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BATMAN AND ROBIN: NEXT GENERATION SPECTRO-IMAGERS FOR SPACE OBSERVATION

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INTRODUCTION

In Earth Observation, Universe Observation and Planet Exploration, scientific return of the instruments must be optimized in future space missions. New concepts using breakthrough technologies must be proposed. Micro-Opto-Electro-Mechanical Systems (MOEMS) will 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. Through extensive utilization of this enabling technology, ***BATMAN flies*** **will provide unprecedented versatile, programmable, optimized in mass, volume and cost, and efficient spectro-imagers for space missions.**

ESA and NASA roadmaps include in terms of missions, for Universe Observation next generation UV to IR Observatories including spectrographs, for Earth Observation, next generation hyperspectral imagers, and for Planetology, LIDARS and spectrographs. ESA roadmap in new technologies includes as a priority the Digital Micro-Mirror Array (DMA) for space optical instruments. ***BATMAN flies*** **is following these roadmaps and proposing breakthrough solutions.**

In Universe Observation, *BATMAN flies* is a deep multi-survey mission in the infrared with a multi-object spectrograph based on a reconfigurable slit mask, using MOEMS devices. Unique science cases are reachable with this instrument:

- Deep survey of high-z galaxies: large sample of 200 000 galaxies down to H=25 on 5 deg^2, and all z>7 candidates at H=26.2 over 5 deg^2
- Deep survey of nearby galaxies: characterization of the IMF in several thousands of young stellar clusters in a large sample of nearby galaxies
- Deep survey of the Kuiper Belt: spectroscopic survey of **all** known objects down to H=22 (700 objects, current sample multiplied by 10).

BATMAN flies concept is based on a spectrograph and an imager working in parallel, fed by a tiltable micro-mirror array. By dynamically correcting the in-coming wavefront, a MOEMS-deformable mirror placed at a pupil before this configuration provides an optimal efficiency on both instruments, regardless of the telescope at the entrance and the type of mission, by correcting dynamically the in-coming wavefront.

At the instrument level, CNES and 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. At the device level, LAM and CSEM are developing a European micro-mirror array called MIRA and able to operate at cryogenic temperatures, and CSEM and IMTEK are developing micro-mirror arrays for maskless lithography. Finally, at system and demonstrator level, LAM together with Obs. Trieste, other Italian institutes and TAS have also designed and tested successfully new concepts for Multi-Object Spectroscopy (MOS) as well as for programmable wide field spectrographs.

Pathfinder towards *BATMAN flies* is already running. BATMAN, the new generation MOEMS-based spectro-imager on the sky is of prime importance for characterizing the actual performance of this new family of MOS instruments, as well as investigating the operational procedures on astronomical objects. Thanks to a French-Italian collaboration, this instrument will be placed on a ground-based 4m-class telescope, the Telescopio Nazionale Galileo (TNG) in the Canarias Islands, at the Nasmyth focus, in 2017. ROBIN, a BATMAN demonstrator on an optical bench, has been built and delivers already images and spectra in parallel, allowing us to validate all expected performances. We have tested the instrument abilities in terms of variable spatial bin and variable spectral resolution, and any combination of the above modes over the whole FOV; in particular, MOS and IFU-like (scanning slit) modes have been studied, with any slit mask configurations (any shape, including long slit) as well as real time reconfiguration.

I. BATMAN FLIES CONCEPT

BATMAN flies concept is based on a spectrograph and an imager working in parallel, fed by a tiltable micro-mirror array (MOEMS-MIRA). By dynamically correcting the in-coming wavefront, a-MOEMS-deformable mirror (MOEMS-DM) placed at a pupil before this configuration provides an optimal efficiency on both instruments, regardless of the telescope at the entrance and the type of mission, by correcting dynamically the in-coming wavefront. The complex system control has to be built in order to control all sub-systems, as well as providing new operational modes not feasible with current technologies. A schematic view of the instrument we are proposing is given in Fig. 1.

