**International Conference on Space Optics—ICSO 2014**

La Caleta, Tenerife, Canary Islands

7–10 October 2014

*Edited by Zoran Sodnik, Bruno Cugny, and Nikos Karafolas*


# *Programmable wide field spectrograph for earth observation*


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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 1056332 · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304191

# PROGRAMMABLE WIDE FIELD SPECTROGRAPH FOR EARTH OBSERVATION

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## INTRODUCTION

In Earth Observation, Universe Observation and Planet Exploration, scientific return of the instruments must be optimized in future missions. Micro-Opto-Electro-Mechanical Systems (MOEMS) could be key components in future generation of space instruments. These devices 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. French and European space agencies, the Centre National d'Etudes Spatiales (CNES) and the European Space Agency (ESA) have initiated several studies with LAM and TAS for listing the new functions associated with several types of MEMS, and developing new ideas of instruments. [1,2,3]

Several MEMS devices have been considered in terms of performance and abilities for different functions:
- Programmable slits
- Programmable micro-diffraction gratings
- Micro-deformable mirrors

For the programmable slits, two devices are promising for developing new applications, a silicon-based MMA designed and realized by laboratories and a commercial array. A European development is under way between LAM and EPFL in order to develop micro-mirror arrays for generating reflective slit masks in future Multi-Object Spectrographs. These programmable reflective slit masks are composed of 2048 individually addressable 100 x 200 µm$^2$ micromirrors in a 32x64 array. Each silicon micromirror is electrostatically tilted by a precise angle of at least 20° for an actuation voltage of 130 V. These micromirrors demonstrated very good surface quality with a deformation below 10 nm, individual addressing using a line-column scheme, and they are working in a cryogenic environment at 162K. [4,5]
The commercial array is the popular DMD device from Texas Instruments. The DMD features 2048 x 1080 mirrors on a 13.68µm pitch and has been previously tested by our team for space applications. [6]
With the programmable slits, several functions have been listed and possible applications found. Functions are selection of objects or parts of a FOV, feeding instruments in two directions, selecting two pointing directions, modulation of the light intensity by zone on a temporal basis, pupil shape configuration, spectral selection and slit masks generation.

Programmable diffraction gratings are a new-class of MOEMS devices. Piston-motion parallel moving ribbons could be set locally as a grating, and then diffract the light. If the incoming light spectrum is dispersed along the device, any wavelength could be selected or removed by tuning the device. We have characterized the performances of two devices: a silicon-based device designed and realized by laboratories (CSEM, LAM, EPFL) [7] and a commercial array from Silicon Light Machines.
With the programmable diffraction gratings, several functions have been listed and possible applications found. Functions are wavelength selection for spectroscopy or spectral tailoring, optical beam selection and attenuation, these two first functions including temporal behaviour, and beam addressing by using the diffraction orders.

Micro-deformable mirrors are used for wavefront correction, mainly in adaptive optics systems. Boston Micromachines Corporation (BMC) produces the most advanced MEMS deformable mirrors. [8]
With the micro-deformable mirrors, several functions have been listed and possible applications found. Functions are wavefront correction (active or adaptive modes depending on loop frequency), optical beam tailoring and focal plane curvature compensation.

Two promising concepts of space instruments for Earth Observation (EO) and Astronomy have been presented. In EO instruments, bright sources in the observed scenes degrade the recorded signal. Our concept consists in an active row of MOEMS for removing them. Experimental demonstration has been conducted and the straylight in the instrument has been removed almost completely. [1]

The second concept is presented in this paper: a programmable wide-field spectrograph where both the FOV and the spectrum could be tailored thanks to 2D micromirror arrays. A demonstrator has been designed, fabricated and integrated. The very promising results obtained on the mock-up of the programmable wide-field spectrograph are presented and analyzed.

## PROGRAMMABLE WIDE FIELD SPECTROGRAPH: CONCEPT

We propose a new concept of a programmable wide-field spectrograph using a MOEMS device (DMD from TI) for individual wavelength tailoring on each field pixel.

