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DEVELOPMENT OF THE FLIGHT MODELS FOR THE SENTINEL-4/UVN NIR-GRATING UNIT

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I. INTRODUCTION

In the frame of ESA‘s earth-observation program “Copernicus”, the Fraunhofer IOF develops for the Sentinel-4/UVN spectrometer, the optical gratings for the near-infrared spectral channel together with its isostatic mounts.
The grating operates in the spectral band between 750nm and 775nm wavelength and is based on a dielectric reflection grating. Such grating concepts have been initially developed for the manipulation and compression of high-power ultra-short laser pulses. However, they also have a number of advantageous properties for spectroscopic applications [1]. In particular, the required high angular dispersion in combination with an extremely low polarization sensitivity of the diffraction efficiency is not achievable with alternative concepts on the basis of metallic reflection gratings. Therefore, we have transferred the dielectric reflection grating concept to space-borne spectrometers for the first time in the frame of the Sentinel-4 project.
The NIR-grating is part of the grating assembly which in addition comprises the NIR spectrograph aperture stop, the mechanical grating mount, the Co-Registration compensation device, the mechanical structure providing mechanical interfaces between grating assembly and the NIR spectrometer optics assembly, and alignment targets allowing for an accurate optical position and tilt measurement. The first three items, being the grating itself, the aperture stop, and grating mount establish the so called grating unit. Its construction and manufacturing is in the responsibility of the Fraunhofer IOF.
The paper will report about the concept and the results achieved for the development of the Sentinel-4/UNV NIR-grating unit.

II. GRATING DESIGN

According to the optical design of the Sentinel-4 NIR Spectrograph the dispersive component is a reflection grating having a period of p=797nm and being illuminated under 24.5° incidence angle. Table 1 summarizes the main optical performance requirements of the grating.

Tab. 1. Relevant optical specification used for the design of the grating structure.

Specification	Required Value
Spectral band	750nm ... 775nm
Grating area	Elliptical, 55.6mm x 60.8mm diameter
Groove density	(1255.2+/-0.5)/mm
Efficiency of nominal diffraction order	$\eta_{-1} > 70\%$
Efficiency of 0th and -2nd diffraction order	<30%
Center of FOV	ax=0.00°; ay=24.50°
Elliptical FOV	ax=2.0°; ay=0.1°
Spherical WFE	<40nm RMS
Aspherical WFE	<20nm RMS
Polarization sensitivity	<4%
Maximum difference of pol. sensitivity for any wavelength within system spectral range	<1.8%

Reflection gratings having such high line densities tend to show a comparable large polarization sensitivity of their diffraction efficiency, i.e. the amount of light reflected into the nominal diffraction order is strongly dependent on the polarization of the incident light. A measure for this dependency is the polarization sensitivity defined by

$$PS(\lambda)=\frac{\eta_{\max}(\lambda)-\eta_{\min}(\lambda)}{\eta_{\max}(\lambda)+\eta_{\min}(\lambda)}. \tag{1}$$

A detailed analyses revealed that the desired optical performance of an efficiency η>70% with a polarization sensitivity *PS*<4% over the full spectral band cannot be achieved with conventional metal coated gratings. Therefore, a grating concept not used for spectroscopic applications before has been adapted to the special requirements of the Sentinel-4/UVN instrument. It is based on a two-level grating structure realized in the uppermost layer of a high-reflective dielectric layer stack deposited on a fused-silica substrate. Such gratings have been initially developed for applications in ultra-short laser-pulse compression where efficiencies near 100% are targeted but polarization sensitivity is of minor importance [2].
In order to apply the concept of dielectric gratings to the Sentinel-4 NIR grating two difficulties needed to be overcome. First, a design operating equally well for the two extreme polarizations (i.e. TE- and TM-polarization) was needed. The second challenge is related to the property of such dielectric reflection gratings to show sharp resonances in the spectral efficiency curve in case that the grating period is in the range of the illumination wavelengths, which is the case for the NIR grating. These resonances are caused by coupling of light into the dielectric layers of the stack via the grating structure. To overcome these difficulties a grating configuration based on an irregular stack of alternating SiO_2 and Ta_2O_5-layers was designed. The grating structure itself is located in the uppermost SiO_2-layer of the stack. A sketch of the final grating structure is shown in Fig. 1 together with the theoretically expected efficiency- and polarization sensitivity performance.

