Feasibility of Diffraction Grating on Free Form Surfaces

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Executive Summary Report

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1. INTRODUCTION

For spaceborne hyperspectral applications, grating-based spectrometers are of special interest due to the high spectral resolution and optical throughput that can be achieved. Nevertheless, most of the available manufacturing techniques, such as direct ruling, holography, lithography or e-beam writing, are typically applicable on simple shape of the grating surface, such as flat or spherical surface. This is a limitation of the degree of freedom offered for the optical design of compact and well-corrected spectrometers. Through this TRP project, we present the results of development, manufacturing and test of Free-Form Gratings, i.e. a ruled grating on surface without any rotational symmetry. Application to the design of a 3-mirrors spectrometer (Offner-type) with advantages in term of optical performances, mass and volume is also considered. Full characterization of the FFG, in terms of shape, diffraction efficiency, polarization sensitivity, scattering and operating spectral range, is reported and discussed.

2. FREE FORM GRATING SPECTROMETER.

2.1 TRADE-OFF

Different configurations are actually used for ground and in space spectrometers. The various optical designs can be classified based on the shape of the grating: flat, concave, or convex gratings.

The flat diffraction gratings are certainly the easiest to manufacture. Czerny-turner and Littrow spectrometers configurations are based on flat gratings. The flat grating is generally associated to complex collimating and focusing optics in order to obtain a good image quality. For example the GOME-2, OMI and SCIAMACHY spectrometers used flat gratings.

Concave diffraction gratings have both dispersive and imaging properties. This makes them ideal for modern spectroscopic systems. The most common designs are the Rowland circle spectrometer and the Dyson spectrometer. This last one bears a simple concentric arrangement of a plano-convex lens and concave mirror. This design is free of all Seidel aberrations at the design wavelength and center of a field imaged at 1:1 magnification. The Dyson principle is the basis of high throughput spectrometers.

Convex diffraction gratings are used in the Offner spectrometer. This configuration offers a larger field of view and lower aberrations. These spectrometers have a concentric structure and a compact design. They consist of a slit, two concave mirrors and a diffraction grating placed on a convex mirror between them. The advantages of the Offner spectrometer are that it operates with a relatively low F-number (≥f/2), it accepts a long slit while maintaining a compact size, it needs only three optical surfaces. Using distinct surfaces for M1 and M3 allow to further reduce smile and keystone distortions.

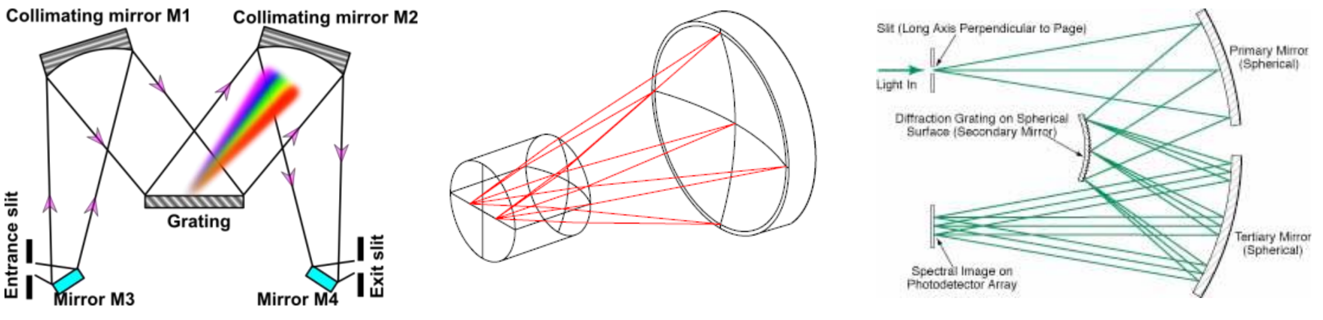

Figure 1 : Schematic design of Czerny-turner (left), Dyson (middle) and Offner (right) spectrometer

2.2 INNOVATIVE SPECTROMETER DESIGN

The Offner and Dyson spectrometer designs are 1:1 systems. One way to increase the signal to noise ratio of a spectrometer is to design an instrument with a magnification power of less than one. With a smaller magnification, the entrance slit is wider and a larger amount of light is collected while the image is smaller and compatible with typical detector size and pixel pitch (typically < 20µm). For this point, the Offner design seems more promising, as its three mirrors offer more degrees of freedom.

