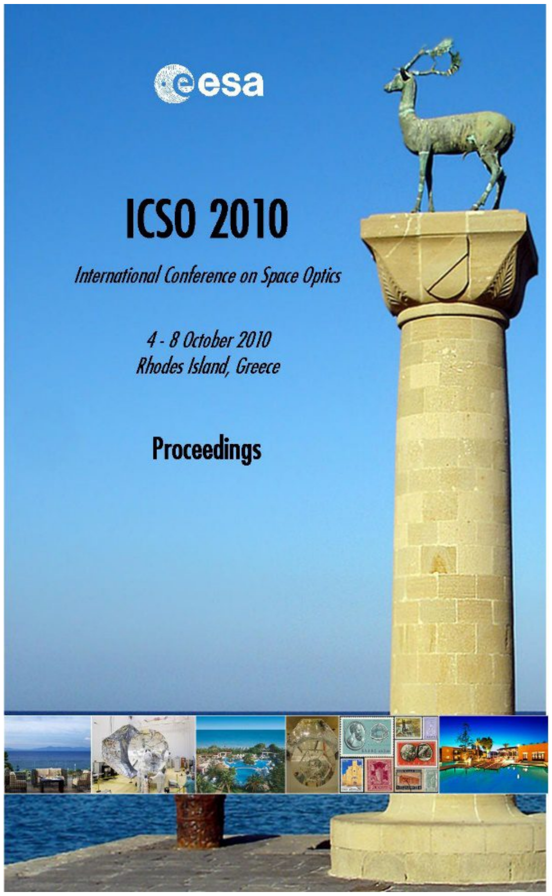

# *Ultra compact spectrometer using linear variable filters*

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# ULTRA COMPACT SPECTROMETER USING LINEAR VARIABLE FILTERS

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## I. INTRODUCTION:

The Linearly Variable Filters (LVF) are complex optical devices that, integrated in a CCD, can realize a "single chip spectrometer". In the framework of an ESA Study, a team of industries and institutes led by SELEX-Galileo explored the design principles and manufacturing techniques, realizing and characterizing LVF samples based both on All-Dielectric (AD) and Metal-Dielectric (MD) coating structures in the VNIR and SWIR spectral ranges. In particular the achieved performances on spectral gradient, transmission bandwidth and Spectral Attenuation (SA) are presented and critically discussed. Potential improvements will be highlighted. In addition the results of a feasibility study of a SWIR Linear Variable Filter are presented with the comparison of design prediction and measured performances. Finally criticalities related to the filter-CCD packaging are discussed.

The main achievements reached during these activities have been:

- to evaluate by design, manufacturing and test of LVF samples the achievable performances compared with target requirements;
- to evaluate the reliability of the projects by analyzing their repeatability;
- to define suitable measurement methodologies

## II. FILTERS REQUIREMENTS

The Ultra Compact Spectrometer study requirements on the filters have been divided for Filter 1 (VIS-NIR) and Filter 2 (VIS-NIR-SWIR). The main requirements for the realization of an LVF for hyperspectral imaging spectrometer for space application are listed in Tab. 1:

**Tab. 1: List of LVF key parameters and requirements**

| Requirement | Definition | Comments | Required Values |
|---|---|---|---|
| Overall Spectral Range | The LVF operating wavelength range | The spectral range width has been chosen in order to be able to exploit, with a single filter, the whole sensor responsivity range | 400 – 1000 nm for filter 1<br>400 – 2500 nm for filter 2 |
| Spectral Resolution (FWHM) | The Full Width at Half Maximum $\Delta\lambda_0$ of the Spectral Response Function for each peak wavelength $\lambda_0$ in the overall spectral range | The values of spectral resolution reachable with LVF design are limited to 10-15 nm (FWHM). Improved FWHMs would require more efforts in terms of design principles and manufacturing. | 20nm @ 443nm<br>15nm @ 665nm<br>15nm @ 740nm<br>20nm @ 940nm |
| Spectral Gradient | The rate of variation of peak wavelength $\lambda_0$ with the spatial coordinate on the LVF along the spectral direction. | Spectral gradient is required to be as higher as possible, to 'sample' with each spectral band, the target for the shortest time possible minimizing satellite vibrations and quick target changes effects. Spectral sampling is obtained by relative movement of Space Craft wrt the Target. | 60nm/mm (as a requirement)<br>250nm/mm (as a goal) |
| Peak Transmittance | Minimum peak transmittance of a monochromatic line $\lambda_0$ for all wavelengths $\lambda_0$ in the overall spectral range | The need of a high value of peak transmittance is correlated to the minimization of exposure time during target acquisition and the spectrometer pupil diameter. | 50% (as a requirement)<br>70% (for filter 1 as a goal)<br>60% (for filter 2 as a goal) |
| Spectral Attenuation | It is the ratio between the energy outside the interval of the parent monochromatic line $\lambda_0$ and the energy inside, for all $\lambda_0$ in the spectral range. | It is required in order to avoid the 'spectral aliasing': considering the pixel pertaining to $\lambda_0$, it collects, in addition, out band signal due to filter spectral attenuation characteristics. | 1% or 5% for filter1 MD; 0.5% for filter 1 AD. The spectral intervals for which the definition is applied are different |

