International Conference on Space Optics—ICSO 2012

Ajaccio, Corse

9–12 October 2012

Edited by Bruno Cugny, Errico Armandillo, and Nikos Karafolas

Efficient optical cloud removal technique for earth observation based on MOEMs device

Frédéric Zamkotsian

Patrick Lanzoni

Arnaud Liotard

Thierry Viard

et al.

International Conference on Space Optics — ICSO 2012, edited by Bruno Cugny, Errico Armandillo, Nikos Karafolas
Proc. of SPIE Vol. 10564, 105643A · © 2012 ESA and CNES · CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2309069

Efficient optical cloud removal technique for Earth Observation based on MOEMS device

Frédéric Zamkotsian, Patrick Lanzoni
Laboratoire d'Astrophysique de Marseille (LAM)
Marseille – France

frederic.zamkotsian@oamp.fr

Arnaud Liotard, Thierry Viard
Thales Alenia Space
Cannes-la-Bocca – France

Wilfried Noell
EPFL
Neuchatel – Switzerland

Abstract – **In Earth Observation instruments, observation of scenes including bright sources leads to an important degradation of the recorded signal. We propose a new concept to remove dynamically the bright sources and then obtain a field of view with an optically enhanced Signal-to-Noise Ratio (SNR). Micro-Opto-Electro-Mechanical Systems (MOEMS) could be key components in future generation of space instruments. MOEMS-based programmable slit masks will permit the straylight control in future Earth Observation instruments. Experimental demonstration of this concept has been conducted on a dedicated bench. This successful first demonstration shows the high potential of this new concept in future spectro-imager for Earth Observation.**

Keywords: Earth Observation, Space instrumentation, Cloud removal, MOEMS.

I. INTRODUCTION

In Earth Observation instruments, observation of scenes including bright sources leads to an important degradation of the recorded signal. Software solutions permit to solve partially this problem. We propose a new concept to remove dynamically the bright sources and then obtain a field of view with an optically enhanced Signal-to-Noise Ratio (SNR). Micro-Opto-Electro-Mechanical Systems (MOEMS) could be key components in future generation of space instruments. They are based on the mature micro-electronics technology and in addition to their compactness, scalability, and specific task customization, they could generate new functions not available with current technologies.

MOEMS-based programmable slit masks will permit the straylight control in future Earth Observation instruments. The proximity of bright sources as clouds close to the scientific targets generates high straylight levels in spectro-imagers. Our concept consists in replacing the plain slit in classical designs by an active row of MOEMS. The scattering within the spectrometer, i.e. after the slit, clearly and largely dominates the overall straylight. The row of MOEMS micromirrors will permit to dynamically remove the bright sources located in the field of view, and then optically enhance SNR.

The MOEMS device foreseen in this concept could be based on the micro-mirror arrays under development in collaboration between LAM and EPFL, for generating reflective slit masks in future Multi-Object Spectrographs. Our current programmable reflective slit masks are composed of 2048 individually addressable micromirrors in a 32x64 array. Each silicon micromirror measures 100 x 200 μm^2 and is electrostatically tilted by a precise angle of at least 20° for an actuation voltage of 130 V. These micromirrors with coating demonstrated a peak-to-valley deformation less than 10 nm. A first experiment of the line-column algorithm for individual mirror addressing was demonstrated. These devices were characterized in a cryogenic environment at 162K and several lines of micromirrors were tilted successfully under these conditions. A dedicated row of micromirrors will be derived from this development.

Experimental demonstration of this concept has been conducted on a dedicated bench. A scene with a contiguous bright area has been focused on a micromirror array (DMD device from Texas Instrument) and imaged on a CCD detector. After the programmable slit, the straylight issued from the bright zone is polluting the scene; the micromirrors located on the bright area are switched off, removing almost completely the straylight in the instrument. This successful first demonstration shows the high potential of this new concept in future spectro-imager for Earth Observation.

