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Grating scattering BRDF and imaging performances: A test survey performed in the frame of the flex mission

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Grating Scattering BRDF and Imaging Performances – A Test Survey performed in the frame of the FLEX Mission

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Abstract— Key components in optical spectrometers are the gratings. Their influence on the overall in-field straylight of the spectrometer depends not only on the technology used for grating fabrication but also on the potential existence of ghost images caused by irregularities of the grating constant. For the straylight analysis of spectrometer no general Bidirectional Reflectance Distribution Function (BRDF) model of gratings exist, as it does for optically smooth surfaces. These models are needed for the determination of spectrometer straylight background and for the calculation of spectrometer out of band rejection performances.

Within the frame of the Fluorescence Earth Explorer mission (FLEX), gratings manufactured using different technologies have been investigated in terms of straylight background and imaging performance in the used diffraction order. The gratings which have been investigated cover a lithographically written grating, a volume Bragg grating, two holographic gratings and an off-the-shelf ruled grating. In this paper we present a survey of the measured bidirectional reflectance/transmittance distribution and the determination of an equivalent surface micro-roughness of the gratings, describing the scattering of the grating around the diffraction order. This is specifically needed for the straylight modeling of the spectrometer.

Keywords—Component; grating; straylight; BRDF

I. GRATINGS MEASURED WITHIN THE SURVEY

The goal of this measurement survey was to measure the BRDF/BTDF of gratings manufactured by different technologies and compare their straylight performance using the same test bench. The following grating technologies have been investigated: holographic grating technology, lithographic grating technology, volume Bragg grating technology and ruled grating.

The ideal case would have been to measure the gratings with the same specifications on the size, groove density, diffraction

efficiency and polarization sensitivity. However, this was not possible since the selection of gratings was partly dictated by the available time and budget but also by the resulting different spectrometer designs, which were considered in the spectrometer trade-off study. Nevertheless, all gratings have been selected to have groove densities above 1000 grooves per mm and all gratings had been measured in the Littrow configuration. The gratings measured in the trade-off are shown in Table 1 below.

The lithographic technology applied by the Fraunhofer Institute is currently limited to flat gratings. This technology allows fabrication of large gratings with very high accuracy groove density and low pitching error. The grating profile has been etched with an etching depth of 1800 nm. Such grating has already been manufactured, space qualified and integrated in the radial velocity spectrometer of the ESA GAIA mission [2,3].

The holographic grating manufactured by Horiba Jobin Yvon is a replica of a master grating. It is a convex reflective grating, which required the test set-up to focus of the illumination beam in front of the grating, such that the grating conjugated diffraction image falls onto the detector.

The ZEISS grating is also a holographic reflection grating, however, it is flat and the grooves are sinusoidal.

The Dichromate Gelatine Volume Bragg grating has been developed by CSL within an ESA Technology Research Programme contract [4]. It is a flat transmission grating. The grating itself consists out of two fused silica substrates attached to each other with the grating in between.

The ruled grating is a commercial off-the-shelf grating from Edmund Optics [5]. Although, not comparable in terms of price and effort with respect to the above mentioned gratings, it has been included in the survey to get an idea about the differences in the straylight level one could expect from ruled gratings.

Manufacturer	Fraunhofer Institute for Applied Optics and Precision Engineering Jena	Horiba Jobin Yvon	Zeiss	Centre Spatial de Liege	Edmund Optics
Techno-logy	lithographic	holographic	holographic	holographic Dichromate Gelatine Volume Bragg Grating	Ruled
Sample ID	UZE079a_1_C1	521 12 040			43210
Type	transmission	reflection	reflection	transmission	reflection
Shape	flat	Concave – radius of curvature 201.4 mm	flat	flat	flat
Dimen-sion	31x31x6.35 mm ³ Useful area: 29x29 mm ²	30x30 mm ² Useful area 24x24 mm ²	60x60x10 mm ³	100x100x20 mm ³	25x25x9.5 mm ³ Useful area: 22x22 mm ²
Groove density	1250 grooves / mm	1200 grooves / mm	1400 grooves / mm – sinusoidal groove shape	1200 grooves / mm	1200 grooves / mm
Spectral range	Optimized for 1100 nm	340-800 nm (aluminium coating)	680 – 780 nm (efficiency # 60%)	677 – 697 nm (efficiency # 60%)	Optimized for 750 nm
Normal AOI	43.5° 23.3 (Littrow under 632 nm)	22.3° (Littrow under 632 nm)	26.25° (Littrow under 632 nm)	22.3° (Littrow under 632 nm)	22.3° (Littrow under 632 nm)
Useful diffract-ion order	-1	-1 (± 6 ° around order -1 to avoid vignetting of the illumination beam by the detector)	-1 (± 6 ° around order -1 to avoid vignetting of the illumination beam by the detector)	-1	-1 (± 6 ° around order -1 to avoid vignetting of the illumination beam by the detector)
Website	http://www.iof.fraunhofer.de/en.html	http://www.horiba.com/scientific/about-us/horiba-jobin-yvon/	www.zeiss.de/gratings	www.csl.ulg.ac.be/	www.edmundoptics.com/

