International Conference on Space Optics—ICSO 2012

Ajaccio, Corse

9–12 October 2012

Optical MEMS for Earth observation

Arnaud Liotard

Thierry Viard

Wilfried Noell

Frédéric Zamkotsian

et al.

Optical MEMS for Earth observation

Arnaud Liotard, Thierry Viard

Thales Alenia Space
Cannes-la-Bocca – France
arnaud.liotard@thalesaleniaspace.com

Wilfried Noell

EPFL – SAMLAB
Neuchâtel – Switzerland

Frédéric Zamkotsian

Laboratoire d'Astrophysique de Marseille (LAM)
Marseille – France

Marco Freire, Benedikt Guldimann, Stefan Kraft

ESA – ESTEC
Noordwijk – The Netherlands

Abstract – Due to the relatively large number of optical Earth Observation missions at ESA, this area is interesting for new space technology developments. In addition to their compactness, scalability and specific task customization, optical MEMS could generate new functions not available with current technologies and are thus candidates for the design of future space instruments. Most mature components for space applications are the digital mirror arrays, the micro-deformable mirrors, the programmable micro diffraction gratings and tiltable micro-mirrors. A first selection of market-pull and techno-push concepts is done. In addition, some concepts are coming from outside Earth Observation. Finally two concepts are more deeply analyzed.

The first concept is a programmable slit for straylight control for space spectro-imagers. This instrument is a push-broom spectro-imager for which some images cannot be exploited because of bright sources in the field-of-view. The proposed concept consists in replacing the current entrance spectrometer slit by an active row of micro-mirrors. The MEMS will permit to dynamically remove the bright sources and then to obtain a field-of-view with an optically enhanced signal-to-noise ratio.

The second concept is a push-broom imager for which the acquired spectrum can be tuned by optical MEMS. This system is composed of two diffractive elements and a digital mirror array. The first diffractive element spreads the spectrum. A micro-mirror array is set at the location of the spectral focal plane. By putting the micro-mirrors ON or OFF, we can select parts of field-of-view or spectrum. The second diffractive element then recombines the light on a push-broom detector. Dichroics filters, strip filter, band-pass filter could be replaced by a unique instrument.

Keywords: *Spectro-imagers, MOEMS, Straylight control, Spectrum control*

I. INTRODUCTION

A. *Presentation of main Optical MEMS*

Optical MEMS could be useful for designing future generation of instruments. In addition to their compactness, scalability, and specific task customization, they could generate new functions not available with current technologies. These devices have been developed or successfully used in a wide range of ground-based commercial applications, from telecom to life science, and from imaging to spectroscopy. MOEMS are not yet widely used for space application, but this technology will most likely provide the key to new science and instrumentation. The first major application will be the micro-shutters array in NIR-Spec for JWST. We have developed a table gathering parameters and information on relevant components for this study. Some of the commercial components are of prime interest for Earth Observation instruments.

Texas Instruments' Digital Micromirror Devices (DMD), [1], are the most popular MOEMS devices available on the market. If the prime use is for displaying images numerous applications may be thought: multi-object selection, spectral selection, hyperspectral imaging, confocal microscopy … However, the flexibility in terms of applications is balanced by the rigidity in terms of customization: TI (or related companies) proposes only a limited number of components (array format and size of the mirrors) and sometimes, three possible coatings on the protecting window (UV, visible, IR). In terms of space compatibility, a full campaign has been already conducted through an ESA contract and do not reveal any show-stopper concerning the ability of the DMD to meet environmental space requirements (vacuum, -40°C, mirror in tilted position during 1500s), [2].

Boston Micromachines Corporation (BMC) [3] produces the most advanced MEMS deformable mirrors. Their main parameters are approaching the requirements values, i.e. large number of actuators (up to 4096), large stroke (up to 5.5 µm), good surface quality, but they still need large voltages for their actuation (150 – 250 V). Space qualification is an issue and to our knowledge, tests have been conducted for that purpose. This year, NASA has selected BMC for two Phase 1 contracts, in order to develop devices and electronics suited for space applications (main goal: wave-front control in space-based high contrast imaging instruments).

Programmable Micro Diffraction Gratings (PMDG) are possible candidates for tailoring spectrum of any beam or could be integrated in compact spectrographs. Polychromix has developed in 2005 a complete NIR spectrometer with the grating organized into 100 groups of 12-element pixels, [4]. This device has also been fully space-qualified and used for the NASA L-CROSS (Lunar Crater Observation and Sensing Satellite) mission to look for water on the Moon. Silicon Light

Machines (SLM) is another device supplier with more pixels (1086 pixels made of 6 ribbons) and FPGA-based electronics for loading the patterns, [5]. It has been purchased and used in an ESA study addressing new applications of this type of MEMS. No space qualification could be foreseen in a near future for this device.

Scanning mirrors are developed in many companies and laboratories for a wide range of commercial applications. Their potential space applications are in LIDARs, switches, target selection, pointing. These components are usually qualified for applications on ground and only few components have been tested in space environment under ESA and CNES studies (for example SERCALO switches, [6]).

B. Earth observation instruments considered for market-pull analysis

All current and future ESA Earth Observation missions were analyzed in order to find MEMS based concepts, which can enhance performances of these instruments.

