

Concept for a Compact Spatial Heterodyne FTIR Using a Fully Grating Based Optical Architecture

Sebastian Fray^{*a}, Thomas Paul-Flügel^b, Antonia Clara Klein^b

^aOHB System AG, Manfred-Fuchs-Straße 1, D-82234 Wessling, Germany;

^bFraunhofer-Institut für Angewandte Optik und Feinmechanik IOF,
Albert-Einstein-Str. 7, D-07745 Jena, Germany;

*sebastian.fray@ohb.de;

ABSTRACT

Fourier transform infrared (FTIR) spectrometers based on spatial heterodyne concepts offer compact and robust solutions for spaceborne Earth observation missions. Motivated by current trends toward small, low complexity, and cost effective payloads with straightforward system integrability, this work investigates an innovative FTIR architecture as an alternative to conventional Michelson interferometer implementations, which typically rely on bulky and alignment sensitive optical configurations such as prisms and retro-reflecting elements. We investigate this innovative spatial heterodyne spectrometer scheme based exclusively on diffraction gratings and nanostructured surfaces, enabling a highly integrated and mechanically stable design. The proposed concept employs three gratings: a first grating acting as a beam splitter, a second grating for beam redirection, and a third grating for beam recombination. All three gratings contribute simultaneously to the dispersive behaviour, allowing for flexible spectral design and reduced optical complexity. Key instrument parameters, including grating constants, geometries, and dimensions, are analysed for a dedicated Earth observation mission configuration. Based on this analysis, the spectral resolving power and spatial performance of the instrument are evaluated and discussed. The results demonstrate the potential of the grating based FTIR scheme to achieve competitive performance while significantly reducing size, mass, and system complexity for future spaceborne optical sensing applications.

Keywords: Spatial Heterodyne Spectrometer, Fourier Transform Spectrometer, Nanostructures, Diffractive Optics, Earth Observation, Infrared Spectroscopy

1. INTRODUCTION

Spatial Heterodyne Spectrometers represent a well-established class of Fourier-transform spectrometers capable of combining high spectral resolving power with compact optical packages. Since the introduction of the SHS principle, numerous applications have been proposed for atmospheric sounding, airglow observations and trace-gas monitoring, where narrow spectral features must be resolved with high accuracy. The absence of moving components further increases their attractiveness for spaceborne applications requiring long operational lifetimes and high robustness.

Examples of SHS-based instruments include SHOW for middle-atmospheric water vapour observations [1], GRIPS for hydroxyl airglow measurements [2] and AtomCube for mesospheric temperature sounding using the oxygen A-band [3]. These instruments illustrate the broad applicability of SHS technology across a wide range of spectral regions and measurement scenarios.

Despite these advantages, conventional SHS architectures remain based on Michelson-type interferometers and require several discrete optical components, including beam splitters, diffraction gratings and reflective elements. This results in non-negligible alignment effort and instrument complexity. For emerging small-satellite missions and highly integrated payload concepts, alternative optical architectures with reduced component counts are therefore of increasing interest.

The objective of the present work is to investigate a fully diffractive SHS architecture based on nanostructured gratings. The study focuses on deriving the governing interferometric relationships, assessing the achievable resolving power and quantifying the fundamental limitations imposed by the geometry of the proposed system.

2. 2. STATE OF THE ART OF SPATIAL HETERODYNE SPECTROSCOPY

The Spatial Heterodyne Spectrometer (SHS) is a spectroscopic instrument that combines the high spectral resolving power of a Michelson interferometer with the compactness and robustness of a grating spectrometer. In a conventional Michelson interferometer, mirrors are placed at the ends of the two interferometer arms and optical path information is obtained by mechanically scanning one mirror. In contrast, an SHS replaces the mirrors with diffraction gratings fixed at a small angle relative to the optical axis. This arrangement generates a stationary interference pattern across the detector plane, eliminating the need for moving components. The resulting spatial fringe frequency is directly related to the wavelength of the incident light, allowing spectral information to be extracted through Fourier transformation of the recorded interferogram.

