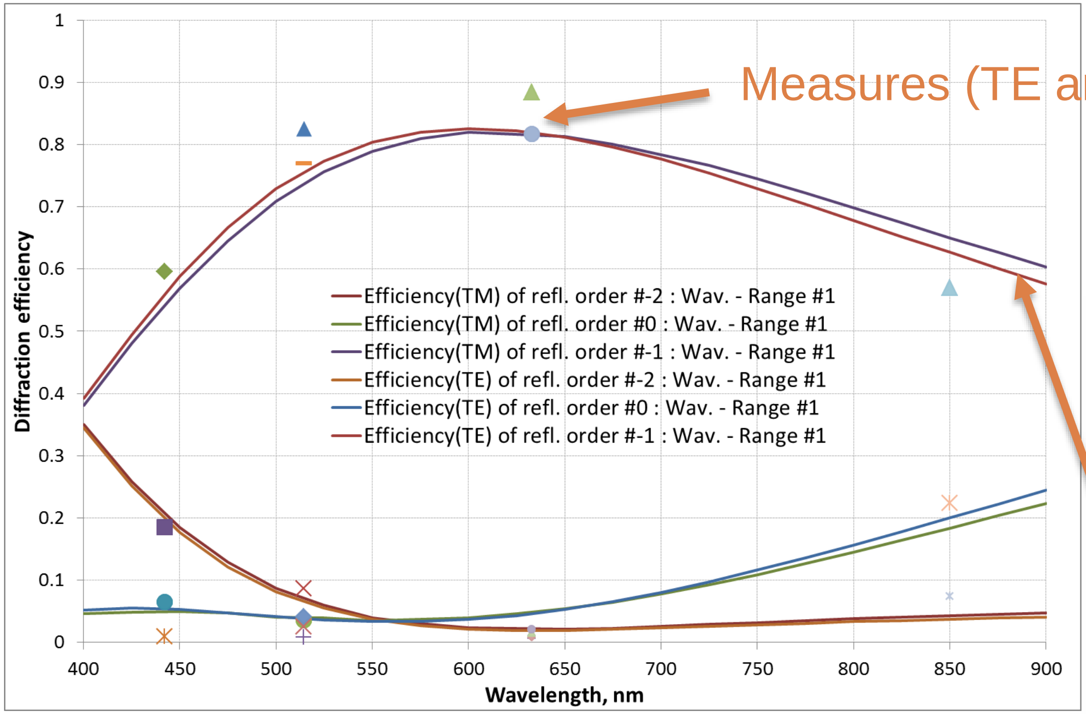


Grating ruling: 57 nm rms SFE



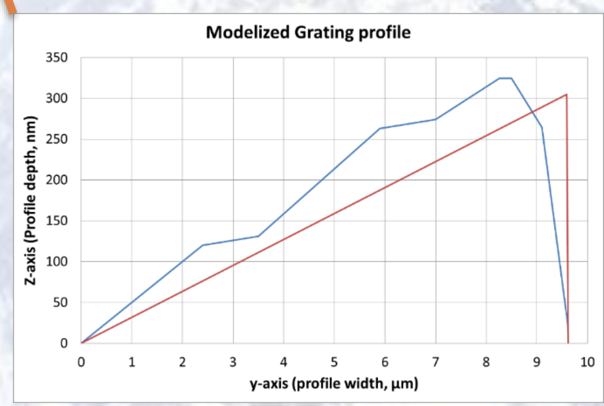
# Diffraction efficiency

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



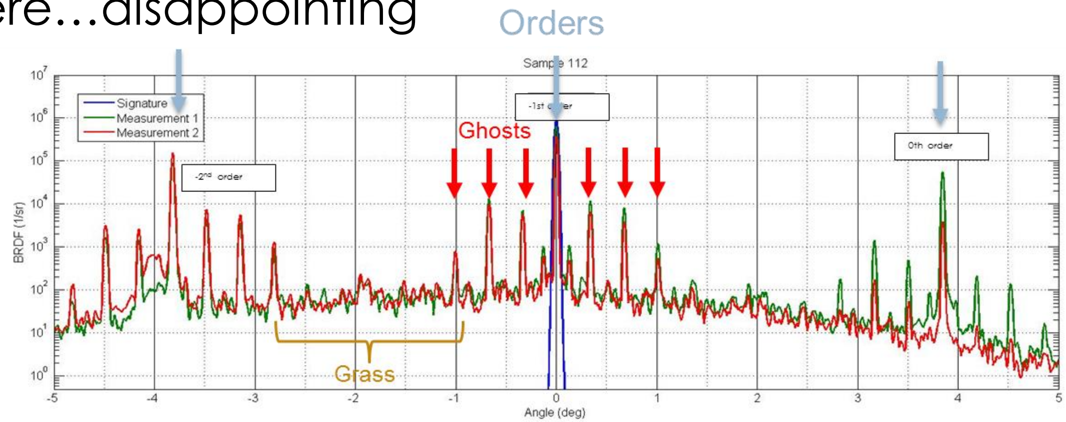

Measures (TE and TM)