## III. ALL DIELECTRIC LINEAR VARIABLE FILTER 1

AD filter 1 has been studied by INSTITUT FRESNEL. The filter is designed with three coatings deposited on three separate substrates, bonded together with the correct alignment in a final step.

The first coating, facing the detector, is a variable bandpass coating. This coating is mainly responsible of the bandpass specifications. It is deposited on 1 mm thick substrate on which chromium marks are drawn to help for the alignment with the detector. The second coating is a variable long wavelength pass filter, mainly responsible for the rejection level in the short wavelength side. This coating is deposited on 1 mm thick "clear" substrate. The third coating is a variable short wavelength pass filter, mainly responsible for the rejection level in the long wavelength side. This coating is deposited on 1.5 mm thick "clear" substrate.

The main reason to split the design in three basing coatings is linked to the high layer count that is necessary to achieve the required specifications. While the layer count required for the bandpass function is about 30 layers, this layer count is about 100 for each short or long wavelength pass function.

The manufacturing of these three variable all-dielectric coatings is a very long task (cumulated time about 10 weeks non stop), due to both the high layer count and the slow deposition speed resulting from the masking mechanism used to achieve the thickness gradient. The manufacturing of the AD filter encountered difficulties related to the masking mechanism used for the thickness gradient, which did not allow the alignment of the three substrates in which the filter is decomposed. To realize the complete LVF, the spectral pattern profiles shown in Fig. 1a and Fig.1b shall be intended, as first approximation, to shift along the spectral gradient, according to the peak wavelength, for the whole spectral range.

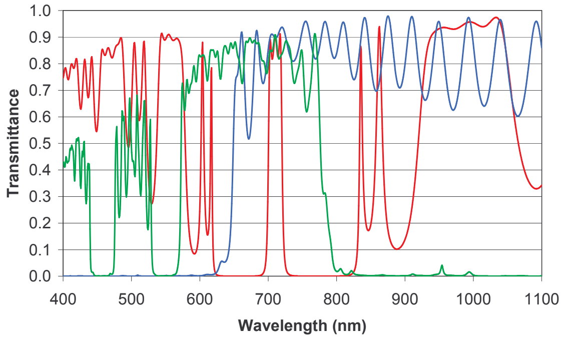

**Fig. 1a:** Theoretical transmittance profile of the three filters for a peak wavelength at 710 nm (band pass: red; short pass: green ; high pass: blue).

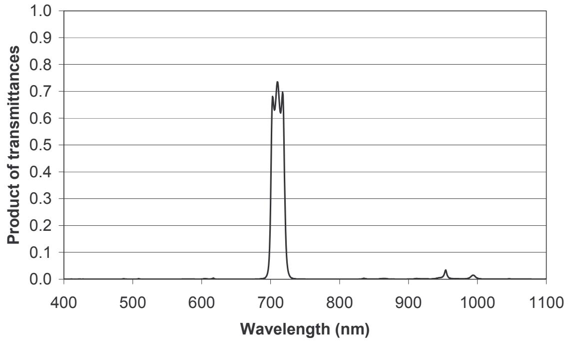

**Fig. 1b:** Theoretical transmittance profile for the three coatings together

Manufacturing problems came from a bending of the mask during deposition, inducing friction with substrates. Of the three obtained filter components, even with degraded optical performance, both the band-pass coating and the long wavelength-pass coating were regarded as "acceptable". On the contrary the optical performance degradation of the short-wavelength pass coating was not considered satisfactory.

Successively the mask issue was fixed, with the design and realization of a new mechanism, allowing the manufacturing of a new short-wavelength pass filter. However, the new filter spectral gradient did not match perfectly the other ones, allowing only a partial verification of the LVF performance in the range.

