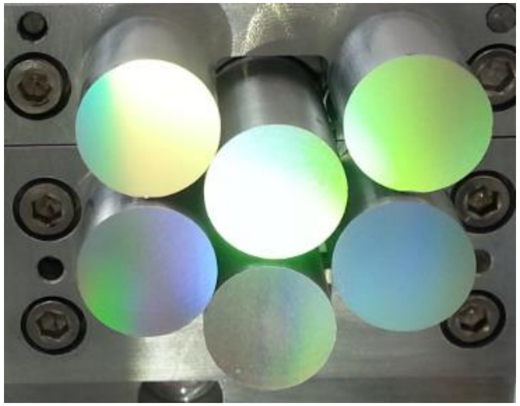
# New opportunities of freeform gratings using diamond machining

Dispersing elements for Astronomy: new trends and possibilities – *11/10/17*

***Cyril Bourgenot*** *– Ariadna Calcines – Ray Sharples*



dpo durham precision optics

CfAI Centre for Advanced Instrumentation

Durham University

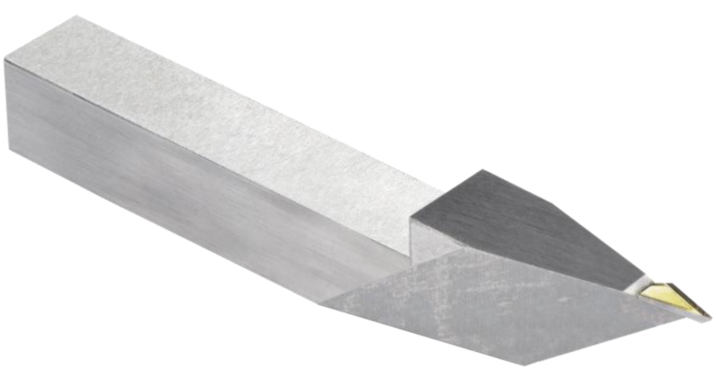
UF UNIVERSITY of FLORIDA

Centre for EO Instrumentation

# Plan of the talk

- Introduction on diamond machining
- Advantages and limitations of this technique
- Integrated  gratings imaging spectrograph
- Overview of elliptical gratings
- Characterisation of diamond machined gratings through a project funded by CEOI

# 5 Axis diamond turning machines

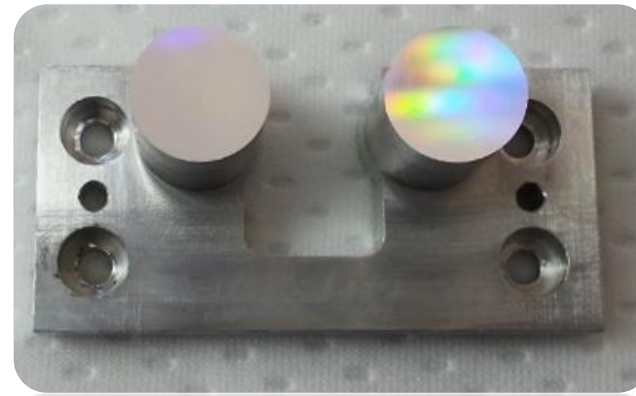


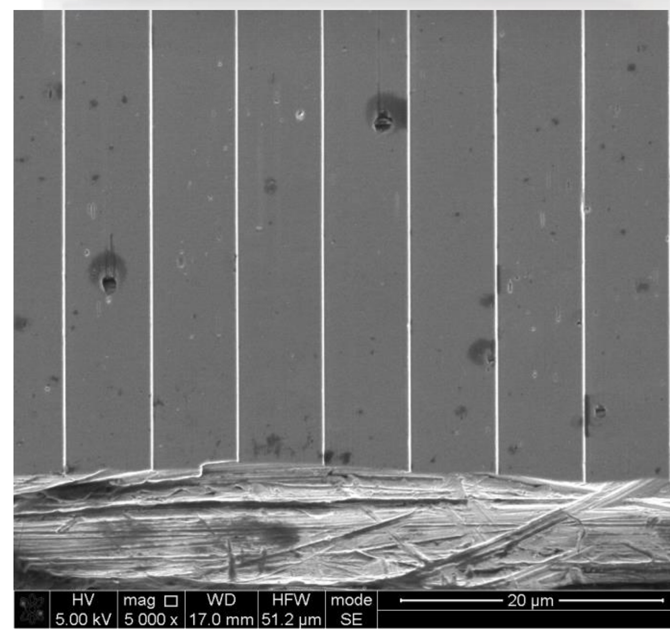
## Basic Specification

- 5-Axis Configuration (X, Y, Z, B, C)
  - Workpiece Capacity : Φ 600mm
  - Travel X:350mm, Y:150mm,Z:300mm
- Granite Base with passive air isolation
- Programming Resolution
  1nm - Linear Axes
  0.036 arcsecs - C-axis
  0.02 arcsecs – B-Axis
- Feedback Resolution 0.034nm on linear axes

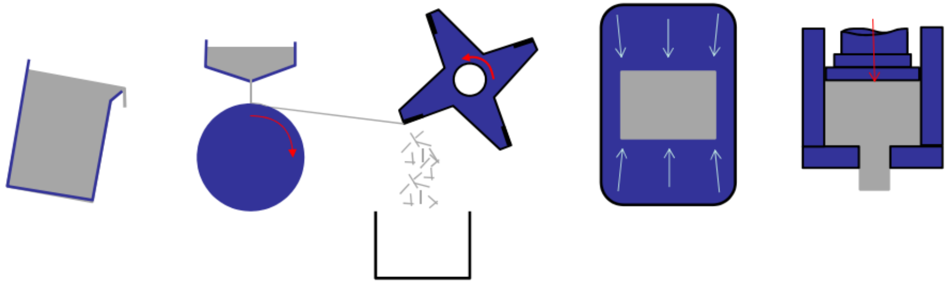
# Advantages and limitations of diamond machining

- Machining in its functional orientation and position
- Blanks can be pre-machined in all sort of shape
- Full control of the groove profile :
  - Echelle grating
  - Multi blaze structure
  - Variably spaced grooves
- improved thermal performance of metal optics at cryogenic temperatures : new type of ultrafine aluminium alloys
- Large sag, steep slope
- Quick set up and program, cost effective
- Tool wear, inducing variations in the groove's shape
- Thermal variation during machining => long machining time