Simulated curve from measured profile



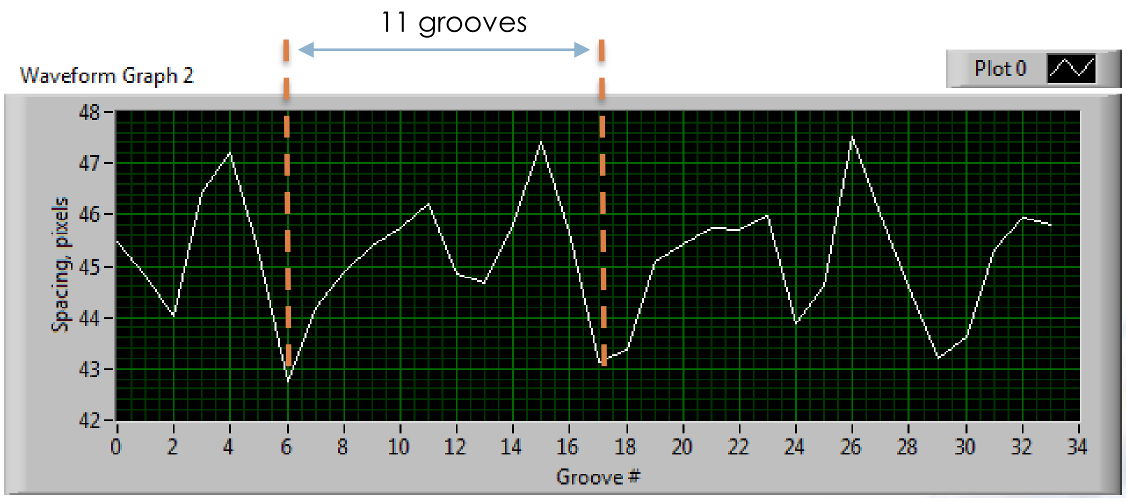
# Grating Roughness

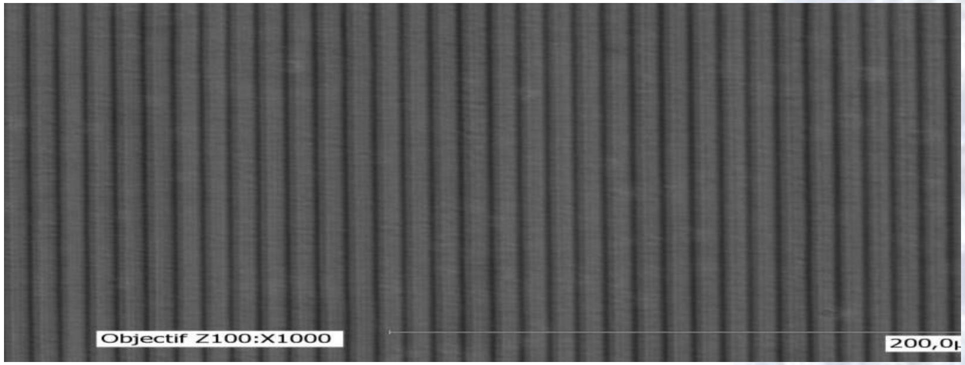
- First trials were…disappointing



# 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*

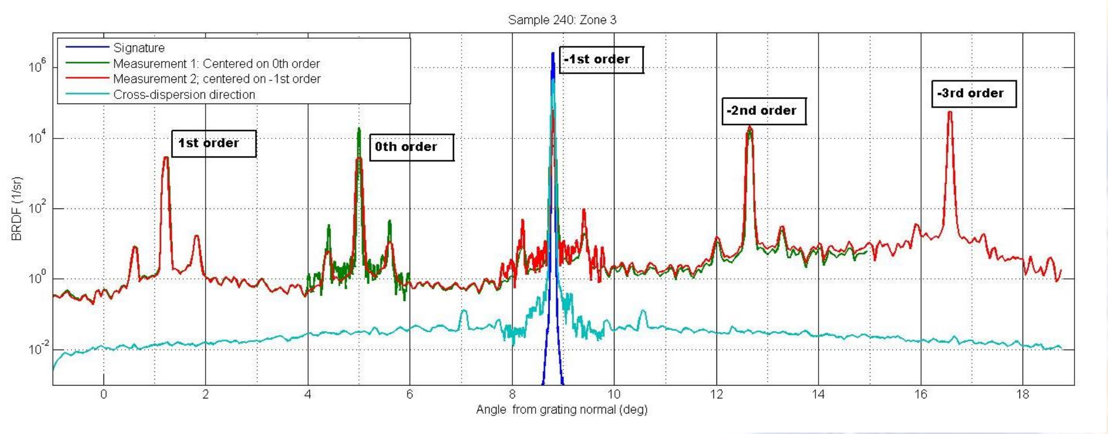