**Tab. 2: Fresnel AD filter 1 performances**

| Characteristic | Goal | Design Prediction | Measurement |
|---|---|---|---|
| Peak Transmittance | 50% (as a req.)<br>70% (as a goal) | 75% | ≈ 25% |
| Spectral Gradient | 60 (as a req.)<br>250 (as a goal) | 90 nm/mm | 87 nm/mm |
| FWHM | 20 nm @ 940 nm | 22 nm | 23 nm |
| Spectral Attenuation | 0.05<br>0.01 | 0.0176 @ 940 nm<br>0.0174 @ 940 nm | 0.032<br>0.031 |

By putting together the three filter components (unbonded), only the characteristics at 940nm have been measured. The results are shown in Tab. 2.

The present results based on measurements performed on each filter section separately, together with a performance evaluation of the unbonded filter assembly, tend to confirm that the transmittance levels (for the filter section realized with the new mask mechanism), the spectral gradient and the FWHM are in good agreement with specifications, but for a proper analysis all coatings should have been manufactured with the same mechanism. As a conclusion all the partials results obtained during this work tend to prove with some confidence that the final goal can be achieved. LVF AD technology allows to obtain, in principle, higher performances with respect to the MD one, both for spectral resolution and transmittance. The samples manufactured and tested during the study partially confirm this assumption. About the SA requirement, AD design guarantees intrinsically its achievement. However this technology presents high criticality due to the manufacturing: 234 variable layers were, in fact, foreseen, deposited on three different substrates, with noticeable assembly complexity to match them in a unique filter.

## IV. METAL DIELECTRIC LINEAR VARIABLE FILTER 1

### *A. VIS-NIR MD filter 1 Design and Manufacturing*

The design of the MD filter 1 was presented by SGA Carsoli. A 33 layers, single side coating on quartz substrate was realized. The predictions for MD 33 layers design are shown in Fig. 2 and Tab. 3. The predicted characteristics were far from the goal; however the chamber dedicated set-up was already realized at the meeting when the updated requirements were agreed. It was then decided to test the characteristics designed because the increase of the FWHM (here better than required) and the deposition of another filter on the backside are known improvements that could still be done on this kind of filter.

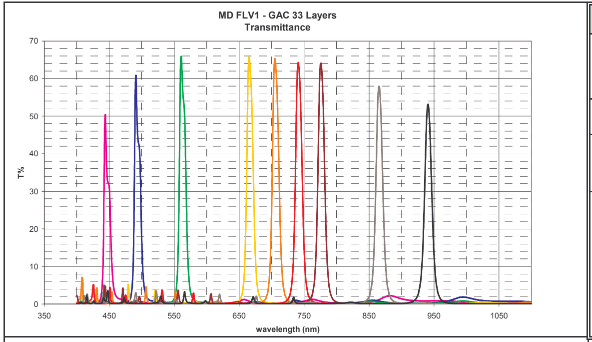

**Fig.2:**Transmittancepredictions for MD LVF filter1

| Characteristic | Requirement | Design Prediction |
|---|---|---|
| Transmission | 50% (as a req.)<br>70% (as a goal) | 50.3% ÷ 65.7% |
| SpectralGradient | 60nm/mm | 60nm/mm |
| FWHM | 20nm@445,940 nm<br>15nm @665,740nm | $\Delta\lambda_{avg}$ = 11nm |
| Spectral Attenuation | 0.05<br>0.01 | 445nm = 0,39<br>665nm = 0,09<br>741nm = 0,12<br>941nm = 0,27 |

**Tab.3:**Design predictions for MD 33 layers LVF filter 1

The basic structure chosen for the LVF1 MD is the Induced Transmittance Filter, as already experimented by ENEA during a previous ESA Contract. Induced Transmittance Filter consists of a MD structure where the metal layer reflectance reduces to negligible values for a single wavelength (depending on thickness), resulting in a narrow band-pass filter. The manufacturing of MD 33 layers has been realized with a dedicated sputtering system in a vacuum chamber with fixed masks shaped according to the required gradient, and a moving sample holder translating linearly in the gradient direction and oscillating back and forth in the uniform direction. The deposition process was software controlled, and the thickness of each layer was checked with an optical monitoring system, allowing on-line reflectance measurements, providing a feedback between the measured performances of the coating and the achievement of the requirements.