# RSA 6061 T6



Melting & alloying

Melt Spinning

Chopping and evacuation

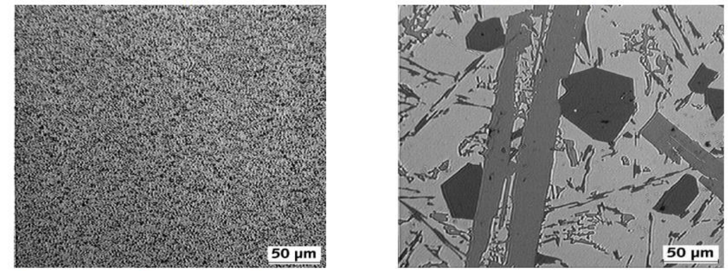
Billet compaction

Extrusion

**Melt Spinning – Microstructure**

Melt spun

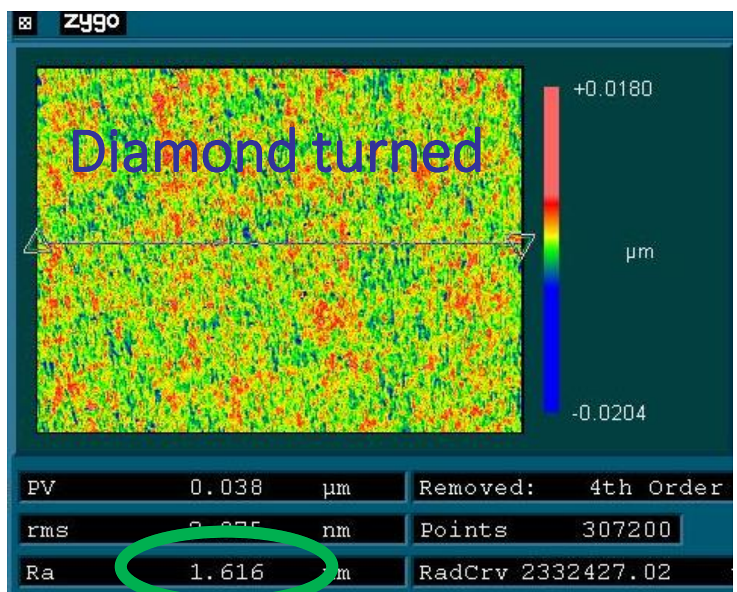
Conventional

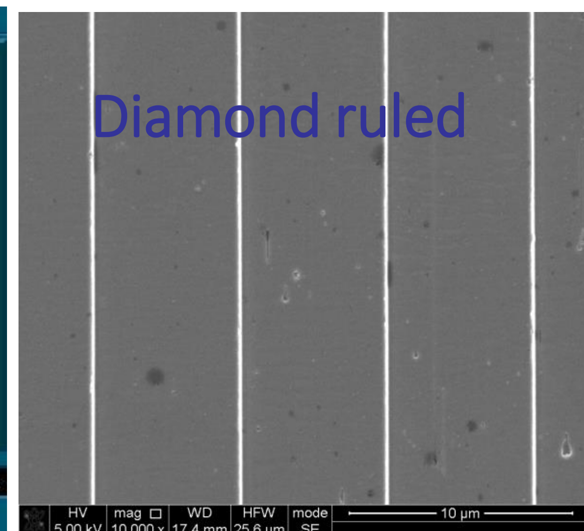



- Lower surface roughness
- Better cosmetic appearance

- Ultra smooth surface where post polishing is not required.

- In the best cutting conditions, roughness can be as low as 1nm RA.



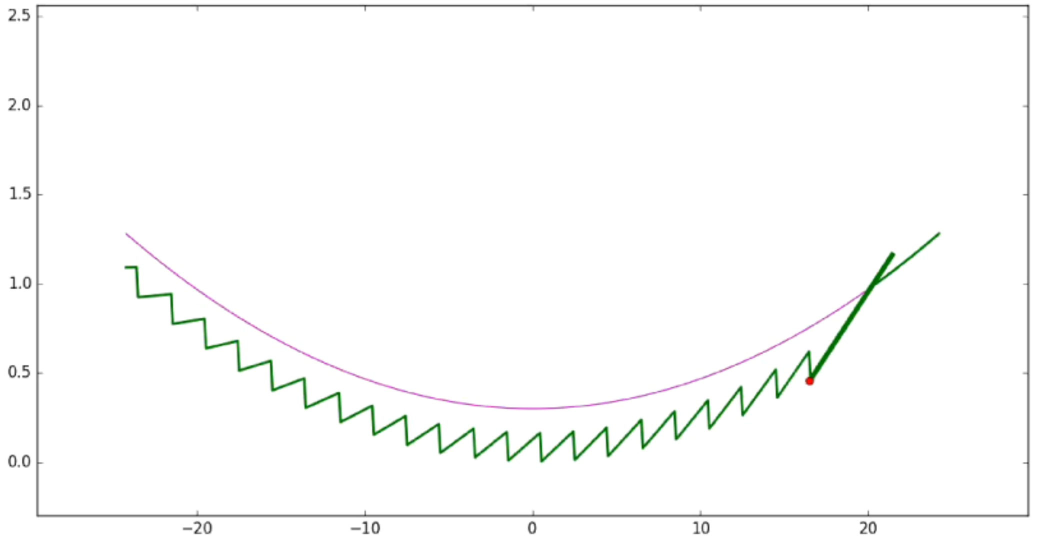



# Grating specification

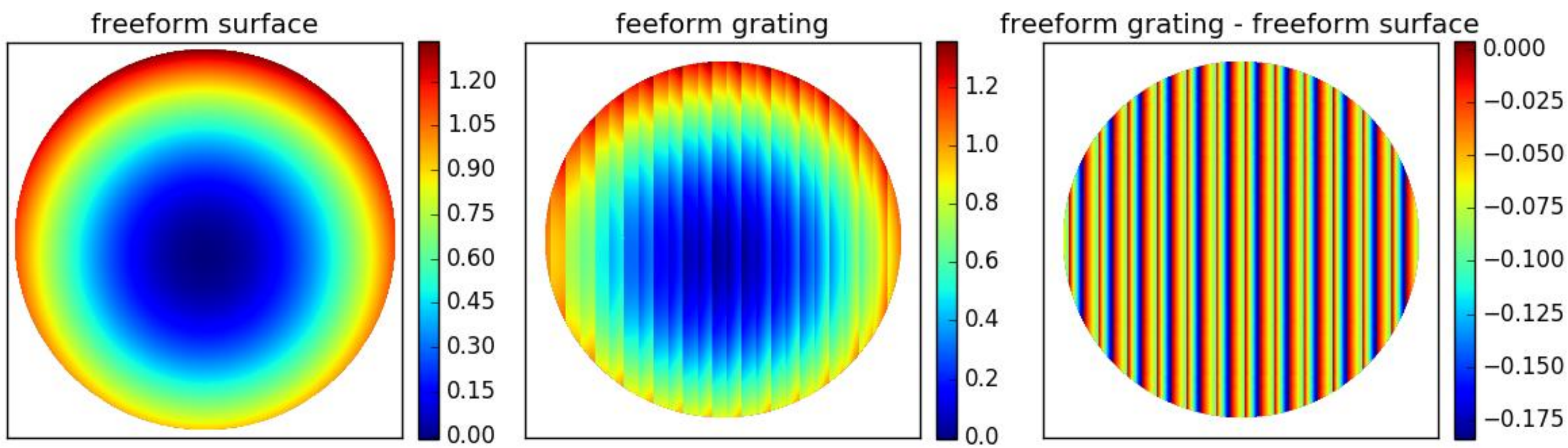
- Max size : ~250mm x 140mm (along the groove direction)
- Frequency : typical 100 lines/mm up to 1000 lines/mm (depending on grating size)
- Material : metallic substrate
  - standard aluminium 6061 T6
  - Melted spun aluminium alloy from RSP (RSA 6061 T6, RSA 443)
  - Brass, coper
  - Nickel plated metal

4 axis of the machine are used at the same time:

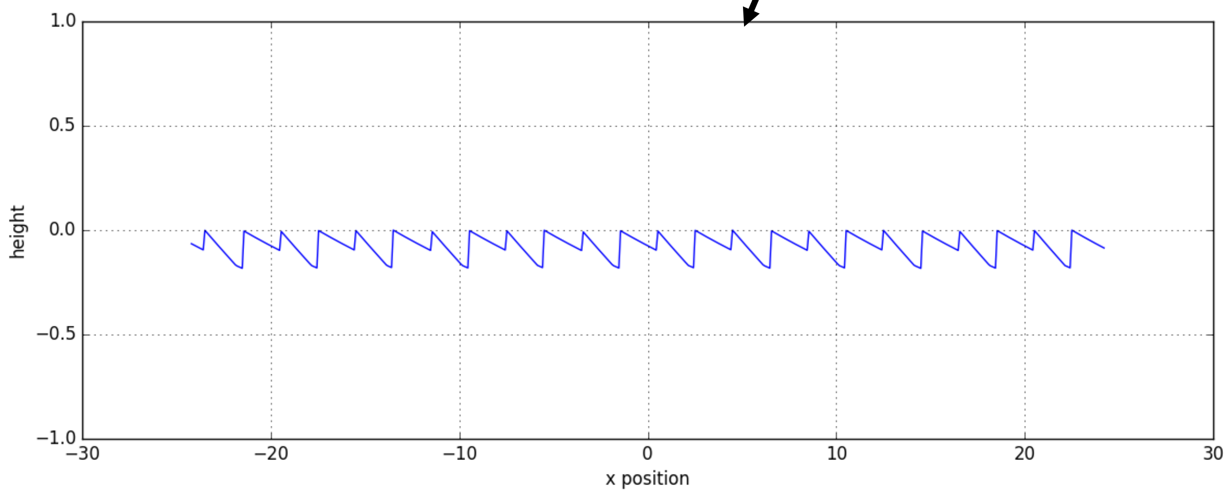
- X,Y,Z => for ruling the grooves on the freeform surface
- B axis => rotation of the tool for keeping the blaze angle constant when the gradient changes