# Grating Roughness

- First trials were…disappointing

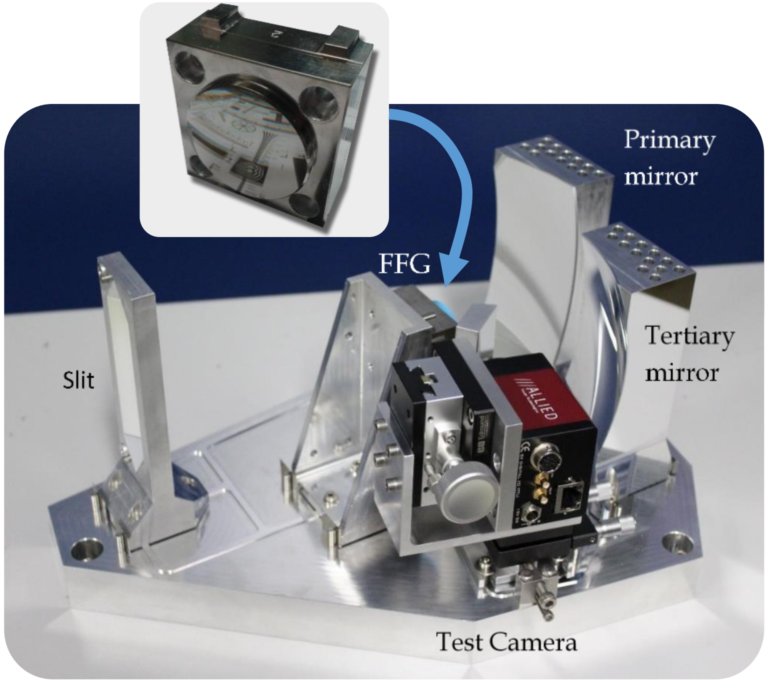

- But perseverance finally paid…




Notable reduction of Ghost ($<10^{-3}$) and grass ($<10^{-5}$)

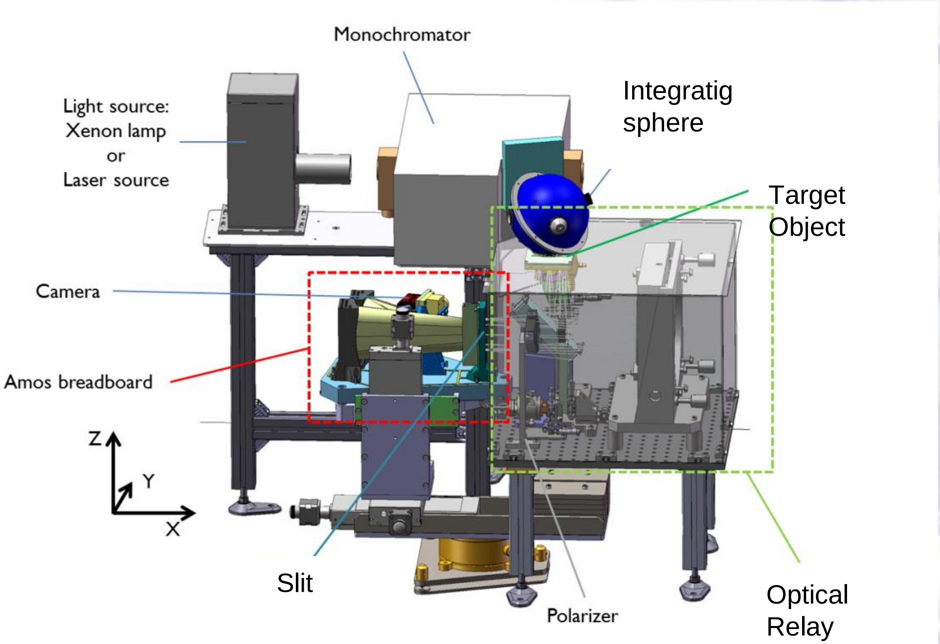
Low Scattering ($<10^{-7}$) -> correspond to Rq=3.5 nm rms