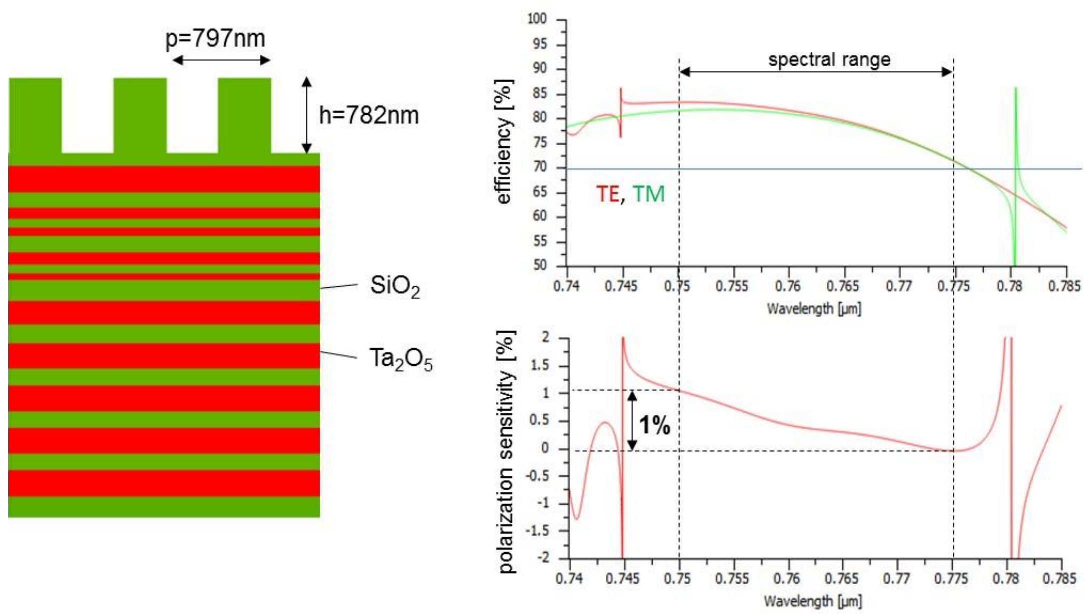

Fig. 1. Left: Optimized design of the all-dielectric Sentinel-4 NIR reflection grating based on binary surface structure etched into the uppermost SiO_2-layer of a SiO_2/Ta_2O_5-layer-stack. Right: expected optical performance (spectral diffraction efficiency and polarization sensitivity) of the optimized grating design.

The diffraction efficiency is well above the requirement within the whole spectral window with a minimum at the longest wavelength λ=775nm of η=72%. The maximum of the polarization sensitivity is approximately 1%.

III. MECHANICAL DESIGN OF THE GRATING UNIT

The sensitive Optical Grating needs to be fixed to the Co-Registration Assembly in a way that its optical performance remains stable after mounting and during its operation over the full mission lifetime. Therefore, a stable mounting framework which provides a simple and reliable mounting interface to the Co-Registration Unit of the complete Grating Assembly has been developed. This mounting framework consists of the grating mounts and the grating supporting structure (GSS), which represents the mechanical interface to the Co-Registration Unit.

The mounting concept has to ensure an almost deformation free kinematic fixation of the fused silica grating substrate. The conditions for the mount are determined by thermal and mechanical loads. Important for the arrangement is the thermal mismatch between the fused silica grating component (thermal coefficient of expansion $\alpha_{FS}=5.1\cdot10^{-7}\ K^{-1}$) and the metallic base plate composed of a Titanium alloy (CTE $\alpha_M=8.5\cdot10^{-6}\ K^{-1}$). Furthermore, the mechanical properties given by the E-module (fused silica: 72GPa; Ti-alloy: 115GPa) are of importance. The mentioned values already show the problem of a hybrid set-up and the requirement to reduce thermal and mechanical stresses.
The choice of Titanium as material for the mount is driven by a high tensile strength, a low mass, and low thermal conductivity. Especially the high tensile strength allows for the construction of small cross sections of joint structures and thus to achieve a high degree of decoupling. The low thermal conductivity ensures a thermal isolation of the grating component. Critical thermal gradients between mounting points are reduced and the resulting thermal deformations remains weak.
The proposed concept is based on a kinematic defined grating fixture via 3 isostatic mounts. These mounts are realized as bipods and bind all 6 degrees of freedom. The mount of the grating substrate is decoupled radially symmetric and compensates the expansion difference of the relevant materials. Therefore, the center position of the grating remains fixed in case of temperature changes. The axial expansion is determined by the bipod height and half of the substrate thickness considering the relevant expansion coefficients.
The mounting of the grating to the bipods is done using Invar-pins directly glued to the fused silica substrate using a suitable space qualified glue. The bipods are then screwed to the GSS made of Titanium. In order to suppress spurious reflections from the mechanical mount the GSS is coated with Acktar fractal black.