Table 1 Gratings of the measurement survey

2 . MEASUREMENT SET-UP

The BRDF of the different gratings has been measured on a commercial CASI test bench from Schmitt Industries INC. [1]. Figure 1 shows the optical lay-out of the CASI system. The laser acts as a source for the measurement of BRDF/BTDF. The laser output is passing through a chopper where part of the light is directed towards a reference detector. The reference detector continuously monitors the laser energy and

when a measurement is performed, any deviation of the optimal power is automatically taken in account by the software making the system insensitive to (small) laser power drifts. The laser beam is cleaned by a spatial filter which is a combination of a microscope objective with a matched pinhole. The light is finally focussed by a parabolic mirror onto the detector mounted on a goniometer stage.

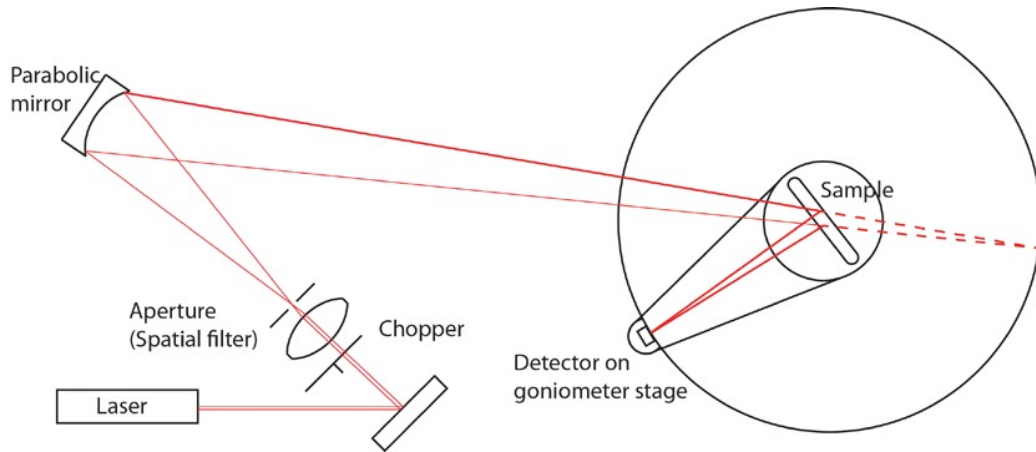


Figure 1 CASI BRDF test bench concept

3. RESULTS

The procedure for measurement of optically smooth flat samples, either reflective or transmissive, is as follows: the first step is the measurement of the instrument signature, this means the measurement of the instrument BRDF itself. This signature provides the background limit of the measurement. In a second step the sample is mounted in the rotation centre of the goniometer, such that the converging laser beam after reflection/transmission from the sample is focussed onto the goniometer circle along which the detector is scanning the grating BRDF/BTDF.

This measurement procedure is only strictly valid for reflecting smooth optical surface and infinitesimal thin transmission surfaces.

The measurement of gratings in the dispersion plane has to be modified because of an additional effect: since the grating is illuminated with a convergent F/100 beam the angle of the incidence beam is varying over the grating surface resulting in a focus position away from the goniometer circle. A BRDF measurement without refocussing of the beam leads to defocussed images in the diffraction orders. Since in general the imaging performance of the grating around the diffraction order is needed, this defocus can be corrected by the CASI illumination system.