EarthCARE, [7],is a joint European-Japanese mission addressing the need for a better understanding of the interactions between cloud, radiative and aerosol processes that play a role in climate regulation. To realize the measurement goals and meet the scientific objectives, a single platform with a payload of two active sounders: Lidar (ATLID) and radar (CPR); and two complementary passive instruments: multi-spectral imager (MSI) and a broadband radiometer (BBR) will be launched into a polar Sun-synchronous afternoon orbit.

Sentinel-2 [8] polar-orbiting satellites will provide systematic global acquisitions of high-resolution multispectral imagery with a high revisit frequency. This mission is tailored towards the needs of operational land monitoring and emergency services. The Sentinel-2 mission is envisaged to fly as a pair of satellites with the first planned to launch in 2013. Sentinel 2 spacecrafts are designed to carry a single multi-spectral instrument.

Sentinel-3 [9] instruments are the SLSTR (Sea and Land Surface Temperature Radiometer), the Ocean and Land Colour Instrument (OLCI), the SAR Radar Altimeter (SRA) for Sea Surface Topography and Wave Height, the dual frequency Microwave Radiometer (MWR) to provide wet tropospheric corrections for radar altimeter, and a package for the precise determination of orbit that comprises a GNSS receiver, a laser tracking mirror and a DORIS receiver. The Mission is in phase C and the launch of the first Sentinel 3 satellite is foreseen to be in 2013. Sentinel-3 is a low Earth orbit (800–830km altitude) operational mission is part of the GMES Program.

The Meteosat Third-Generation (MTG) system [10] is being established through cooperation between EUMETSAT and the ESA. The MTG series will comprise six satellites, with the first spacecraft likely to be ready for launch from 2017. The in-orbit configuration will consist of two parallel positioned satellites, the MTG-I (imager) and the MTG-S (sounder) platforms. MTG-I satellites will fly the Flexible Combined Imager (FCI) and an imaging lightning detection instrument the Lightning Imager (LI). The MTG-S will include an interferometer the InfraRed Sounder (IRS) with hyper-spectral resolution in the thermal spectral domain, and the Sentinel-4 instrument, the high resolution Ultraviolet Visible Near-infrared (UVN) spectrometer.

Activities are on going for the definition of the follow-on EUMETSAT Polar System (Post EPS, [11]), to replace the current satellite system in the 2020 timeframe and contribute to the Joint Polar System to be set up with NOAA. Through consultation with users and application experts, requirements have been defined for a range of candidate missions mainly in support of operational meteorology and climate monitoring. A number of on-board instruments, satellite platforms and ground support infrastructure are under study in coordination with ESA, NOAA, DLR and CNES. Feasibility studies are planned until 2011 with the main objective to define the baseline configuration for subsequent detailed design, development and operation programmes to be proposed and coordinated within the involved organizations.

Different High-resolution imagery programmes were analyzed, in Low Earth Orbit: Pléiades HR and in Geostationary Earth Orbit: Geo-Oculus and Optical Aperture Synthesis telescope.

C. Estimation criteria of payloads improvements

A list of the criteria proposed to assess the improvement provided by MEMS technology to the Earth Observation missions is proposed. As the criteria are changing from instrument to instrument, a full ranking/selection of the solutions with such a number of criteria is something very heavy and subject to discussion. We propose to work with 3 meta-criteria with almost equal weights: Performance, System, and Programmatic.

TABLE I.   EVALUATION CRITERIA FOR PAYLOAD / INSTRUMENT
                     IMPROVEMENT.

Performance	System	Programmatic
Radiometric performance	Design effort	Calibration procedure
Spectral performance	Manufacturing effort	Test procedures
Geometric performance	Assembly effort	Reliability
New services	Alignment effort	Cost
Relaxation on	Volume	TRL/maturity
requirements of other parts	Mass	Solution modularity
of the system	Power	Availability

D. Optical MEMS-based Earth observation instruments

A first selection of market-pull and techno-push concepts is done. In addition, some concepts are coming from outside Earth Observation. All these twelve concepts are relevant. Finally, after an objective trade-off based on criteria presented before, two concepts are selected for a preliminary study. Considering the meta-criteria cited above, a trade-off exercise is performed within the twelve concepts.

Two concepts are therefore selected and are addressed in the next section: Digital Mirror Array for cloud discarding; and Digital Micromirror Device for spectral selection with field-of-view.

II. Digital Mirror Array for Cloud removal

According to, for one hand, the luminance of clouds and sun-glints, and for the other hand, the straylight level in the instrument; the sub-system proposed here is to replace the current slit by an active row of MEMS. The current maximum value in NearIR is around 60 %. This straylight is detrimental to the Earth observation signal. The scatter within the spectrometer clearly and largely dominates the overall straylight, i.e. after the slit, and more precisely by the detector backscatter. Placing a MEMS in the entrance slit of the spectrometer to filter the light coming from clouds and the light coming from the sea should improve the straylight performance of this instrument. For doing that, the instrument was designed and analyzed optically speaking. A CAD design has been realized in association with the mass, volume and power budgets.

The instrument aims at observing the ocean and land. But we must know that the sea observed in infrared wavelength is very dark, we could get very bright signal reflected by clouds. In order to prevent from the CCD saturation, a very high dynamic is required for the detector. The straylight in the spectrometer (Detector backscattering) in IR band is so important that each time a cloud is present in the field-of-view, the image is considered as lost. In consequence we propose to enhance this instrument by placing MEMS in the entrance slit of the spectrometer to filter the light coming from clouds and the light coming from the sea.