An additional novelty of the developed concept is the direct integration of the grating aperture into the grating surface. The aperture is formed by a so-called black-chromium layer which exhibits a reflectivity well below 5% over the relevant spectral band. This layer is also structured in a lithographic process ensuring a very high position- and size-accuracy in the range of a few micrometers only. The direct integration of the aperture into the grating surface allows for a significant simplification of the mechanical grating mount as it avoids the need for a separate mechanical diaphragm.
The final mechanical design of the grating mount is shown in the following figure.

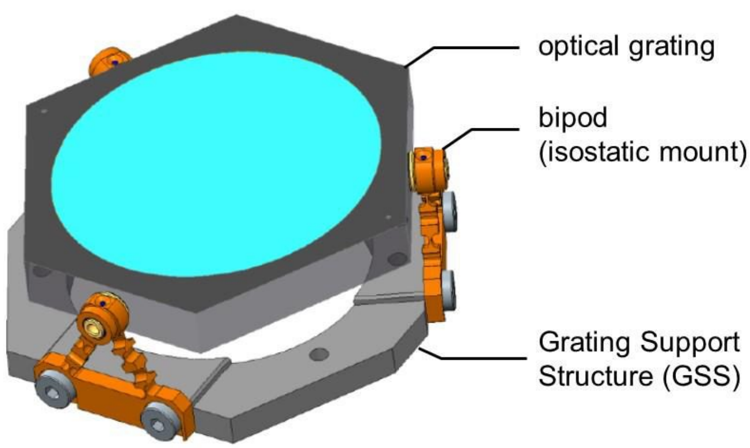

Fig. 2. CAD model of the Grating Unit

This mounting framework allows the grating unit to be treated as a stable, self-standing subassembly for the purpose of integration into the Grating Assembly.

IV. GRATING FABRICATION PROCESS

The realization of gratings as discussed in the preceding sections requires a high precision patterning process on large areas. Thus, it is mandatory to include the available knowledge about the designated technological realization approach and its limitations already in the grating design.
The structuring process for the grating is based on electron-beam lithography in combination with reactive ion-etching technologies for the transfer of the grating pattern into the top SiO_2-layer of the HR-stack. A schematic overview of the process is shown in the following picture.

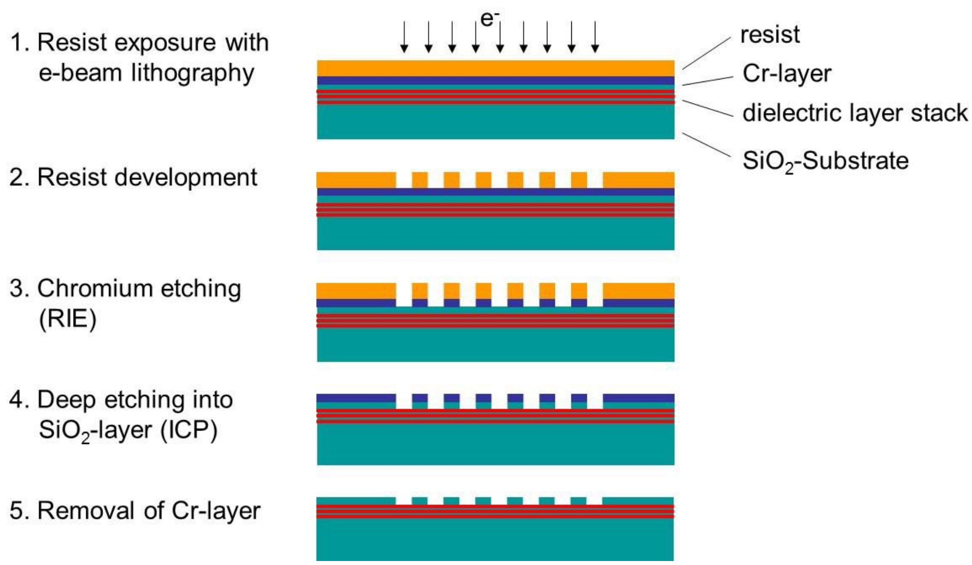

Fig. 3. Process for the realization of the grating structure by e-beam lithography and reactive ion etching.