### *B. VIS-NIR MD Filter 1 Verification*

The verification of the MD filter 1, shown in Fig.3, was carried out with a dedicated VIS-NIR test set-up realized at SG-Florence. In VIS-NIR test set-up a monochromatic light beam with wavelength ranging from 400nm to 1050nm illuminated uniformly a lambertian diffuser, conjugated by an optical relay system on the LVF sample under test (fixed in a dedicated holder), with F/# 3. The illuminated LVF sample was in turn relayed on the image plane of a cooled CCD camera by means of a quasi-telecentric VIS-NIR compensated objective. LVF sample characterization was carried out by illuminating the whole LVF sample with monochromatic light (1 nm bandwidth) starting from 400nm to 1050nm with 1nm step, and acquiring, for each wavelength, a complete CCD frame. The scan was performed twice, with LVF sample and with an equivalent uncoated substrate (to compensate for optical path changes), then the ratio, pixel by pixel, of the two frames was taken, for each wavelength, in order to obtain the Spectral Response Function (SRF), to within the uncoated substrate transmittance. The measured SRF for some positions on the LVF filter1 are shown in Fig.4.

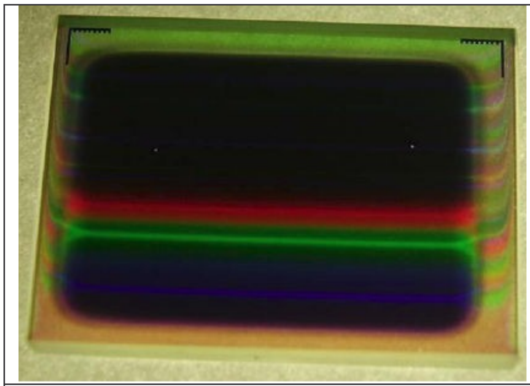

**Fig.3**: LVF MD filter 1 (33 layers)

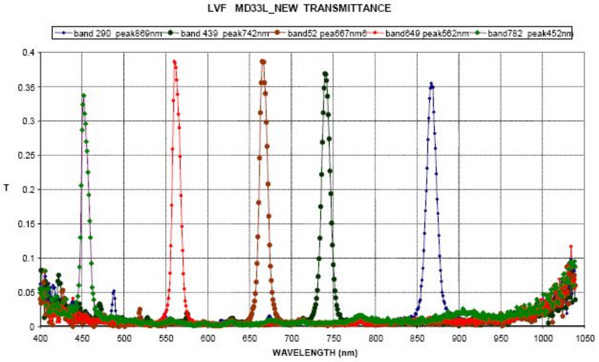

**Fig.4**: Spectral Response Function of LVF MD filter 1

The key feature of VIS-NIR test set-up was its ability to allow transmittance measurements close to the operating conditions of LVF in spectrometers: converging incident beams and high spatial resolution, instead of conditions typical of spectrophotometer measurements (collimated beam and low spatial resolution) and design predictions (carried out assuming collimating beams). The VIS-NIR test set-up has been characterized and calibrated: the calibration has been carried out by comparing the averaged spectrophotometric transmittance measurements performed on two reference uniform filters by SG-Carsoli, ENEA and FRESNEL INSTITUT, with the results found by measurements performed on the same filters with SG-Florence VIS-NIR Test Set-up.

**Tab. 4: SG-Carsoli MD filter 1 performances**

| Characteristic | Requirement | Design Prediction | Measurement |
|---|---|---|---|
| Transmittance | 50% (as a req.) 70% (as a goal) | 50.3% ÷ 65.7 | 35% ÷ 40% |
| Spectral Gradient | 60nm/mm | 60nm/mm | 59.5 nm/mm |
| FWHM | 20nm@ 445,940nm<br>15nm @665,740nm | $\Delta\lambda_{avg} = 11$nm | 10nm @ 452nm<br>14nm @ 867nm |
| Spectral Attenuation | 0.05<br>0.01 | 445nm = 0,39<br>665nm = 0,09<br>741nm = 0,12<br>941nm = 0,27 | 560nm = 0,66<br>665nm = 0,56<br>740nm = 0,68<br>867nm = 0,70 |

LVF 1 MD main performances (predictions and measurements) are summarized in Tab. 4.
All the values of SA are larger than the goal, while the FWHM values are better. Increasing the FWHM, still remaining within the requirement, could improve the Spectral Attenuation of the filter.