A. Instrument level

This instrument is made of a ground imager and a spectrometer. The ground imager images the earth on the entrance slit of the spectrometer. This spectrometer disperses the light and forms a dispersed image of the entrance slit onto the focal plane array. The ground imager collects the light through the calibration mechanism Earth aperture and the scrambling window, and forms an image of the Earth in the plane of the spectrometer entrance slit. The focal length of the ground imager is 67,3 mm, so that it images a 272 m ground pixel onto a 22.5 micron spectrometer entrance slit width, from a nominal altitude of 815 km. Then the spectrometer disperses the light and forms a dispersed image of the slit on a CCD array. The resulting image of the slit is bi-dimensional: one dimension corresponds to the spatial extension of the slit, and the other one corresponds to the decomposition of light into all its spectral components from the visible to near infrared (390 - 1040 nm).

The goal of the sub-system presented in this paragraph is to cope with high flux coming clouds or sun glint. The TABLE II. summarizes the consequences of the observation of clouds and sun-glint. As far as the MEMS is able to filter light coming from clouds, we should couple it with a detection set-up and process. Three set-ups are proposed. Passenger small camera looking in advance, in the slit plane, we could place a detector or pick-up mirror + detector parallel to the spectrometer slit with spatial shift related to temporal advance (shift divided by EFL multiplied by H and divided by v) We can also use the light reflected by the MEMS is the OFF position and send it to an additional detector. As clouds are large and bright with a very high contrast with the intended signal, their detection

could be based on a simple process based on analogue threshold could be performed onboard.

TABLE II. SIGNAL POLLUTION BY EXTRAORDINARY STRAYLIGHT

	Occurrence	Gravity	Sub-system effect
Clouds	Common, Depends on the scene location, Random	Important, Lcloud = 1e3 Lref Straylight, Signal pollution	High potential
Sun glint	Rare, Can be predicted	Unaffordable, Lsg = 1e6 Lref, Detector saturation	Medium potential because of the reference flux to sun-glint flux ratio

According to, for one hand, the luminance of clouds and sun-glints, and for the other hand, the straylight level in the instrument; the sub-system proposed here is to replace the current slit by an active row of MEMS. Considering the ratio between the sun-glint flux and the reference flux, the sub-system does not seem to be able to afford such a difference. However as the detector is no longer saturated, recovering the full capacities of the instrument should be faster.

B. Optical MEMS: MIRA

LAM and EPFL are engaged in a European development of micromirror arrays, called MIRA, for generating reflective slit masks in future Multi-Object Spectrographs, [12], [13]. This program includes devices realization and characterization set-ups developments [14], [15]. A first generation of up to 64×32 micro-mirrors fulfilled the requirements presented in the introduction paragraph and was fabricated.
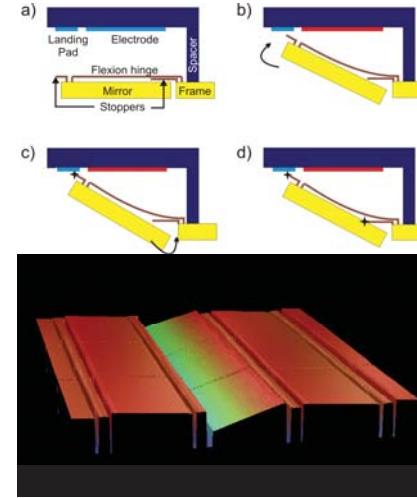

Figure 1. Micro-mirror for multi-object spectroscopy:
(Up) (a) Concept of the micro-mirror device. (b-d) A system of landing beam and stopper beams was introduced that provides uniform tilt-angle over the whole micro mirror array.
(Down) Frontside of the mirror chip with micro-mirrors of size 100x200 µm². One row is actuated, implementing the long slit mode.

The basic concept is shown in Figure 1. A single cell of the device consists of a silicon mirror suspended by poly-silicon beams. The beams are fixed on a frame, which maintains the mirrors together. The frame lies on a spacer that provides a precise distance between the mirror and the electrode. A

system of landing beam and stopper beams on the mirror and on the frame was developed to assure a precise and constant tilt angle. When a DC voltage is applied on the electrode an electrostatic force appears between the electrode and the mirror and the micro-mirror begins to turn until the landing beam touches the landing pad. The mirror starts to turn in the opposite direction until it hits the stopper beams attached on the frame and remained electrostatically fixed in this position.

Replacing a slit by a MEMS involves contrast issues. Indeed the previous slit is made by chromium deposition and etching on a silica substrate. Contrast obtained is around one thousand near the slit (membrane porosity) and around one million a bit further. We should get a similar contrast between ON and OFF micro-mirrors states. Different factors are assessed during the MEMS device development such as rugosity (BRDF), diffraction by gaps, light reflected by substrate behind the micro-mirrors.

C. Optical design

The optical design is based on conventional space spectro-imagers. The main modification is that the usual slit is in transmission. In the new design the optical MEMS is a micro-mirror, the spectrometer has been turned. All the previous elements are kept such as the scrambling window unit, the catadiotric objective, the concave grating and the focal plane as we can see in the Figure 4.

D. Straylight analysis

The results of end-to-end straylight simulations have been post-processed. These simulations are performed with ASAP with all the different realistic coatings and flux. This straylight analysis is spit in four parts: Ground imager scattering, Ground imager ghost, Spectrometer scattering, and Spectrometer ghosts.