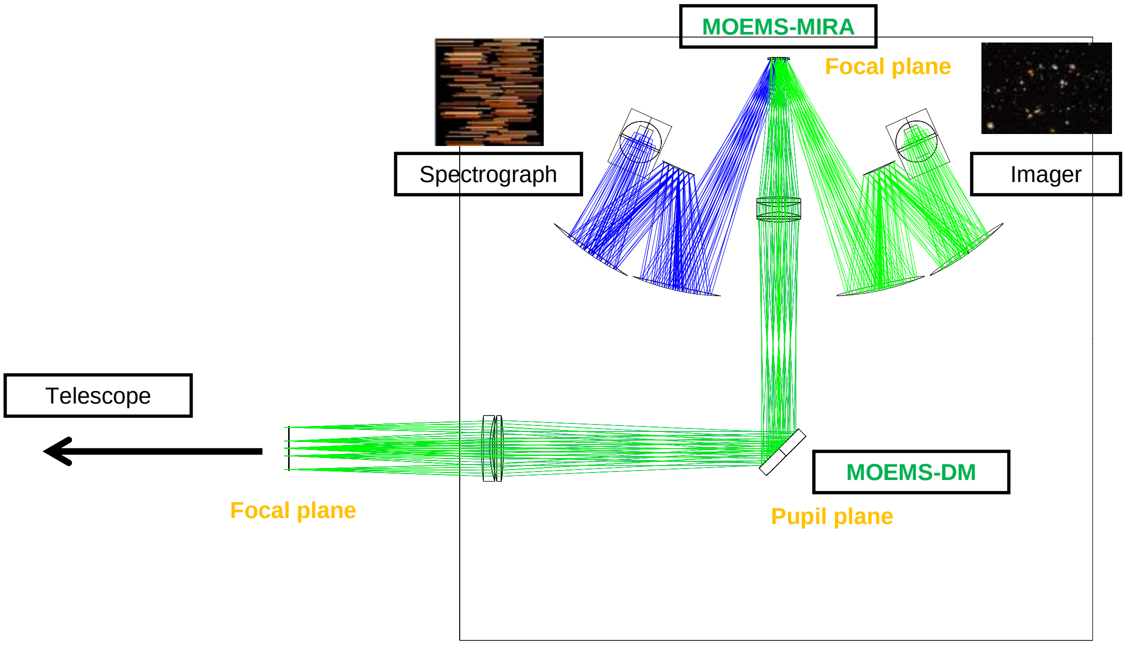

Fig. 1. *BATMAN flies* conceptual design

In our concept, one point is not yet addressed, the wavefront sensing. However, we see several sensing possibilities within 3 classes:
- measurement on the wavefront and control loop (or open-loop)
- measurement on the scientific image (phase diversity for example) and correction
- internal metrology and open-loop correction

Multi-object spectroscopy (MOS) is a key technique for large field of view surveys. MOEMS programmable slit masks could be next-generation devices for selecting objects in future infrared astronomical instrumentation for space telescopes. MOS is used extensively to investigate astronomical objects by optimizing the Signal-to-Noise Ratio (SNR): high precision spectra are obtained and the problem of spectral confusion and background level occurring in slitless spectroscopy is cancelled. Fainter limiting fluxes are reached and the scientific return is maximized both in cosmology and in legacy science. Major telescopes around the world are equipped with MOS in order to simultaneously record several hundred spectra in a single observation run. Next generation MOS for space like the Near Infrared Multi-Object Spectrograph (NIRSpec) for the James Webb Space Telescope (JWST) require a programmable multi-slit mask. Conventional masks or complex fiber-optics-based mechanisms are not attractive for space. The programmable multi-slit mask requires remote control of the multi-slit configuration in real time. During the early-phase studies of the European Space Agency (ESA) EUCLID mission, a MOS instrument based on a MOEMS device has been assessed. Due to complexity and cost reasons, slitless spectroscopy was chosen for EUCLID, despite a much higher efficiency with slit spectroscopy.

A promising possible solution is the use of MOEMS devices such as micromirror arrays (MMA) [1,2,3] or micro-shutter arrays (MSA) [4]. MMAs are designed for generating reflecting slits, while MSAs generate transmissive slits. By placing the programmable slit mask in the focal plane of the telescope, the light from selected objects is directed toward the spectrograph, while the light from other objects and from the sky background is blocked or send toward an imager.