II. DIGITAL MIRROR ARRAY FOR CLOUD REMOVAL

Earth Observation instruments aim 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.

According to the luminance of clouds and sun-glints, the straylight level in the instrument is around 60 % in NearIR. 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.

A. 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 located at the entrance of the spectrometer. All other elements are kept such as the scrambling window unit, the catadiotric objective, the concave grating and the focal plane [1]

B. 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 (Fig. 1).

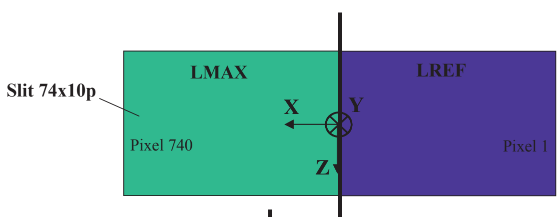

Figure 1. Across-track transition scene

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 (Fig. 2). 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.

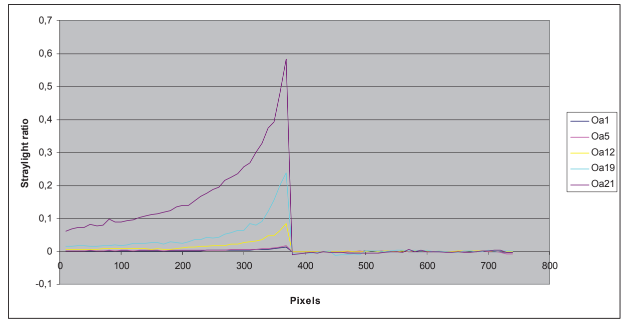

Figure 2. Stray light ratio without the cloud removal

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. 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. It is not easy to get rid of it.

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. This straylight is inherent of back-illuminated thinned CCD detector working at wavelength higher than 900 nm.

2) Integrated straylight with a 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 Fig. 3, this level is definitely lower (around 5% for 1020 nm band). This graph shows the benefits of using such optical MEMS at the entrance of the instrument.

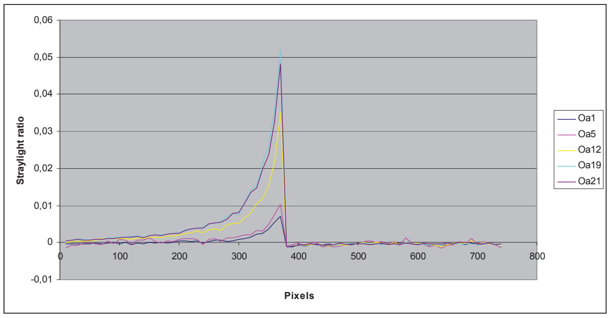

Figure 3. Stray light ratio in presence of the cloud removal

III. First experimental demonstration at LAM

Laboratoire d'Astrophysique de Marseille (LAM) has, over several years, developed different tools for modeling and characterization of MOEMS devices [2,3].

A. Experimental set-up

Experimental demonstration of this concept has been conducted on a dedicated bench (Fig. 4). 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.