## V. VIS-NIR-SWIR LINEAR VARIABLE FILTER 2

### *A. MD filter 2 Design and Manufacturing*

The VIS-NIR-SWIR filter 2 was designed and manufactured with MD technology by ENEA. The coating design for Filter 2 consists of two filter sections, deposited on the same substrate, respectively for the VIS-NIR range (440-930nm) and the SWIR range (930-2500nm), and separated by a gap of 0.4mm. Fig.3 shows the final filter 2 sample. The requirement guidelines were to produce a filter which, mounted on a unique detector, sensitive in a wide spectral interval, realized a spectrometer operating on the whole VIS-NIR-SWIR spectral range, drastically reducing at the same time its overall dimensions. The VIS-NIR sub-range was obtained, using a transmission coating of 21 layers and a blocking filter of 38 layers glued on backside substrate. In the SWIR subrange, as in the VIS-NIR case, a MD coating with the same materials and number of layers was proposed. The deposition was performed with radiofrequency magnetron sputtering in a dedicated chamber, with a specifically designed masking system based on a moving blade driven via software. Fig. 4 shows a picture of the masking system. An on-line optical monitoring system, allowing the measurement of the back-side reflectivity of the coating during its fabrication was also implemented.
The main performances predicted for the VIS-NIR and SWIR sub-ranges are summarized in Tab. 5.

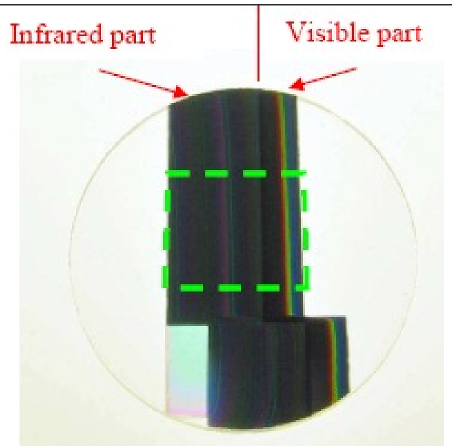

**Fig. 3:** Filter 2 sample

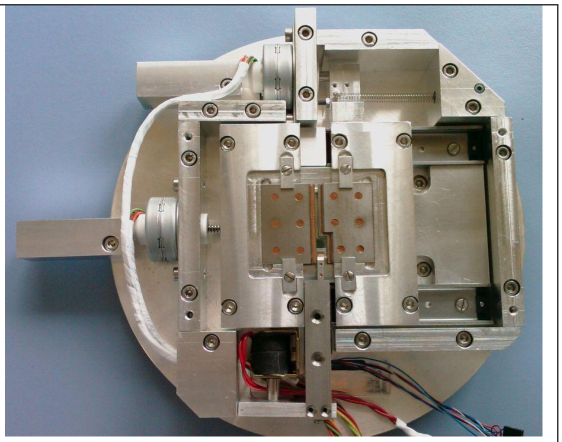

**Fig. 4:** Masking apparatus

*B. MD filter 2 Verification*

The set-up for filter 2 verification was essentially composed by a QTH source with a fiber optics illuminating LVF sample housed in a dedicated translation stage. After passing the sample, light was collected by a fiber optics and carried to the detector. Each section of LVF Filter 2 was characterised with a different detector: a standard spectrometer working in 400-1000nm range for the VIS-NIR sub-range, and a calibrated spectroradiometer, with useful signal-to-noise ratio in the 700-2200nm range, for the SWIR section. The results of measurements of the VIS-NIR and SWIR sub-ranges, are summarized in Tab.5:

**Tab. 5: ENEA VIS-NIR-SWIR MD filter 2 performances**

| | VIS-NIR section | | | SWIR section | | |
|---|---|---|---|---|---|---|
| **Characteristic** | **Requirement** | **Design**$^{(*)}$ | **Measurement**$^{(\dagger)}$ | **Requirement** | **Design** | **Measurement** |
| Peak Transmittance | 50%(as a req.)<br>70% (as a goal) | 46% @940nm<br>62% @560nm | 48% – 58% | > 60% | 56,4 - 61,7% | 25– 31 %$^{(**)}$ |
| Spectral Gradient | 235nm/mm | | 235nm/mm | 250nm/mm | | 284nm/mm |
| FWHM | 20nm @445nm, 560nm, 865nm<br>15nm@665, 740nm | Δλ = 10-12nm | 14nm – 17nm | λ/Δλ = 100 | Δλ=14-16nm | 10 – 16 nm |
| Spectral Attenuation | 0.05<br>0.01 | 0,151 @443nm<br>0,022 @665nm<br>0,056 @740nm<br>0,144 @940nm | <1%$^{(\Delta)}$ | 0.5 % | 0,07-0,19 | (‡) |

