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ADVANCED LARGE FOV UV/VIS/NIR/SWIR SPECTROMETERS FOR FUTURE EARTH OBSERVATION INSTRUMENTS

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I. INTRODUCTION

Today, optical instruments with FOV of ±30 degrees or more can be achieved by combining several optical modules thus increasing the complexity at instrument level in the design, integration, validation and calibration phases. For instance the MERIS instrument on the ENVIronment SATellite (ENVISAT) has a 68.5 degree FOV shared between 5 identical modules. Each one of those modules needs to be calibrated independently and the modules require to be co-registrated, which leads to stringent constraints at system level in terms of stability. Reducing the number of modules to achieve large FOVs will have potentially beneficial impact on the mass and volume of the instrument and will ease the calibration and co-registration process.

Benefiting from a longstanding experience in Earth Observation missions, and especially in the field of dispersive spectrometers with Ocean and Land Colour Imager instruments (MERIS and OLCI), Thales Alenia Space has studied for ESA different concepts of advanced large FOV UV/VIS/NIR/SWIR spectrometers able to be implemented in the frame of Sentinel-3 Second Generation and GMES II programs. The targeted application is an ocean/land colour measurement instrument from low Earth orbit, with at least the same FoV (70°) and spectral range (340-1040 nm) than OLCI, but a Ground Sampling Distance nearly two times better (150 m), and a reduced volume.

The main objectives of the study were to assess the limits of the currently available spectrometer architectures and to identify the technologies needed to achieve the requirements, then to propose opto-mechanical designs for a spectrometer based on these technologies, and at last to define an instrument development roadmap including the technology development roadmap. To tackle these needs, the following tasks were performed by TAS and consultants:

- Perform a system analysis and identify the design drivers;
- Propose several optical concepts and assess the state-of-the-art for each design driver and key technology as well as first order instrument performance;
- Elaborate the opto-mechanical design for two concepts and their associated optical performance;
- Establish a detailed definition of the optical parts;
- Identify the critical components with respect to the current state-of-the-art and set-up Technology and Instrument Roadmaps leading to TRL 5.

The present paper focuses mainly on the optical design activities. The sizing of the instrument was optimized to fulfill all the requirements. A major constraint being to stay within a small volume, the collimator and imager functions of the spectrometer were proposed to be achieved with a single optics used in double-pass. The significant heritage in design and realization of spectrometers at Thales Alenia Space allowed a comprehensive approach of potential solutions. Several types of spectrometers were assessed, among which the Offner concept, the Dyson concept, and the double-pass TMA

II. OVERVIEW OF THE REQUIREMENTS

Two sciences cases are identified for advanced LFOV missions. The first case foresees measurements of ocean color in the UV, visible and infrared with a GSD of 150m with a volume reduction compared to past and spectrometers in development. The second case includes the first case but with addition of a SWIR channel for atmospheric correction.

To fulfill the sciences cases, the proposed spectrometer should be compliant with the following main characteristics:

- Be smaller than the OLCI spectrometer.
- Image a FOV of ±35° with a limited number of modules (1 or 2). For comparison past spectrometers had a similar FoV but with a higher number of modules (5) leading to an increased instrument complexity.
- Image 24 bands from 340nm to 1040nm with width between 10 and 50nm and 3 SWIR bands as an option. The significant extension toward UV, with respect to past spectrometers, has an heavy impact on the design, and leads to solutions for which state-of-the-art technologies are not mature enough. Instrument transmission and detector efficiency are concerned.
- Image with a GSD of 150m. Associated with the FOV requirement, this leads to a number of pixels across track equal to 7600. This is a driver for the detector design and has an impact on data rate (around 2000Mb/s). Constraint on detector (but not on the instrument data rate) is relaxed as the number of modules increases.
- Have an optical transmission > 30% over the entire FoV. For comparison past spectrometers were specified at 10%.
- Have a spatial co-registration better than 0.1 SSI, it is 10 times better than specified for OLCI, and therefore very challenging. This requirement goes in favor of a pixel size as large as possible. For a 10 µm pitch, 10% SSI co-registration means 1 µm (all-included) for the misalignments. This is the value allocated to the FPA alignment accuracy on OLCI. In the frame of the Large FoV Spectrometer the level of co-registration will require pitch larger than 15 µm typically
- Have a MTF at Nyquist, excluding detection, better than 50%.