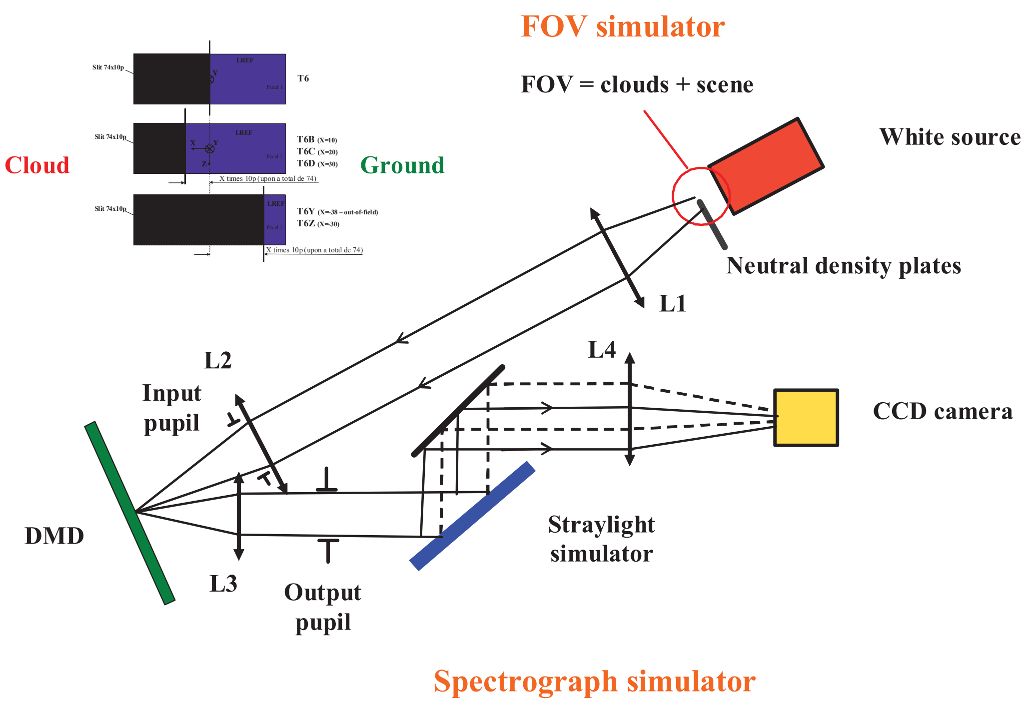

Figure 4. Experimental set-up for cloud removal demonstration

B. Experimental results

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 Fig. 5 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 (Fig. 5 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.

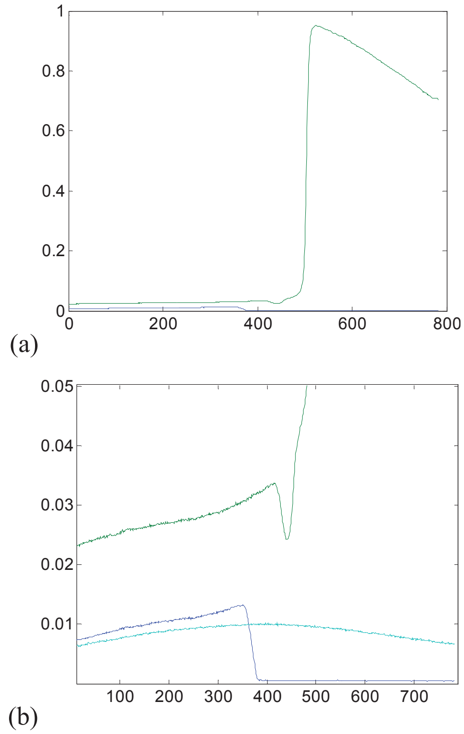

Figure 5. Cloud removal experiment; a) profile of the FOV including the scene (left part) and the clouds (right part) when the programmable slit is all ON (green curve) and when the micro-mirrors located on the bright area are switched OFF (blue curve); b) Close-up view of the transition area; the light blue curve represents the perfect scene, without clouds.

IV. MOEMS CANDIDATE

In Europe, an effort is currently under way to develop single-crystalline silicon micromirror arrays for future generation infrared multi-object spectroscopy [4]. A collaboration within the Laboratoire d'Astrophysique de Marseille (LAM) and the Ecole Polytechnique Federale de Lausanne (EPFL) has for purpose to develop a European programmable MMA that can be used as reflective slit mask for MOS, the project is called **MIRA**. The requirements for our MMA were determined from previous simulation results and measurements [2]. It has to achieve a high optical contrast of 1000:1 (goal: 3000:1), a fill factor of more than 90 % and a mechanical tilt angle greater than 20°. Furthermore, the performance must be uniform over the whole device; the mirror surface must remain flat in operation throughout a large temperature range and it has to work at cryogenic temperature.

