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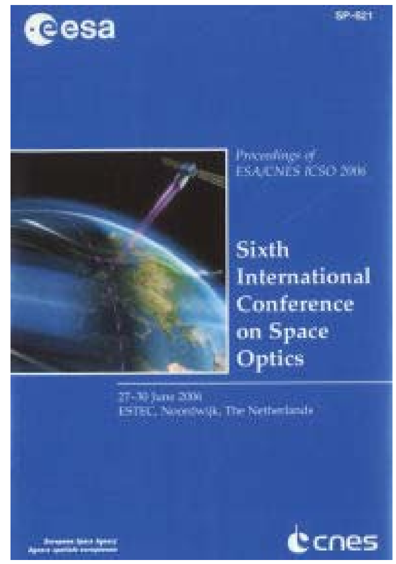

Wedge filter imaging spectrometer

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WEDGE FILTER IMAGING SPECTROMETER

Alain Sémery(1), Jean-Michel Reess(1), Frédéric Lemarquis(2) , Pierre Drossart(1), David Laubier(3), Pernelle Bernardi(1)

(1)Observatoire de Paris / LESIA, Place J. Janssen, 92195 Meudon cedex, France.
alain.semery@obspm.fr
(2)Institut Fresnel, Domaine Universitaire de Saint Jérôme, 13397 Marseille cedex 20, France.
frederic.lemarquis@fresnel.fr
(3)CNES, 18 Avenue Edouard Belin, 31401Toulouse cedex 9, France.
david.laubier@cnes.fr

ABSTRACT

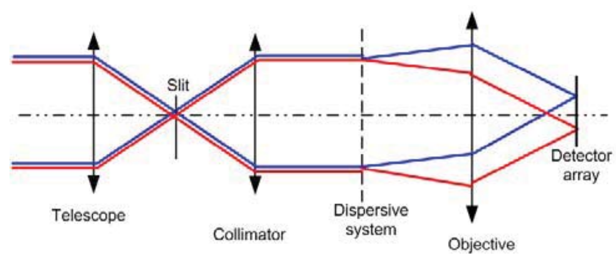
The development of the planetary exploration for landers makes it more and more necessary to have at our disposal small and light instruments. This is why we are developing in our laboratory a light imaging spectrometer with a wedge filter making the spectral splitting. This design already developed in other laboratories has the great advantage to need a limited number of optical components. However its drawback is that at a given instant the different spectral pixels don't see the same spot in the field. We propose a new design to remedy this drawback by the adjunction of a dispersive system in the fore-optics.

1. INTRODUCTION

Since 1996 in LESIA (Laboratory for Experiments in Space and Instrumentation in Astrophysics) we have been involved in the design and realization of imaging spectrometer in the visible and infrared intended to determine the ground and atmosphere composition of planets. Three of them are in space: OMEGA/Mars Express (with IAS Orsay, IFSI Rome, and IKI Moscow) in orbit around Mars, VIRTIS/Rosetta (with IAS Rome, DLR Berlin, and Galileo Avionica Florence) on the road toward Churiumov-Gerasimenko comet and VIRTIS/ Venus Express since April 2006 in orbit around Venus. They are high-performance instruments, with wide spectral bandwidth (0.4 ÷ 5 µm), good spectral resolution (up to 2000) and good spatial resolution. But these instruments, in the 30 Kg range, have been designed for large orbiters. Now the development of small missions on mini or micro satellites and mostly the planetary exploration by means of landers make it more and more necessary to have at our disposal smaller and lighter instruments. Though at each new generation of instrument, the performances with the same mass are increased, we cannot hope to get the same performances with very small instruments. In this case each instrument must be designed for a precise goal. It's why we are developing in our laboratory [1], with the support of CNES, two kinds of very small imaging spectrometers, one dedicated to the high spectral resolution and the second dedicated to larger spectral bandwidth with a low spectral resolution. This last type is based on the use of a wedge filter.