The scenes are contrasted scenes Lmax/Lref whom separation is across-track.
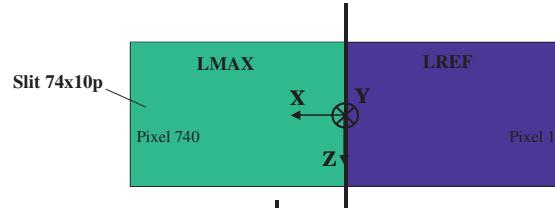

Figure 2. Across-track transition scene

1) Integrated straylight without cloud removal system

The maximum value in spectral band 1020 nm is around 60 %, definitely higher than the value in other bands. This straylight is detrimental to the Earth observation signal. The scattering within the spectrometer clearly and largely dominates the overall straylight, i.e. after the slit, and more precisely by the detector backscatter.
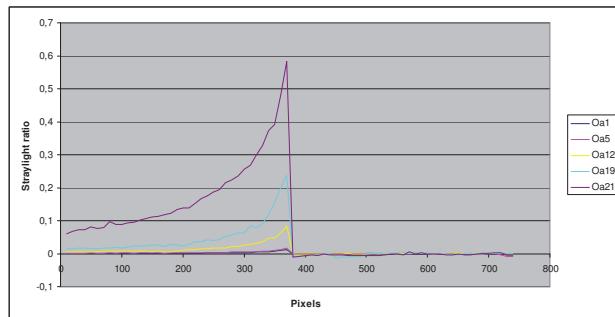

Figure 3. Stray light ratio without the cloud removal

The main contributor is here the detector backscattering. This straylight is inherent to all back-illuminated thinned CCD detectors, which are used with wavelength close to or larger than 1 micron. Indeed this thinning procedure improves performances in blue or near-UV.

Another additional contributor is the scattering occurring inside the silicon. It affects the photons in NIR. One explanation for this phenomenon, as well as for the previous one, is that the silicon is more or less transparent beyond 1 micron.
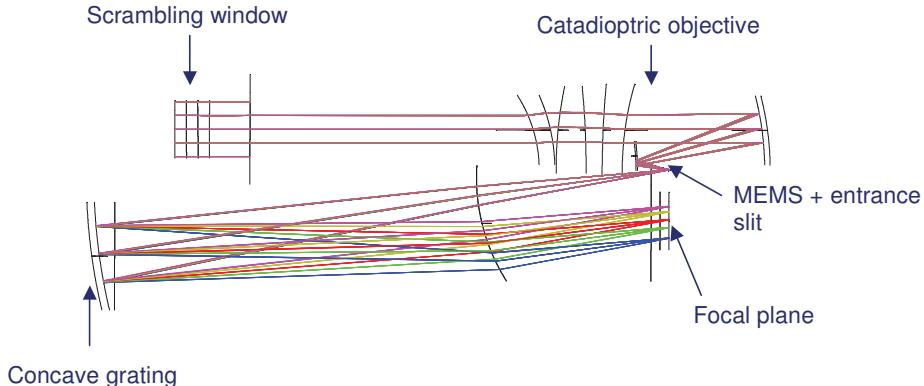

Figure 4. Global overview of the MEMS-based instrument.

Photon can easily cross the substrate and reflect on the electrodes or in the layer underneath and scatter inside the material. Since the absorption is quite low, photons can make a long trip before scattering. Once again this effect is inherent to the back-illuminated thinned CCD. And it is not so easy to get rid of them.

Total straylight at 1020 nm for a pixel 15-pixel apart from the transition is around 30% plus the internal diffusion (up to 20%, higher than 3%). A straylight level between 33 % and 50 % can be expected. This value is a bit less than the previous 60 % but it remains quite high. Once again, this straylight is inherent of back-illuminated thinned CCD detector working at wavelength higher than 900 nm.

2) Integrated straylight in presence of cloud removal system

Stopping the light coming from the cloud before entering in the spectrometer should decrease these values. Simulations are post-processed for an ideal cloud remover filtering a cloud spread on left-hand side of the slit.

In presence of the concept we propose, making the assumption we can predict the cloud location in the entrance slit, the straylight introduced by the spectrometer can be fully cancelled. In consequence only the straylight introduced by the ground imager is remaining. As we can see in Figure 5. , this level is definitely inferior (around 5% for 1020 nm band). This graph shows the benefits of using such an optical MEMS in the entrance slit of the spectrometer.

E. Mechanical designs

As presented in the previous paragraph, the main modifications between a conventional spectro-imager and the new instruments are: a spectrometer reversal, the introduction of a MEMS and its board, and the use of additional slit. The optical design is superimposed to the CAD view in the Figure 6. The blue box is the MIRA board, which dimensions are 10 x 10.5 x 2.5 cm^3. The area of mechanical conflict is shown. The MIRA board is above the focal plane array. Of course, the MIRA board can be redesigned but we must pay attention to this zone, which is quite dense.
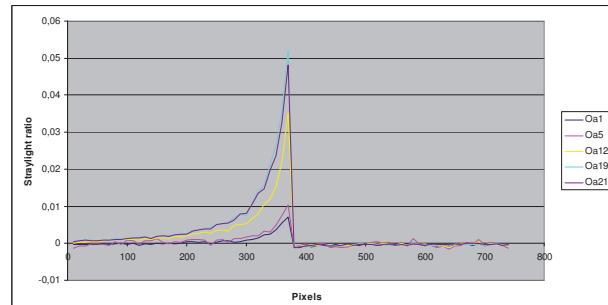

Figure 5.   Stray light ratio in presence of the cloud removal

F. First experimental demonstration at LAM

Experimental demonstration of this concept has been conducted on a dedicated bench. A scene with a contiguous bright area (factor 10^2) has been focused on a micro-mirror array and imaged on a CCD detector. The micro-mirror array is a DMD device from Texas Instrument made of 13.5µm mirrors. After the programmable slit, the straylight issued from the bright zone is set to the right level, i.e. equal to the scene signal level and pollutes the scene.