III. INSTRUMENT CANDIDATE CONCEPTS AND SELECTION

A. Families of concept

During the study several families of concepts have been identified, using the following rules:

- One or two modules: single FOV of 70° or two FoV of 35°;
- Same optical/detection functions in each module: Telescope / Spectrometer / Focal plane;
- Each module handles the whole spectral range UV / VIS / NIR (+ optional SWIR if possible);
- Within each module, each function handles the spectral range in one or more channels. Two cases are considered:
    - o UV + VIS + NIR (+ SWIR optionally) in a single channel
    - o Separate channels : E.g. UV/VIS + NIR channel, or UV/VIS/NIR + SWIR optional channel.

Chosen family of concepts is based on a different separation between the UV/VIS/NIR channels and the SWIR. The UV/VIS/NIR channels are separated with the help of a spectrometer whereas the SWIR channel is directly imaged on a second adapted focal plane. This separation was found to be the only way to keep the SWIR option in the race. The number of modules in this family of concepts is one or two.

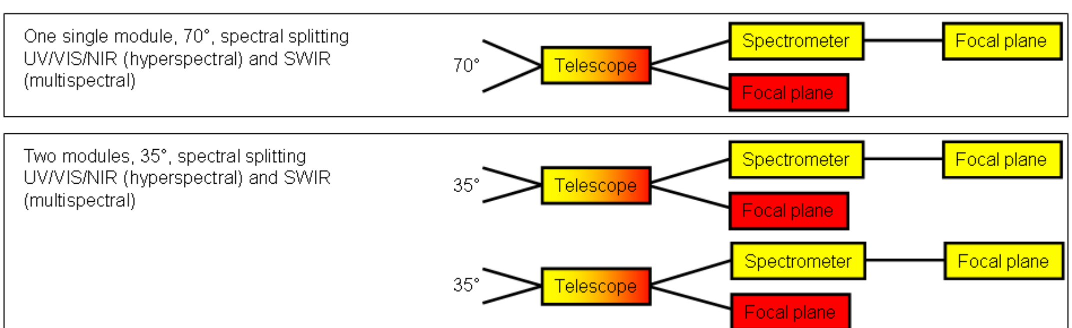

Fig. 1 Chosen family of concepts

B. Rationale for concepts selection

At the end of the first phase of the Study, the Concepts Review led to the selection of two instrumental concepts to be investigated in more details during the second phase. The rationale of the method proposed for assessing the best candidates was as follows:

- Step 1: Identification of possible optical concepts for the telescope function and the spectrometer function.
- Step 2: For each possible concept, assessment through optical analysis (rough optimisation) of the optical design most able to fulfil the needs. The exercise was performed at telescope and spectrometer levels, separately, then at instrument level (ie assembled telescope + spectrometer).
- Step 3: Identification of selection criteria (preference for one module, instrument compactness, accessibility of the entrance pupil for efficient calibration).
- Step 4: Comparison versus selection criteria of the most promising optical designs at instrument level.
- Step 5: Down-selection of two instrumental concepts.

Detection aspects were willingly put aside of the trade-off analysis (they were out of the scope of the study). However specifications for the best suited detectors were derived.

C. Possible optical concepts

The instrument can be of two kinds:

- Classical imaging spectrometer instrument with entrance telescope, slit, collimator, disperser and imager (Fig. 2)
- Imaging spectrometer instrument with a double-pass optic used as collimator and imager (Fig. 2)

The constraint on instrument volume strongly favors the double-pass concept.