The main advantages of this technological approach include a high pattern resolution combined with a high homogeneity across the whole grating area (precise control of local fill-factor, shape and depth of the grating structure), extremely low impact of the writing process on wave-front errors, and low stray-light introduction by the lithographically generated structures.

The lithography system to be used for the exposure of the grating pattern is a SB350 OS electron-beam writer (Vistec Electron Beam GmbH). This system is capable to handle mask-blank substrates of up to 230mm x 230mm x 9mm size. Such a substrate made from fused silica has been used to expose 4 gratings in parallel by electron-beam lithography on a single mask-blank. Figure 4 shows a Scanning Electron Microscope image of a cross section of the final grating structure obtained at an engineering model. The cut was prepared with a focused ion beam in the processing stage where the Cr-mask was still on the grating lines.

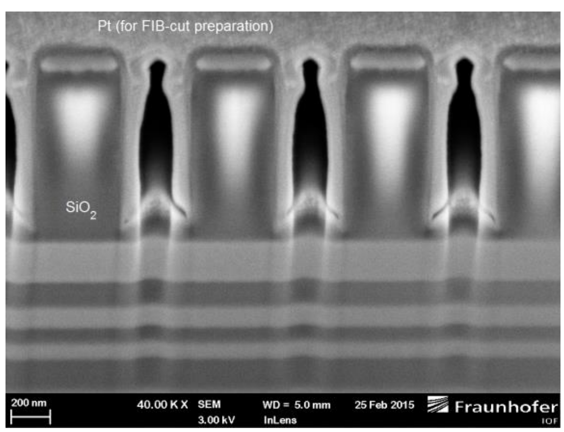

Fig. 4. Scanning-Electron-Microscope image of a cut through the grating structure

After the etching steps the four gratings were separated and their individual substrates were cut to a hexagonal shape.

After the structuring of grating and the non-reflecting aperture the grating was isostatically mounted onto a base-plate via Invar-pins and Ti-bipods. The assembly is performed utilizing a three-coordinate measurement tool to ensure the required positioning accuracy of a few micrometers only. Figure 5 shows the assembled Qualification Model of the Sentinel-4 NIR Grating Unit.

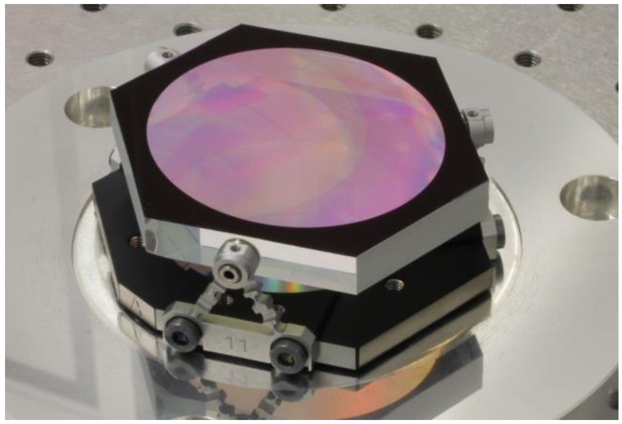

Fig. 5. Qualification Model of the Sentinel-4 NIR grating unit

V. OPTICAL PERFORMANCE

The Qualification Model (QM) of the Sentinel-4 NIR grating has been extensively characterized to validate its compliance with the optical requirement specifications (see Tab. 1). The performed measurements include a characterization of the spectrally and spatially resolved diffraction efficiency, polarization sensitivity, stray-light performance, and wave-front quality.

In a first measurement the diffraction efficiency of the nominal -1st diffraction order has been mapped across the grating area for the two extreme polarizations (TE, TM) at a set of 6 discrete wavelengths for an fixed angle of incidence of ϑ_{in}=24.5°. The used light source was a tunable laser diode with a bandwidth of 0.1nm. Figures 6 and 7 show a mapping of the measured diffraction efficiency across the grating area for λ=765nm and the spatially averaged spectral dependency of the efficiency, respectively.