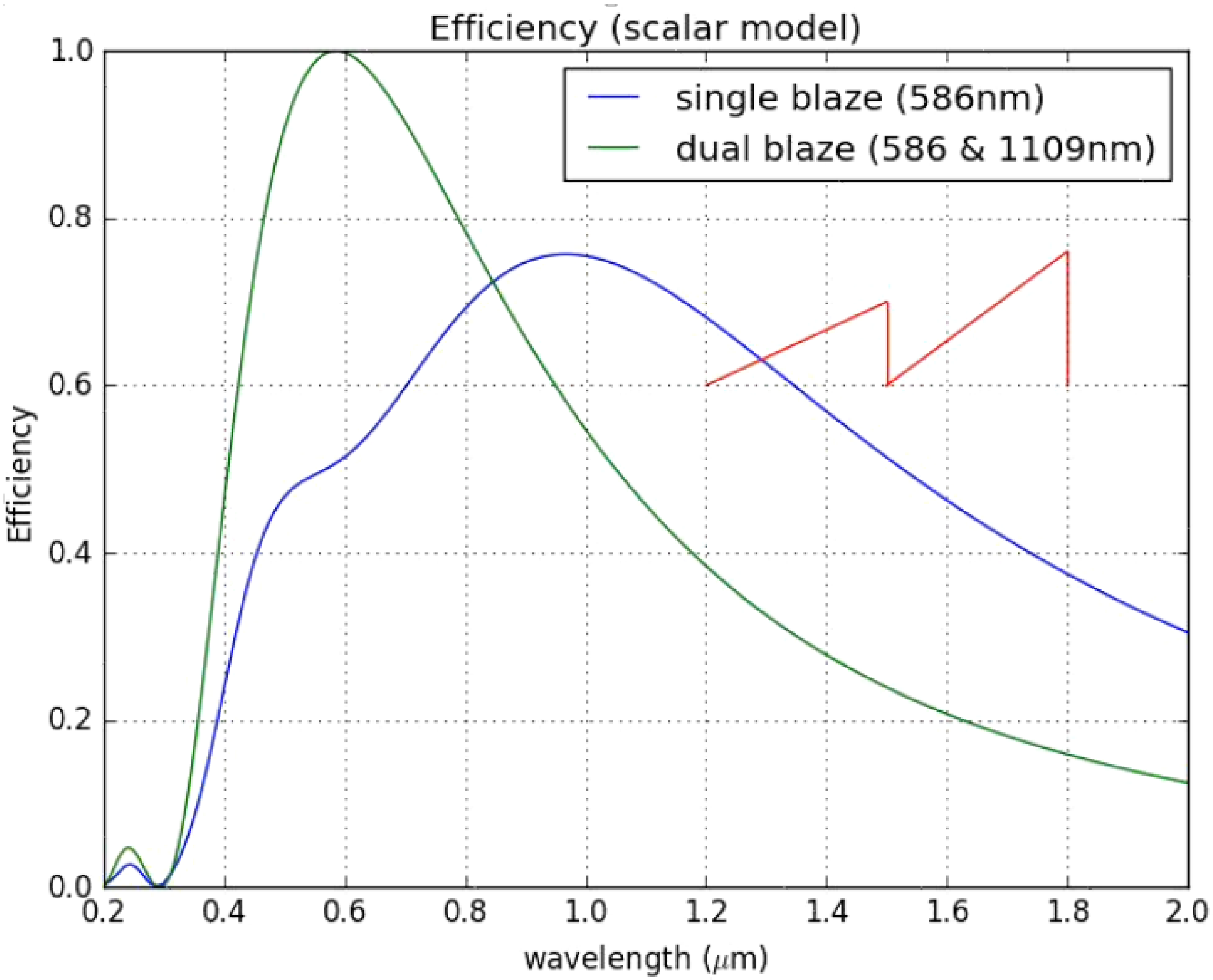
# Multi blaze




- Coarse grating : 2mm period
- Blaze angle : 3 and 6 degrees



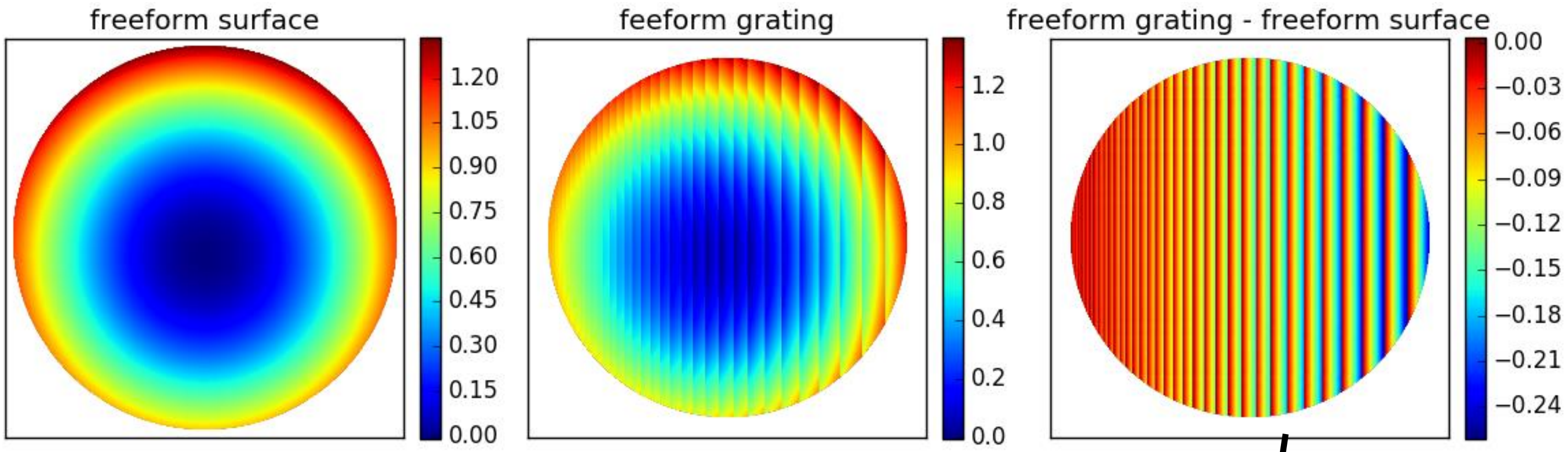
# Dual Blaze



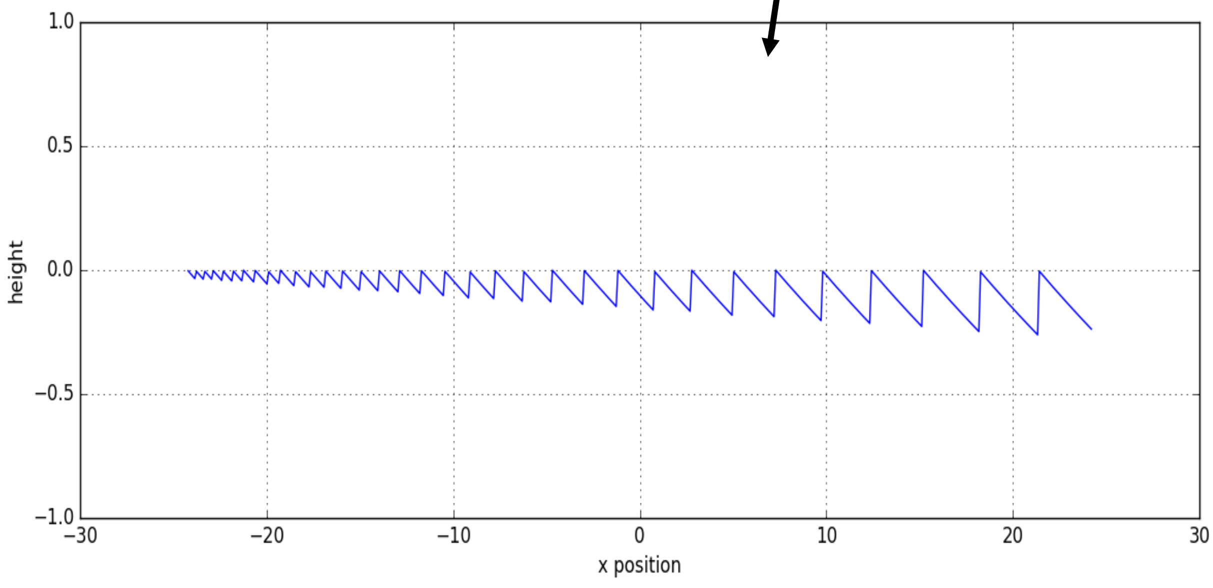

- Frequency : 10 microns
- Input angle : 3°
- Diffraction order : +1

*R. Casini and P. G. Nelson, "On the intensity distribution function of blazed reflective diffraction gratings," J Opt Soc Am A Opt Image Sci Vis, vol. 31, no. 10, pp. 2179–2184, 2014.*