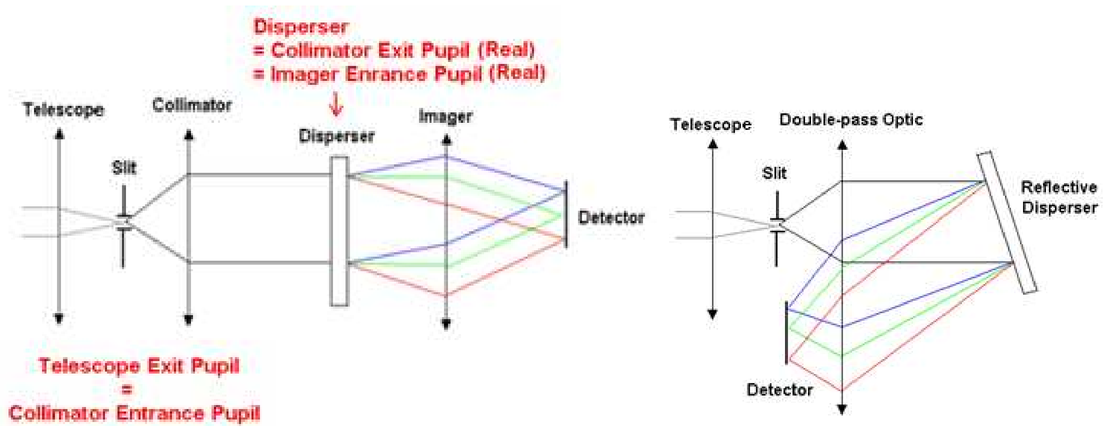

Fig. 2 Classical instrument and constrains on pupil (left) and Double-pass instrument (right)

D. Design characteristics and constraints

Design drivers are as follows:

- Need of a compact instrument;
- Need of minimum number of modules;
- Need of an accessible Entrance Pupil, as a nice-to-have. An accessible Entrance Pupil enables a compact and efficient scrambler. However this is not a must, since TAS has patented a scrambler which is efficient even outside a pupil plane. An accessible Entrance Pupil enables also a compact and efficient calibration mechanism, although calibration outside the pupil plane can also be considered (as in OLCI)

Also, in double-pass design, the dual-pass optic is used as collimator and imager, so that the collimator focal length is equal to the imager focal length. Furthermore, the telescope focal length is equal to the instrument focal length.

At last, the design of the instrument is constrained by the position of the different pupils (cf Fig. 2**Erreur ! Source du renvoi introuvable.**). Indeed, at slit level, the telescope Exit Pupil shall be equal to the collimator Entrance Pupil, and the collimator Exit Pupil and imager Entrance Pupil shall be real and shall be on the disperser. These are strong constraints on the optical design.

E. Telescope design

Many telescopes designs were studied (reflectives solutions : TMA, Schwarzschild, Walrus,… but also refractive designs). For each concept, a set of performance and characteristics was assessed :

- Maximum f-number and the FoV reachable with a good image quality;
- Pupil accessibility;
- Total volume of the telescope (expressed in liters);
- MTF (minimum over the whole FoV at 40 cy/mm, before tolerancing);
- Mirrors manufacturing complexity;
- First MTF tolerancing as an indication of the sensitivity of the performance to misalignments & manufacturing quality.