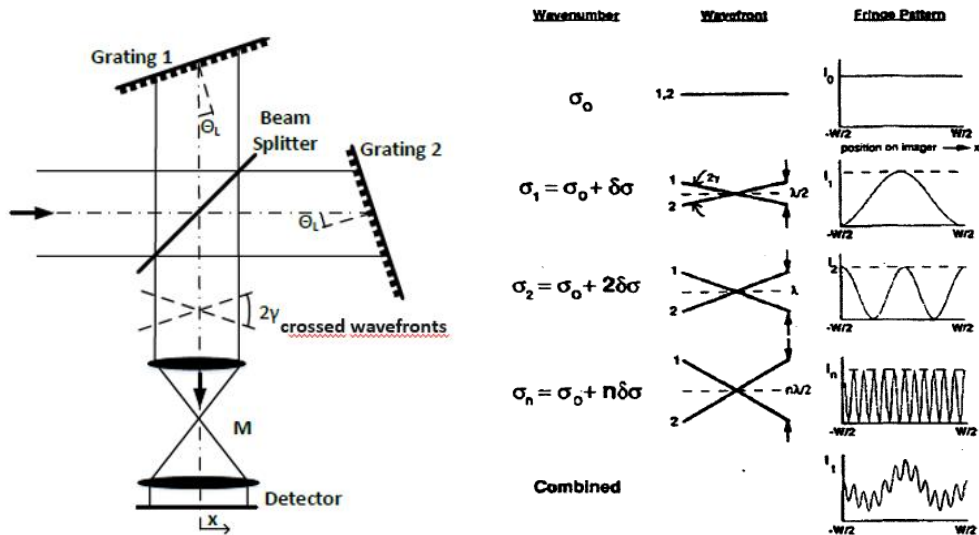


Figure 1 Conventional Michelson-type SHS concept [4]

A key advantage of the SHS architecture is its ability to achieve very high spectral resolving power within a compact optical package. The resolution is primarily determined by the illuminated grating width rather than the overall instrument length, enabling resolving powers exceeding $R = \lambda/\Delta\lambda > 10^4$ in relatively small instruments. Furthermore, the absence of moving parts significantly enhances mechanical reliability and simplifies operation in space environments, where vibration tolerance, long-term stability, and reduced mechanism count are highly desirable.

The SHS operates around a predefined Littrow wavelength, for which light propagating through both interferometer arms produces no spatial fringes. Spectral components displaced from the Littrow wavelength generate interference fringes with spatial frequencies proportional to their wavelength offset. The recorded detector image therefore contains a superposition of fringe patterns corresponding to all wavelengths within the instrument passband. Fourier analysis converts the measured interferogram into the source spectrum.

For space science applications, SHS instruments provide several important benefits:

- High spectral resolution in a compact instrument volume.
- High optical throughput compared with slit-limited dispersive spectrometers.
- No moving mechanisms, reducing complexity and increasing reliability.
- Excellent suitability for remote sensing of narrow spectral features, such as atmospheric trace gases and airglow emissions.

Main drawbacks are

- small bandwidth of below 60 nm
- entanglement of the spectral information with spatial information of one dimension
- absolute wavelength cannot be retrieved, it is defined by the spectrometer geometry and in particular by the Littrow angle of the gratings
- Center wavelength needs to be calibrated

3. FULLY DIFFRACTIVE SHS CONCEPT

The grating-based Spatial Heterodyne Spectrometer (GSHS) is an interferometric spectrometer architecture that employs a set of diffractive optical elements to simultaneously perform beam splitting, beam steering, spectral dispersion, and beam recombination within a highly compact optical layout. In contrast to classical SHS configurations based on Michelson interferometers with Littrow gratings, the grating-based approach integrates several optical functionalities directly into the grating elements, enabling a simplified and mechanically robust instrument design.