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 [5,6].

Currently, we are using as a pathfinder the only available component with more than 2 millions independent micromirrors, the Digital Micromirror Device (DMD) chip from Texas Instruments (TI) that features 2048 x 1080 mirrors and a 13.68µm pixel pitch. 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** [7]**.**

Our goal is to make a robust and efficient instrument for a space mission. Selecting a good starting point was really important. Even if complex, we succeeded to design a preliminary system, developing ideas proposed many years ago for the JWST near-infrared multi-object spectrograph [2]. BATMAN baseline is resumed in Table 1.

Primary mirror diameter	1 m
Obscuration	10 %
Objects selector	DMD with 2048 – 1080 micro-mirrors or MOEMS-MIRA
Micro mirror scale	0.75 arcsec
Field of View	25 x 12 arcmin^2
Wavelength range	[0.85-1.7] µm
Two arms instrument	One imaging and one spectroscopic channels
Spectral resolution	500 - 1000
Optical transmission (total)	0.6
Detectors size	Two 2k x 4k detectors
Pixel scale	0.75 arcsec
Readout noise	9 electron/pixel
Dark current	0.1 electron/pixel/second
Quantum efficiency	0.75

Table 1: Baseline of DMD-based instrument

The preliminary *BATMAN flies* optical design is based on a DMD device. The entrance beam is adapted in F-number by the fore optics and is split by the DMD into 2 arms, a spectrograph arm and an imaging arm (Fig. 1). BATMAN is based on a double Offner relay system with a 1:1 magnification between the DMD pixels and the detector pixels. 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. The two identical spherical mirrors have a diameter of 160mm and a radius of curvature of 438mm. The most critical component of the system, the convex grating, has a 225mm radius of curvature with 150 l/mm line density, leading to a spectral resolution of 500-1000 according to the slit size (one or two micro-mirrors).

This will make the system simple and efficient. Additionally it will not suffer from chromatic aberrations. Delivered image quality onto the detector is high enough to not degrade resolving power and spatial resolution, too. Typical monochromatic spot diameters are <0.8 arcsec over the whole FOV for whole wavelength range. Simulated spectra are shown in Fig. 2.

Missions

Our instrument concept will be studied in order to be adapted among our 3 science goals:

- Universe Observation
- Earth Observation
- Planet Exploration

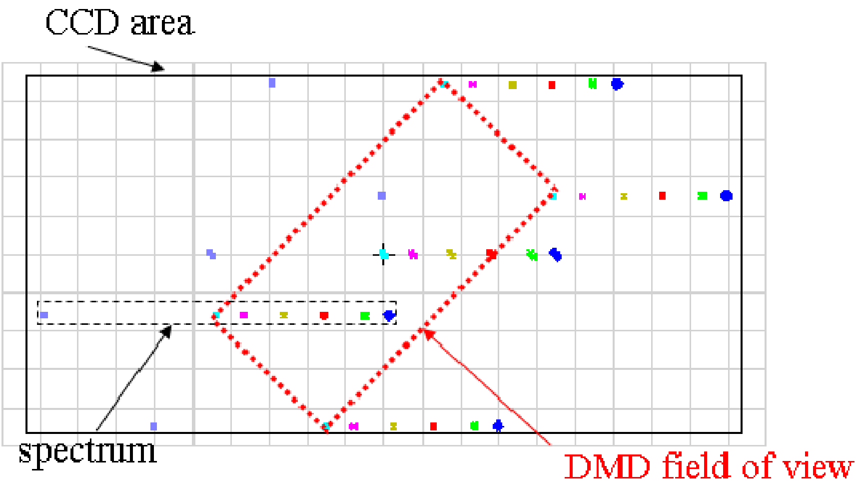

Fig. 2. Spectroscopic channel; simulated spectra on the detector.