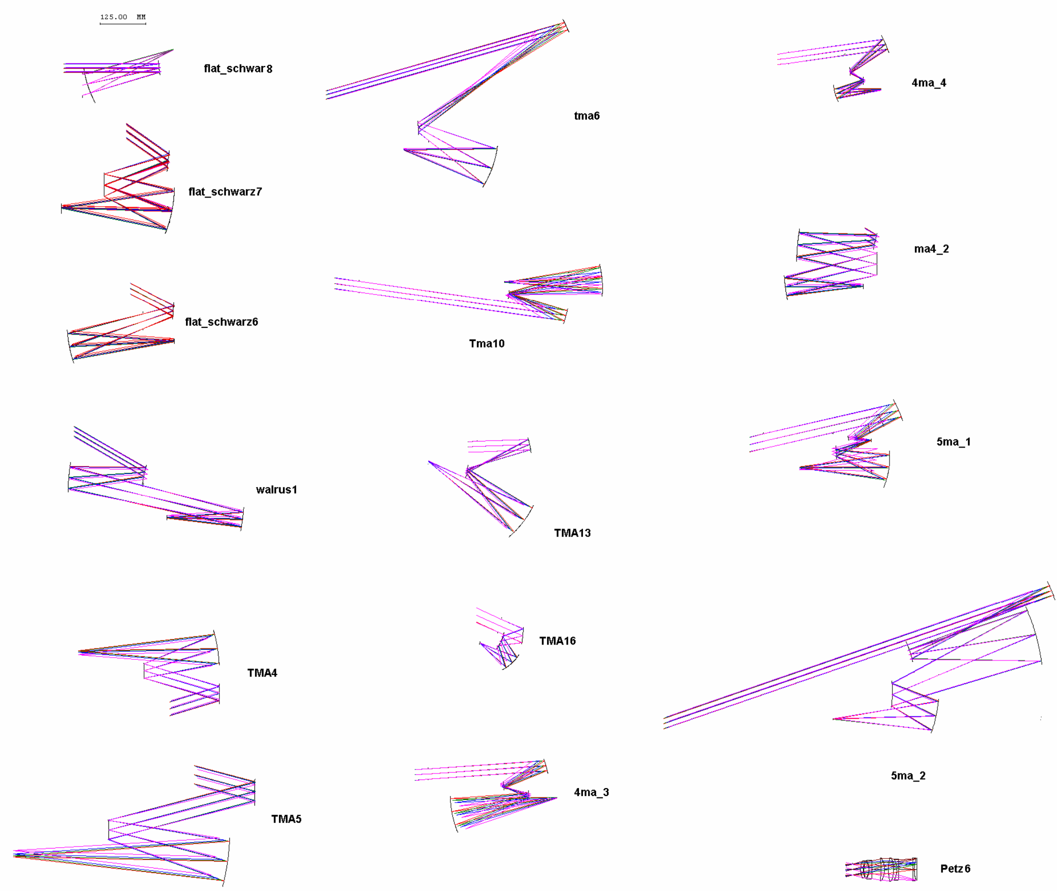

Fig. 3 Studied telescopes at the same scale

Among them, few telescopes were able to meet simultaneously all the instrument needs (compact / few modules / accessible entrance pupil, and compatibility with spectrometer entrance pupil). None of them was based on a single module (70° FoV).

In the following table the telescope designs are divided in 4 groups depending on their assets. In each group the best candidate is highlighted.

Low Volume / Real Entrance Pupil / Telecentric	Low Volume / Telecentric	Low Volume / Real Entrance Pupil / Real Exit Pupil	Low Volume / Real Entrance Pupil / Imaginary Exit Pupil	Real Entrance Pupil / Telecentric
x	flat_schwarz6	MA4_4	TMA16	MA5_2
	flat_schwarz7	TMA13		TMA6
	flat_schwarz8	MA4_3		TMA10
	walrus1	MA5_1		
	tma4			
	tma5			
	ma4_2			

Fig. 4 Groups of candidate telescopes

F. Spectrometer design

As explained above, priority was given to double-pass spectrometers in order to reduce the overall instrument volume. We have thus studied the telescopes listed above in dual-pass configuration. In order to reduce volume, the grating was put in pupil plane. Optics with no real exit pupil have thus not been studied because they led to large volumes (ex: tma4, tma5,…). Some telescopes were too compact and could not be used as double-pass spectrometers (ex: ma4_2, tma10, walrus, 5ma) because of lack of space to accommodate them.