The proposed SHS scheme is based on three diffraction gratings arranged to form the interfering optical paths. The first grating acts as a beam splitter, dividing the incident optical wavefront into two coherent beams. These beams are subsequently redirected by the second grating, which determines the optical path geometry and introduces wavelength-dependent angular dispersion. Finally, the third grating recombines the two beams and aligns them onto a common propagation axis, allowing the formation of a spatial interference pattern on the detector plane.

Unlike conventional SHS in which separate components are required for beam splitting, redirection, and dispersion, all three gratings incorporate simultaneously multiple of those functions like the 1st grating, which serves as a beam splitter and contributes to the dispersive signal. The superposition of the dispersed wavefronts generates an interferogram whose spatial frequency content is directly related to the spectral composition of the incident radiation. The input spectrum is subsequently recovered through Fourier analysis of the measured interference pattern.

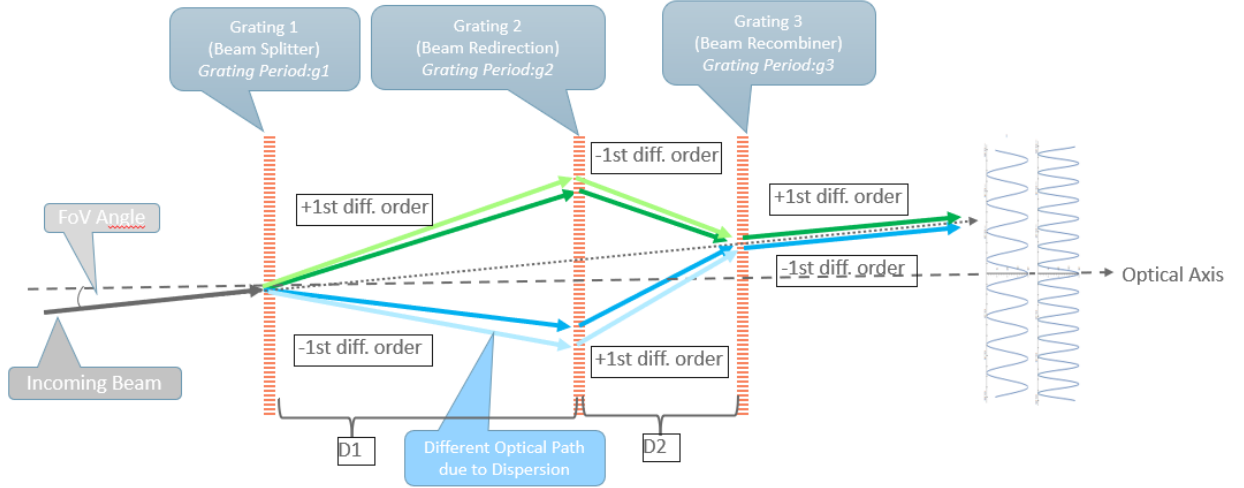
A defining characteristic of the grating-based SHS concept is the combination of multiple optical functions within a single class of optical element. The three-grating configuration enables:

- Beam splitting by the first grating.
- Beam redirection and path formation by the second grating.
- Beam recombination and co-alignment by the third grating.
- Spectrally dispersed signal generated by first two gratings.

This high degree of functional integration reduces the number of discrete optical components required within the instrument and simplifies the optical architecture compared with conventional interferometric spectrometers.

The grating-based SHS offers several advantages that make it particularly attractive as an alternative to Michelson type spectrometers.

- Combination of optical functionalities
- Easy integration
- Precise lithographic control of optical parameters
- Compactness