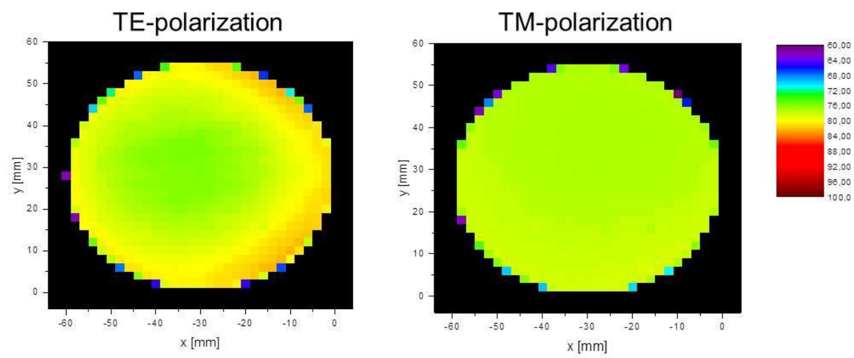

Fig. 6. Sentinel-4 NIR grating QM: efficiency of the nominal -1st diffraction order at λ=765nm mapped across the grating aperture for the two polarizations parallel and perpendicular to the grating grooves

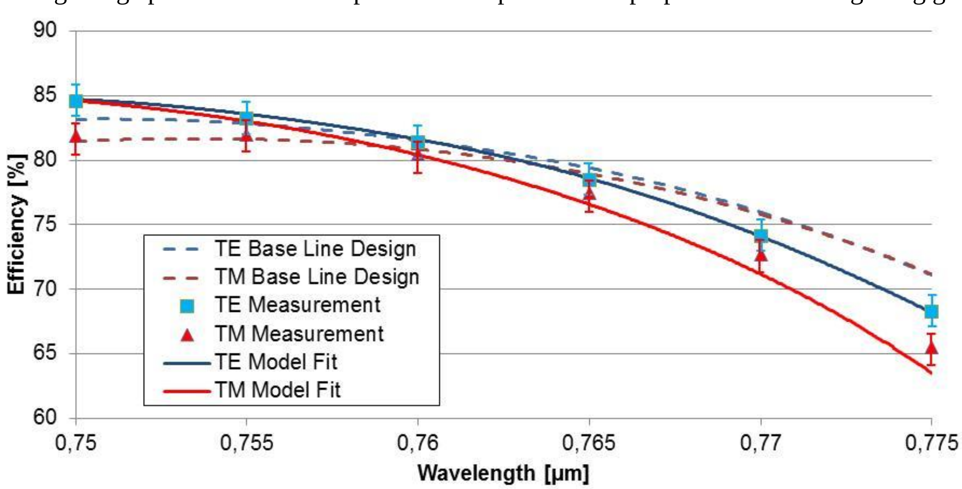

Fig. 7. Sentinel-4 NIR grating QM: spectral dependency of the diffraction efficiency

The measurement results show that the efficiency requirement is fulfilled for wavelengths λ<772nm. Between 772nm and 775nm wavelength the efficiency is below the requirement of η>70% with a minimum of 66.9% at λ=775nm. After a detailed analysis of this situation it could be shown that this deviation is a consequence of a spectrally shifted reflection curve of the dielectric layer stack under the grating by about 10nm towards shorter wavelengths. As the overall systems concept of the NIR-spectrometer contains some margin for the overall transmission it was finally concluded that this deviation is considered uncritical.
The polarization sensitivity derived from the measurements in Fig. 7 has a maximum of 2.04% being fully compliant with the requirement of PS<4%.

The stray-light performance of the QM-grating has also been characterized by a measurement of the 2D bidirectional reflection distribution function (BRDF) using the ALBATROSS-set-up available at the Fraunhofer IOF. This measurement has been performed at a wavelength λ=770nm and at a fixed angle of incidence of 24.5°. Cross sections extracted from the 2D BRDF along and perpendicular to the dispersion direction are displayed in Fig. 8.