Beside these double-pass spectrometers, we also studied Dyson/Offner spectrometers, and two examples of classical spectrometers (collimator+imager).

For each of the spectrometers the following characteristics and performances were assessed :

- Maximum f-number and slit length (equivalent to a FoV) reachable with satisfactory image quality;
- Position of entrance pupil;
- Number of spectrometer needed to achieve the required FoV;
- Total volume of the spectrometer;
- MTF (minimum over the whole FoV at 40cy/mm, before tolerancing);
- Transmission (assuming: one mirror transmission = 98%, one lens transmission = 96%);
- Complexity of manufacturing.

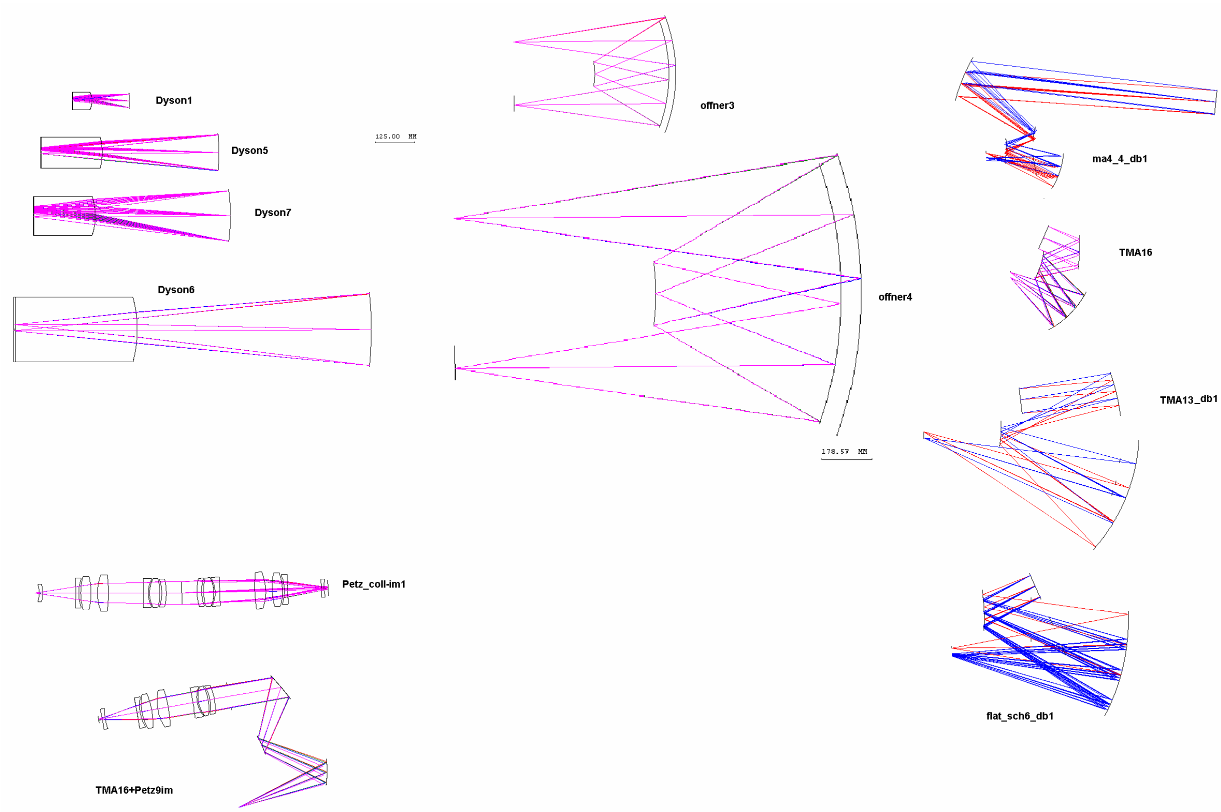

Fig. 5 Studied spectrometers at the same scale

Among them, a few was able to meet simultaneously all the instrument needs (compact / few modules / accessible Entrance Pupil, and the constraint with telescope exit pupil) and none was based on a single module.