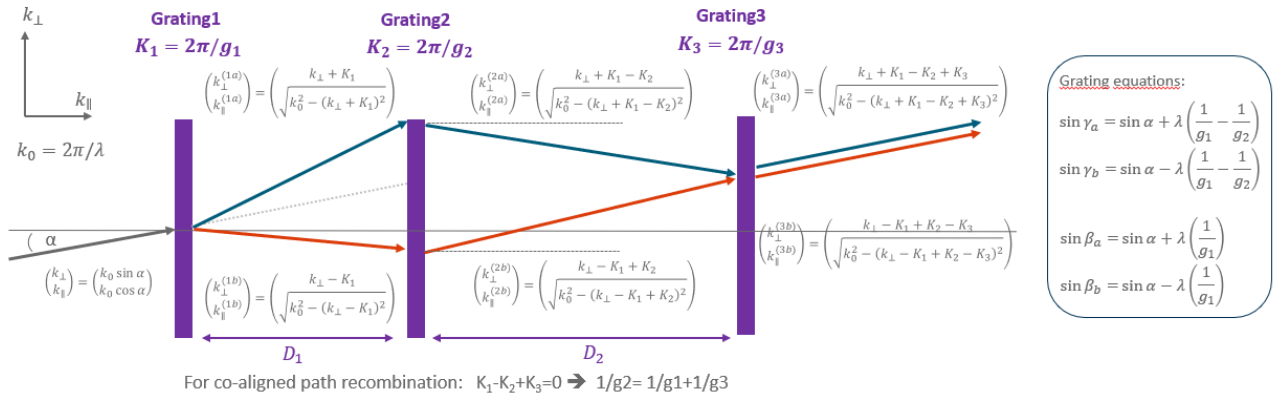


For co-aligned path recombination: $1/g_2 = 1/g_1 + 1/g_3$

Figure 2 Overview of the nanostructures-based SHS concept

4. ANALYTICAL MODEL

A wave-vector analysis was performed to derive the optical path difference between both interferometer arms. By decomposing the diffracted wave vectors into components parallel and orthogonal to the optical axis, it can be shown that only the longitudinal components contribute significantly to the interference signal for small field angles.



For co-aligned path recombination: $K_1 - K_2 + K_3 = 0 \Rightarrow 1/g_2 = 1/g_1 + 1/g_3$

Figure 3 Beam splitting scheme and decomposition of wave vectors

Wavevectors along the direction parallel to the optical axis:

After 1st grating:

$$k_{||}^{1a} = \sqrt{k_o^2 + (k_o * \sin \beta_a)^2} = k_o \sqrt{1 + \left(\sin \alpha + \frac{\lambda}{g_1} \right)^2}$$

$$k_{||}^{1b} = \sqrt{k_o^2 + (k_o * \sin \beta_b)^2} = k_o \sqrt{1 + \left(\sin \alpha - \frac{\lambda}{g_1} \right)^2}$$

After 2nd grating:

$$k_{||}^{2a} = \sqrt{k_o^2 + (k_o * \sin \gamma_a)^2} = k_o \sqrt{1 + (\sin \alpha + \frac{\lambda}{g_1} - \frac{\lambda}{g_2})^2}$$

$$k_{||}^{2b} = \sqrt{k_o^2 + (k_o * \sin \gamma_b)^2} = k_o \sqrt{1 + (\sin \alpha - \frac{\lambda}{g_1} + \frac{\lambda}{g_2})^2}$$

Phase accumulated along the direction parallel to the optical axis:

Upper path:

$$s_{up} = k_{||}^{1a} * D1 + k_{||}^{2a} * D2 = D1 k_o \sqrt{1 + (\sin \alpha + \frac{\lambda}{g_1})^2} + D2 k_o \sqrt{1 + (\sin \alpha + \frac{\lambda}{g_1} - \frac{\lambda}{g_2})^2}$$

Lower path:

$$s_{low} = k_{||}^{1b} * D1 + k_{||}^{2b} * D2 = D1 k_o \sqrt{1 + (\sin \alpha - \frac{\lambda}{g_1})^2} + D2 k_o \sqrt{1 + (\sin \alpha - \frac{\lambda}{g_1} + \frac{\lambda}{g_2})^2}$$