In this section we show the measurement results for the different gratings that were investigated. The BRDF/BTDF measurements for the gratings were done in dispersion as well as cross-dispersion direction. For all gratings the performance of the Littrow diffraction order is provided in an angular range of +/- 2°.

As a reference we provide BRDF curves of optically smooth samples with a surface micro-roughness of 2nm and 5nm, 10nm and 25nm. The BRDF curves of smooth surfaces are modelled according to the Wein formula [6]:

$$BRDF(\beta) = \frac{\Delta n}{\pi} \left[\frac{\left(\frac{2\pi}{\lambda}\right)^4 \sigma^2 L^2}{1 + \left[\frac{2\pi}{\lambda} L(\sin(\beta))\right]^2} \right]$$

Where $L = 100 \frac{\lambda}{2\pi}$

- σ ... surface micro-roughness
- β ... scatter angle
- λ ... wavelength
- Δn . change in index of refraction

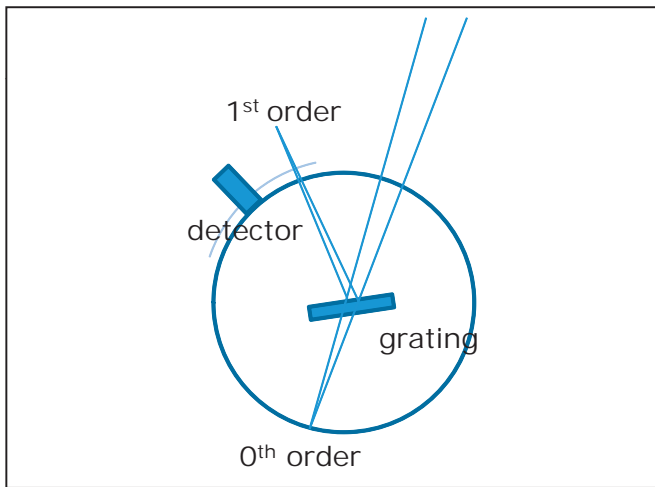


Figure 2 Dispersion direction

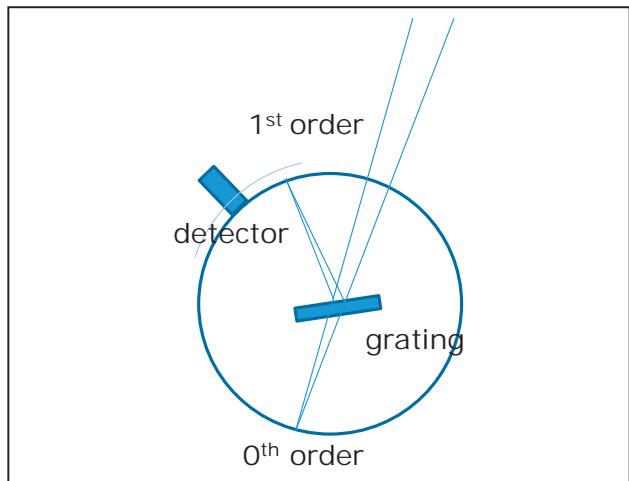


Figure 3 Cross-dispersion direction

These reference plots allow at one hand side a quantitative comparison of the different gratings and on the other hand side the possibility to define the grating scattering by a simple ABg description for the development of the grating spectrometer straylight model.

In the following sections A) to E) we provide the measurement results for all gratings of the survey. Two plots are provided for each grating, the BRDF or BTDF in dispersion and in cross-dispersion direction. While the measurement of the dispersion direction shows the grating scatter performance around the -1st Littrow order, while the measurement in cross dispersion direction shows the scatter performance around the 0th order.

A. Fraunhofer Institute IOF lithographic grating

The lithographic grating manufactured by the Fraunhofer Institute IOF Jena is shown in Figure 4. The grating is a flat transmission grating.

In the test configuration the grating surface was positioned on the back surface. The unstructured front surface of the grating did not have an anti-reflection coating. The grating BTDF shows a relative large plateau around the diffraction peak within an angular range of $\pm 0.5^\circ$, which intensity is larger a smooth surface of a surface micro-roughness of 10 nm.