In the following table the spectrometer designs are divided in 5 groups depending on their assets. In each group the best candidate is highlighted.

Dyson type	Offner type	Double-pass		
		Real Entrance Pupil / Imaginary Exit pupil	Real Entrance Pupil / Real Exit pupil	No Real Entrance Pupil
dyson5	offner3	TMA16_DB1	MA4_4_DB1	Schwarz6_DB1
dyson6	offner4		TMA13_DB1	
dyson7				
dyson1				

Fig. 6 Groups of candidate spectrometers

G. Outcomes of the concepts review: solutions at instrument level

The combination of telescopes and spectrometers led to 20 possible instrument concepts. From the telescopes and spectrometers listed above, the following best candidates were discussed at the Concepts Review:

Selected Telescops		Selected Spectrometer	
flat_schwarz6	(Telecentric)	dyson5	(Telecentric)
MA4_4	(Real Exit Pupil)	offner3	(Telecentric)
TMA16	(Imaginary Exit Pupil)	TMA16_DB1	(Imaginary Etrance Pupil)
MA5_2	(Telecentric)	MA4_4_DB1	(Real Entrance Pupil)
		flat_schwarz6_DB1	(Telecentric)

Fig. 7 Selected telescopes and spectrometers

The following two concepts were selected for further design in the second part of the Study, emphasizing compactness versus the preference of having a single-module instrument:

MA4_4 (four mirrors astigmatic) – TMA16DB : 2 modules, flat grating, compact. Later on, the telescope has been replaced by a TMA.

FlatSchwarz6 (Schwarzchild) – Dyson5: 2 modules, concave grating, very compact.

IV. INSTRUMENT OPTO-MECHANICAL DESIGN

The outcome from the concept review allowed to identify two spectrometers concepts that have been further assessed in the second part of the study. On these two concepts, requirement apportionments to sub-systems and performance estimations have been made. Mechanical design and accommodation have been realized as well.

A. Concept 1

In the first concept, represented in Fig. 8, the scrambling window is placed in the entrance pupil of the instrument, and a folding mirror enables to accommodate the telescope and the double-pass TMA in a small volume. The telescope images the Earth on the slit, and the double-pass TMA images the slit to infinity. The grating disperses light, and the double-pass TMA images this dispersed light on the detector.
The instrument has a focal of 81.4mm, f# of 3.3 and FOV of 70° (35° for each module).