Substitutions made:

$$\frac{1}{g_{eff}} = \frac{1}{g_1} - \frac{1}{g_2} \quad (= -\frac{1}{g_3})$$

Phase difference (OPD):

$$\begin{aligned} OPD &= \frac{2\pi}{\lambda} (s_{up} - s_{low}) \\ &= \frac{2\pi \left(-D1 \sqrt{1 - \left(-\frac{\lambda}{g_1} + \sin[\alpha]\right)^2} + D1 \sqrt{1 - \left(\frac{\lambda}{g_1} + \sin[\alpha]\right)^2} - D2 \sqrt{1 - \left(-\frac{\lambda}{g_{eff}} + \sin[\alpha]\right)^2} + D2 \sqrt{1 - \left(\frac{\lambda}{g_{eff}} + \sin[\alpha]\right)^2} \right)}{\lambda} \end{aligned}$$

Phase difference for small FoV angles α (Taylor expansion at $\alpha=0$):

$$OPD = -4\alpha\pi \left(\frac{D1}{g_1 \sqrt{1 - \frac{\lambda^2}{g_1^2}}} + \frac{D2}{g_{eff} \sqrt{1 - \frac{\lambda^2}{g_{eff}^2}}} \right)$$

This expression illustrates how a zero frequency in the interferogram, which is needed to achieve a well centered Fourier spectrum, can be realized. This is only the case when the grating constant $1 / g_{eff}$ becomes negative and consequently $(1/g_2)$ becomes larger than $(1/g_1)$.

The resulting two beam interference signal dependent on OPD can be written as:

$$I(OPD) = 2(1 + \cos[OPD])$$

The resulting analytical expression reveals that the optical path difference depends on the field angle, grating constants and separation distances between the gratings. Unlike conventional SHS systems, the phase evolution is not strictly linear with field angle. Instead, higher-order terms are generated, which results in chirped interferograms over extended angular ranges (see Figure 4)

This behaviour constitutes the principal physical difference between conventional Littrow-based SHS configurations and the investigated grating-based architecture

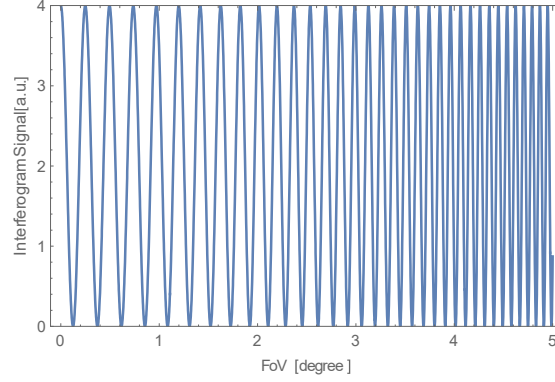


Figure 4 Chirped interference signal for large FoV.

5. RESOLVING POWER

The limitation of the field of view, and consequently of the optical path length, leads to a reduction in spectral resolution. It is therefore necessary to derive a mathematical expression for the spectral resolving power and to determine its impact, and the constraints it imposes on the design parameters.

The spectral resolution is related with the sensitivity of the OPD with respect to the wavelength λ , which is inferred by determining of the derivative $dOPD$ of the optical phase difference wrt. λ . Using the common expression for the spectral resolution $R = \lambda/d\lambda$ the expression for $dOPD$ becomes:

$$dOPD = \frac{\partial OPD}{\partial \lambda} d\lambda = \frac{\partial OPD}{\partial \lambda} \lambda \frac{d\lambda}{\lambda} = \frac{\partial OPD}{\partial \lambda} \lambda \frac{1}{R}$$

Two distinct wavelength can be separated in the Fourier spectrum when they lead to a change in the interferogram by 1 fringe or a phase change of 2π .

$$2\pi = dOPD = \frac{\partial OPD}{\partial \lambda} \lambda \frac{1}{R}$$

$$R = \frac{\partial OPD}{\partial \lambda} \frac{\lambda}{2\pi}$$

Compiling the $(\partial OPD/\partial \lambda)$ entering it into the above formula for R results in:

$$R = -2\alpha\lambda^2 \left(\frac{D1}{g1^3 \left(1 - \frac{\lambda^2}{g1^2}\right)^{3/2}} + \frac{D2 \left(\frac{1}{g1} - \frac{1}{g2}\right)^3}{\left(1 - \left(\frac{1}{g1} - \frac{1}{g2}\right)^2 \lambda^2\right)^{3/2}} \right)$$