An innovative design of a Free form grating spectrometer with 2:1 magnification has been proposed during this project. It has been demonstrated that this design is compliant with the requirements of the project, typically derived from Tropomi instrument (Sentinel 5 precursor).

The concentric design of the 1:1 Offner relay guarantees a perfect compensation between spherical and astigmatic aberration generated by M2 and those generated by M1-M3. In the proposed compact design, this symmetry is broken and so, spherical aberration and astigmatism are no more compensated. Nevertheless, it is possible to maintain aberrations almost constant in the FoV, so that the wavefront error can be corrected at the spectrometer pupil, namely on the M2 surface. All attempts to achieve acceptable MTF with cylindrically symmetric M2 lead to very poor results.

Reduction of the F-number operated by the 2:1 design results in a significant improvement of the SNR and a substantial reduction of size. The spectrometer fits in a volume of a cube with sides 175 mm.

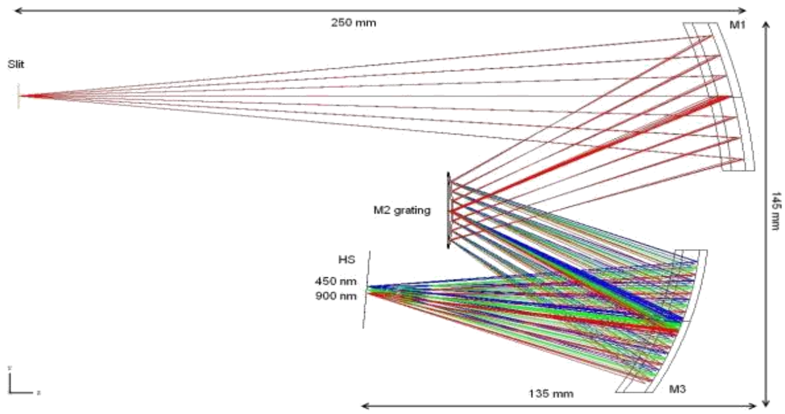

Figure 2 : Schematic view of spectrometer volume.

An overview of the of the FFG spectrometer performances is reported in Table 1.

Table 1 : Free-Form Grating spectrometer design performances

Optical performance	FFG spectrometer
Entrance slit	60 mm x 30 µm
Grating frequency	104 lp/mm
Spectral range	450-900 nm
MTF*	>0.7
Throughput*	>70%
Polarisation Sensitivity*	<2%
Spectral resolution	2.5 nm
Keystone	1.1 µm
Smile	1.9 µm
SNR*	>400
Global size	116 x 145 x 130 mm

3. MANUFACTURING

The grating substrate is made of Kanigen (NiP) plated aluminum 6061T6 alloy and diamond machined. The pattern is engraved on a free form substrate. This type of grating (free form) is a first in our knowledge for this type of manufacturing.

The diamond machining of the optical surface of the grating is performed on 5 axes ultra-precision lathe, in two steps:

- Machining of the substrate as a free form part (4 axes machining). The surface is positioned accurately (<10µm in each direction) thanks to a mechanical reference system. The error on the surface form accuracy with respect to the theoretical free form has been measured to be lower than 50nm RMS.

- Machining of the grating grooves. The orientation of each groove is maintained constant with respect to the normal of the surface. In other words, the groove orientation constantly varies on the grating with respect to a fix axes system. The positioning of the grooves is done by accurately positioning the optical surface of the substrate with respect to the machine axes system thanks to the mechanical reference of the part.

