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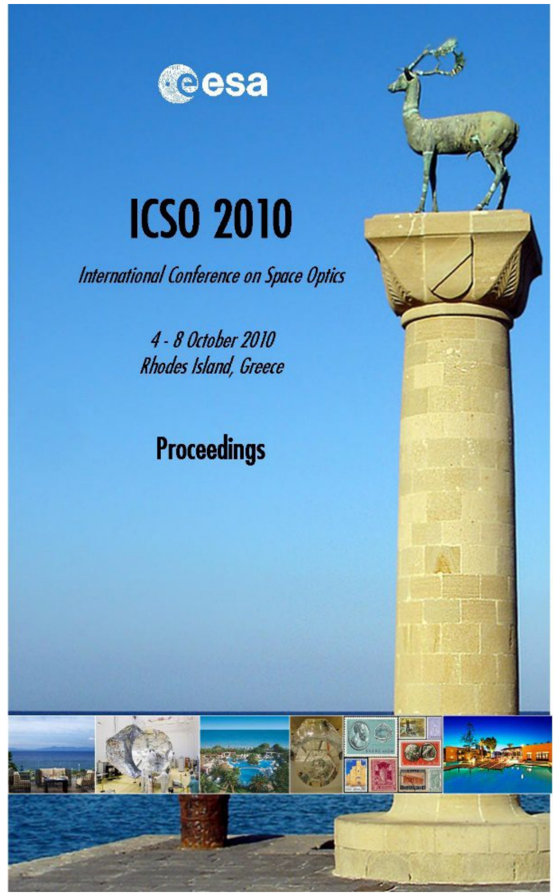


## *A very demanding spectrometer optical design for ExoMars Mission*

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# A VERY DEMANDING SPECTROMETER OPTICAL DESIGN FOR EXOMARS MISSION

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## INTRODUCTION

The objective of this report is to present the study performed for a specially demanding solution of a spectrometer [1] design based on a transmissive holographic grating especially designed to actuate as the dispersion element. The main driver of the design has been to obtain a device with a clear reduction in mass, power and mechanical envelope with respect to the previous configuration based on a prism and/or Echelle grating. This simplification is produced mainly at expense of the waveband range. This study has been carried out by Laboratorio de Instrumentación Espacial (LINES) optical designers from Instituto Nacional de Técnica Aeroespacial (INTA).

## OPTICAL DESIGN AND PERFORMANCE

The optical subsystems have been designed attending to their main functionalities that have been summarized as:

**Collimator subsystem**: This first element collects the energy supplied by the fibres and collimates it to reach the grating element. The spectrometer includes one entrance fibre optic port. A specially designed mechanical coupler should be considered for the implementation of this element. The optical fibre is multimode with 50 microns core.

**Dispersive element**: It is composed by a transmission grating that disperses spectrally the flux produced by the collimator subsystem. It is a Volume Phase Holographic Grating from Wasatch Photonics, working at 32.84° Angle Of Incidence (AOI) with efficiency up to 70% at the whole spectral range (535-675nm).The Angle Of Diffraction (AOD) is 32.84° too. The use of gratings as a dispersive element has been widely found on the literature [2].

**Collector subsystem**: This optical system collects the energy dispersed through the grating and focuses it onto the detector. The selected detector is the CCD231-84 from e2V which is a front illuminated scientific sensor.

Special glasses have been selected to compensate thermal defocusing in a wide thermal range (from -40 to -10º C). In order to assure that the Abbe number and the thermal change in focal length of the optical elements have been tuned.

The three subsystems above mentioned, collimator, grating and collector, whose main element is the diffraction grating have been designed to separate the spectral lines in one row on the detector. This means that we actually are considering a much more basic grating that those considered in our first designs but the versatility of our actual design allows us to incorporate a Multiplexed grating such, as the Holoplex from Kaiser Optical System [3], with minor changes in our collector subsystem if required.