Besides the dependencies on the FoV/incidence angle and wavelength, the spectral resolution shows the following dependencies:

- The terms $(1 - \dots)^{3/2}$ are ~ 1 .
- Square dependency on λ $\rightarrow$ infrared applications
- Linear dependency on grating distances D1 and D2 $\rightarrow$ limited by mech. envelope
- Cubic dependency on grating constants $\frac{1}{g1}, \left(\frac{1}{g1} - \frac{1}{g2}\right)$ $\rightarrow$ limited by diffraction angles and diffraction efficiencies of nanostructures

A parameters study for a design parameter set representative for a compact instrument footprint has been performed to analyse the dependency of the resolving power on free parameters. The following parameters has been selected as fixed:

Table 1 Design parameters for a parameter space study

Parameter	Value	Comment
Wavelength λ	1550 nm	OH spectroscopy (GRIPS)
Grating constant of grating 2 $\frac{1}{g2}$	600 lines/mm	Maximum diffraction angle provided by nanostructures
Half FoV α	0.6°	Quasi-linear FoV regime
Overall axial dimension D1+D2	< 50 mm	Compact instrument footprint
Grating constant of grating 1 $\frac{1}{g1}$ and grating distance D1	Free parameters	
grating distance D2	D2 is fully determined by all other parameters	Determined by condition for beam recombination

In Figure 6 the result of the parameter space analysis is presented. It shows that within the listed assumptions on compactness and technological limits the resolving power R in the range of below 200. A maximum R =125 can be achieved for the following parameter values:

1/g1= 96 lines/mm

D1= 40 mm

D2=4 mm

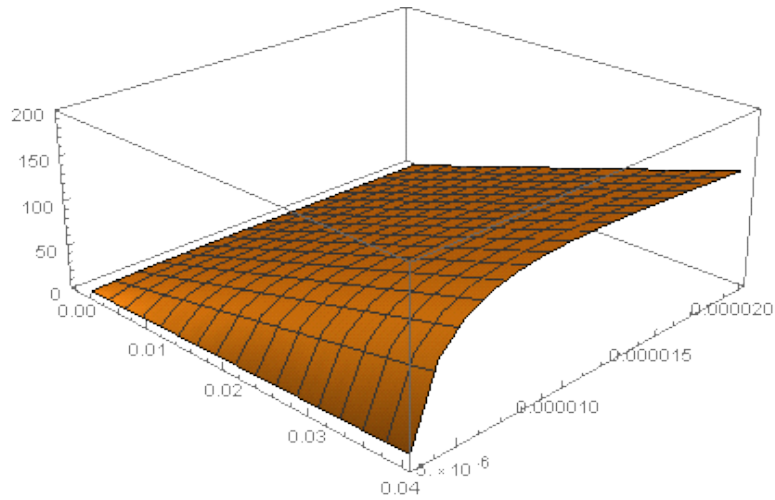


Figure 5 Parameter space to maximize the spectral resolution (R dependent on D_1 [m] and g_1 [m])

Compared to conventional SHS instruments, which typically achieve resolving powers exceeding 5,000, the nanostructure-based SHS concept presented here provides a spectral resolution that is approximately one to two orders of magnitude lower. Since the grating constants are largely constrained by the limitations of current nanostructure technology, the primary means of increasing the resolving power is to enlarge the physical dimensions of the SHS.

To reach resolving powers of conventional SHS systems, the grating separation D_1 would need to be increased by a factor of approximately 10 to 50. This would result in instrument dimensions exceeding 500 mm and potentially reaching 2,500 mm. Under such conditions, the key advantage of the nanostructure-based SHS concept, namely its compactness, would largely be put in question.

6. NUMERICAL VALIDATION

To verify the analytical findings, a paraxial optical model was implemented in OpticStudio. The interference signal was evaluated using coherent Huygens point-spread-function calculations. The simulated interferograms reproduce both the frequency evolution and the phase behaviour predicted by the analytical model. Excellent agreement was observed over all investigated wavelength detunings.