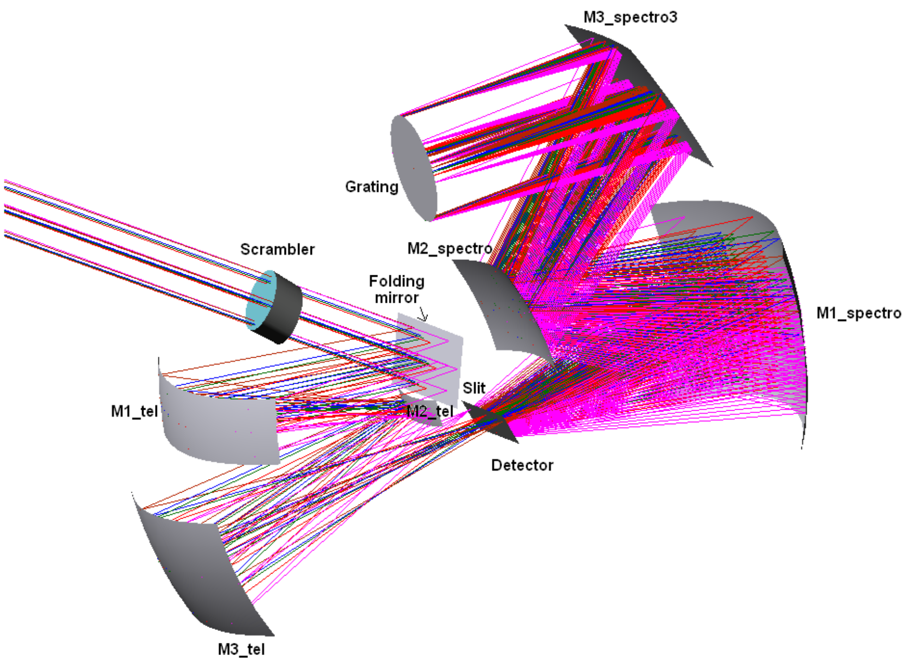

Fig. 8 Instrument overview – Concept 1

B. Concept 2

In the second concept, represented in Fig. 9, the scrambling window is placed in front of the telescope, but not in a pupil. The telescope images the Earth on the slit, and the Dyson spectrometer disperses and images the slit on the detector.

The instrument has a focal length of Focal=81.4mm, a f# of 3.3 and a FOV of 70° (35° for each module).

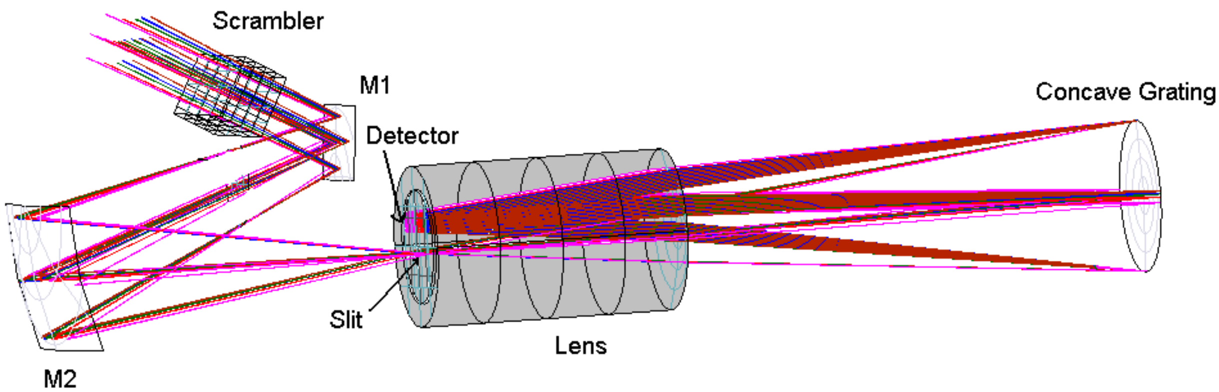

Fig. 9 Instrument overview – Concept 2

C. Estimated performance of both concepts

For the two concepts, requirements apportionment toward sub-systems was made. Mirrors reflectivity and grating efficiency are the main drivers for the optical components. The grating efficiency is particularly stringent for Concept 1, whereas it is relaxed for the Concept 2 and is marginally compliant with classical gratings (35% in the UV instead of the 50% required. Gratings based on new technologies could achieve the required level of performance.

Grating solutions able to meet the requirement were studied extensively by Thales Research and Technology in the frame of this Study. Candidate gratings are based on sub-wavelength binary structures. The nano-structured patterns are made of SiO2 or Si3N4 and the effective index depends on the fill factor (i.e. the width-to-period ratio). These type of gratings have already been developed but not for a design in reflection and with a curved surface. Some solutions in silica have been tested in transmission on small samples and evaluated numerically for a transitive design. They present high efficiency (up to 60-80%), a flexibility to adapt the shape of the spectral efficiency profile and a good polarization behavior. However specific development are clearly needed, in particular regarding the expected size and shape of the component to be realized.

The performance of both instrument concepts have been estimated, and main outcomes are listed in Fig. 10.