CONCEPT AND FABRICATION

Our MMA concept is based on the electrostatic double plate actuator. A micromirror is suspended by two flexion hinges, which were attached to a sustaining frame. To generate an electrostatic force, an electrode is placed underneath the micromirror and pillars are placed to set a precise electrostatic gap. A stopper beam is placed under the frame to set precisely the tilt angle of the micromirror after actuation and electrosatically lock it in this position.

The 100 x 200 μm^2 micromirrors were made of single-crystal silicon, assuring optical flat surfaces. Silicon being transparent in the infrared range, a gold thin-film coating was deposited on the topside of the mirrors. The cantilever-type suspension was made of a deposited polycrystalline silicon layer deposited on the back of the mirror. The electrodes were also made of single-crystal silicon.

For MMA realization, a combination of bulk and surface silicon micromachining was used. They were made of two wafers: one for the mirrors and one for the electrodes, which were processed separately and assembled by wafer level bonding. For applications in modern and future telescopes large arrays are required. We developed a new process where the mirror chip is bonded on top of the electrode chip and microfabricated pillars on the electrode chip provide the necessary spacing between the two parts. Prototypes of MMA with 2048 individually addressable micromirrors (64 x 32 mirrors) have been successfully realized (Fig. 6) [5].

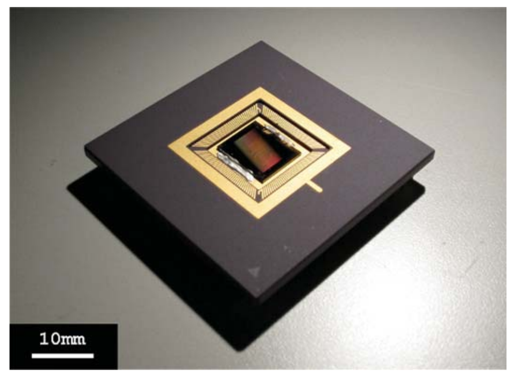

Figure 6. 64 x 32 micromirror array with high fill factor in the vertical direction provinding long slits. Each mirror measures 200 x 100 μm^2.Two wafer level bonding steps are required to process these arrays.

MICROMIRROR ARRAY CHARACTERIZATION

MMA have been tested at LAM on bench set-ups dedicated to the characterization of MOEMS devices.

Micromirror surface flatness measurement and actuation

The surface quality of the micromirror is measured by phase-shifting interferometry, and a total deformation of 10nm peak-to-valley is measured, with 1nm roughness. These mirrors can be electrostatically tilted by 24° at an actuation voltage of 130V. In many MOS observations, astronomers need to have the spectrum of the background nearby the studied object ("long slit" mode). Our locking mechanism is designed in order to ensure this goal and a performance of a few arc-minutes angle difference has been obtained on first prototypes.

The fill factor characterized by SEM was 82.3% for the mirror surface and 98% in the direction along the micromirror lines.

Individual addressing of the mirrors is based on a line-column scheme. As a proof of concept, a 2x2 sub-part of a MMA of 32x64 micromirrors was actuated successfully [5].

Contrast measurement

The contrast of a micromirror was characterized on a dedicated optical bench at LAM. A light source having a diameter of 200 µm has been focused on a micromirror. Two pictures were recorded: for a micromirror at rest (OFF state) and for a micromirror tilted (ON state). The light intensity of each picture was integrated over the micromirror surface and the ratio between the pictures provided the contrast. Finally, for a micromirror tilting by 24°, a contrast ratio of 1000:1 was obtained.

Operation at cryogenic temperature

In order, to avoid spoiling of the astronomical objects spectra by the thermal emission of the instrument, the micromirror array has to work in a cryogenic environment.

For characterising the surface quality and the performance of our MMA's at low temperature, we have developed a cryo chamber optically coupled to a high-resolution Twyman-Green interferometer. The interferometer provides a sub-nanometer accuracy, and the cryo-chamber allows pressure down to 10^{-6} mbar and cryogenic temperatures (Fig. 7).