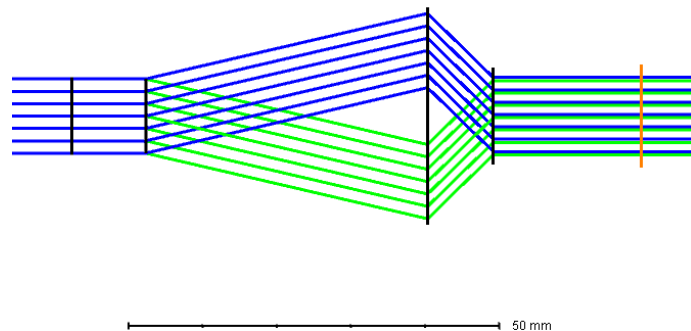
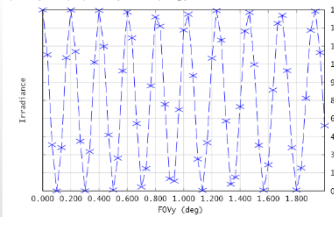
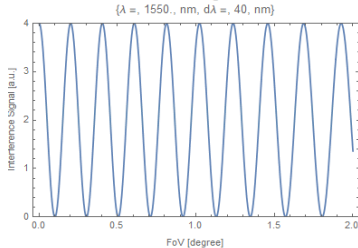
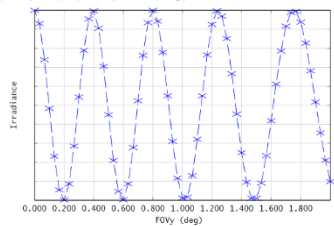
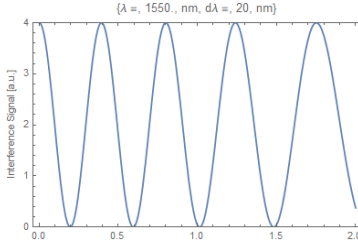
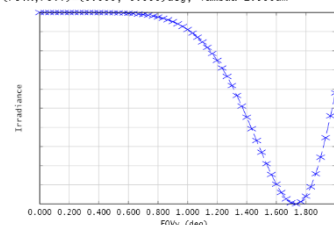
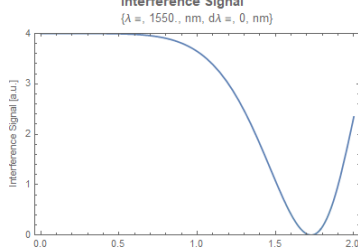
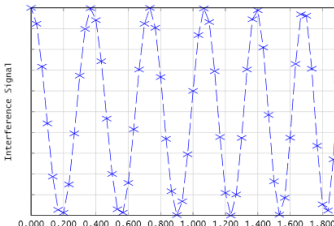
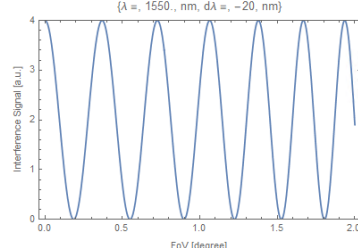
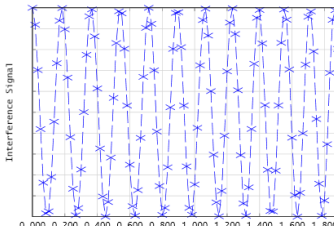
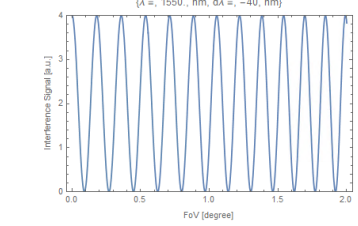


Figure 6 Optical layout of the simpler afocal SHS model

Fehler! Verweisquelle konnte nicht gefunden werden. shows the simulated interference signals for different detuning and compares it directly with the corresponding analytical interference signal. Very good agreement between the

interference patterns can be observed, demonstrating the consistency and validity of both the simulation and the analytical model. The only discrepancy is a inversion of the sign of the detuning.