(*):The design predicted values are obtained by taking into account the contribution of the blocking filter glued on the backside of VNIR section

(Δ):Spectral attenuation was difficult to be estimated with the VNIR measurement set-up, the accuracy being comparable to the expected value of the out-band transmittance. At few spectral points the maximum out-band transmittance values aren't negligible but they remain below 1%.

(**):Due to the limited resolution of SWIR test set-up, the real transmission peaks and FWHMs may be, respectively, higher and narrower than measured.

(†):The measured values are relevant to the VIS-NIR section without blocking filter

(‡): This quantity is difficult to be measured with SWIR test set-up, because of the non negligible noise just 2 FWHMs outside the peak

LVF MD technology presents the advantage to require a limited number of coating layers, which allows a relative simplicity of implementation and at the same time the achievement of the main performances required to a medium resolution spectrometer, except for the limited Spectral Attenuation. This was demonstrated both for VIS-NIR and SWIR spectral range. Regarding the SA, during the study a theoretical design improvement has been proposed, based on an additional variable band-pass filter deposited on the filter back surface.

For the filter 2 this solution was partially tested, realizing a variable blocking filter sample, and testing it alone. The measurement results confirm that if this filter was integrated on the LVF VIS-NIR filter2 the assembly could have met the SA requirement.

## VI. ENVIRONMENTAL TESTS ON FILTERS

Witness samples of all three filters have been subjected to environmental stresses in order to assess their resistance to space environment.

Details of environmental tests are described in Tab. 6.

Most of the required tests have been performed at ENEA (Radiation, Thermal vacuum cycling and Humidity), while several tests have been performed by each partner using their own facilities. Each partner manufactured 4 or 5 representative samples for the thermal vacuum cycling, the radiation (gamma ray) and the humidity test.

Thermal cycling on Filter 1 has been performed using SG Carsoli test facilities, while Filter 2 was tested at ENEA.

**Tab. 6: Environmental Tests**

| | |
|---|---|
| **Thermal cycling test** | 8 thermal cycles **Filter1**: 333K to 203K<br>**Filter2**: 333K to 173K<br>Level of one hour, slope 2K/min |
| **Radiation** | The coating shall withstand a total radiation dose of 20 Krad, accumulated during a mission lifetime of 7.5 years. |
| **Humidity** | 48 hours at 40 °C and 90% humidity |

The environmental tests have demonstrated the ability of optical components to meet all performance requirements.

## VII. FILTER INTEGRATION ON CCD

The final task of ESA contract was to realize a LVF-based BreadBoard (BB) spectrometer in the VNIR spectral range. In order to realize the Focal Plane Assembly (FPA) of the spectrometer, MD filter 1 manufactured by SG-Carsoli was glued onto a backside illuminated CCD model 55-20 provided by E2V. The filter was glued directly on the CCD sensitive surface to reduce the ghosts deriving by the back reflection between the CCD and the LVF coating. But this minimum gap induced interference fringes due to the “etalon effect”; they were generated by the “degree of partial coherence” acquired by the radiation after passing through the LVF filter coating ($\Delta\lambda$ =FWHM ≈ 10nm). During FPA integration on BB Spectrometer the fringes have been characterized and compensated with a dedicated algorithm, having checked their independence with respect to CCD temperature, objective F#, target distance, sensor integration time. Furthermore a new solution has been studied for filter integration, which foresees filter bonding on a frame spacer fixed on the CCD package at a controlled distance of about 100um. In this case the spectrometer fore optics should be telecentric in order to reduce the ghosts induced by the back reflection.

## VIII. CONCLUSIONS

For LVF realization, although there were difficulties to achieve the requested performances, the two concepts (AD and MD) showed to be both feasible. According to the application it is possible to perform trade-offs between achieving more robust but less performing filters (MD) or implement more performing but more critical to manufacture filters (AD).

With the BB spectrometer (realized with one Linear Variable Filter mounted on a CDD) several acquired images, out-door and in-door, were assembled in “hyperspectral cubes”; the valuation of these cubes has demonstrated the promising performances of such “single chip spectrometer” configuration.

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