In Fig. 1. we show the linear dispersion achieved in our design, the line spread 10.5 mm in the image plane corresponding to 13.3 nm/mm. This geometry can be changed by changing the properties of the grating.

In the following paragraphs we describe the main characteristics of each spectrometer subsystem.

*Holographic grating*

The VPH grating, supplied by Wasatch Photonics, is recorded on dichromated gelatine placed between two pieces of glass (fused silica) like a sandwich. The epoxy used to sealing the grating is Epo-Tek NOA61. The gelatine contains periodic changes of index that were created by the interference of two laser beams and photochemically processed. Fig. 2. shows a front and side view of this kind of gratings.

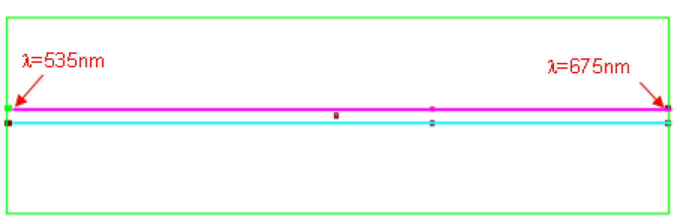


**Fig. 1.** Waveband and spectral lines of the spectrometer.

*Collimator subsystem*

The collimator subsystem is designed in the spectral range of 535 to 675nm and the best quality is assured in order to maintain the achromatic collimation degree for all the wavelengths range. It is clear that this reduced range can be well controlled by using standard optical design. The numerical aperture of the fibre limits the minimum #F-number of this subsystem in order to avoid loss of power in the system, with this in mind the #F required is the minimum required 2.27, higher values are possible if the SNR study confirm the feasibility [1].
The solution that fulfils all the requirements is showed in Fig. 3.
The collimator is composed by two doublets (NLAF2, NSF4, NBK10, SF10 from SCHOTT). The optical quality and the collimating degree are good enough to assure the correct behaviour of the dispersing element. The Focal length selected is 82.13 mm and the #F-number designed is 4.88.

*Collector subsystem*

The third subassembly is the collector which collects the dispersed energy by the diffraction grating and focuses it on the detector. It is compound by four singlets. The glasses have been selected to allow cover the waveband required (535-675nm). The stop aperture has been selected to be a real surface located before the grating in order to control as much as possible the size of this commercial element. In other configurations in which the aperture stop is in the middle of the Gauss doublet used to collect the energy in this arm, the size of the grating was considered very large. This size forced to design a much more complicated collimated subsystem. The actual situation, real entrance pupil, assures the most compact optical design.
The #F number designed for the collector subsystem has been 2.5 to have margin to be coupled to the previous subassembly. The focal length is 38.13 mm. A view of the proposed design is showed in Fig. 4.