The resulting signal with the clouds and the polluted signal is recorded on a CCD camera. In order to restore the signal, the micro-mirrors located on the bright area are switched off, removing almost completely the straylight in the instrument.

In Figure 7. a), the profile of the FOV including the scene (left part) and the clouds area (right part) is shown: the green curve represents the FOV when the programmable slit is all ON, and the blue curve, the FOV when the micro-mirrors located in the bright area (clouds) are switched OFF.

A close-up view (Figure 7. b) permits to see the benefit of removing optically the polluting source, where the straylight produced by the bright area is nearly completely removed; the light blue curve represents the perfect scene, without clouds.

This successful demonstration shows the high potential of this new concept in future spectro-imager for Earth Observation.
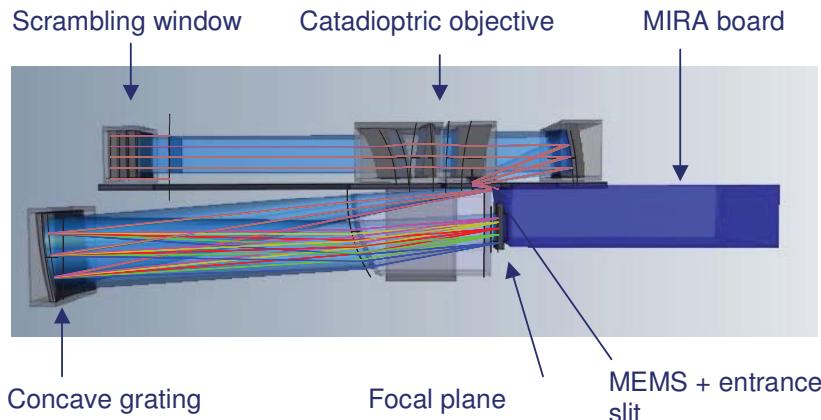

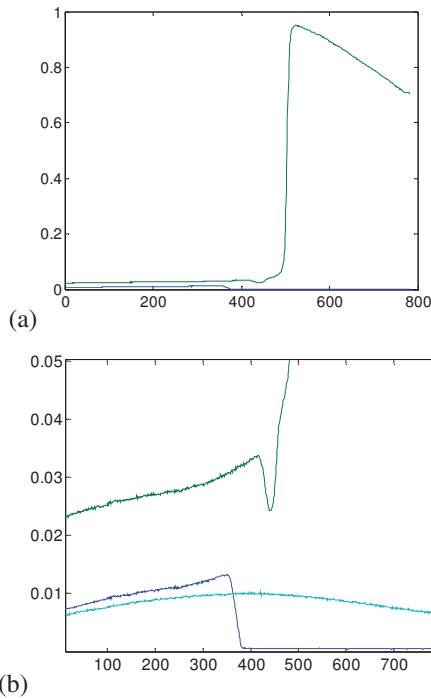Figure 6.   Superimposition of the optical design and of the CAD view

Figure 7. Cloud removal experiment; a) profile of the FOV including the scene (left part) and the clouds (right part) when the programmable slit is all ON (green curve) and when the micro-mirrors located on the bright area are switched OFF (blue curve); b) Close-up view of the transition area; the light blue curve represents the perfect scene, without clouds.

III. DIGITAL MICROMIRROR DEVICE FOR SPECTRAL CALIBRATION WITH FIELD-OF-VIEW

In a previous paper, [16], it shows how DMD can be advantageously used in a space spectrometer for having tunable spectral channels associated to large field of view. We have developed a methodology able to design very quickly a spectrometer. We have demonstrated that great performance could by achieved with such spectrometer: large field-of-view associated to high spectral performance. The possibility to play with spectral selection for an instrument having a wide field-of-view has a great potential. Dichroics filters, strip filter, band-pass filter could be replaced by a sub-level instrument. It offers the possibility to perform multi-applications missions. But this system is quite complex since two gratings and a DMD component compose it.

The principle is to use a DMD component to select the wavelengths by acting on intensity. Indeed, this component is placed in the focal plane of a first diffracting stage (using a grating for instance) and is used as a wavelength selector by reflecting or switching-off the light by deflection. It becomes then possible to realize a programmable and adjustable filter in λ and $\Delta\lambda$.

The spectrometer shall first disperse the light onto the DMD thanks to a grating for instance associated with a focusing optic and then recompose the beam after wavelengths selection (MOEMS level) by exactly the same dispersive component (same grating in our example). This kind of implementation allows to tune the filtering function in spectral bandwidth and in central wavelength quasi instantaneously.

The acquisition mode of such design is sequential with the advantage to use a simpler focal plane: dimension can be reduced to a linear detector instead of a 2D matrix detector array.