### *A. Concept*

For a linear 1D field of view (FOV), the principle is to use a 2D micromirror array (MMA) component to select the wavelengths by acting on intensity (Fig. 1). 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. On the MMA surface, the spatial dimension is along one side of the device and for each spatial point, its spectrum is displayed along the perpendicular direction: each spatial and spectral feature of the 1D FOV is fully adjustable dynamically and/or programmable for each exposure or even during an exposure by using the temporal behaviour of the component. It becomes then possible to realize a programmable and adjustable filter in lambda and delta-lambda. A second stage recomposes the beam after wavelengths selection by exactly the same dispersive component (same grating), leading to an output 1D image. This kind of implementation allows to tune the filtering function in spectral bandwidth for each spatial pixel quasi instantaneously.

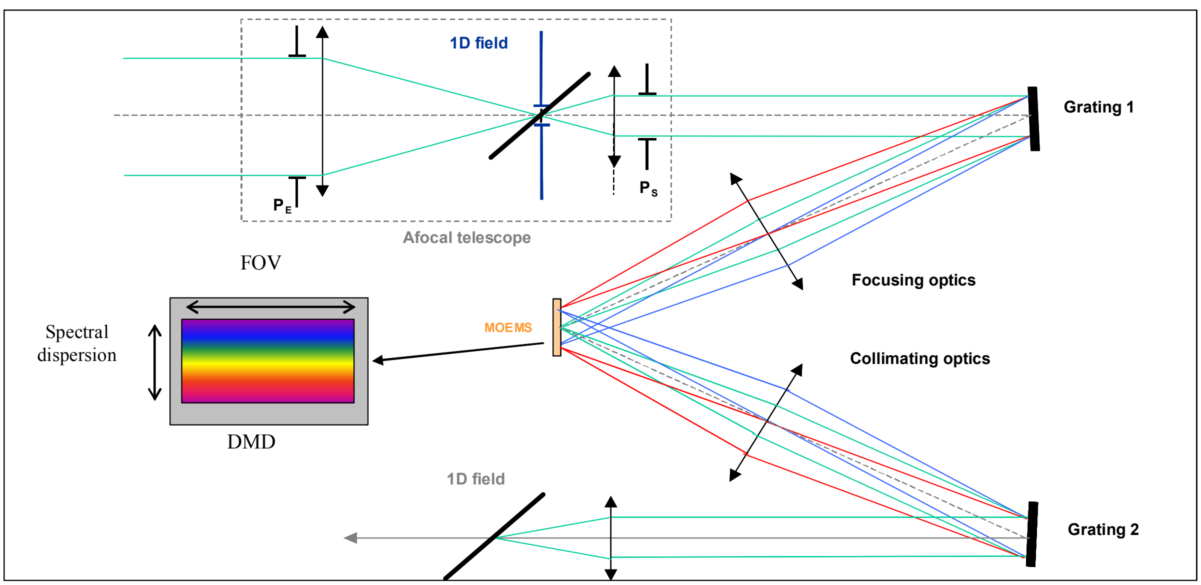


**Fig. 1.** Principle of the programmable wide-field spectrograph using a MOEMS device (DMD from TI) for wavelength tailoring on each field pixel.

### *B. Slit generator*

Digital Micromirror Devices (DMD) from Texas Instruments could act as field and wavelength selection reconfigurable mask. The largest DMD chip developed by TI features 2048 x 1080 mirrors on a 13.68µm pitch, where each mirror can be independently switched between an ON (+12°) position and an OFF (-12°) position. This component has been extensively studied in the framework of an ESA technical assessment of using this DMD component (2048 x 1080 mirrors) for space applications (for example in EUCLID mission). Specialized driving electronics and a cold temperature test set-up have been developed. Our tests reveal that the DMD remains fully operational at -40°C and in vacuum. A 1038 hours life test in space survey conditions (-40°C and vacuum) has been successfully completed. Total Ionizing Dose (TID) radiation tests, thermal cycling (over 500 cycles between room temperature and cold temperature, on a non-operating device) and vibration and shock tests have also been done; no degradation is observed from the optical measurements. These results do not reveal any concerns regarding the ability of the DMD to meet environmental space requirements [6].