* Average over the spectral range

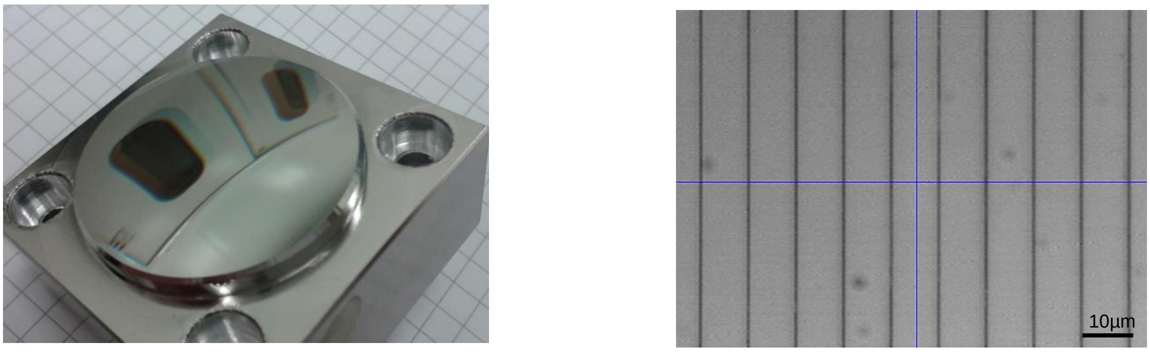

Figure 3 : left : Picture of the machined free form grating - right : microscope view of grating groove

4. TESTS AND RESULTS

According to the test plan [RD3], the following tests have been performed on the ruled free form grating:

- Surface form error characterization
- Diffraction efficiency (including polarization dependency)
- Roughness and profilometry
- Bidirectional Reflection Distribution Function (BRDF)

Two different free form grating (FFG#2-N and FFG#3) have been machined and measured. Only the best achieved results are reported here below.

4.1 SURFACE ERROR AND MTF

The surface form error of the manufactured gratings has been measured with respect to a spherical reference, with the M2 axis tilted (measurement of WFE in order -1). The residual SFE map (after subtraction of nominal shape) is shown at Figure 4. In these maps grating grooves are horizontal, parallel to x axis. The map is limited to a clear aperture of 30 mm diameter.

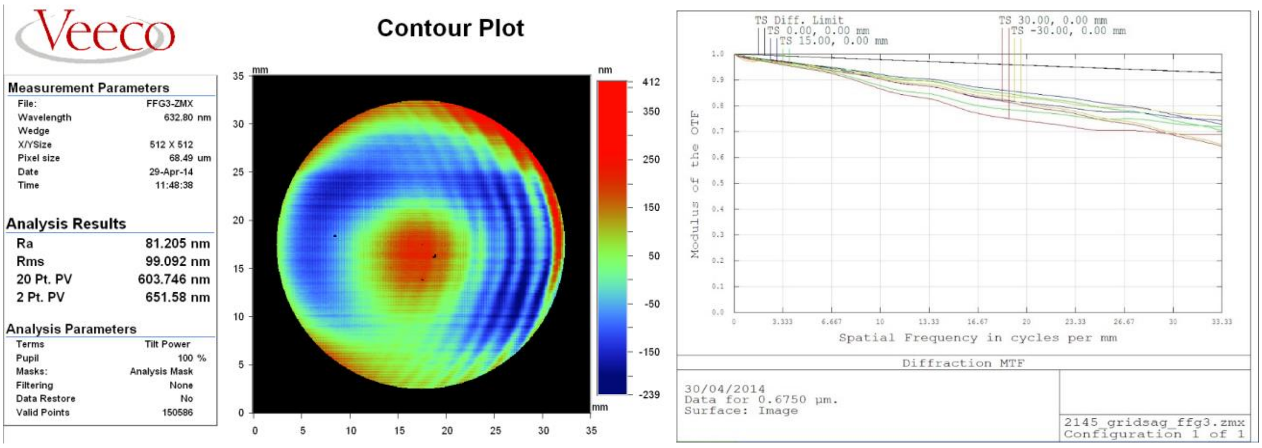

Figure 4: Residual SFE (right) of the FFG#3 and corresponding MTF (left)

Figure 4 also shows the “as-built” MTF at 675 nm obtained by including the FFG SFE maps in the spectrometer Zemax model. The MTF is around 70% at 675 nm.

4.2 DIFFRACTION EFFICIENCY

4.2.1 Setup and results

Efficiency characterization of FFG has been performed at the Optical laboratory of the University of Liège (Hololab- Pr. Serge Habraken). The goal of this measurement is to check diffraction performances and get a better understanding of its behavior, thanks to the modeling and fitting with rigorous diffraction theory (PC Grate software).