The grating shows two spikes symmetric around the diffraction order. A similar spike is also visible in the cross-dispersion direction. These spikes are the effect of the grating internal reflection. It is suspected that they can be minimized by an AR coating.



Figure 4 IOF lithographic grating

1) Dispersion direction (file: IOF_results)

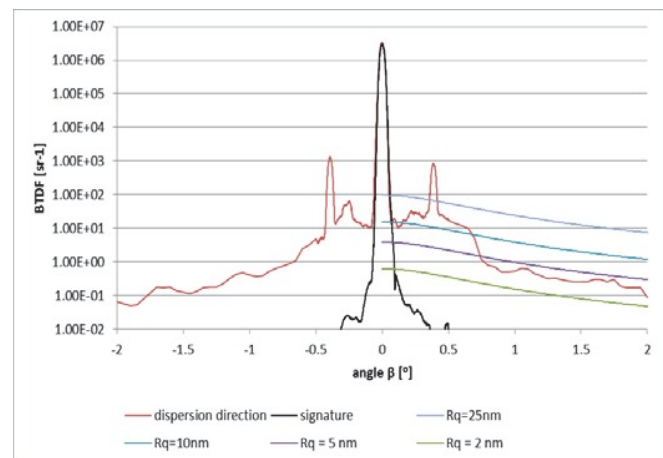


Figure 5 IOF lithographic grating in dispersion direction

2) Cross-dispersion direction (file: IOF_results)

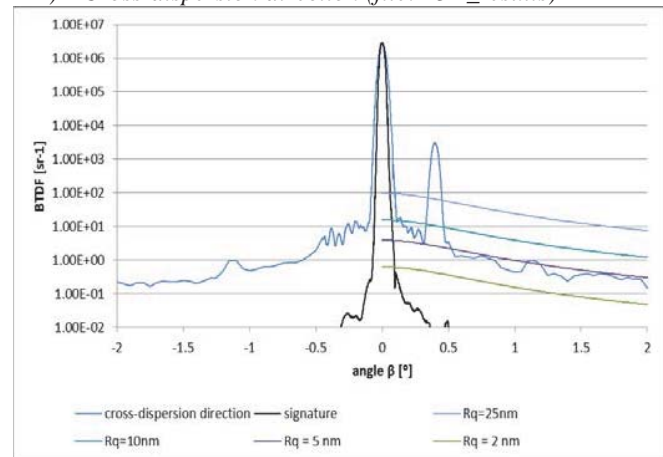


Figure 6 IOF lithographic grating in cross-dispersion direction

B. Horiba Jobin Yvon holographic grating

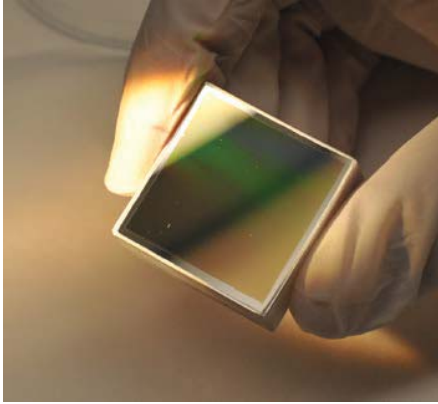


Figure 7 Horiba Jobin Yvon holographic grating

The grating is a convex reflection grating and shown in Figure 7.

The reflective convex grating manufactured by Horiba Jobin Yvon provides a very good straylight performance. The central plateau around the diffraction peak is limited to $\pm 0.2^\circ$. The grating can be approximated by an equivalent surface rms micro-roughness between 5 nm and 10 nm.

The grating is free of any ghosts.