# ELOIS: Breadboard Performances




**BREADBOARD**

**TEST SETUP**



# First results from breadboard tests

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

Theoretical spectrum

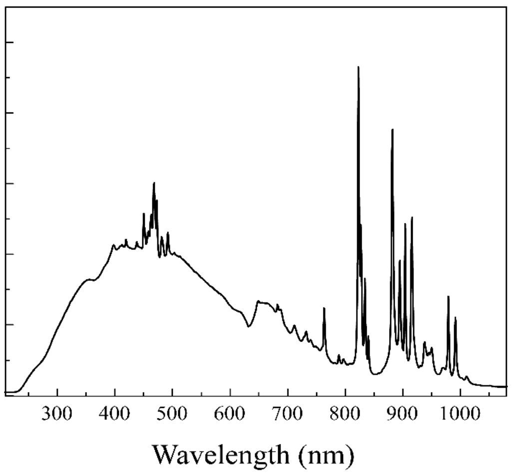
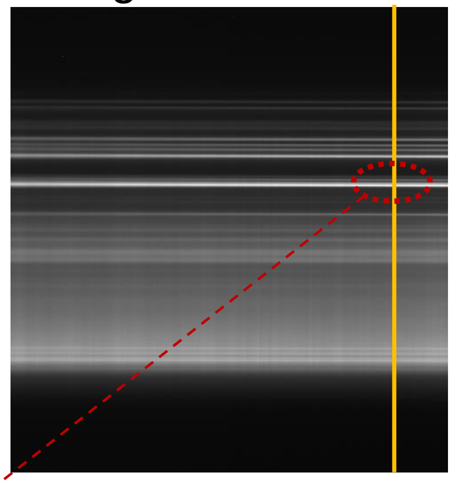
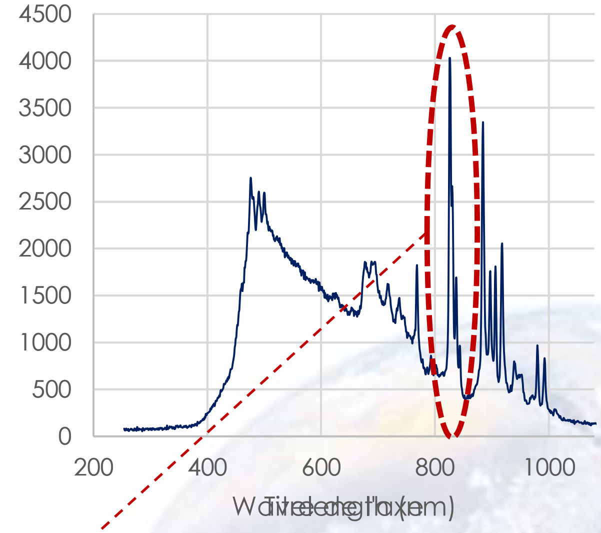
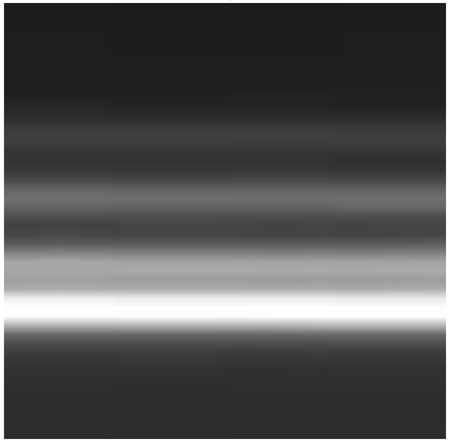
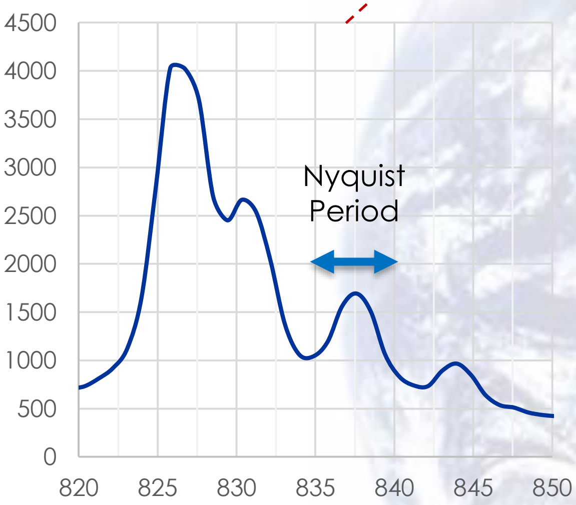