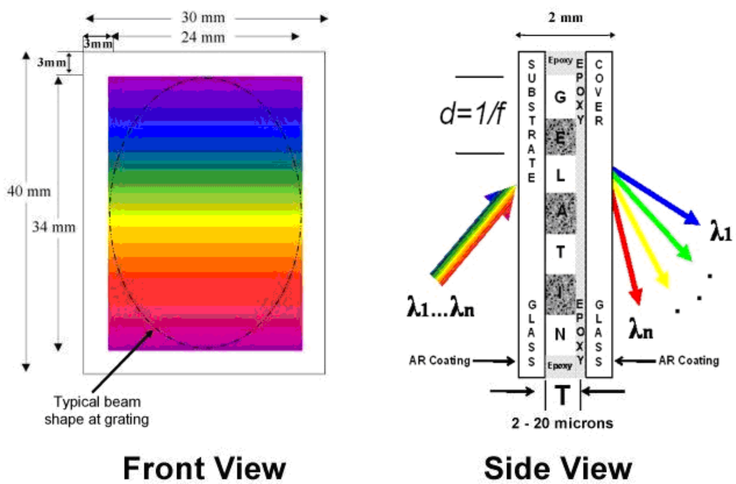


**Fig. 2.** Example of a VPH grating from Wasatch Photonics

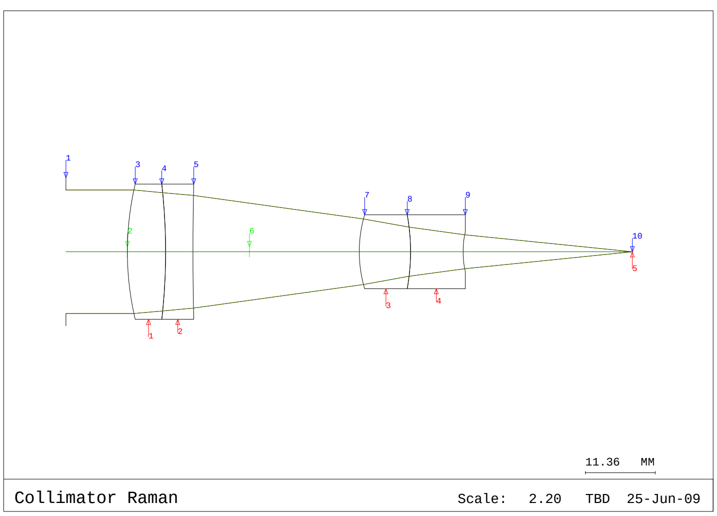


**Fig. 3.** Collimator Subsystem

The collector subsystem shows an additional decentered angle of 3.02º to compensate the diffraction orders at the required spectral range. The spectral resolution obtained and the extension of each spectrum on the focal plane is included in Table 1.

CRITERIA FOR SELECTING THE OPTICAL GLASSES

The system has been designed with different glasses from SCHOTT: NLAF2, NSF4, NBK10, SF10, NLAK22. The 'N' in the name of these glasses means that they are free of lead.

All optical elements included in this configuration are well known for space applications. In this sense the LINES/INTA lab has developed its own protocol program to characterize the influence of the space environment in the optical materials. As it is well-known, the main problem is the appearance of color centers that produce lost of transmittance. We have characterized previously a list of more than 20 glasses with the radiation effect well characterized versus the space radiation dose that will be used for the final design. With this knowledge the selection the glasses and its qualification could be a much easier task.

The only component that is considered critical is the grating. Low information level is available from the provider and it has been necessary to procure several gratings to perform an extensive space qualification of the device. The Dichromated gelatine shows a good behaviour with respect to the gamma radiation damage as was tested by [4], [5]. But it is necessary to know the behaviour of the whole Volume Phase Holographic Grating (VPHG), under space conditions such as thermal cycling, space radiation and mechanical test. This work is under development at this moment in our lab.

Table 2 shows the main characteristics of the glasses used for spectrometer optical design.

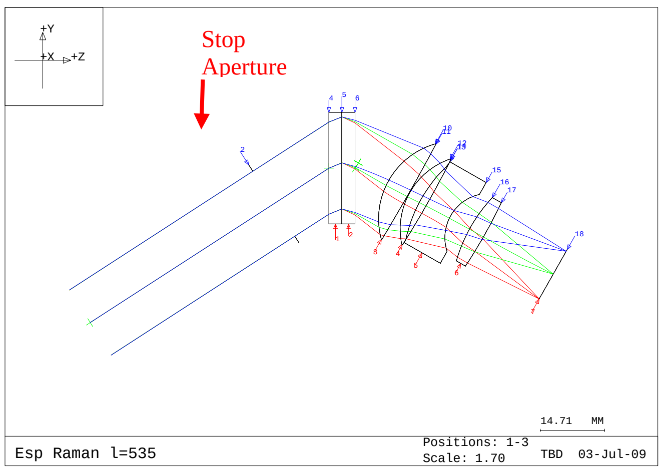


**Fig. 4.** Collector Subsystem

**Table1.** Spectral data of the spectrometer

| | Spectral Range (nm) | Dispersion (nm/px) | Extension CCD (mm) | Extension (px) |
|---|---|---|---|---|
| *Band 1* | 535-675 | 0.2 | 10.5 | 700 |