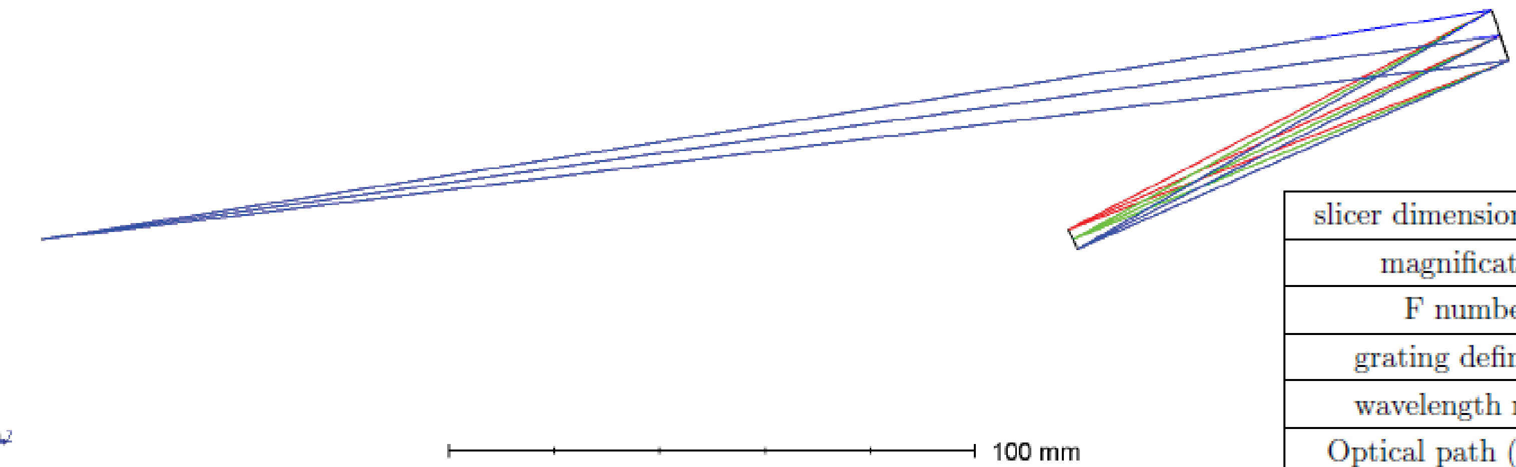
# Linear variation frequency




- Coarse grating : 0.4mm => 3.6mm
- Blaze angle : 5°



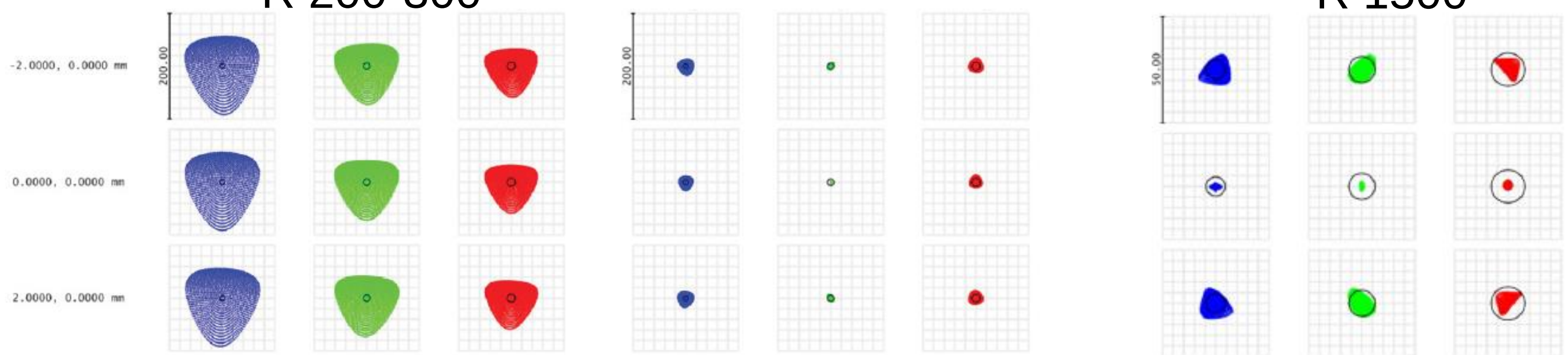
# Design of elliptical gratings




| | |
|---|---|
| slicer dimension (FOV) | 4mm x 0.1mm |
| magnification | 0.32 |
| F number | F/9 |
| grating definition | 0.15 line / um |
| wavelength range | 400nm - 700nm |
| Optical path (object) | 280mm |
| off axis angle | 8° |