In Europe an effort is currently under way to develop single-crystalline silicon micromirror arrays for future generation infrared multi-object spectroscopy (collaboration LAM / EPFL-CSEM). First arrays with 2048 micro-mirrors have been successfully designed, realized and tested at 160K [4,5]. On a longer time scale, these arrays could be used in programmable wide-field spectrograph for Earth Observation.

*C. Flight model*

A flight model of a programmable wide-field spectrograph has been designed by TAS with LAM collaboration. Parameters of this instrument are: 30km field-of-view (FOV) on ground, with 15m ground resolution, spectral range 0.4-2.4µm, spectral resolution 2nm / 5nm /10 nm; intermediate focal plane (DMD) 2000x1000 pixels (pitch 15µm); focal plane Si pixel detector (pixel size 15 µm); spectrograph entrance slit size 30mm x 15 µm.

Prism and grating-based designs have been studied and the grating concept has been selected. This concept has been adapted for the demonstrator design (see next paragraph).

## PROGRAMMABLE WIDE FIELD SPECTROGRAPH: DEMONSTRATOR

A mock-up has been designed, fabricated and tested. The micromirror array is the largest Digital Micromirror Device (DMD) from Texas Instruments in 2048 x 1080 mirrors format, with a pitch of 13.68µm. Our optical design for both spectrographs, mounted before and after the DMD plane, is a compact design, all-reflective with F/4 on the DMD component and robust 1:1 Offner relays.

*A. Demonstrator optical design*

Our goal is to make a robust and efficient instrument for a space mission. Selecting a good starting point was really important. In order to simplify as much as possible the optical layout of the system, we fixed some constraints:
(a) focal ratios feeding DMD should be close to F/4, thus allowing relatively easy decoupling from the incoming an outcoming beams on the DMD surface;
(b) incoming beam must hit DMD surface at normal incidence, everywhere on the DMD chip, translating into a simpler relay system not introducing tilted image planes and being telecentric;
(c) all optical components should lie in plane, for easy integration and alignment;
(d) use as much as possible only plano and spherical optics, to reduce cost and delivery time.

Even if complex, we succeeded to design such a system, developing ideas proposed many years ago for the JWST near-infrared multi-object spectrograph [9], and developed more recently for BATMAN project [10].

Our optical design is based on a double Offner relay system placed in serial, with a 1:1 magnification between input field elements and the DMD pixels, and the DMD pixels and the detector pixels (Fig. 2). DMD orientation is at 45° (rotation around z-axis) with respect to the bench, due to the fact that the micromirrors are tilting along their diagonal. A simple spectrograph layout has been set up, based on two identical spherical mirrors acting as collimator and camera, and a low density convex grating to disperse light. We have ordered two identical spherical mirrors with a diameter of 115mm and a radius of curvature of 285mm. The most critical component of the system is the convex grating, due to complex manufacturing and tight alignment tolerances. A Jobin-Yvon (Horiba group) grating has been chosen from their available list of gratings, leading to a component with 150 gr/mm line density, 140mm radius of curvature and 40mm in diameter.

This makes the system simple and efficient, not suffering from chromatic aberrations. Delivered image quality onto the DMD and onto the detector is high enough to not degrade resolving power and spatial resolution, too. Typical monochromatic RMS spot diameters are 20µm at the intermediate focal plane (DMD surface) and 10µm at the focal plane, over the whole FOV for wavelengths between 450nm and 750nm.