1) Dispersion direction (file: JY_results)

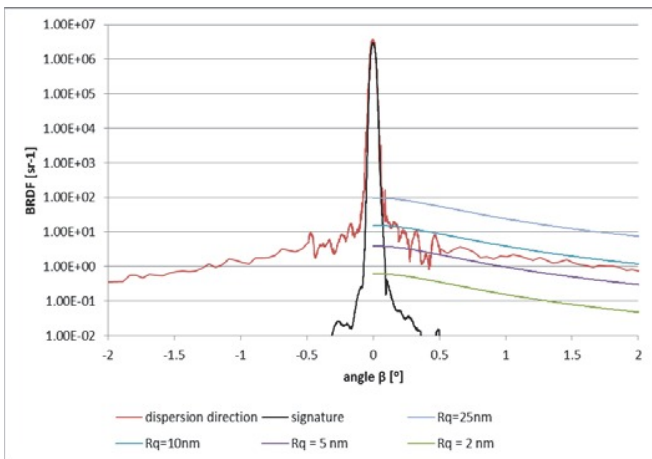


Figure 8 Horiba JobinYvon holographic grating in dispersion direction

2) Cross-dispersion direction (file: JY_results)

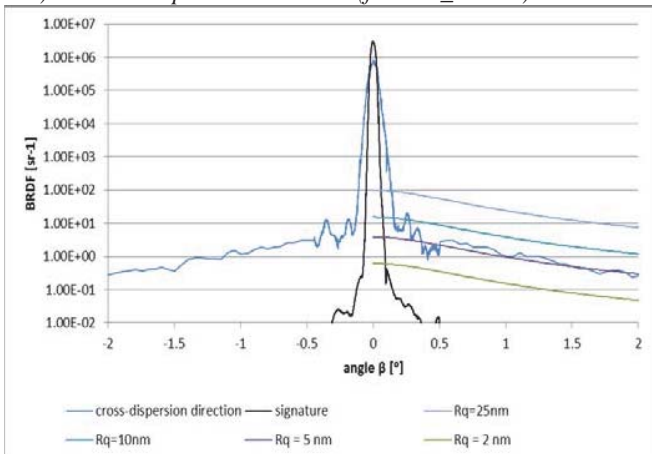


Figure 9 Horiba JobinYvon holographic grating in cross-dispersion direction

C. ZEISS holographic grating

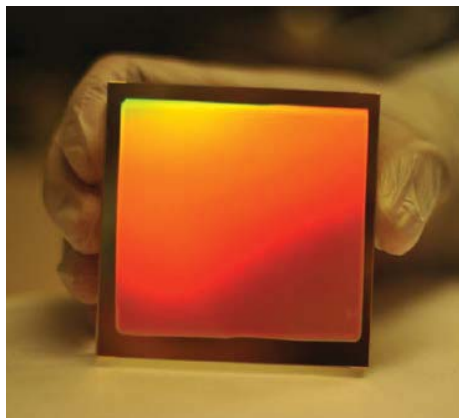


Figure 10 ZEISS holographic grating

The holographic grating manufactured by ZEISS is a flat reflective grating and is shown in Figure 10.

The straylight performance of the ZEISS grating is dominated by a large scattering plateau around the diffraction peak, which is larger an equivalent surface micro-roughness of 25 nm ranging until $\pm 0.2^\circ$ around the diffraction peak which falls down to a second plateau of around 10 nm equivalent surface micro-roughness until $\pm 0.5^\circ$. For angles larger $\pm 1^\circ$ off the diffraction peak, the grating equivalent surface micro-roughness is about 5 nm.

The equivalent surface microroughness of the grating in cross-dispersion direction is between 10 nm and 25 nm.

The grating is free of any ghosts.

1) Dispersion direction (ZEISS_results)

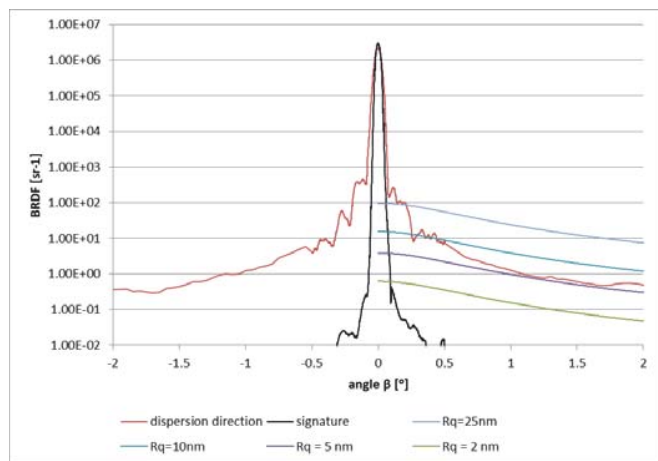


Figure 11 ZEISS holographic grating in dispersion direction

2) Cross-dispersion direction (ZEISS_results)