Efficiency measurements have been repeated for both s (TE) and p (TM) polarization ant at 5 different wavelengths, covering the spectral range of the application:

- 442 nm (HeCd laser)
- 514.5 nm (Ar+ Laser)
- 532 nm (Frequency Doubled Nd:YAG laser)
- 632.8 nm (HeNe laser)
- 850 nm (IR Laser Diode)

Additional efficiency measurements at 514.5 nm have been repeated at different location of the grating in order to verify the uniformity of the performances over the surface.

A reference flat super polish sample has been used to accurately measure the reflectivity of plating material at laser line wavelengths. The computed diffraction efficiency are corrected accordingly (i.e. considering a 100% reflecting coating) in order to characterize the grating parameters independently to any additional thin film.

A summary of the measurements (in the central area of the FFG) at all selected wavelength is depicted in the table below:

Table 2: Efficiency measurements at different wavelength on central area of the grating

	Measured Diffraction Efficiencies								
	TM-pol				TE-pol				Polar. Contrast
Wavelength (nm)	η_{-2}	η_{-1}	η_0	η_{+1}	η_{-2}	η_{-1}	η_0	η_{+1}	(TM−TE)/(TM+TE)
442	17.0%	68.7%	7.7%	1.0%	17.0%	66.8%	8.9%	0.8%	1.4%
514.5	4.8%	85.2%	2.5%	1.1%	4.6%	84.6%	2.4%	1.3%	0.4%
532	4.0%	87.5%	2.0%	1.6%	3.7%	83.5%	2.5%	1.7%	2.3%
632.8	0.9%	86.0%	2.6%	3.3%	0.9%	80.4%	3.0%	3.9%	3.3%
850	2.3%	57.7%	15.3%	3.3%	1.7%	51.4%	21.1%	5.4%	5.8%

We also checked how the efficiency is varying along the surface of the grating. A variation of about ± 6 % is observed through the useful area. This is likely related to geometry of the tool and grooving process that generate small errors in groove depth away from the equator.

4.2.2 Diffraction Efficiencies analyses

The next chart shows a direct comparison between the experimental results and the theoretical predictions. A good fitting is achieved by computing the performance of a grating with slight rounding of the edge between grooves, considering that the ruled profile is less sharp and that a "cusp" is formed into the groove.

- Continuous lines: TE
- Dashed lines: TM
- Measured efficiencies: isolated symbols with red dominant color for TE and blue dominant color for TM.

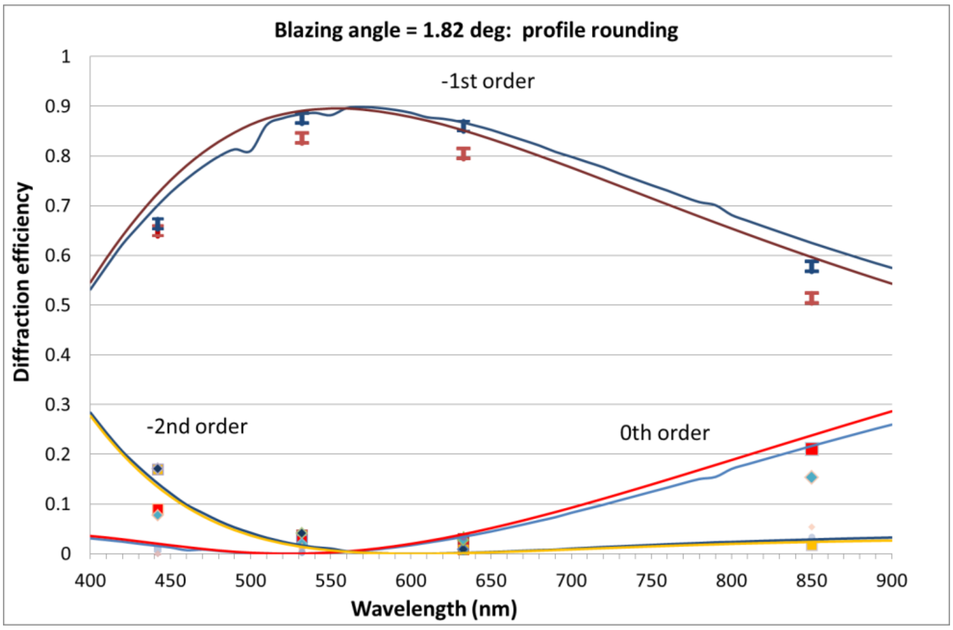

Figure 5: Effect of profile rounding on diffraction efficiency for a blazing angle of 1.82°. Red-gold dominant color: TE - Blue dominant color: TM

4.3 ROUGHNESS

The grating grooves have been characterized by white light interferometry (WYKO profilometer).