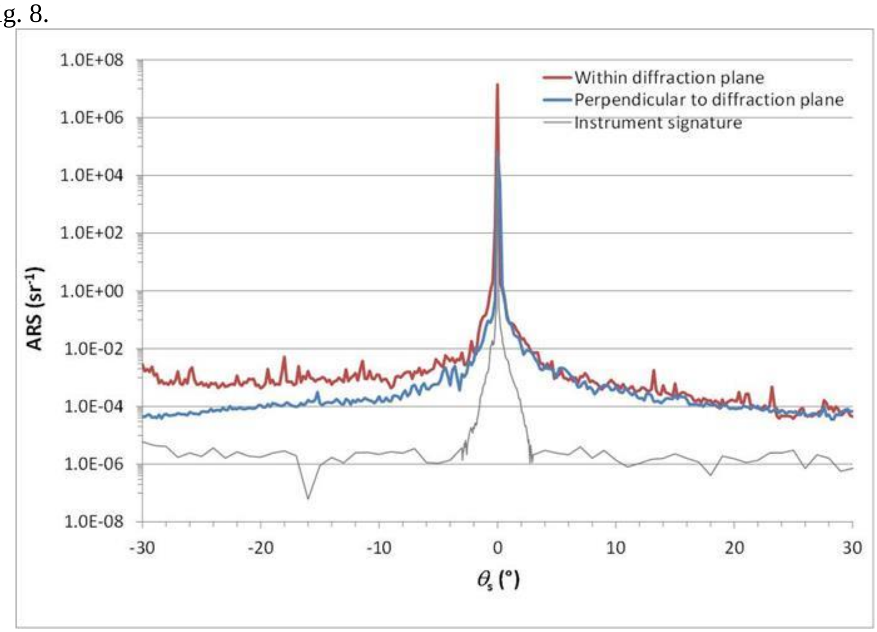

Fig. 8. Sentinel-4 NIR grating QM: cross sections of the 2D BRDF measurements along and perpendicular to the dispersion direction.

The displayed curves reveal compliance of the grating with the stray-light requirement. In particular, there are no ghost peaks observable which would indicate positioning imperfections of the sequential lithographic exposure process.

The surface quality of the Sentinel-4 GRU QM grating has been characterized interferometrically during different steps of the mounting process. Figure 9 shows the wave-front measurement just before the mechanical integration of the grating into the Grating Unit. The wave-front error is 19.8nm (rms) and 6.0nm (rms) including and excluding the spherical contribution, respectively.

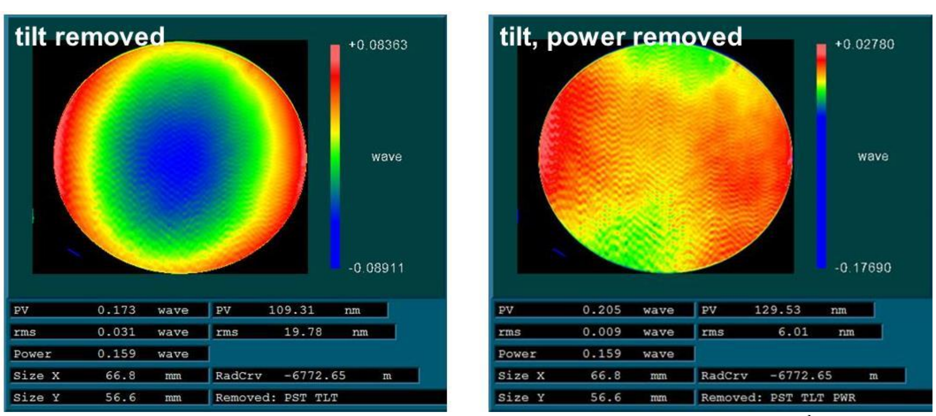

Fig. 8. Sentinel-4 NIR grating QM: interferometric wave-front error measurement in 0th diffraction order with (left) and without (right) spherical contribution.

Additional measurements of the integrated Grating Unit have shown no degradations of the wave-front performance due to the mounting process. Thus, the grating fulfills the wave-front requirements with a comfortable margin.

SUMMARY

The optical design, mechanical mounting concept, and achieved results for the Sentinel-4 Grating Unit have been reported. The developed approach contains several novelties for space borne spectrometers. One is the use of a high resolution all-dielectric reflection grating. Another one comprises the direct integration of the system aperture into the grating surface by a lithographically structured black-chromium aperture.
Characterizations of the optical performance have shown full compliance with most of the requirement specifications. Only the efficiency requirement is slightly violated for the wavelength range from 772nm to 775nm. This deviation could be traced back to a spectral shift by $\Delta\lambda \approx$-10nm of the reflectivity curve of the dielectric layer stack underneath of the grating. However, a detailed analysis of the situation taking the full NIR-instrument performance into account leads to the conclusion that the observed deviation is uncritical.
The Qualification Model (QM) of the Grating Unit has been delivered to the project partner Astrium DS in September 2015. Meanwhile also the FM1 and FM2 gratings have been successfully fabricated and characterized showing a similar optical performance as the QM.

ACKNOWLEDGEMENT

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