Our MMA is conceived such that all structural elements have a matched coefficient of thermal expansion (CTE) in order to avoid deformation or even flaking within the device when cooling down to the operating temperature, especially on the mirrors themselves be covered with a gold layer, gold having a different CTE than silicon.

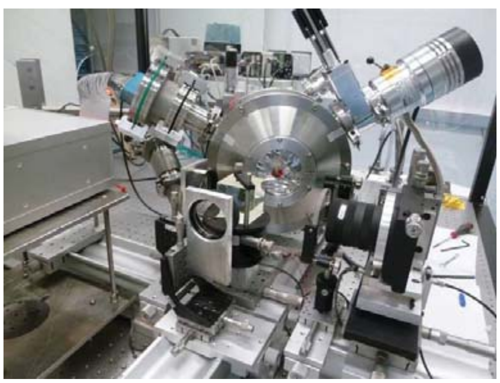

Figure 7. Cryogenic chamber installed on our interferometric setup. MMA with 64 x 32 micromirrors is integrated (100 x 200 µm^2 micromirrors).

The chamber has a glass window that allows observing and measuring the sample chip during cryogenic testing. The micromirror device is illuminated and imagined by a CCD camera on the outside; the micromirror device is rotated such that the light of the tilted mirrors (ON state) is sent to the CCD camera. The presence of a glass window at the entrance of the chamber is an issue for getting fringes with a high contrast. Thanks to the use of a plate in the reference arm identical to the chamber window, we could get a high contrast in our measurements.

The MMA device is packaged in PGA chip carrier (Fig. 6). The PGA is inserted in the chamber on a ZIF-holder integrated on a PCB board. Large copper surfaces on the PCB facilitate cooling down the system. A 100-pins feed-through connector links the chip with a custom built MMA control electronics. Temperature sensors are connected to the aluminum support and to the grid zip connector adjacent to the sample chip, in order to monitor the tests.

The micromirrors could be successfully actuated before, during and after cryogenic cooling at 162K (Fig. 8). Several lines of 32 micromirrors were successfully tilted with a driving voltage of 148V. We could measure the surface quality of the gold coated micromirrors at room temperature and at 162 K without large deformation difference.

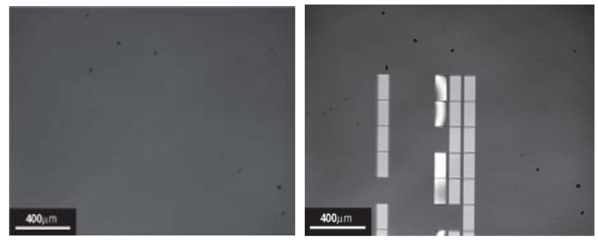

Figure 8. Interferometric observations of the lines of micromirrors during the cryogenic experiment at 162K: micromirrors at rest (OFF state) and in ON state when 148V is applied. Mirrors are tilted by 24°.

V. CONCLUSION

In Earth Observation instruments, observation of scenes including bright sources leads to an important degradation of the recorded signal. Our new concept based on MOEMS devices is to remove dynamically the bright sources and then obtain a field of view with an optically enhanced SNR.

Experimental demonstration of this concept has been conducted successfully, and shows the high potential of this new concept in future spectro-imager for Earth Observation.

REFERENCES

[1] A. Liotard, F. Zamkotsian, W. Noell, T. Viard, M. Freire, B. Guldimann, S. Kraft, " Optical MEMS for space spectro-imagers," *Proceedings of the SPIE conference on Astronomical Instrumentation 2012*, Proc. SPIE **8450**, Amsterdam, The Netherlands (2012)

[2] 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)

[3] 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)

[4] 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).

[5] M. Canonica , F. Zamkotsian, P. Lanzoni, W. Noell, N. de Rooij "Large MEMS-based programmable reflective slit mask for multi-object spectroscopy fabricated using multiple wafer-level bonding," *Proceedings of the SPIE conference on MOEMS 2012*, Proc. SPIE **8252**, San Francisco, USA (2012)