Image from ELOIS



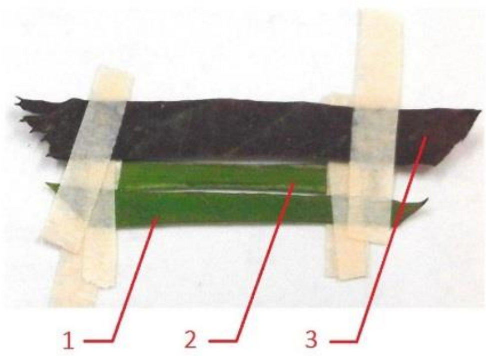


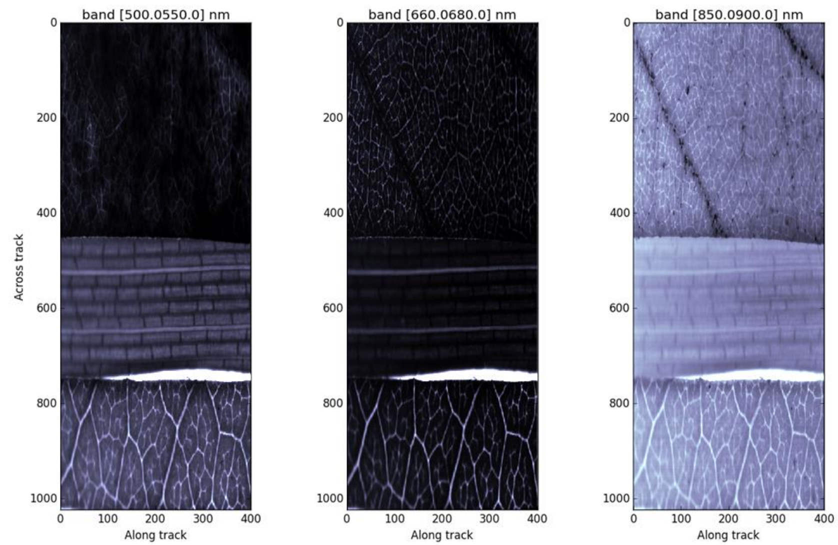


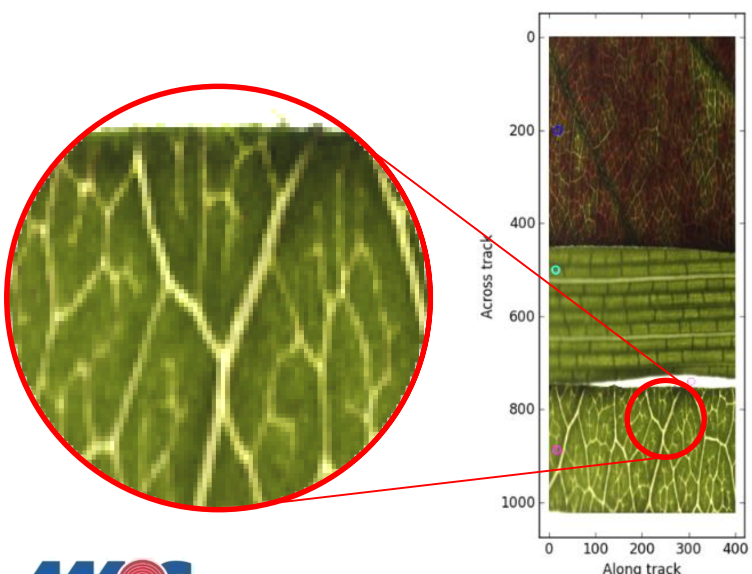

The resolution of the spectrometer is well achieved !