**Table 2.** Optical materials:: $n_d$ is the index of refraction for line d, $V_d$ is the Abbe number, dn/dT is the temperature coefficient of refractive index, $\alpha$ is the thermal expansion coefficient and $T_i$ is Internal transmission of the glass.

| **MATERIAL** | **$n_d$** | **$V_d$** | **dn/dT ($10^{-6}$/K)** | **$\alpha$ ($10^{-6}$/K)** | **$T_i$ (530nm) (10mm)** |
|---|---|---|---|---|---|
| **NLAF2** | 1.7439 | 44.85 | -1.3 | 8.06 | 0.997 |
| **NSF4** | 1.7551 | 27.38 | -1.2 | 9.45 | 0.993 |
| **NBK10** | 1.4978 | 66.95 | 1.10 | 5.8 | 0.997 |
| **SF10** | 1.7272 | 28.41 | 4.9 | 7.5 | 0.991 |
| **NLAK22** | 1.6513 | 55.89 | 0.9 | 6.6 | 0.997 |

*Athermalization*

The choice of the materials for the optical design has a great impact on both, the achromatization and the athermalization of the instrument. The ideal case is to select pairs of glasses that compensate both the chromatic aberration and the sensitivity to changes in temperature. In order to have a first approach to this choice of materials, it is required to calculate the change of the focal length of the doublets with both the wavelength and the temperature. Following the classical procedure [6] to perform this compensation we obtain the final requirement to achromatize a doublet composed by two elements A and B (1).

$$V_A \cdot \varepsilon_A = V_B \cdot \varepsilon_B \quad (1)$$

where $V_A$ is the Abbe number of element A and $\varepsilon_A$ is expressed for each glass as

$$\varepsilon = \frac{1}{n-1}\frac{dn}{dT} - \alpha \quad (2)$$

being $\alpha$, the thermal coefficient of the corresponding glass.

Consequently, it can be concluded that finding pairs of glasses whose $V \cdot \varepsilon$ product are equal (or similar) can help to athermalize and achromatize a doublet.

In our first thermal analysis of the spectrometer we found that the system had an appreciable sensitivity to temperature changes, so it was necessary to redesign the optics due to the original doublets on the collimator were not athermalized. Finally it was found a better combination of glasses for the doublets with the glasses from SCHOTT shown their optical properties in the previous section.

The thermal behaviour of the SPU was calculated taking in to account the system integration conditions, 20ºC and the operative conditions, -10ºC to -40ºC.

We have used the Environmental CodeV capability to estimate the focus shift with respect to the temperature range for the whole system. The range obtained for thermal defocus was from 44microns at -40ºC to 23microns at -10ºC.

The influence of this focus shift in the resolution and image quality on our spectrometer has been studied. We have found that the defocus introduced by temperature variation does not affect the spectral resolution of the spectrometer.

THE WHOLE SYSTEM

The complete spectrometer is composed by the merger between the three subassemblies explained before. The presence of a real entrance pupil (stop aperture) located in the collimated path and the high quality obtained for each separated component assures that the complete optical system works correctly. The final location of the stop pupil is not critical in the design and can be fixed by mechanical requirements and not for optical reasons.

The combined system is a 2x relay that translates the optical fibre plane to the detector plane. The image #F is 2.23 and the system has the capability to collect flux enough to detect the Raman peaks as required. This was showed in a specific SNR simulation of the flux level collected by the system for the calcite material that was used as a reference sample. A view of the final optical system is shown in Fig. 5.