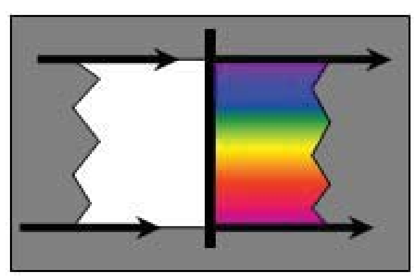
2. CLASSICAL IMAGING SPECTROMETER

The imaging spectrometers mentioned above, are based on the pushbroom principle in which both dimensions of a detector array give a spatial dimension (one sample line) and a spectral dimension (one spectrum per spatial sample). The second spatial dimension is commonly given by the motion of the vehicle or a scanning mirror. The optical principle of such an instrument is given in the following figure:



The slit determines the field of view of the instrument. The collimator and the dispersive system make images of the slit in all the wavelengths spread over the spectral direction, and theses images are focused on the detector pixels using the objective.

3. USE OF A WEDGE FILTER



A wedge filter (or linear variable filter) has a spectral transmission variable along one direction. Roughly it is

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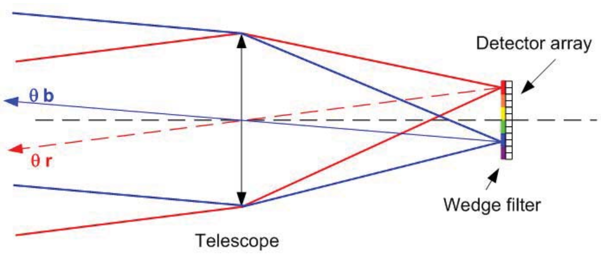
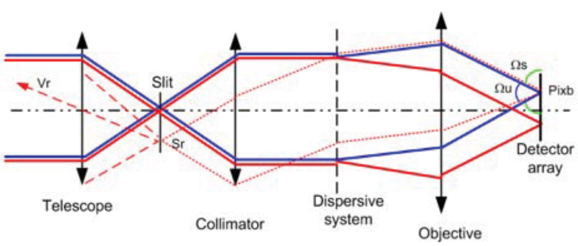
an interferential multilayer filter with thickness varying along one direction. The spectral variation law can be linear or an other function depending on the capability of the process control. We have a contract with Institut Fresnel in Marseille to develop specific wedge filters accommodated to our need.
Several authors [3] [4] [5] propose to associate a wedge filter with a telescope and a detector array to make a very simple pushbroom imaging spectrometer as it is shown on the following figure:



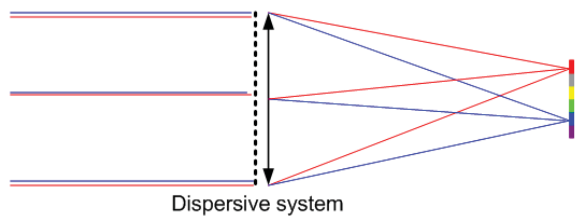
This design has many advantages (but also drawbacks) over the classical one:
The first main advantage of such a spectrometer is due to the low number of optical components and thus a low mass and a compact instrument.
The second advantage is the foolproof spectral registration, due to the fact that the filter is rigidly connected to the detector array. That means that an internal spectral calibration device is not needed.
The last advantage is the reduction of the thermal background for infrared instruments:



Let's consider the pixel Pixb on the figure above of a classical design. The useful light (blue) comes from the slit in the Ωu solid angle but the pixel also sees the slit face in all the other wavelengths in the same solid angle and the whole spectrometer cavity in all the wavelengths in the Ωs solid angle. A shutter in the slit plane allows measuring the background and in the case of infrared spectrometer (above 2 µm) it is necessary to cool down the cavity. N. Gat [2] proposes to use a linear variable filter in the detector plan to reduce the background. Indeed in the wedge filter spectrometer design, each pixel sees only its useful wavelength.
The main drawback of this design is that at a given time each pixel doesn't see the same patch on the ground (θb, θr on the upper figure). This misregistration is well noticed by J. Jeter [4]. He remedies by image resampling, but that needs very good orientation information.