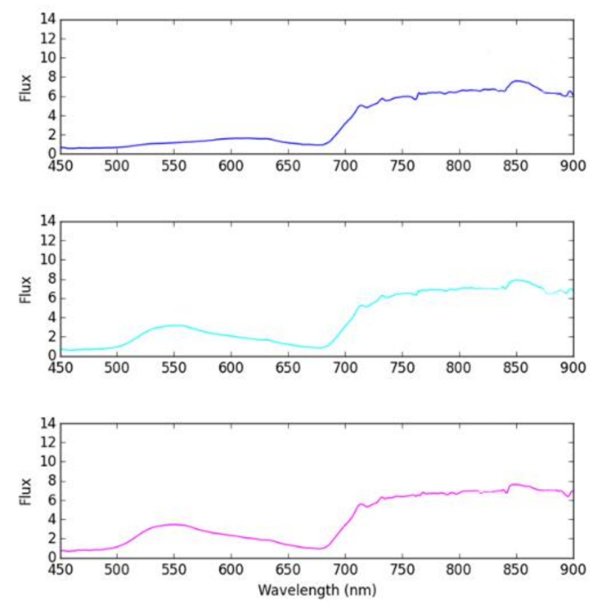
# Hyperspectral Image acquisition : Vegetation Samples




1 : Honeysuckle (Lonicera periclymenum)
2 : Bunchgrass (Brachypodium sp)
3 : Blackberry (Rubus fruticosus)

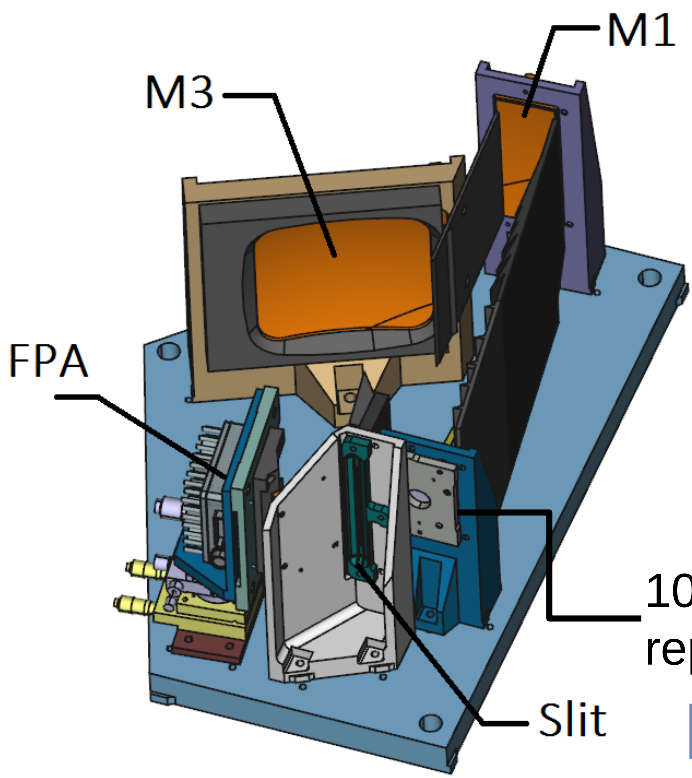


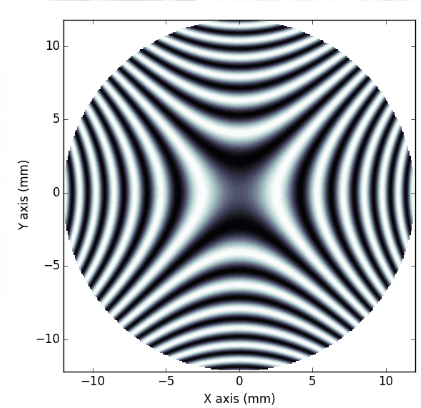



# New perspectives : CHIMA - High Spectral resolution instrument

- 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)