The roughness has been measured at 3 locations on the FFG#3 grating (center and two edges locations). Roughness close to 4 nm RMS has been measured inside single groove which is close to the limit of the roughness measured on non-ruled optical surface machined by Single Point Diamond turning.

4.4 BIDIRECTIONAL REFLECTION DISTRIBUTION FUNCTION (BRDF)

4.4.1 Scattered Light

The surface scatter from a grating is generally an order of magnitude in excess of that a mirror, and is expected to be the worst contributor to complete spectrometer scattering performance.

- The presence of spatial frequencies in groove pattern other than that of the nominal groove spacing results in secondary spectra, called ghosts. *Rowland ghost* are due to longer-term periodicity errors.
- The presence of random (rather than periodic) irregularities leads to faint background between orders, whose intensity varies roughly with the inverse square of the wavelength. This background is called *grass* because it looks like blade of grass when observed with coherent light.

Ghosts and grass are in-plane scattered light, while the diffusion from surface roughness, dust, scratch or any irregularities results in scattering in all directions.

4.4.2 Setup and results

BRDF measurements have been performed at ESTEC on the CASI instrument (http://sms.schmitt-ind.com/products/casi-scatterometer/). As the BRDF measurement system cannot accommodate convex samples, the measurements have been performed on flat samples representative of the ruling process on the freeform surface.

4.4.2.1 *Results on FFG#3 samples*

Measurement on FFG#3 associated sample (sample #112) in the direction of dispersion and perpendicular to dispersion are presented at Figure 6 and Figure 7. Measurements have been performed centred on the 0th order and centred on the -1st order (data angular position have further been shifted to match the orders in the figure).