4. ADDING A DISPERSIVE SYSTEM

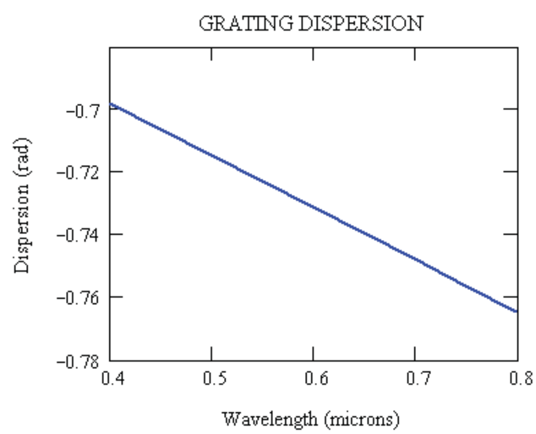
We can remedy the above mentioned drawback by adding a dispersive system in front of the telescope as it is shown in the following figure:

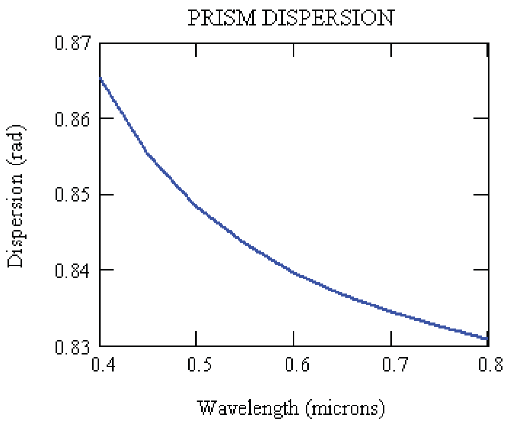


In such a system, if the wedge filter has the same variation law as the dispersion law of the dispersive system (grating or prism) each point of the detector sees the ground in the same direction.
We must note that the dispersive system works in collimated beams thus in the best condition.
The global adjustment between both groups [dispersive system + telescope] and [filter + detector] is not so important while a slight shift relatively to the theoretical position gives a fixed shift in the boresigth angle, that can be calibrated.

5. DISPERSION LAW

In our system the filtering law of the filter must follow the dispersion law of the dispersive system. For a grating the law is quasi linear as shown on the figure below. In the case of a prism the law is no more linear.



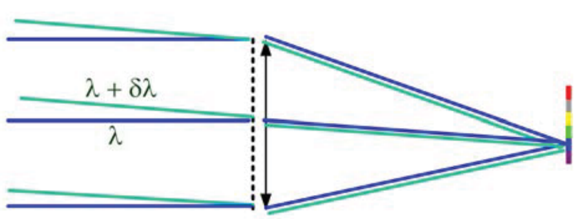


Our partners in Institut Fresnel of Marseille [6][7] who provide us with the filters are able to produce any filter dispersion law by a very good control of the mask and therefore control the thickness of the layer of the filter at any points.

6. FIELD OF VIEW

In a classical imaging spectrometer as shown in §2, the IFOV is given by the slit width which must be imaged on the detector. It is no more the case in the proposed design. Let's consider a perfect system with a very high resolution filter: each point even inside a single pixel sees the same direction in the object field, because the wavelength on the filter follows the wavelength given by the dispersive system.

In fact the field is given by the local spectral bandwidth of the filter: let's consider the blue beams (λ) on the following figure. They come from a point on the axis and are focused on the blue position of the filter. Due to the bandwidth of the filter, the wavelength λ+δλ is also transmitted by the filter, but the corresponding direction in the object field is slightly shifted from the axis direction. This effect makes the field of view.

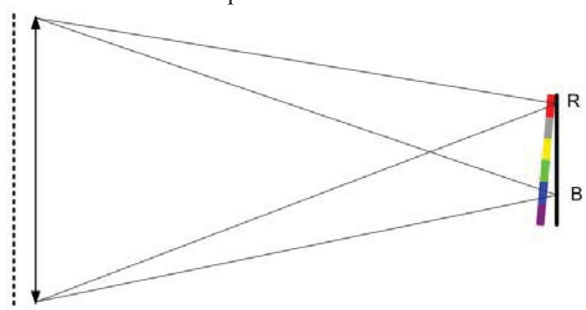


7- BANDWIDTH VARIATION WITH WAVELENGTH

Very high spectral resolution filters can be manufactured in Institut Fresnel in Marseille. Typically for such wedge filters we can achieve δλ = 1 nm at 0.6 µm which gives a resolution (λ / δλ) of 600.

As we said in §5, the transmission law of the filter can deviate from a straight line but commonly the bandwidth is proportional to the wavelength. Therefore, the field of view varies with the wavelength along the spectral dimension. To remedy that we have three options: the first one consists in taking the larger field to determine the sampling. The second option would consist in the realization of filters with a constant bandwidth along the spectrum. This option is not straightforward, but achievable.