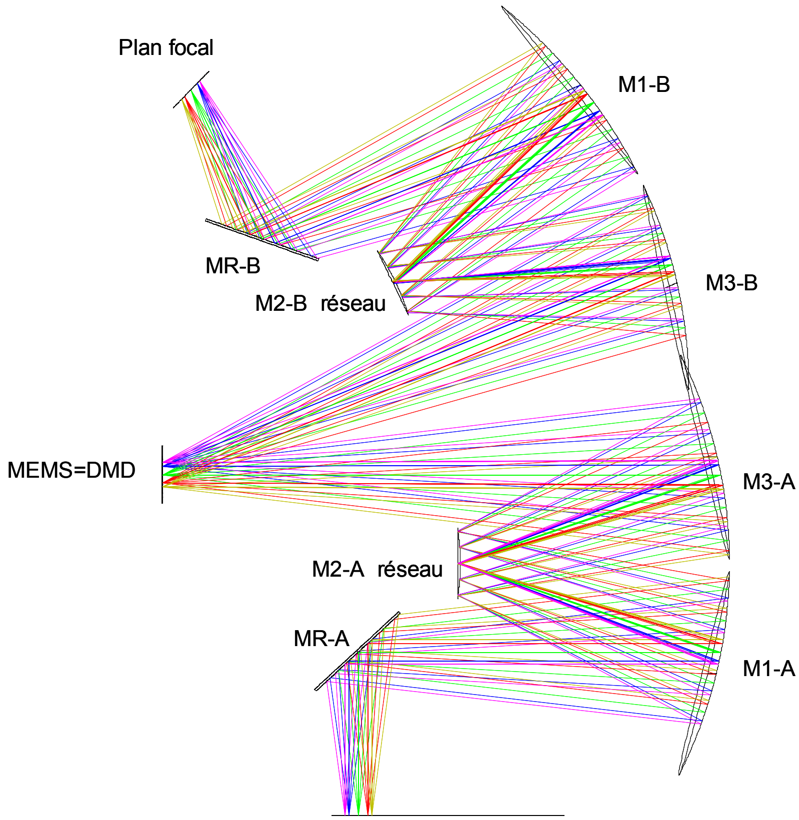


**Fig. 2.** Optical design of the programmable wide field spectrograph demonstrator.
Light from the telescope is coming from below (1D entrance slit), passing through two Offner-type spectrographs in serial separated by the DMD, up to the detector at the top of the drawing.

*B. Demonstrator opto-mechanical design*

The general mechanical design of the mock-up consists of a main optical bench supported by three legs (Fig. 3). This bench supports two spectrographs in serial. An OLED at the entrance simulates the field of view. Earth images are displayed using their RGB values. We have developed a software in Matlab in order to drive the input beam with adjustable image size on the OLED, programmable slits (shape, width), colors selection as well as the possibility to have a scanning slit-FOV, mimicking a push-broom type Earth Observation.