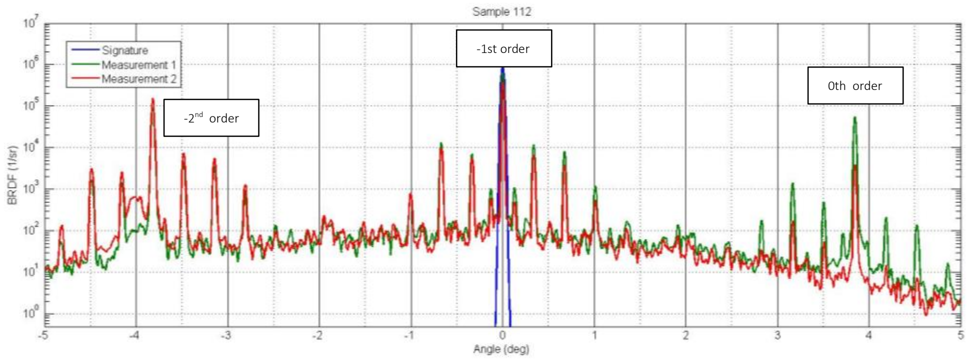

Figure 6 - BRDF measurement in the dispersion direction on FFG#3 sample

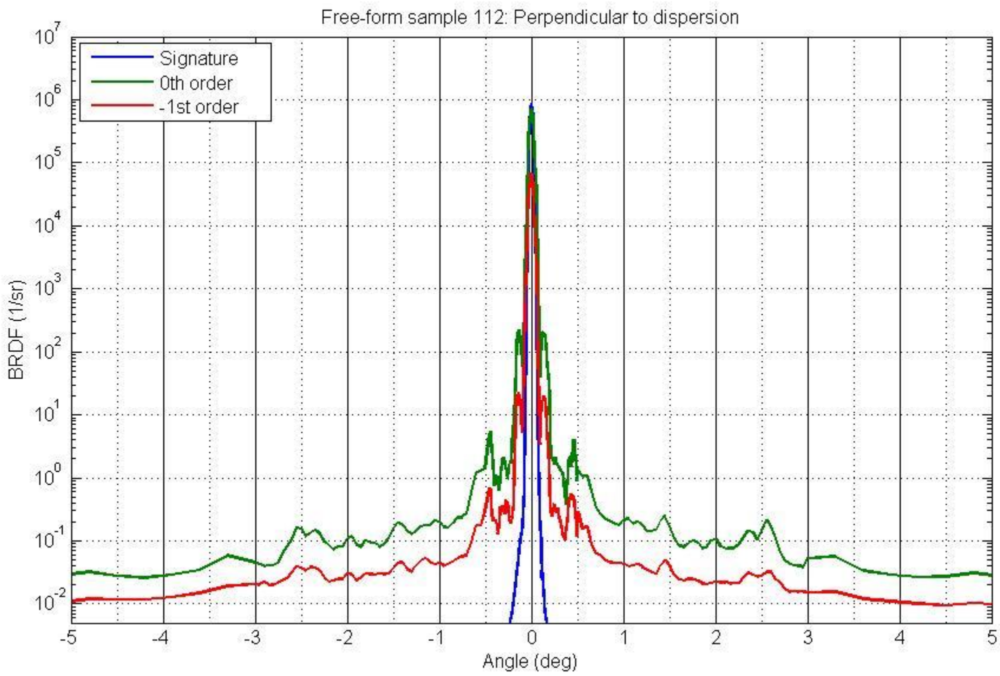

Figure 7 - BRDF measurement in the perpendicular to dispersion direction on sample #112

In the direction of dispersion, several spurious spot (at least three on the left and on the right of the main orders) are remarkably visible.

The total relative energy in these spots have been measured about 10% of the energy in the main order.

Apart from these peaks the strayligth level is around 1e-4 in the dispersion direction. In the direction perpendicular to dispersion the strayligth level is 3 orders of magnitude lower, around 1e-7.

The spurious spots are assumed to be Rowland Ghosts, i.e. resulting from periodic errors in the grating groove spacing.
Microscope inspection and additional samples measurement have demonstrated that an accuracy problem on one axis of the lathe is the origin of the observed Rowland ghosts.

A second lathe with extended capabilities has been commissioned at AMOS and new FFG grating (identified as FFG#2-N) and an additional flat sample (sample #240) have been machined.

Visual aspects and diffraction patterns of the FFG#2-N and samples #240 suggested a real improvement in the ghost's reduction. This is confirmed by the BRDF measurement on sample #240.

Only a single pair of faint ghosts (< 1e-3) are visible around the main diffraction peak. Moreover, the grass level is also reduced by factor of 10 (about 1e-5), indicating that not only the periodic error is strongly reduced but also the random error in the groove period.

Important improvement is also observed in the direction perpendicular to the diffraction plane (spatial scattering), with a scattered light level that sharply decrease to 1e-7 and then slowly to 1e-8.