Table 2 Comparison of modelled and analytically derived interference signal

Simulated Interference Signal (Optics Studio)	Analytical Interference Signal
(FOVx,FOVy)=(0.000, 0.000)deg; $\lambda=1.510\mu\text{m}$ 	Interference Signal ($\lambda = 1550 \text{ nm}$, $d\lambda = 40 \text{ nm}$) 
(FOVx,FOVy)=(0.000, 0.000)deg; $\lambda=1.530\mu\text{m}$ 	Interference Signal ($\lambda = 1550 \text{ nm}$, $d\lambda = 20 \text{ nm}$) 
(FOVx,FOVy)=(0.000, 0.000)deg; $\lambda=1.550\mu\text{m}$ 	Interference Signal ($\lambda = 1550 \text{ nm}$, $d\lambda = 0 \text{ nm}$) 
(FOVx,FOVy)=(0.00, 0.00)deg; $\lambda=1.57\mu\text{m}$ 	Interference Signal ($\lambda = 1550 \text{ nm}$, $d\lambda = -20 \text{ nm}$) 
(FOVx,FOVy)=(0.00, 0.00)deg; $\lambda=1.59\mu\text{m}$ 	Interference Signal ($\lambda = 1550 \text{ nm}$, $d\lambda = -40 \text{ nm}$) 

7. CONCLUSIONS

A concept for a grating-based Spatial Heterodyne Spectrometer (SHS) was presented and analyzed in detail. The interference signal was derived analytically, and optimal parameters for maximizing the spectral resolution were identified, while taking into account technological limitations of nanostructure fabrication, such as diffraction and deflection angles.

Based on these design parameters, a paraxial optical model of the SHS interferometer was implemented in OpticStudio. A coherent calculation of the interference signal was achieved using an evaluation of the Huygens point spread function. Very good agreement between the simulated and the analytical signals was obtained.

However, the interference pattern exhibits a pronounced nonlinearity in the phase difference. This imposes limitations on the achievable optical path difference and, consequently, on the spectral resolution. For a compact design with an axial length on the order of 50 mm, a resolving power of approximately 116 is obtained, which corresponds to a wavelength resolution of about 13 nm at a wavelength of 1.55 μm .

Compared to conventional SHS systems, which typically achieve resolving powers exceeding 5000, the instrument length would need to be increased by a factor of approximately 10 to 50 in order to attain a similarly high spectral resolution.

ACKNOWLEDGEMENTS

The authors acknowledge funding from the European Space Agency (ESA).

REFERENCES

- [1] (PAT12) Aabid Patel, "Spatial Heterodyne Observations of Water (SHOW) Instrument Characterization" Master thesis, 2012, YORK UNIVERSITY TORONTO, ONTARIO, CANADA
- [2] (STR21) Stehr, Johannes, Knieling, Peter, Olschewski, Friedhelm, Mantel, Klaus, Kaufmann, Martin and Koppmann, Ralf. "GRIPS-HI, a novel spectral imager for ground based measurements of mesopause temperatures" *tm - Technisches Messen*, vol. 88, no. 10, 2021, pp. 655-660. <https://doi.org/10.1515/teme-2021-0043>
- [3] (KAU18) Kaufmann, et. al.: A highly miniaturized satellite payload based on a spatial heterodyne spectrometer for atmospheric temperature measurements in the mesosphere and lower thermosphere, *Atmos. Meas. Tech.*, 11, 3861–3870, <https://doi.org/10.5194/amt-11-3861-2018>, 2018.
- [4] (HAR92) Harlander, J., Reynolds, R. J., Roesler, F. L., and Li, G., Spatial Heterodyne Spectroscopy: Laboratory Tests of Field Widened, Multiple Order, and Vacuum, Ultraviolet Systems. *SPEE Proceedings*, Vol. 1743, pg. 28-59, 1992.