HORIBA
JOBIN YVON

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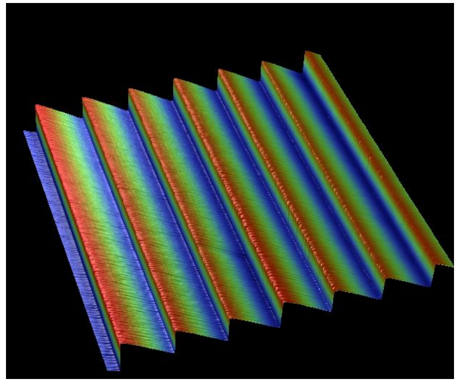
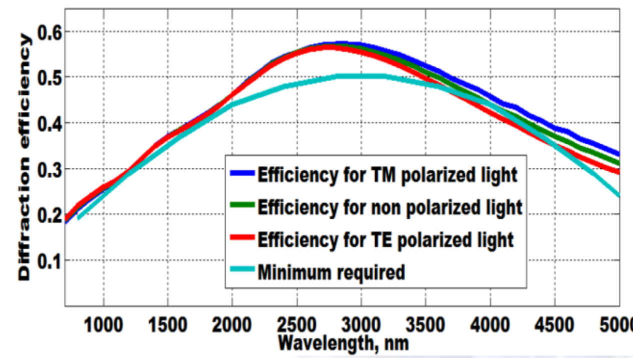
# New perspectives : Multi-blazed Gratings

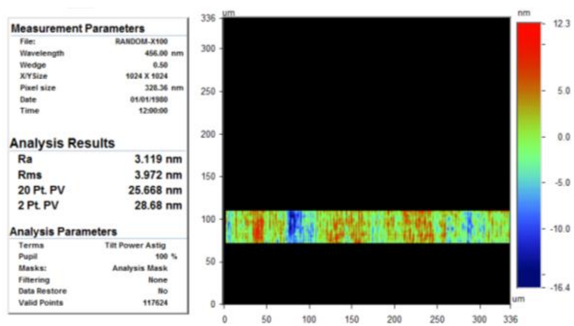
Measured profile



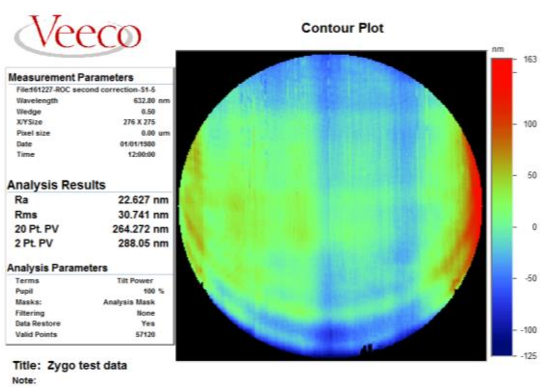
| Optical performance | Chandrayaan II gratings |
|---|---|
| Grating frequency | 20 lp/mm |
| Spectral range | **700-5000 nm** |
| Shape | Spherical convex |
| Multi-blazed | 9 blaze angles |