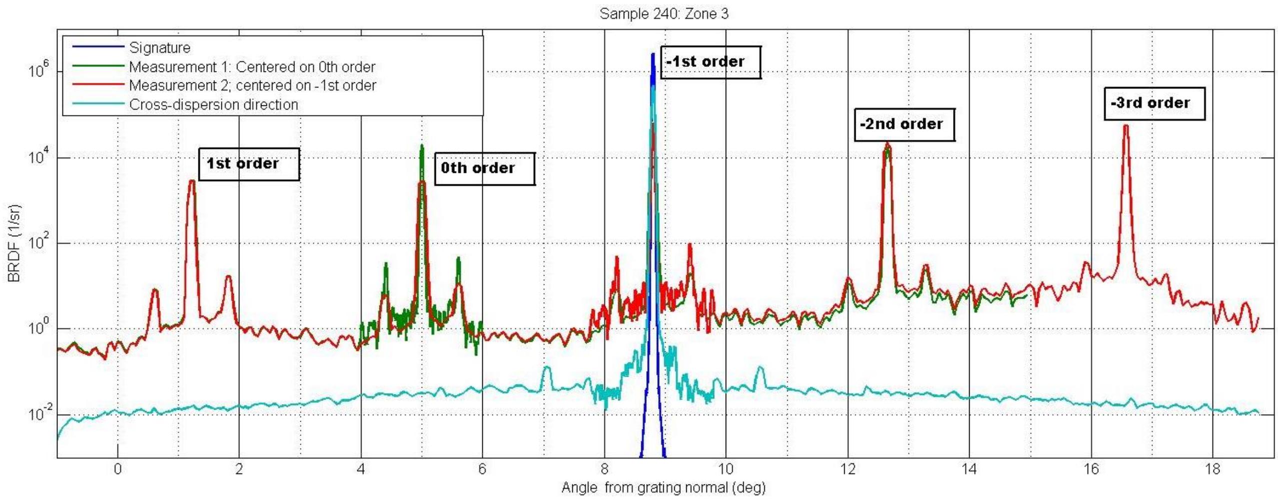

Figure 8 : BRDF Measurement of sample #240

The BRDF measures of sample #240 have been introduced in the out-of-band rejection model of the spectrometer. The result is an out-of band signal lower than 0.15%, showing that the rejection is largely in line with the instrument requirements (<1%).

In order to compare the BRDF measurement results with the specification and to evaluate an equivalent roughness value the measurement results have been fitted with the Harvey-Shack model.

Obtained roughness value are of 3.3 nm and 4.4 nm for sample 112 and 175 respectively. This is close to the specification (4 nm rms) and in agreement with roughness measurement in the grooves presented at section 4.3. On sample #240, machined with the finest lathe, Harvey-Shack fitting cannot be adjusted over the whole curve. Nevertheless, analyses with a strayligth software (FRED) concludes in a strayligth level comparable to an about 3 nm RMS roughness mirror.

5. CONCLUSION

During this project, we have proposed an original design for hyperspectral imagers that benefit from using a Free Form Grating instead of a planar or spherical grating. FFG secondary mirror in an Offner configuration spectrometer with reducing magnification leads to a compact imaging spectrometer design with high image quality and radiometric performances.

For the first time to our knowledge, we have confirmed experimentally the feasibility of cost-effective manufacturing of such a Free Form Grating by diamond machining on aluminium substrate. Two manufacturing and test campaigns were necessary to achieve almost fully compliant grating. It has been demonstrated that the most recent Single Point Diamond Turning lathe combined with a robust control scheme are able to achieve the extreme axes accuracy required to prevent excessive strayligth and scattering in grating up to 100 lp/mm.

The following tests have been performed on the freeform gratings manufactured by AMOS:

- Surface Quality (SFE)
- Diffraction efficiency
- Polarization sensitivity
- Roughness
- BRDF

Table 3 reports the as-built compliance status of the two deliverable FFG with respect to SOW specifications.

Table 3 : As built compliance status of the FFG with respect to SOW

#	Definition	Specification	As-built value		C/NC	
1	Spectral bandwidth (nm)	450 nm	450 nm		C	
2	Spectral operating range (nm)	450 to 900nm	450 to 900 nm		C	
3	Spectral resolving power	<2.5 nm	2.5 nm		C	
6	Length of the entrance slit (mm)	60 mm	60 mm		C	
7	Width of the entrance slit (µm)	30 µm	30 µm		C	
8	F-number (input/output)	5 -> 2.5	5->2.5		C	
8	Magnification	1/2	1/2		C	
9	Keystone (µm)	< 3 µm	1.1 µm		C	
10	Smile (µm)	< 3 µm	1.9 µm		C	
			FFG#3	FFG#2-N	#3	#2-N
11	MTF	> 0.6 at 33 lp/mm	~0.65	~0.55	C	NC
12	Straylight: BRDF of the grating	< BRDF of highly reflective mirror with 4 nm RMS surface roughness	3.3 nm – 4.4 nm RMS	<3 nm Roughness not measured	C	C
13	Straylight : OoB rejection	<1%	Rowland Ghost >10%	<0.2 %	NC	C
14	Sensitivity to Polarization (%)	< 5 %	6.3 % (@900 nm)	4%	NC	C
15	Diffraction efficiency (% average over the spectral range)	> 70%	72%	63%	C	NC
16	Minimum diffraction efficiency over the spectral range	> 40%	51.8%	47%	C	C

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