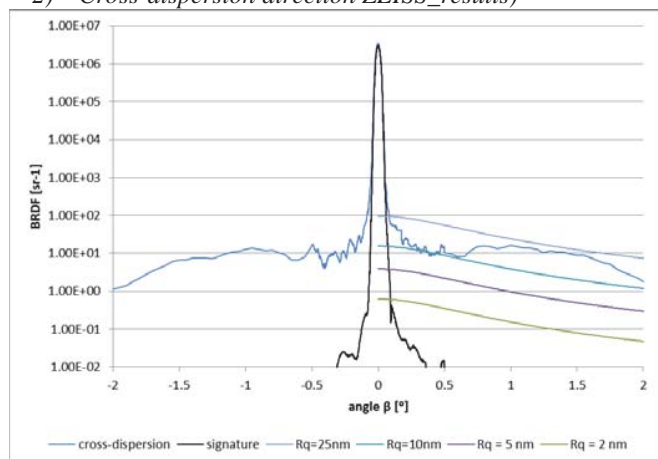


Figure 12 ZEISS holographic grating in cross-dispersion direction

D. Centre Spatial de Liege Volume Bragg grating



Figure 13 CSL Volume Bragg grating

The Volume Bragg grating, shown in Figure 13, is based on a volume grating realized in di-chromate gelatine, which is covered in between two fused silica plates.

The straylight performance of the CSL volume Bragg grating shows a steeper fall-off than the other gratings.

For an angular range lower than $\pm 0.5^\circ$ around the diffraction peak the equivalent surface micro-roughness is between 25 nm and 10 nm, but it falls off to lower 5 nm at angles larger $\pm 1.5^\circ$.

The transmission grating has an internal reflection, causing a ghost image.

1) Dispersion direction (file: VBG results)

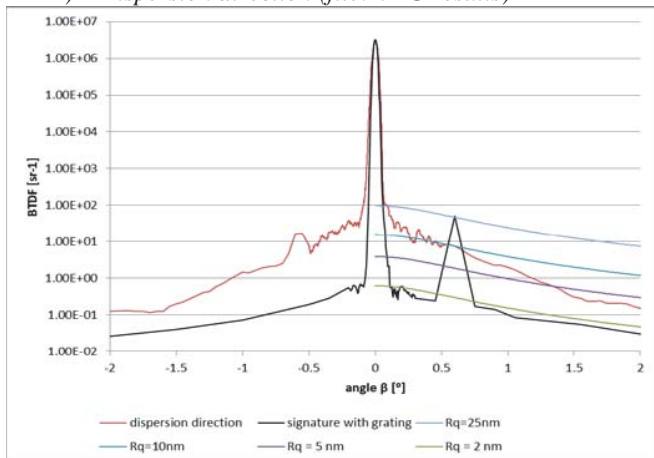


Figure 14 CSL Volume Bragg grating in dispersion direction

1) Cross-dispersion direction (file: VBG results)