A. Instrument design parameters

This instrument aims at Earth observation in different spectral channels. The satellite works in push-broom acquisition (linear field-of-view at 700 km altitude with a 7 km/s speed. This stating point is in close relation with the applications. The target should have a large field-of-view (swath higher than 10 km) with a medium spatial resolution, [17] Ground Sampling Distance (GSD) around 5 m. It should be noticed that the goal of this instrument is not to extract some lines in the spectrum but more using a linear combination of lines to discriminate some scientific signatures. In this way we don't need a high SNR for one line.

Instead of a linear detector, we could envisage a matrix with 2000 columns for 5 to 20 lines. This detector should have two addressable modes. The first one is "Time Delay Integration", as the scene moves on the detector because of the satellite speed; charges are transferred line after line in phase with the scene. The consequence is that the integration time can be increased by a factor 5 to 20 without changing the attitude of the spacecraft and loosing part of the Earth tracks.

Figure 8. Synthesis of mission user's needs, [17]]

By implementing optical MEMS it could be possible to perform the multi filtering function without any strip filters (cf. Figure 10.). In this solution, the focal plane is constituted for instance by 4 (or more) adjacent detector lines, and all these lines are taken simultaneously with the same waveband color selected by the optical MEMS device. Thanks to its very fast response, it is possible to change the waveband color just after the needed integration time. By this way, the 4 following lines will be taken in an other color with only one line of spatial (or temporal) separation. After a period of 4 integration times, the same on ground scene will be observed sequentially in the 4 color channels.

B. Optical MEMS: DMD

The DMD concept is detailed in Figure 9. DMDs are component comprising hundreds of thousands micro-mirrors which are individually tiltable. Each micro-mirror measures a few microns. Thus, the incident beam can be redirected in many micro-beams oriented in two determined directions. Two electrodes control the position of each mirror via the electrostatic force. The reflected intensity in one direction can be modulated by periodically tilting the micro-mirrors during a fraction of the time.

In the first generation, the mirror width is 16µm, [1]. It can be tilted by 10° around its flexure arm in a binary way. A Scanning Electron Microscope (SEM) photograph (Figure 5-14) shows in false colors the different elements of an individual matrix mirror. The flexure arm width (in pink) is two microns and its thickness a few hundreds nanometers.

More recent DMD chips feature 2048 x 1080 mirrors, a 13.68µm pixel pitch, and a tilt angle of ±12°.

ESA has engaged with Visitech and LAM in a technical assessment of a DMD chip for space application, [2]. These results do not reveal any showstopper concerning the ability of the DMD to meet environmental space requirements. Insertion of such devices into final flight hardware would however still require additional efforts such as development of space compatible electronics, and original opto-mechanical design of the instrument.
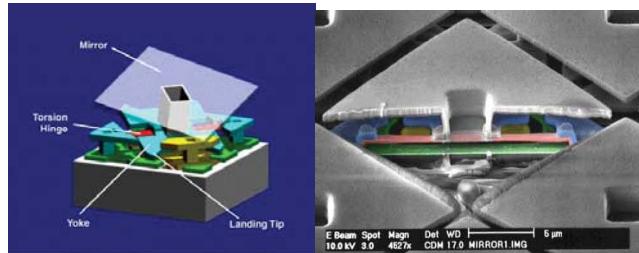

Figure 9. Texas Instruments' DMD: Principle and SEM photograph, courtesy Texas Instrument

C. Optical design

As we perform a symmetric action on the light, part of the design could be used twice. For doing that, a grating is placed in the pupil in a collimating beam. DMD is placed at focus, the pupil image being at infinity (telecentric system). In this case, light is perfectly backtracking. However, entrance beam and exit beam cannot be separated, that's the raison why two grating are used finally. The major problem is that the MEMS need to be tilted for 12° according to the (X+Y) diagonal direction.

Five meters is a quite small ground sampling distance (medium resolution). Diffraction and radiometry lead to the quite large entrance pupil diameter (>200mm). In consequence, a telescope is placed as fore optics. Considering the F/# and the field-of-view, a Ritchey-Chrétien design seems to be sufficient. But a TMA of a Korsch design could be envisaged in needed.
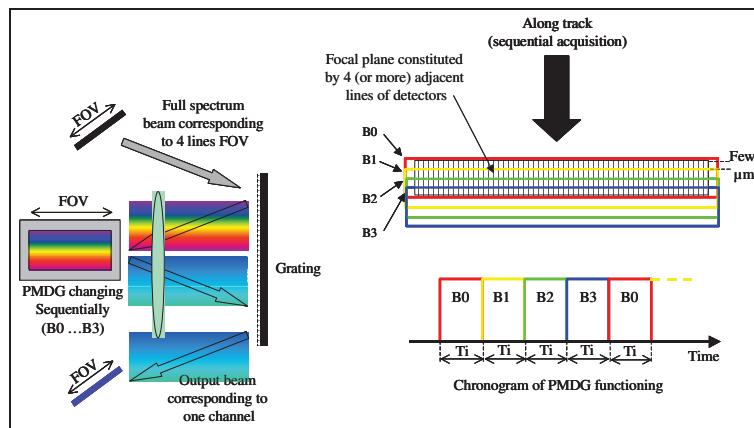

Figure 10. Possible solution using DMD.
The filtering is obtained sequentially thanks to the very fast response of this MOEMS component. In this case, DMD could require improvements in term of dimension depending on the mission FOV
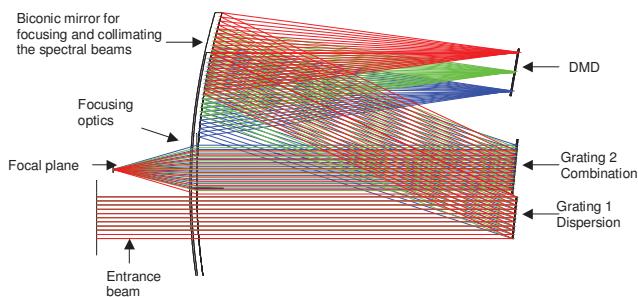
Figure 11. Optical MEMS based spectrometer

The Ritchey-Chrétien telescope is gathered with the spectrometer. Collimating lens after the slit and the focusing lens after the grating 2 are cemented achromatic doublets. This choice avoids multi-reflection and leaves some space to bend the instrument. Moreover, these lenses are more adapted to the aperture and field-of-view considered with respect to a single aspheric mirror.