R 200-300

R 1500

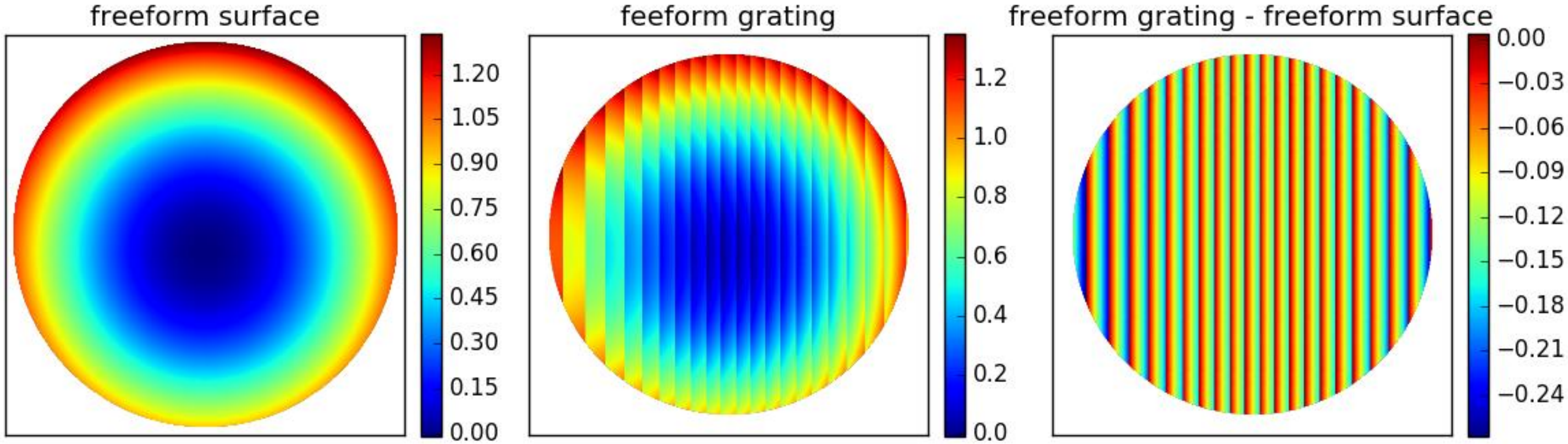



Sphere constant pitch ⇨ Asphere constant pitch ⇨ **Asphere variable pitch**

0.15 micron variation

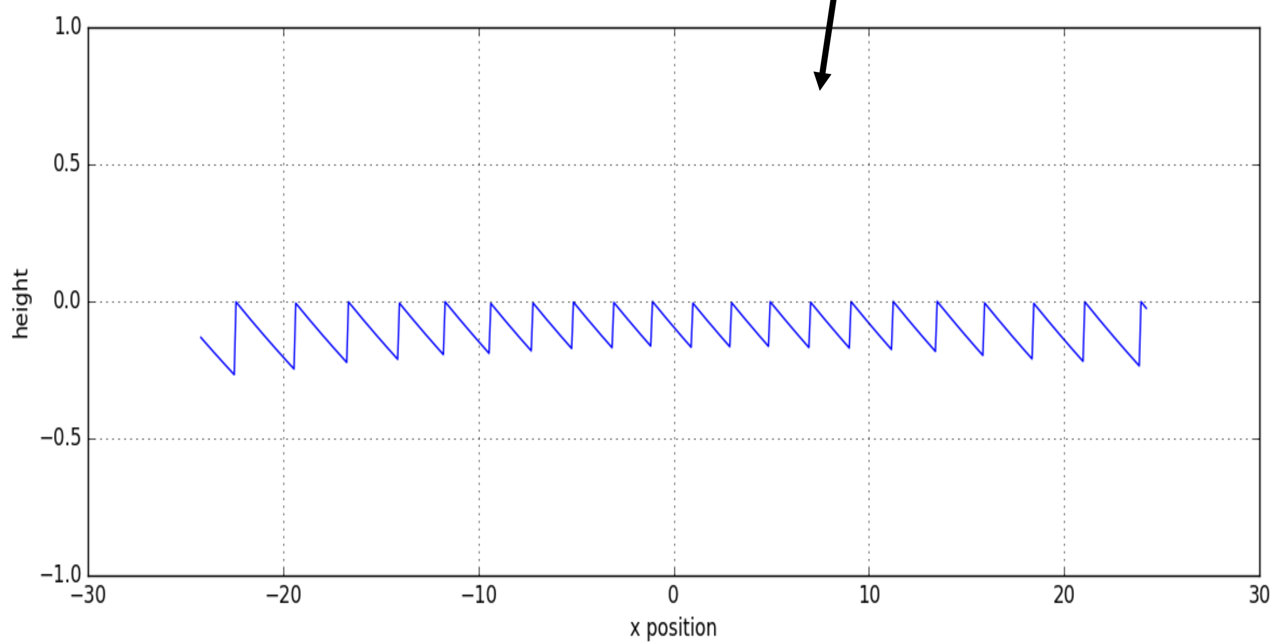
*C. Bourgenot, D. J. Robertson, D. Stelter, and S. Eikenberry, "Towards freeform curved blazed gratings using diamond machining," vol. 9912, p. 99123M, 2016. – SPIE 2016*