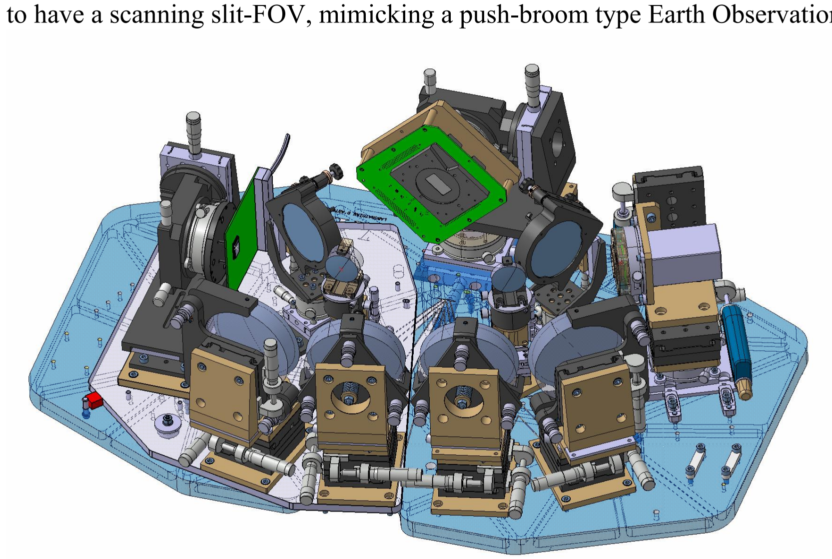

**Fig. 3.** Opto-mechanical design of the programmable wide field spectrograph, 3D general design view

The optical components are mounted in dedicated mounts with stops and screws and could be aligned along all degrees of freedom thanks to stages with micrometer accuracy. In order to minimize cost, the design intends to use only one type of material which is aluminium alloy (except for mirrors that are made in silica). The main bench is light weighted.

Due to the wide FOV covered by the DMD, we will cover it only partially and we add motorized stages on the input beam optical system as well as on the detector, in order to address the full FOV sequentially.

*C. Demonstrator integration*

The demonstrator has been integrated and aligned on a damped table (Fig. 4). The optical beam is generated on the left-hand side by an OLED; the DMD is located at the top center and two spectrographs are located, one before the DMD for dispersing the light of each field pixel on the DMD, and a second one, identical to the first one, for combining the tailored wavelengths on each field pixel towards a unique output 1D line on the detector.

Images are recorded by the CCD camera located at the right-hand side of the picture. The grey ribbons at the top of the picture consist of 300 wires for controlling the DMD. Optical path scheme is etched on the bench.

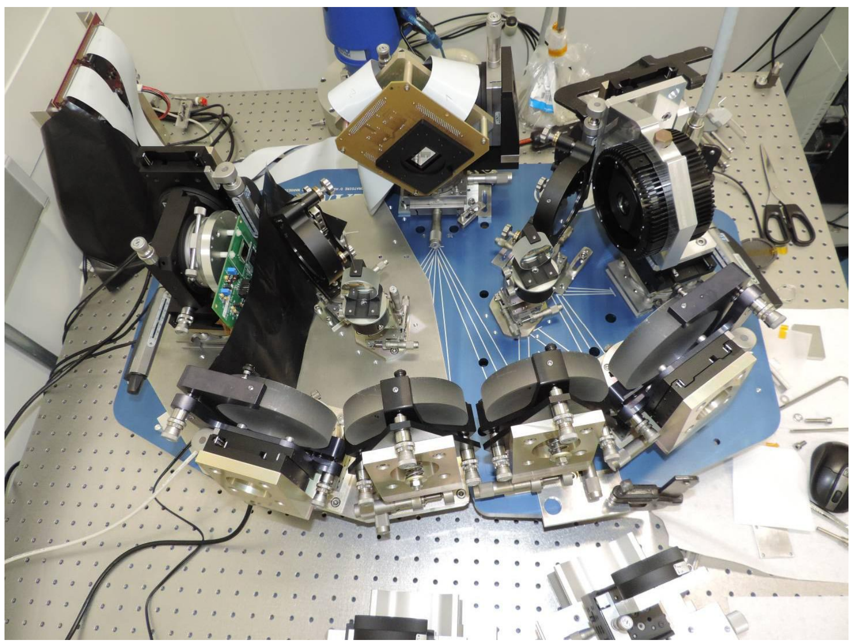

**Fig. 4.** Integrated demonstrator picture
Input/OLED is on the left, the DMD at the top, and the output/detector on the right.

Alignment strategy uses a combination of mechanical and optical measurements. Each optical sub-system is referenced by its vertex and center of curvature from the Zemax file; alignment tools are placed at the sub-systems location and mechanically located with a mechanical 3D measurement machine; actual positions away from the theoretical positions are calculated and optically aligned thanks to a micro-alignment telescope, using the screws mounted on each element, allowing the movement of the element within the 6 degrees of freedom.