Concept 1 main non-compliance concerns spectral co-registration. Such concept would therefore need to implement smile and keystone correction by processing. Further optimization of these performance at optical level was not further investigated.

Concept 2 meets all the requirements.

	Concept1	**Concept2**
Nominal MTF @Nyquist (minimal value for all FoV, all wavelengths)	>0.6	>0.73
Toleranced MTF @Nyquist (minimal value at 1s, all FoV, all wavelengths)	>0.47	>0.56
Maximal keystone (nominal value)	<120um	<0.8um
Maximal smile (nominal value)	<650um	<0.7um
GSD	150m	150m
Transmission	>30%	>30%
Polarization rate	<1%	<1%

Fig. 10 Performance of both concepts

In order to be fully aware of gains obtained with these new designs, we have tuned Concept 2 so that it be compliant to the OLCI requirements only (i.e. twice relaxed versus the LFOV requirements). Thanks to that we could estimate the gain on volume for two equivalent designs.

The volume of one optical module compliant to the LFOV requirements is 5.3L. The volume of one optical module compliant to the OLCI requirements only is 1.7L.

Fig. 11 provides with the same scale the volume of the Concept 2 OLCI-tuned (2 modules), compared to the OLCI concept (5 modules).

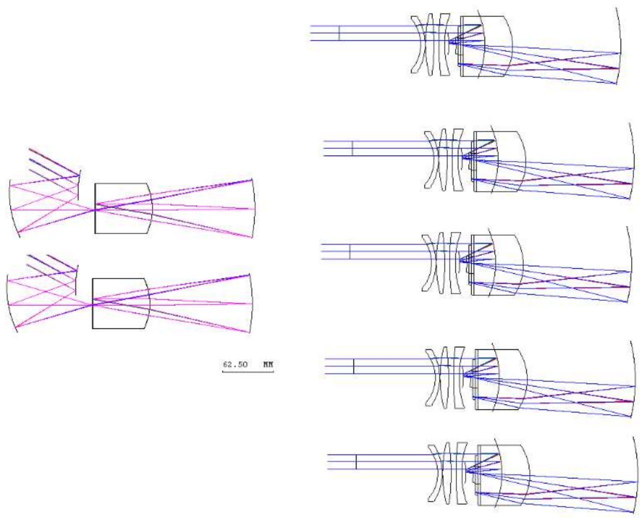

Fig. 11 Concept 2 compliant to OLCI requirements (2 modules) versus OLCI optical design (5 modules) at the same scale

V. CONCLUSION

The Advanced Large Field Of View Spectrometers study identified concepts for future EO missions.
The requirement review pointed out the main stringent, but achievable, requirements for such mission : large spectral range with extension toward UV and, as an option, toward SWIR, small volume, small GSD (150m) and high optical transmission (>30%).
Families of concepts have then been identified: single module concepts, with only one telescope covering the whole FoV, two modules concepts, with the FoV split in two, and also alternatives with one or two modules in which the separation between the UV/VIR/NIR and the SWIR occurs right after the telescope before the spectrometer. This last family enables a SWIR option in multispectral mode.
More than 20 instrument concepts have been studied. Among them, two concepts have been pushed forward: the first one based on a double pass spectrometer and the second one based on a Dyson spectrometer. Both concepts use a plane reflective grating. With better image quality and a volume equivalent to 75L, the concept based on a Dyson spectrometer proved to be the most promising one, fulfilling all the requirements with an instrument having two modules.
Two technological areas have been identified as critical and needing dedicated developments to achieved the required level of performance: anti-reflective coatings in the UV band and gratings efficiency on a large spectral band. Preliminary performance have been assessed, involving coatings based on dielectric multilayers and gratings with two types of promising technologies (nanostructured gratings and achromatic blazed gratings).
The need to secure performance by dedicated instrument breadboarding activities has been pointed out. The technological roadmap and the instrument roadmap have been elaborated.