# Quadratic variation frequency

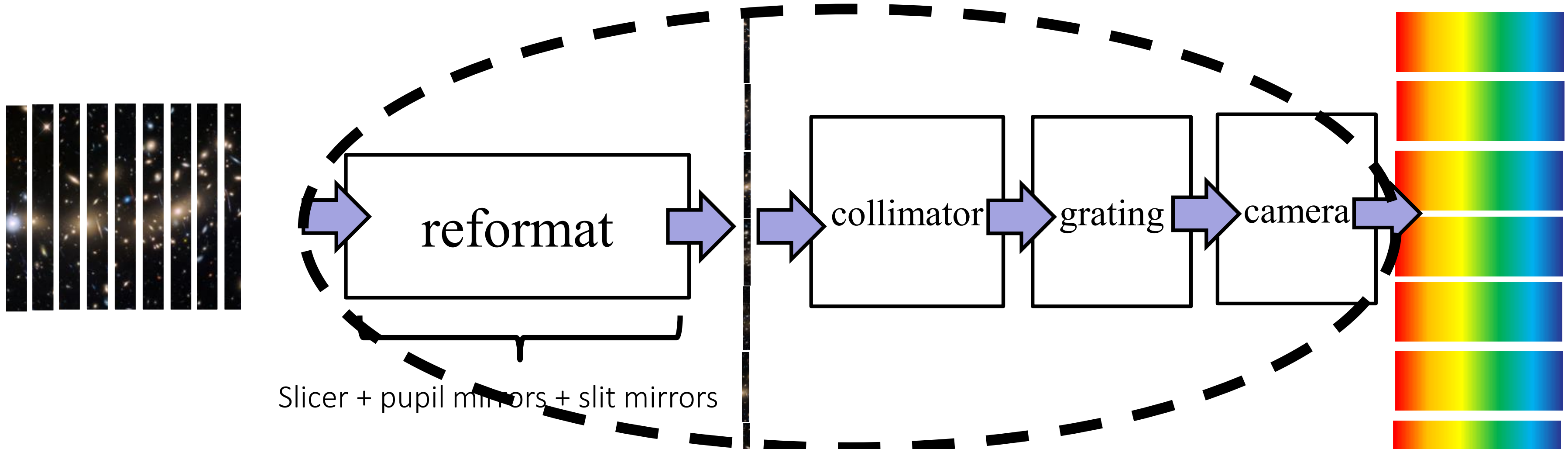



- Coarse grating : 2mm => 3.25mm

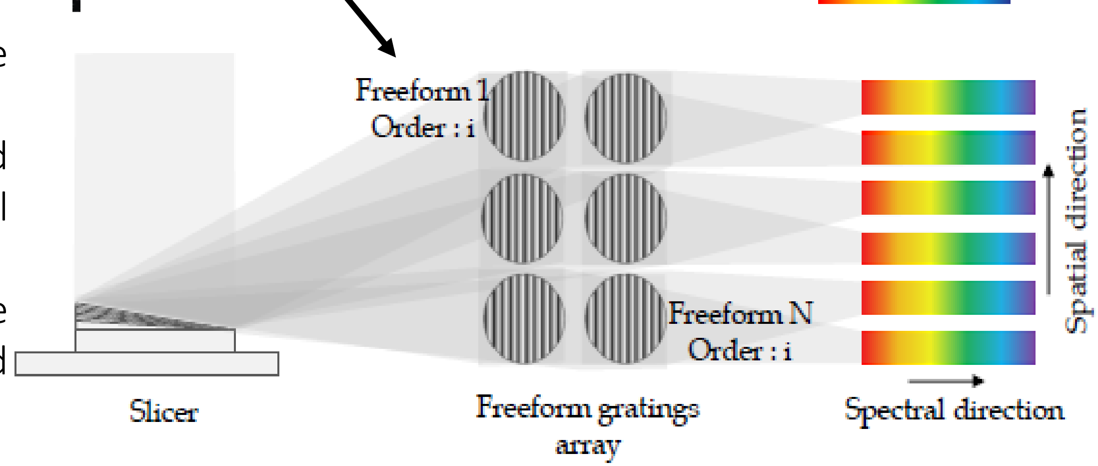
- Blaze angle : 5°



# Freeform gratings – improved compactness

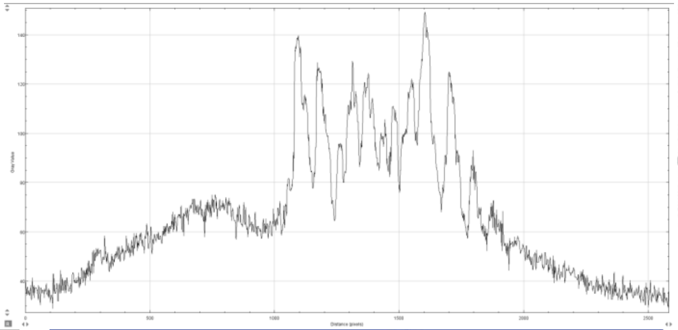


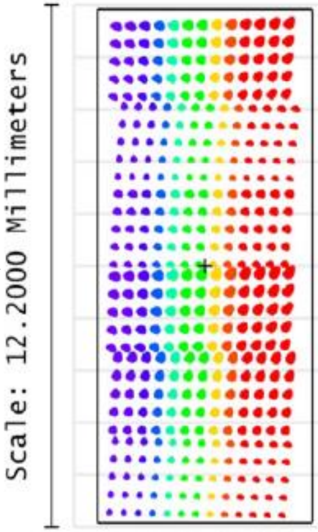

- Grating fabricated onto a curved (freeform) surface
- the dispersion element can be integrated with the IFS pupil mirrors
- replace the pupil mirror, grating and camera optics with a single optical element.
- This will significantly reduce the complexity and increase modularity and compactness



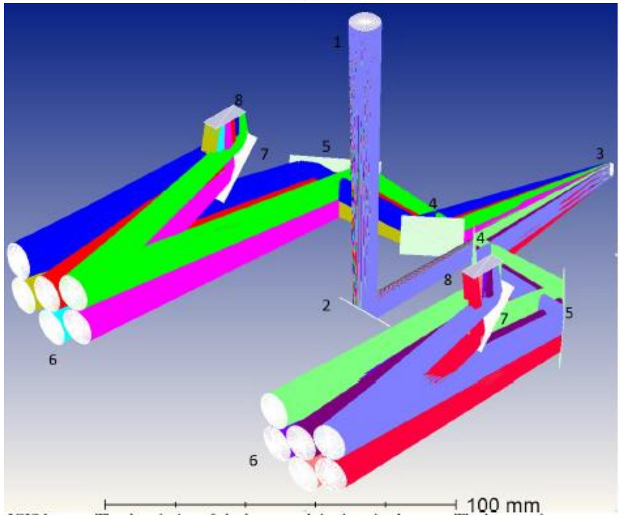
# First integrated grating imaging spectrograph (IGIS)

- Collaboration between Durham University and University of Florida
- Airborne IFU working at low spectral and spatial resolutions in the visible range
- Design all aluminium
- Diamond machined in its functional position
- 12 slices covering a FOV of 1.1 x 0.3°



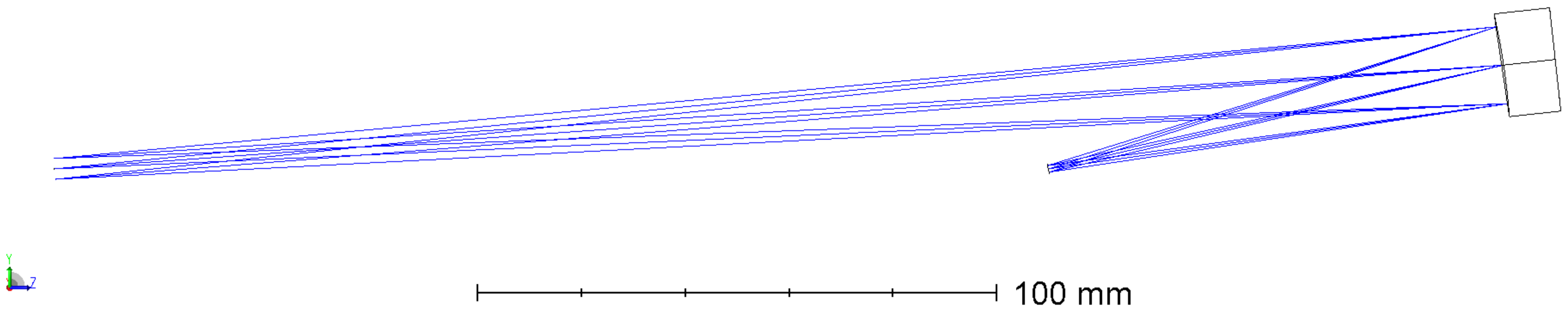



| | |
|---|---|
| slicer dimension (FOV) | 4mm x 0.1mm |
| magnification | 0.32 |
| F number | F/9 |
| grating definition | 0.15 line / um |
| wavelength range | 400nm - 700nm |
| Optical path (object) | 280mm |
| off axis angle | 8° |



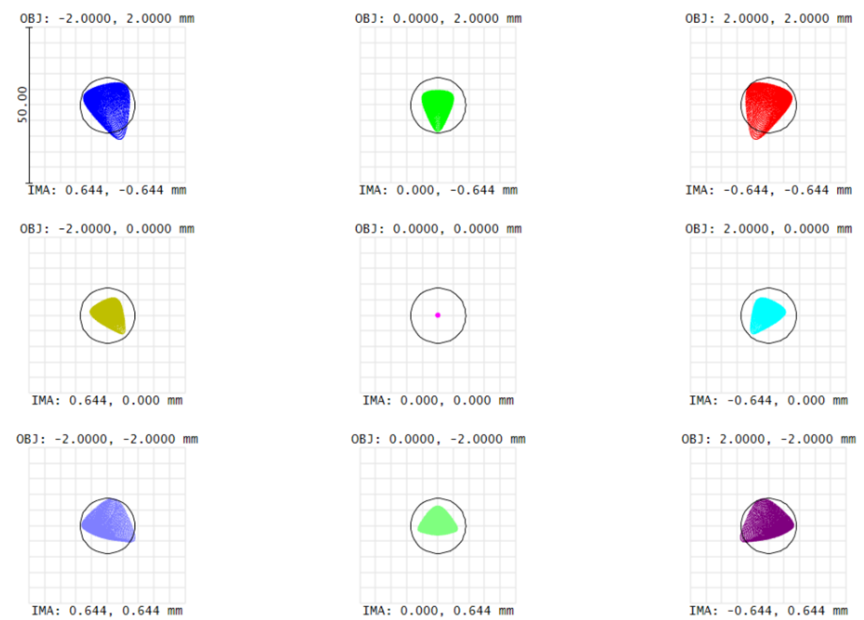

C. Bourgenot, D. J. Robertson, D. Stelter, and S. Eikenberry, "Towards freeform curved blazed gratings using diamond machining," vol. 9912, p. 99123M, 2016.

# Elliptical surface

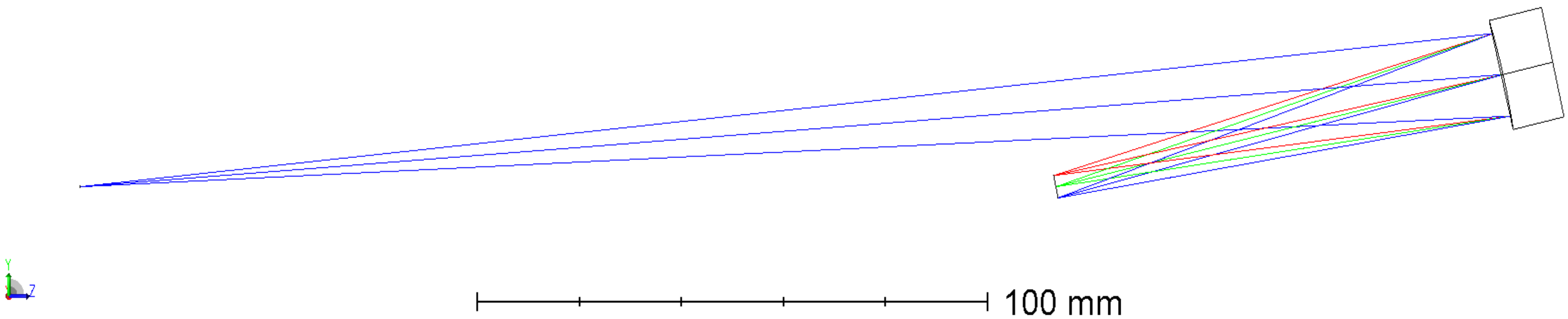



## Tilted Ellipse

- F/6
- Wavelength : 1.2 µm
- Square FOV :4mm
- Off axis :20mm
- Magnification : x0.3