Typical roughness
~ 4nm RMS




Typical grating SFE
~ 30nm RMS

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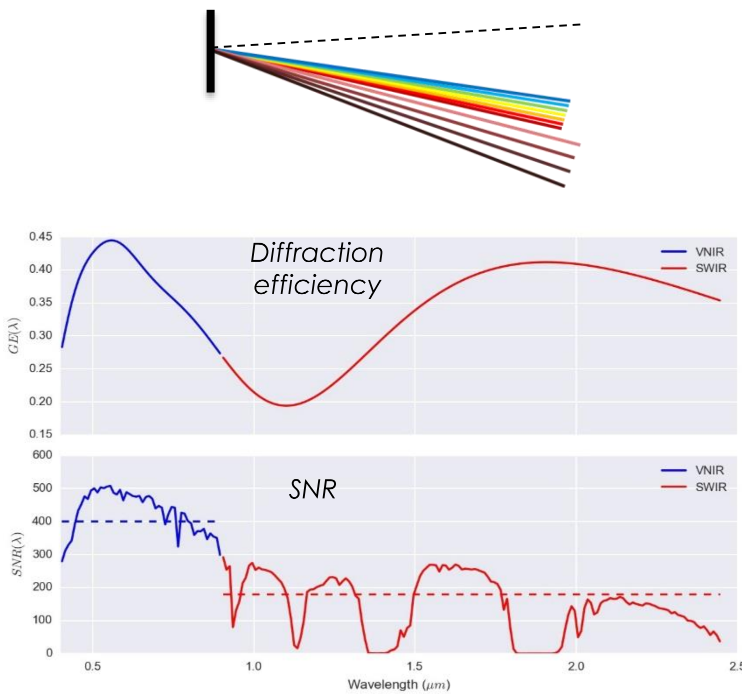
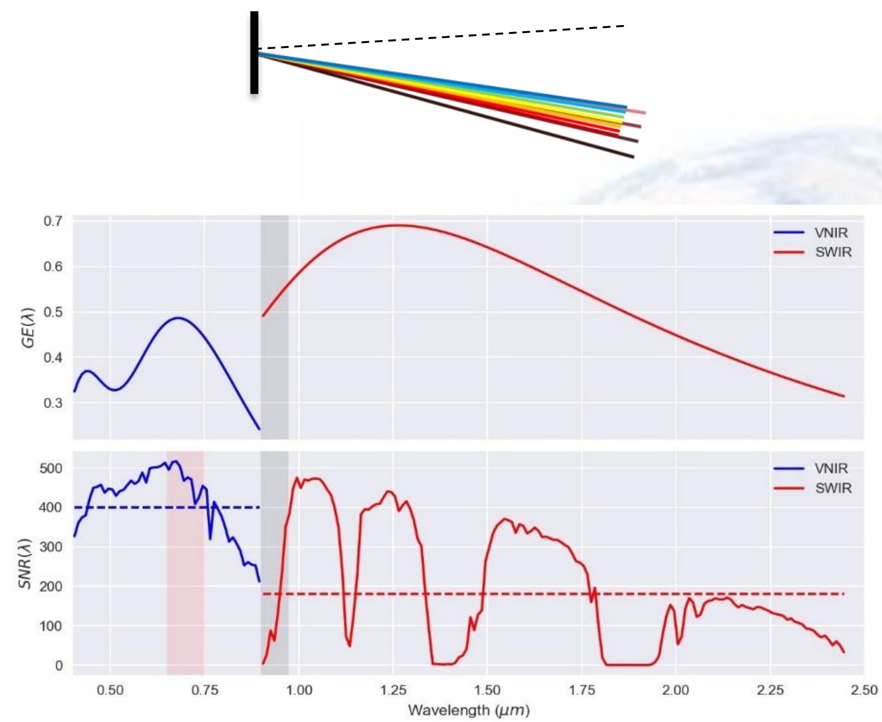
# New Perspectives : ELOIS VNIR/SWIR

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

VNIR+SWIR Order 1

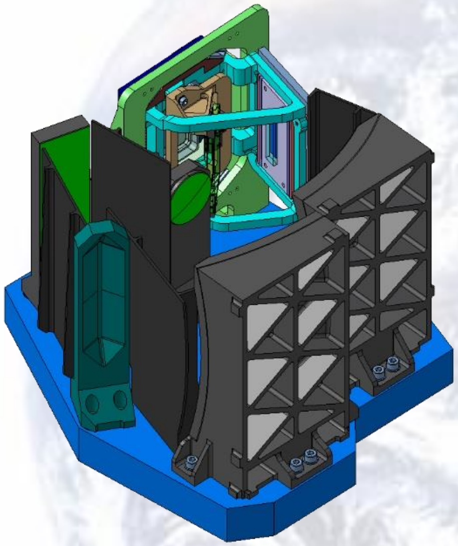



VNIR Order 2
SWIR Order 1



# New Perspectives : ELOIS VNIR/SWIR

| Requirement | Performance |
|---|---|
| Spectral range | 400-2450 nm |
| Ground sampling distance (@650 km) | 35 m |
| Swath width | 70 km |
| Mass | 40 kg |
| Volume | 550 x 650 x 450 $mm^3$ |
| Number of bands | 210 |
| Spectral FWHM | <12 nm (uniform over range) |
| MTF | >0.3 |
| SNR at 0.3 albedo<br>VIS<br>NIR<br>SWIR | <br>> 400<br>>250<br>> 100 |
| Radiance accuracy | > 95% |
| Polarisation sensitivity | <3% absolute, 2% between bands |
| Out of band rejection | <1% |





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# 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)