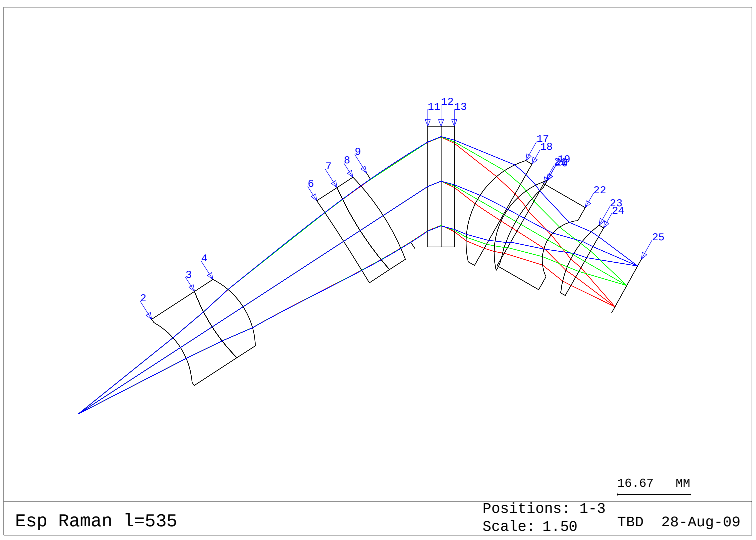


**Fig. 5.** Optical set-up of the spectrometer

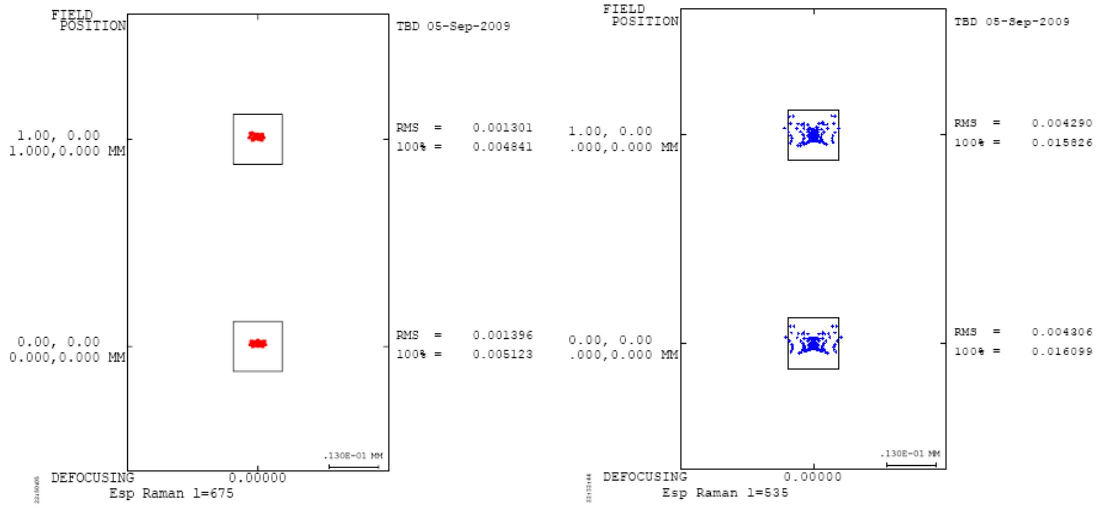


**Fig. 6.** Spots diagrams of curves for 675 nm.

In this case the reference element is the grating and from this system the rest of the elements should be mounted. The MTF of the complete system shows that the quality is very high at the Nyquist frequency (33.33lp/mm).
The spots diagram of the whole system is shown in Fig. 6. in which we include the square dimension of the pixel size (13 microns).

CONCLUSIONS

The design of a spectrometer unit that withstand with the Martian environment is a very demanding optical effort. The very small optical instrument required can be based on a single transmisive holographic grating especially designed to actuate as the dispersion element. The selection of glasses is of vital importance to assure the behavior of the instrument in the operative thermal range. A big effort has been performed in to simplify as much as possible the instrument considering the manufacturing tolerances that assure the optical performances required avoiding the need of refocusing mechanism.

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