The third solution consists in introducing a slope between the detector plan and the filter:



At shorter wavelengths (in B), the beams pass through a larger portion of the filter that increases the apparent δλ which makes the field.

As the filtering function can be assimilated to a Gaussian function and not a crenel, some of the beams are attenuated reducing the transmission of the instrument, and consequently the resolution of the instrument is lower than the filter one

The value of the slope depending on almost all the parameters of the instrument (aperture, total bandwidth, filter resolution, telescope aperture, dispersive system parameters), there is no straightforward calculation to determine it and we have to use a software simulation to find its optimum by iteration process.

7. EXAMPLE OF DESIGN

7.1 Instrument parameters

Telescope:

Focal length	100 mm
Aperture diameter	25 mm

Array detector

Pixel size	40 µm in the spectral direction
Number of pixels	250 in the spectral direction

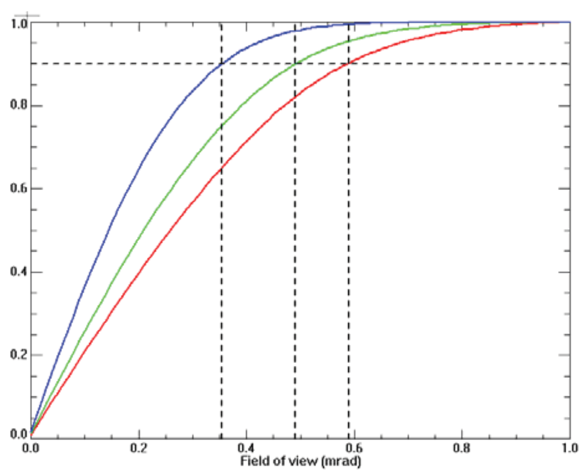
Dispersive system: we choose a grating

Number of grooves	183 mm^{-1}

Total bandwidth	0.4 ÷ 0.8 µm
Filter resolution	λ / δλ = 400

7.2 Performance evaluation:

We determine the field of view, the spectral band and the transmission for each pixel.
Beams filling the pupil in a FOV and spectral bandwidth larger than the expected ones are integrated. Only beams (attenuated by the spectral function of the filter, considered as a Gaussian) falling on a given pixel are considered and contribute to the energy received by the pixel.
We consider that the effective instrument field of view for a given pixel is the one that integrates 90% of the total energy.
To perform that, we plot the contribution of the field of view to the total energy versus the field of view.
The following graphic represents the result of the simulation for a distance d=0 between the filter and the detector, for three wavelengths: 0.8 µm (in red), 0.6 µm (in green) and 0.4 µm (in blue). That confirms that the field of view varies with the wavelength. We can notice that the field is not exactly proportional to the wavelength.



7.2 Optimisation of the angle between the filter and the detector

By iterations we look for the optimal distance between the filter and the detector in order to give the same field of view along the spectrum. We make this optimisation for 3 wavelengths (0.4 µm, 0.6 µm and 0.8 µm). For the first step we take d=0 for 0.8 µm since this wavelength gives the larger field of view.

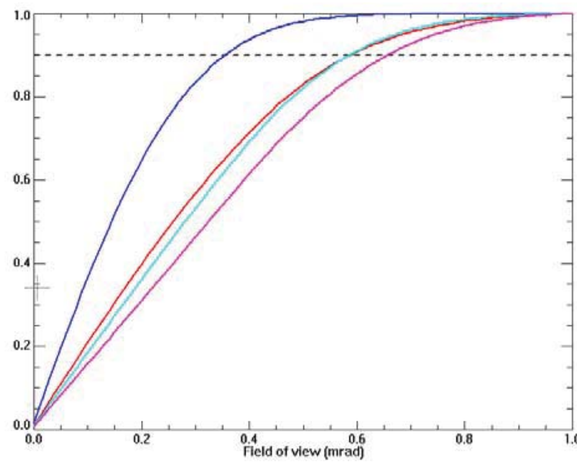
7.2.1 Optimisation for 0.4 µm

The following graphic shows the results of the simulation for distances:

0.8 µm (reference)
d = 0 red curve

0.4 µm
d = 0 blue curve
d = 0.12 mm green curve
d = 0.15 mm pink curve

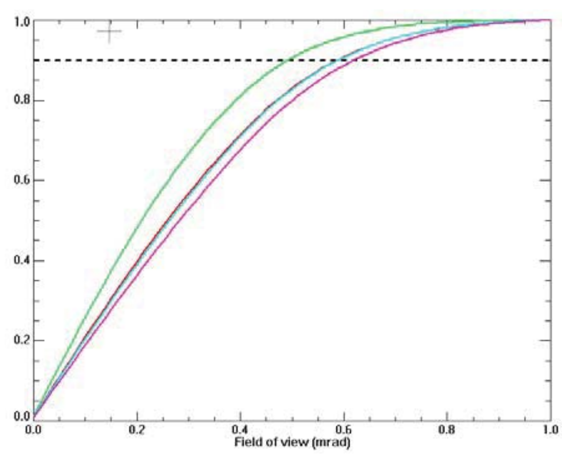
We can see that the optimal distance is d = 0.12 mm



7.2.1 Optimisation for 0.6 µm

The distances are:
d = 0 green curve
d = 0.1mm blue curve
(overcome with the red one)
d = 0.12 pink curve

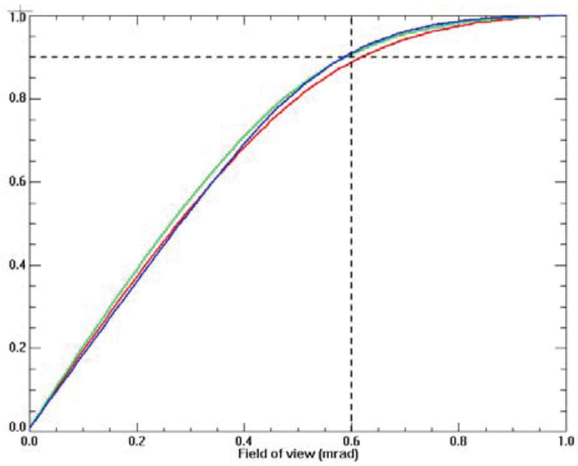
The optimum is obtained for d = 0.1 mm.



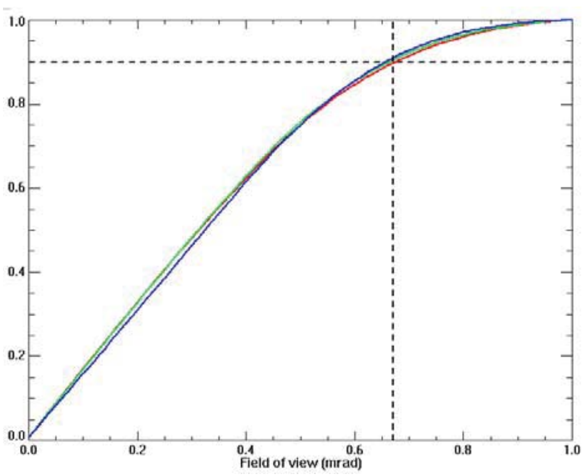
7.2.3 Global optimisation

As the filter is flat, if we consider the found distances for 0.4 µm and 0.6 µm, the distance for 0.8 µm must be 0.08 mm.

The result of the simulation with these three values is shown on the following graphic:



The fields of view are very similar for the three wavelengths.
We also examine if we can remove the slope and put the filter parallel to the detector at a given distance. We simulated step by step and found a good result for a distance d = 0.15mm, with a slight increasing of the field of view. The curves are shown in the following graphic:



7.3 PERFORMANCE SUMMARY

The filter has a constant resolution (λ/δλ). The distance between the filter and the detector increases the apparent δλ, therefore the resolution is decreasing.

Wavelength	Field of view	Resolution	Transmission
0.4 µm	0.6 mrad	115	0.12
0.6 µm	0.6 mrad	170	0.16
0.8 µm	0.6 mrad	230	0.2

8. CONCLUSION

The proposed spectrometer cannot have the same level of performances than a classical one, and its scientific purpose cannot be similar. Anyway such very light (0.5 Kg range) and low resolution spectrometer is well adapted for landers and/or small orbital payload on micro satellites.
The final goal of this development work is to be able to choose the best concept and the best trade-off for a given scientific purpose, taking into account our experience in the classical design and our knowledge of most of the other concepts.

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