Each spectrograph has been aligned independently before final integration on DMD both sides. First spectra have been obtained and measured; typical spot diameters are within 1.5 detector pixels (8.3µm detector pixels), and spectra generated by one micro-mirror slits are displayed with this optical quality over the whole visible wavelength range. This alignment procedure has been defined during the integration of ROBIN, the mock-up of BATMAN instrument, based on an optical design very close to the programmable wide field spectrograph design. [10]

In order to locate precisely images and spectra on the DMD surface, we have built an additional optical bench imaging the DMD surface, this bench being behind the spherical mirror M3-B as defined in Fig. 2. M3-B mount is precisely located using pins and shims and could be removed and replaced with a very high precision; when removed, DMD surface could be imaged thanks to the additional optical bench. This bench is made with two doublets with a 0.5 magnification allowing a full imagery of the DMD surface on an additional CCD camera.

Fig. 5 shows images of the input (OLED) plane and intermediate focal plane (DMD surface). The OLED displays a white slit at 45° with respect to the horizontal (and vertical) axis. After passing through the first spectrograph, the slit is dispersed on the DMD surface; spatial and spectral directions are labelled on Fig. 5; 0-th order is partly imaged on the DMD surface as a white narrow stripe (image of the entrance slit), and -1 order is faintly displayed at the bottom-center of this picture. Using these images and exact wavelength locations, thanks to interference bandpass filters, we have determined **the exact spectral dispersion** to be 200nm wavelength range dispersed along 353 micromirrors, i.e. **0.57 nm / micromirror**.

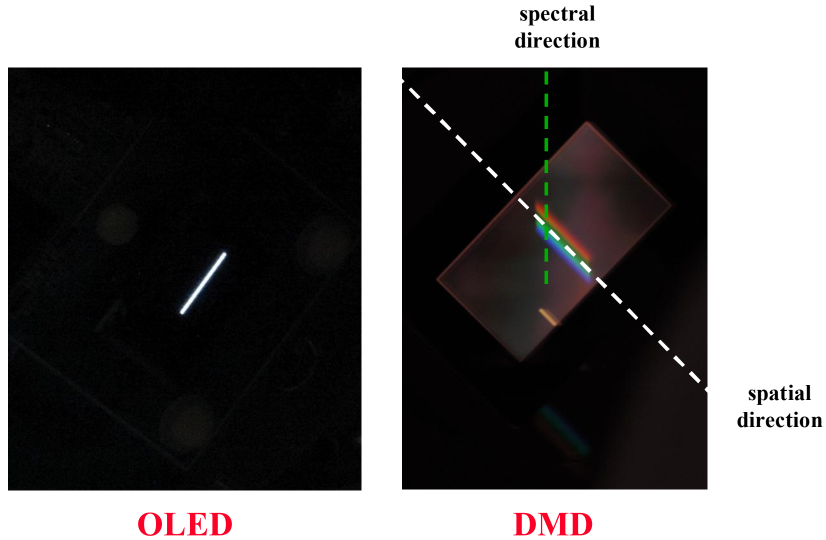


**Fig. 5.** Images of the input (OLED) plane and intermediate focal plane (DMD surface). Dispersed spectra (1st order) are displayed on the DMD surface, while 0th-order and -1 order are also recorded on the image. Spatial and spectral directions are labelled.

*D. Demonstrator in operation*

A synthetic linear FOV mimicking Earth views is generated on the OLED and typical images have been recorded on a CCD camera at the output focal plane of the instrument. The FOV exhibits different features including bright objects and "colored" elements (Fig. 6).