D. Mechanical designs

In Figure 12. a general view of the nominal instrument is shown. It is based on a flat angle bracket. One part is supporting the telescope; the other is supporting the instrument. The instrument is baffled with the yellow cover to prevent from straylight.

As this instrument should work in NIR and SWIR (from 0.4 to 2.4 microns), the focal plane is put in a canister with coolers. Blue box represents the DMD board, which dimensions are 15x15x5 (thickness) cm^3.

IV. ROADMAP FOR OPTICAL MEMS DEVELOPMENT

Device architecture and packaging: DMDs cannot be customized in terms of optical architecture, pixel and array sizes. On the DC2k chip (2048 x 1080 micro-mirrors), the device must be used as it is, with a visible-coated window and dedicated electronics. Insertion of such devices into final flight hardware would however still require additional efforts such as development of space compatible electronics, and original

opto-mechanical design of the instrument. For the electronics, an FPGA-based system will be the most efficient way for driving the device. For reduced device size, current electronics architecture could be developed for space applications within a development time of 2 to 3 years. Large effort has to be made for developing the full electronics architecture; however, the development time could be shorter if classical architecture is selected, reducing the development time to 3 years. The estimated TRL level is 4-5 for the device itself (excluding driving electronics).
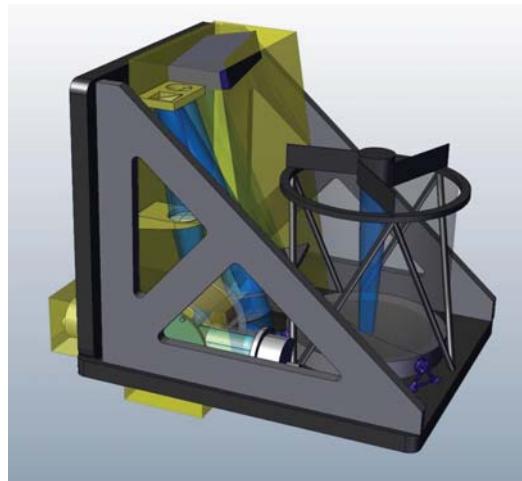

Figure 12. General view of this instrument

MIRA is well suited for cloud removal applications as it provides a long slit where individual mirrors could be tilted for sending the field-of-view on the detector or not tilted for removing the light (clouds) from the scene. In terms of geometrical parameters, LAM and EPFL have developed mirrors up to 250 x 500 µm^2 showing high surface quality; then the required 100 x 225 µm^2 mirrors array are feasible straight forward by using exactly the same architecture. We have also developed arrays dimensions up to 20x20mm^2, then the device size needed for the cloud removal application is reasonable. This step might be developed in 3 years time.
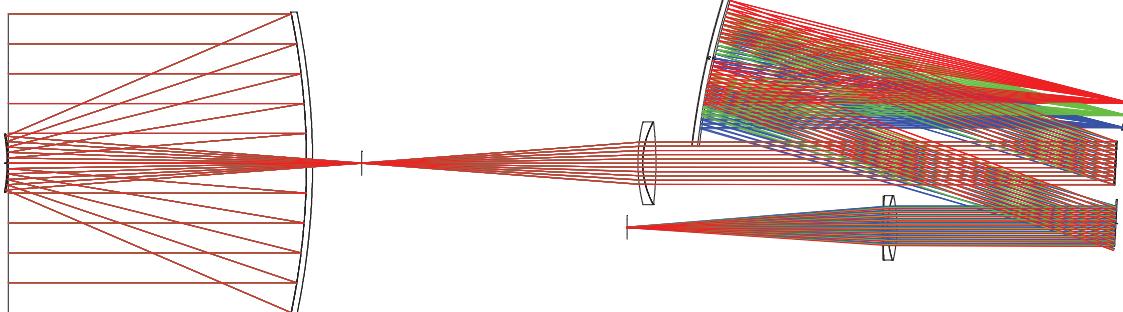

Figure 13. Optical layout of the assembled instrument

In terms of space environment compatibility, tests in a cryo chamber have been successful, down to 92K. Qualification of this component for space applications will take advantage of the work conducted by LAM on DMD devices during EUCLID studies, and funded by ESA, [2]. This step could be done in 2 years time, after the first and second steps. The current electronics must be redesigned for suitability with space environment. This step could be done in 2 years time, in parallel with the first and second steps. An alternative solution is to co-integrate a hardened electronics (ASIC) below the micro-mirror array in order to drive individually each micro-mirror. This step could be done in 3 years time, in parallel with the first and second steps. The estimated TRL level is 3-4 for the device itself (excluding driving electronics).