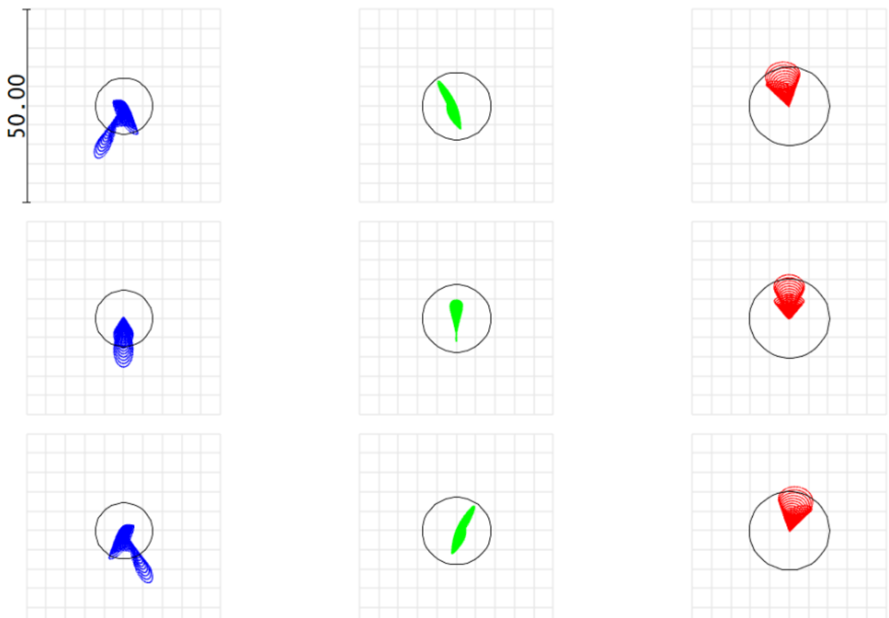


# Elliptical grating diff order 1

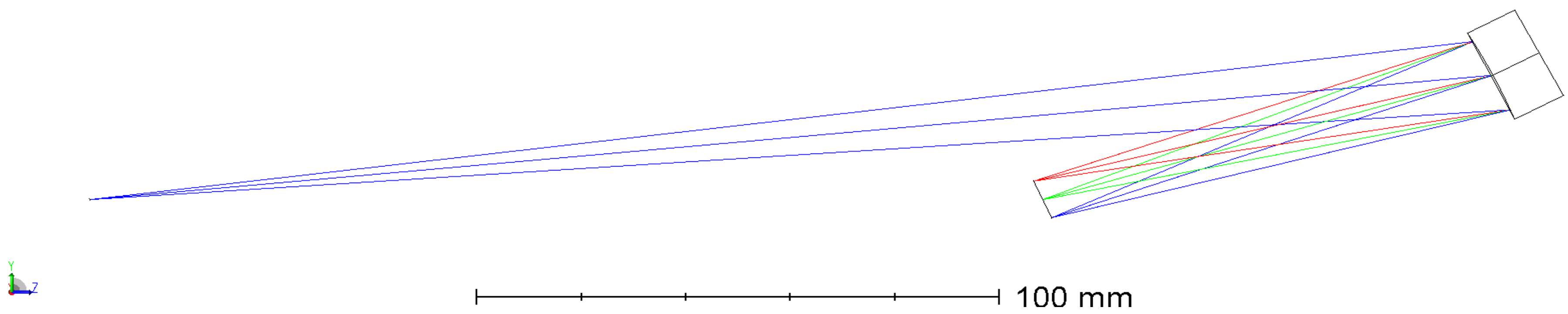



## Elliptical grating

- F/6
- Wavelength : 1.05-1.35 µm
- Spatial FOV : 4mm
- Off axis :20mm
- Magnification : x0.3
- Period : 150 l /mm
- Diffraction order : 1
- R : 2250



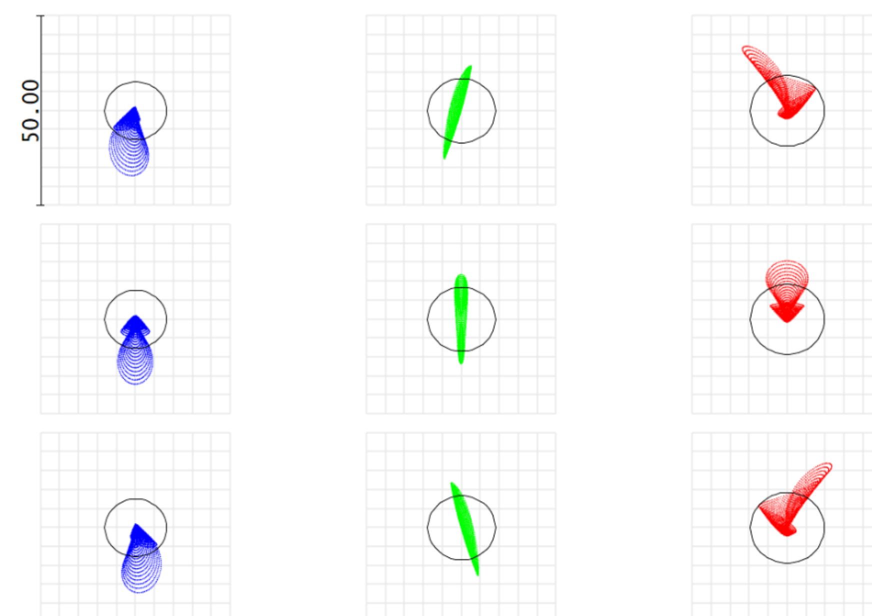
# Elliptical grating diff order 3




## Elliptical grating

- F/6
- Wavelength band : 1.1-1.3 µm
- Spatial FOV : 4mm
- Off axis :20mm
- Magnification : x0.3
- Period : 150 l /mm
- Diffraction order : 1
- R : 6750

=> Higher diffraction order possible at the cost of reduced wavelength bandwidth.

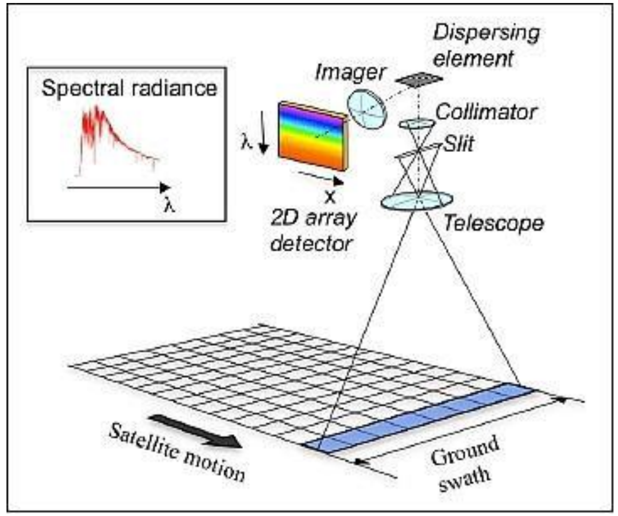


# CEOI Project description

- Investigate technical feasibility, performance and limitations of metallic freeform blazed gratings produced by diamond machining.
  - Materials comparison :
    - RSA 6061 versus RSA 443 with Nickel plating
    - Same grating design (pitch/blazed angle freeform shape)
- Develop the software tool for the machining of :
  - Multiblaze structure
  - Variable frequency grating
- Determine the optimal cutting parameters
  - Feedrate & tool wear
- Grating Characterisation in term of :
  - Spatial and spectral resolution
  - Surface form error
  - Roughness
  - efficiency