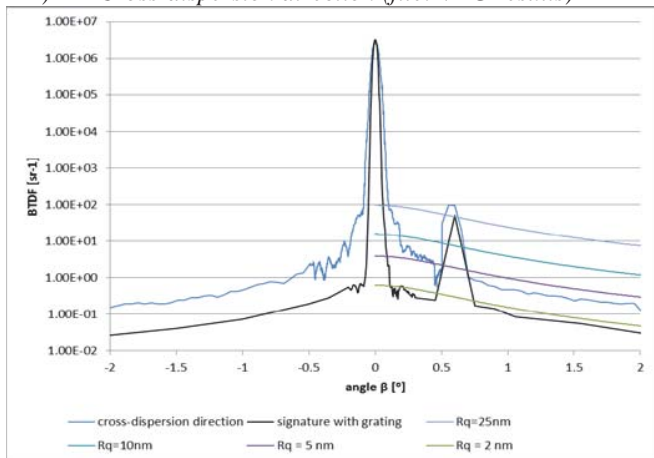


Figure 15 CSL Volume Bragg grating in cross-dispersion direction

E. Edmund Optics ruled grating

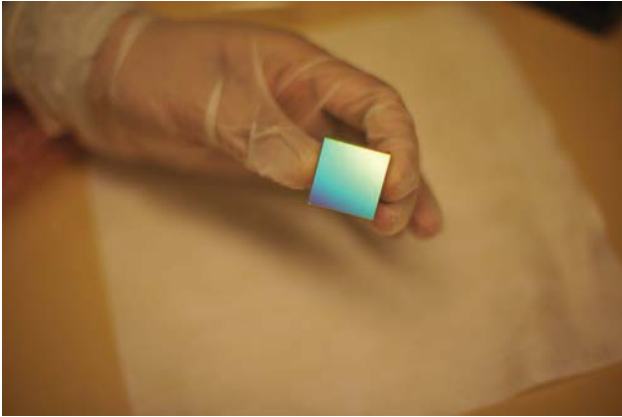


Figure 16 Edmund Optics ruled grating

The straylight performance of the ruled Edmund Scientific grating has a plateau larger 25 nm equivalent surface micro-roughness for an angular range of less than $\pm 0.5^\circ$ around the diffraction peak. For larger angles the scattering performance can be approximated by a 10 nm equivalent surface micro-roughness.

The grating is free of ghost images.

1) Dispersion direction (file:Edmund_results)

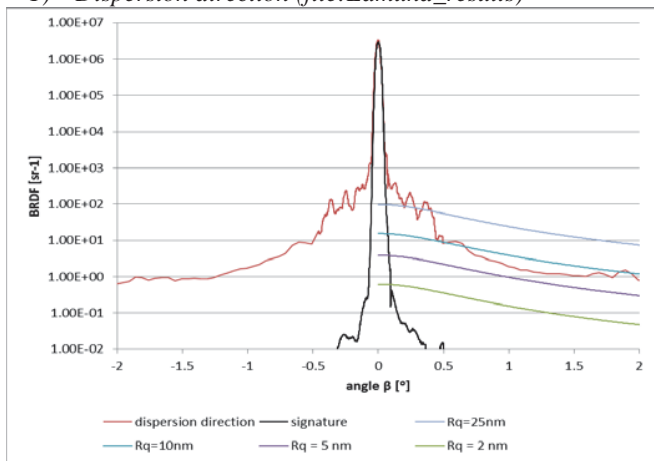


Figure 17 Edmund Optics ruled grating in dispersion direction

2) Cross-dispersion direction (file:Edmund_results)

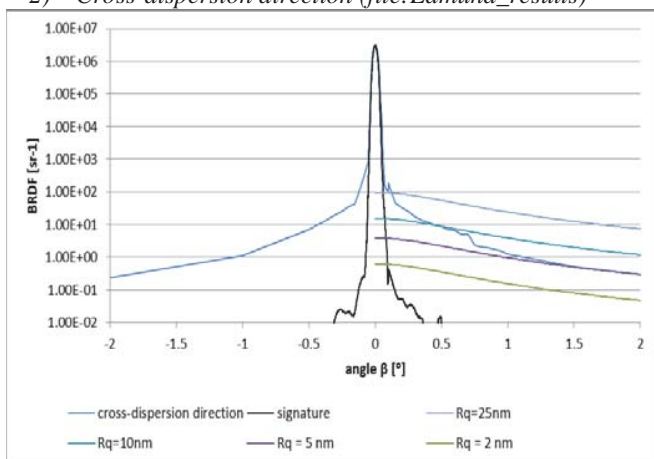


Figure 18 Edmund Optics ruled grating in cross-dispersion direction

IV. DISCUSSION

The measurement results shown in the previous section give an indication about the straylight performances that can be expected from gratings manufactured using different technologies. It shows as well, that the selection of a technology does not guarantee automatically a minimum of grating straylight, as shown with the holographic gratings.

Although the differences in the plots seem to be marginal it must be considered that the plots are given on a logarithmic scale.

Since the grating is usually located in an image of the pupil instrument plane its scattering will cover the field of view of the instrument.

V. LITERATURE

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