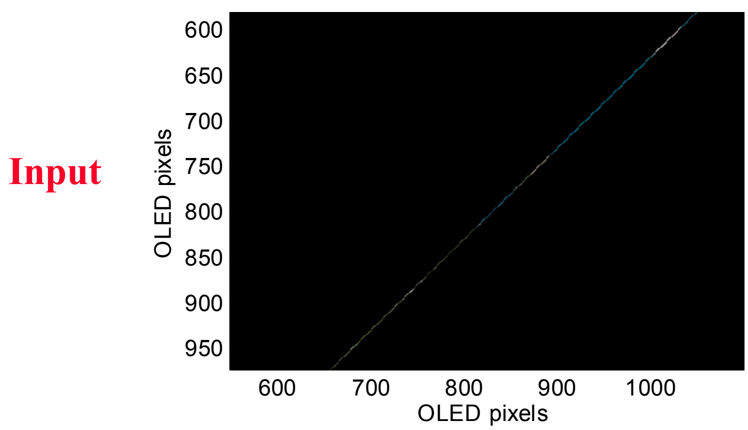


**Fig. 6.** Typical Earth-type images are displayed on the OLED as a "slit" image

When the DMD is set with all mirrors in ON position, this means that no lambda selection is made over the whole FOV, the output image is identical to the input image (Fig. 7). At the input, the OLED is set as a scanning slit with a one-pixel width; at the DMD level, the 0th order is masked by switching OFF the mirrors where 0th-order light is projected (see Fig. 5), and the output is the recombined slit, image of the entrance slit. The image is an intensity image on the CCD camera; spatial resolution is slightly degraded with respect to the one-pixel wide entrance slit, as it is expected by the optical design of our demonstrator. Note that removing optically the 0th-order decreases the straylight in the instrument.

By tailoring the DMD, we could modify each pixel of the input image: for example, it is possible to remove the bright object by turning OFF all corresponding mirrors for this object on the DMD (spatial and spectral), see Fig. 8. We can also, for each spatial pixel modify the spectral signature in the DMD plane by turning ON and OFF the micromirrors located along the dispersed direction for this pixel; for example, in Fig. 9, both bright object as well as all "blue" color along the whole 1D image are removed.

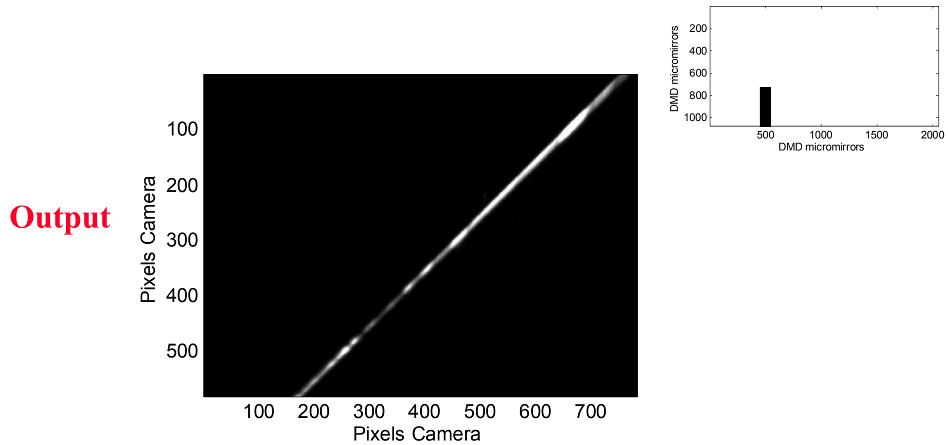


**Fig. 7.** End-to-end measurement: image recorded at the output of the programmable spectrograph with all DMD pixels ON except those removing $0^{th}$ order light. DMD surface behavior is also shown (black pixels are OFF)