# Hyperspectral imager for Earth Observation

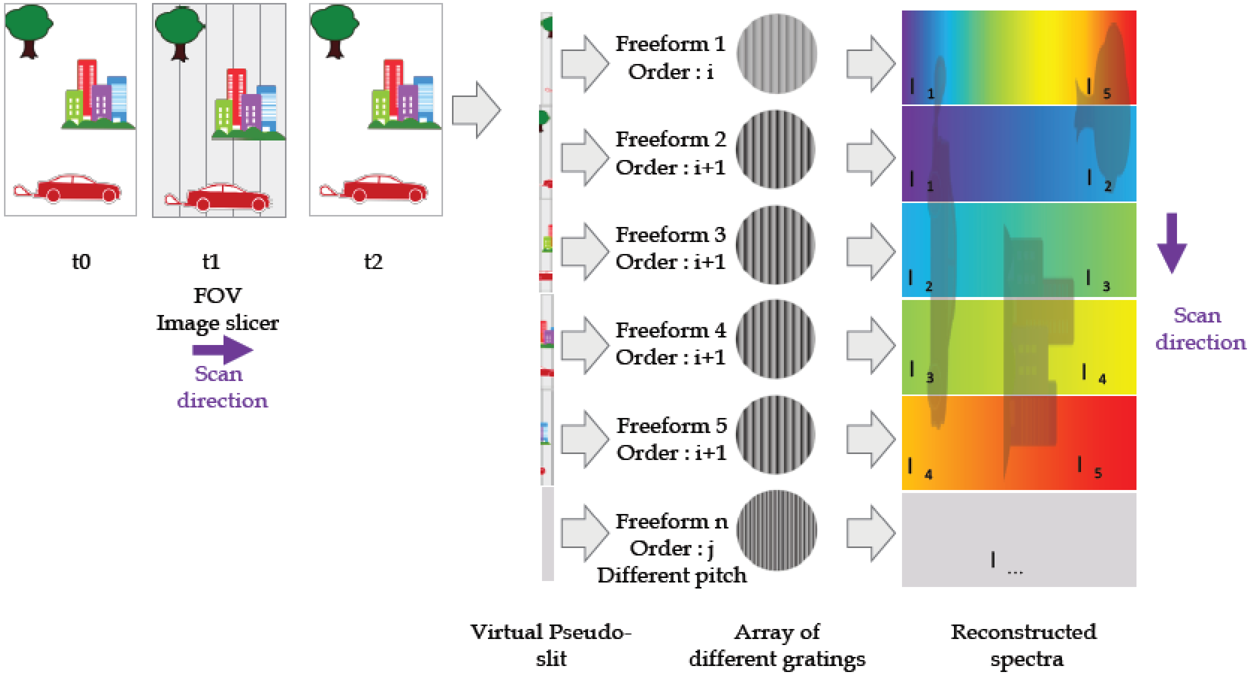
*Pushbroom*




Overcome the limitation by incorporating gratings within IFU and by customizing them for spectral resolution and bandwidth.

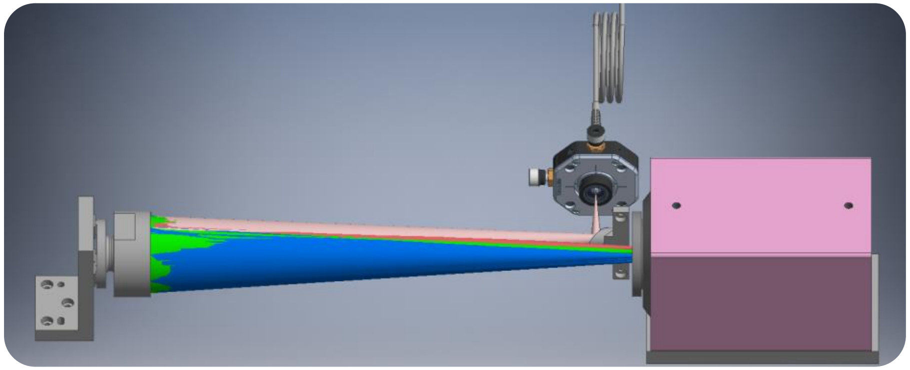
Customization can be :

- Different groove spacing
- Different order
- Different blaze angle



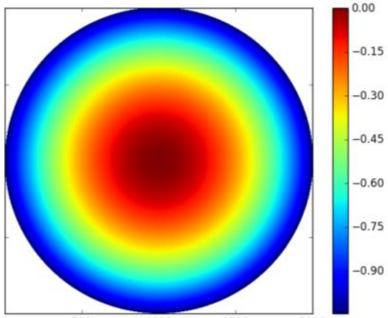
# CEOI Project description

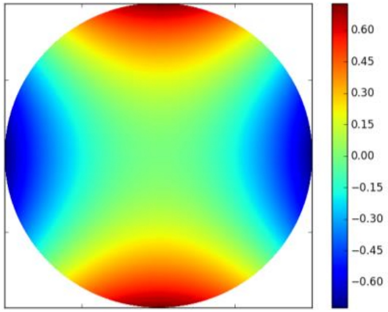
| | |
|---|---|
| FOV object (along the spatial direction) | +/-2mm |
| FOV image (along the spectral direction) | +/-3.5mm |
| Magnification | -1 |
| Input F number | F/6.6 min |
| Distance object | 300mm |
| Grating diameter | Φ50mm |
| Optimisation Wavelength | [471nm,588nm,692nm] |
| number of line / mm | 100 |
| Diffraction order | 1 |
| incidence angle at 588nm - centre of the grating | 2.95° |
| shape | Ellipsoid |



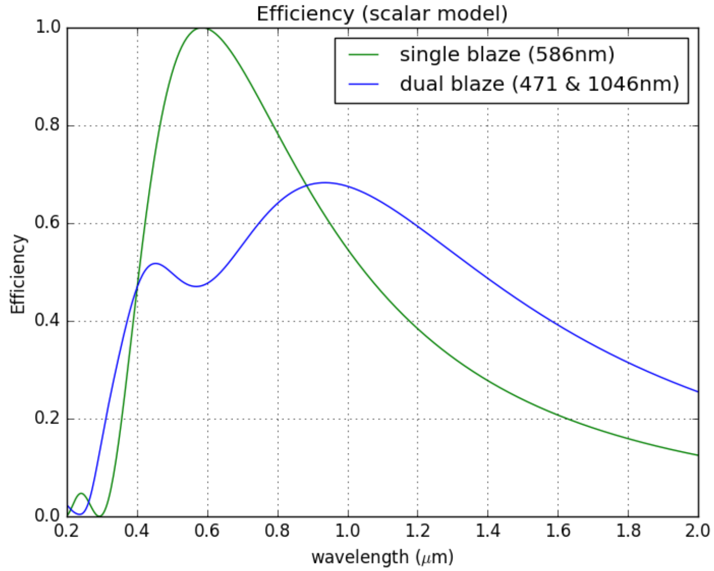
- Design of a 50mm grating, optimised for some of the strong lines of a Neon lamp.
- Theoretical R : 4500

➢ Elliptical surface composed of a nominal spherical surface (1mm) + astigmatic surface (1.5micron)




Freeform SAG (mm) Freeform SAG at best fit sphere (micron)



# conclusion

- Diamond machined freeform gratings can complement alternative technologies such as ion beam etching with holographic masks and offer a full control on the blaze structure. They can easily be implemented with :
  - ✓ multi-blaze (broadening of the wavelength bandwidth)
  - ✓ variable frequency (further improvement in the spectral resolution)

  on high sag, large slope surfaces.

- A new design of Integral field spectrometer : integrate freeform gratings onto the pupil mirrors, significantly reducing the complexity, at the cost of a FOV and spectral range set by the design parameters.

- Work in progress at Durham University for the development of novel machining strategies to produce and improves metallic diamond machined gratings.