V. CONCLUSION

This paper analyzes what the optical MEMS could bring to the Earth observation payloads and instruments. This investigation was performed at the same time with a top-down approach, and with a bottom-up approach. In both cases, it results that MOEMS could bring satisfying new services/functionalities. The "cloud removal" concept is a very good example of that.

This investigation shows also that an optical MEMS could be necessary for the "cloud removal" concept. This dedicated component for this application has still to be developed. However a row of micro-mirrors seems to be feasible within a reasonable timeframe thanks to the MIRA development.

According to the results obtained during the preliminary designs performed in this study, and the first results of the LAM's proof-of-concept set-up, the concept of cloud removal for a spectro-imager seems to be very promising. It could be interesting to enlarge this approach to all spectro-imagers from ESA, which are facing the straylight problem. In addition to this detailed design, a demonstrator of this concept in the labs should be essential.

In parallel to this instrument study, it could be appropriate to develop this component. This programmable slit based on a row of micro-mirrors would be a generic building block for spectro-imagers. Some specifications and first idea of the component were presented. However it could be useful to define a specific task in this study aiming at refining these specifications.

VI. ACKNOWLEDGEMNTS

REFERENCES

[1] L. J. Hornbeck, "Digital light processing and MEMS: timely convergence for a bright future", in Proceedings of Micromachining and Microfabrication Process Technology, K.W. Markus, ed., SPIE 2639, 2, Austin, USA (1995)

[2] F. Zamkotsian, P. Lanzoni, E. Grassi, R. Barette, C. Fabron, K. Tangen, L. Valenziano, L. Marchand, L. Duvet " Successful evaluation for space applications of the 2048x1080 DMD," in Proceedings of the SPIE conference on MOEMS 2011, Proc. SPIE 7932, San Francisco, USA (2011)

[3] S. Cornelissen, T. G. Bifano "Advances in MEMS deformable mirror development for astronomical adaptive optics", in Proceedings of the SPIE conference on MOEMS 2012, Proc. SPIE 8253, San Francisco, USA (2012)

[4] S. Senturia "Programmable diffraction gratings and their uses in displays, spectroscopy, and communications", in Proceedings of the SPIE conference on MOEMS 2004, Proc. SPIE 5348, San Jose, USA (2004)

[5] J. Trisnadi, C. Carlisle, R. Monteverde "Overview and applications of Grating Light Valve based optical write engines for high-speed digital imaging", in Proceedings of the SPIE conference on MOEMS 2004, Proc. SPIE 5348, San Jose, USA (2004)

[6] P. Herbst, C. Marxer, M. Sotom, C. Voland, M. Zickar, W. Noell and N. de Rooij, "Micro-optical switches for future telecommunication payloads: achievements of the SAT 'N LIGHT Project", ESA 5th Round Table on Micro/Nano Technologies for Space, Noordwijk, The Netherlands, Oct. 3-5, 2005.

[7] J-L Bezy "EarthCARE Technical & Programmatic Annex" April 2004, http://esamultimedia.esa.int/docs/EEUCM/EarthCARE_TPA.pdf

[8] P. Martimort "Sentinel-2 the optical High resolution mission for GMES operating services" ESA Buletin 131 p.19, August 2007

[9] C. Donlon, "Sentinel-3 OLCI and SLSTR", Medspiration/GlobColour symposium, 20th November 2008

[10] http://www.eumetsat.int/Home/Main/Satellites/MeteosatThirdGeneration/index.htm

[11] P. Schlüssel, "Post-EPS user and mission requirements for future sounders" 25th October 2010, http://airs.jpl.nasa.gov/nasa-sounder-workshop/slides/Schluessel_Post-EPS.ppt.pdf

[12] S. Waldis, F. Zamkotsian, P.-A. Clerc, W. Noell, M. Zickar, N. De Rooij, "Arrays of high tilt-angle micromirrors for multiobject spectroscopy, " IEEE Journal of Selected Topics in Quantum Electronics 13, pp. 168–176 (2007).

[13] M. Canonica, S. Waldis, F. Zamkotsian, P. Lanzoni, W. Noell, N. de Rooij, " Development of MEMS-based programmable slit mask for multi-object spectroscopy ", in Proceedings of the SPIE conference on Astronomical Telescopes and Instrumentation, Proc. SPIE 7739, San Diego, USA (2010)

[14] F. Zamkotsian, J. Gautier, P. Lanzoni, "Characterization of MOEMS devices for the instrumentation of Next Generation Space Telescope," in Proceedings of the SPIE conference on MOEMS 2003, Proc. SPIE 4980, San Jose, USA (2003)

[15] A. Liotard, F. Zamkotsian, "Static and dynamic micro-deformable mirror characterization by phase-shifting and time-averaged interferometry", in Proceedings of the SPIE conference on Astronomical Telescopes and Instrumentation 2004, Proc. SPIE 5494, Glasgow, United Kingdom (2004)

[16] Th. Viard, Ch. Buisset, F. Zamkotsian, V. Costes, L. Venancio, "MOEMS for prospective space applications", SPIE MOEMS-MEMS 2011, San Francisco, USA, 2011

[17] S. Michel, M.-J. Lefrevre-Fonollosa, S. Hosford, "HYPXIM – a hyperspectral satellite defined for science, security and defence users" Proc. 'Hyperspectral 2010 Workshop', Frascati, Italy, 17–19 March 2010 (ESA SP-683, May 2010)