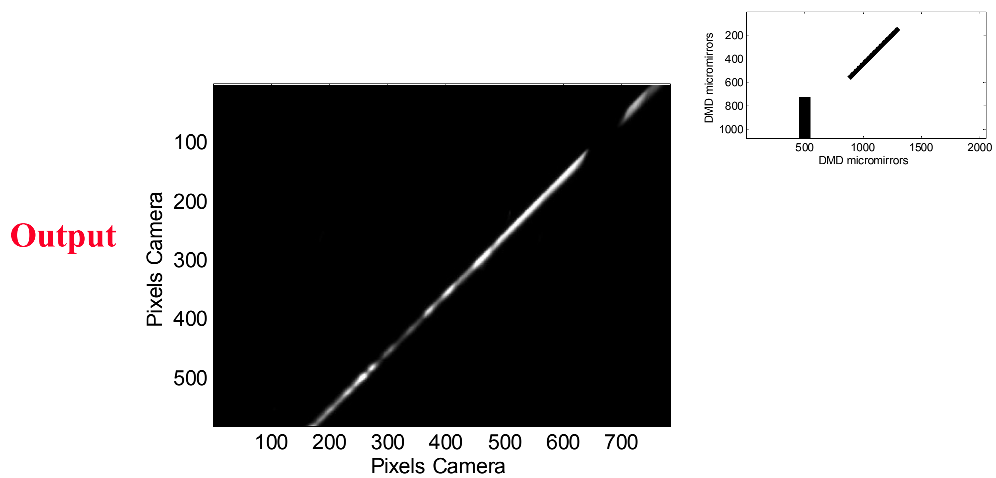


**Fig. 8.** End-to-end measurement: image recorded at the output of the programmable spectrograph; the bright object and the diffraction $0^{th}$ order light are removed. DMD surface behavior is shown (black pixels are OFF)

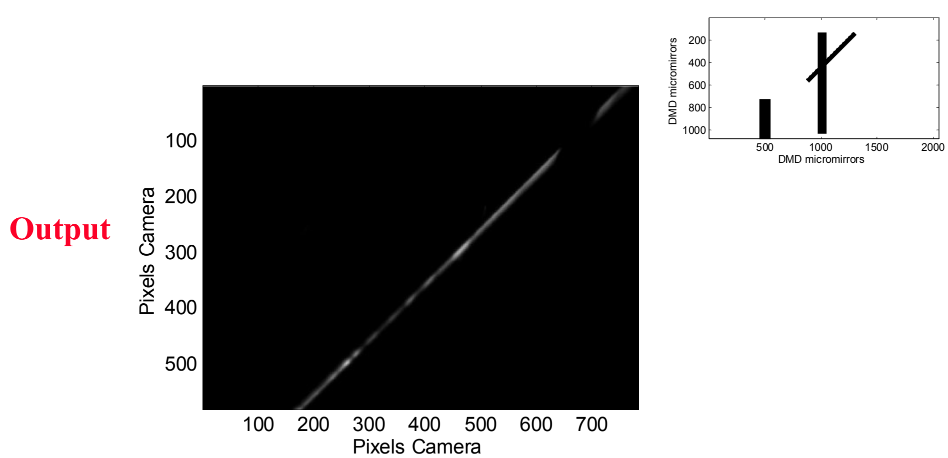


**Fig. 9.** End-to-end measurement: image recorded at the output of the programmable spectrograph; the bright object, "blue" color along the whole 1D image and the diffraction $0^{th}$ order light are removed.
DMD surface behavior is shown (black pixels are OFF)

## CONCLUSION

In Earth Observation, Universe Observation and Planet Exploration, scientific return of the instruments must be optimized in future missions. Micro-Opto-Electro-Mechanical Systems (MOEMS) could be key components in future generation of space instruments. MOEMS devices 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.

In Earth Observation, we propose an innovative reconfigurable instrument, a programmable wide-field spectrograph where both the FOV and the spectrum could be tailored thanks to a 2D micromirror array. A mock-up has been designed, fabricated and tested. The very promising results obtained on the mock-up of the programmable wide-field spectrograph reveal the efficiency of this new instrument concept for Earth Observation.

Pathfinder towards micromirror array based spectrographs in space is already running: thanks to CNES and ESA former and on-going studies, MOEMS devices are considered for integration in space missions both for Space and Earth Observation. DMDs have been tested in space environment and no showstopper has been revealed. A multi-object spectrograph, BATMAN, is currently under construction for demonstrating the unique performances of micromirror array based spectrographs; this instrument is scheduled to be mounted for an on-sky demonstration in the coming year on a ground-based 4m-class telescope.

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