Our objectives are to elaborate the MOEMS components requirements compatible with Universe Observation, Earth Observation and planetology, to identify the possible future space applications and to assess the instrument environment specifications. After identifying the design drivers coming from Earth observation, Astronomy and planetology, we will be able to set completely the DM specific requirements and to analyze MIRA constraints to be used in space (volume, power …). Developing innovative optical concepts covering all space applications and including both MOEMS devices will be the next step. Instrument architectures for the selected optical concepts will then be derived, including mechanical design and thermal environment assessment at MOEMS component levels. A possible pathfinder will be to propose a demonstrator concept relevant to future missions, in order to validate our models.

Control System evaluation and preliminary architecture

A first control system architectural design will be done. The software technologies and architectural paradigms utilised in the preliminary instrument study are the result of the Instrumentation and Control Group expertise gained in the last years of activity in the ground-based astronomical projects, at Trieste Observatory. The software technologies that will be used for the final instrument operating in space will be investigated in a following phase. The first development will be done with commercial, off-the-shelf components that provide tools for rapid implementation allowing a quick proof of the concept. Examples of such technologies are Programmable Logic Controllers or more specialized Programmable Automation Controllers. Some of the more advanced components available on the market include also building blocks based on FPGA technology. Then, the platform should be shifted to a completely FPGA based solution with System on Chip concept. The same structure as in the first stage is implemented on chip, but taking into account the specific requirements of airborne applications. The components used will be still of the commercially available off the shelf to maintain the costs at a reasonable level, but choosing components that can be migrated to space compliant type.

II. MOEMS DEVICES

Two MOEMS devices are considered in *BATMAN flies* optical suite: one deformable mirror (MOEMS-DM) and an array of tiltable mirrors (MOEMS-MIRA).

MOEMS-DM

Major requirements for a space-deployed AO system depend heavily on the target mission; yet there are certain mission-independent qualities that arise from the nature of space-deployment. First and foremost, the developed AO system should be lightweight, robust and power efficient. The DM that sits at the heart of the AO system should be versatile, scalable in size and actuator count and space-qualified. Current DM technologies fail to meet such strict requirements in one way or another. In *BATMAN flies*, we would like to address this gap and ring the benefits of AO into various types of space missions, including Universe Observation and the search for exoplanets.

The DM is usually the key limiting component in an AO system, and this is also true for *BATMAN flies*. In order to render the DM for variety of missions, the target specifications are set to provide low-frequency/large stroke and high-frequency/small stroke wavefront correction. The mechanical structure and fabrication process should be compatible with large actuator counts combined with actuator pitches in the order of 1 mm to provide large field of view, particularly for large telescope applications. The summary of the specs we aim to reach for the DM are summarized in table 2.

Parameter	**Unit**	**Target Spec.**
Actuator count		200 +
Pupil diameter	mm	10 +
Actuator pitch	mm	0.5 typical
Mirror best flat in close loop	nm	5
Tip/tilt stroke	µm	40
Focus/astigmatism stroke	µm	30
Inter-actuator stroke	µm	2
Maximum operating voltage	V	100
Bandwidth	KHz	2.5 +
Operating temperature	K	30
Coating		custom

Table 2: Target specifications for the deformable mirror system set to maximize.

The *BATMAN flies* DM represents a major leap forward in DM technology. Batch microfabrication techniques can attain unprecedented precision in DM fabrication leading to higher device uniformity and reproducibility. This in turn improves wavefront correction fidelity. The highly integrated nature of the DM ensures smaller device inertia, and thus, improved response time. This aspect will be critical to push the limits of the capabilities of adaptive optics not only for astrophysics, but also life-science microscopy and ophthalmology. Also, vertical comb drive actuator not only provides displacement-independent force, it also provides considerably higher force density compared to regular parallel-plate actuators and render electrostatic actuators a viable choice for the application proposed here.

This task is conducted by IMTEK with support from LAM and CSEM, and expertise of TAS and Trieste Observatory. The realization of the device is scheduled at CSEM and the complete characterization at LAM.

MOEMS-MIRA

In Europe, an effort is currently under way to develop single-crystalline silicon micromirror arrays for future generation infrared multi-object spectroscopy. A collaboration within LAM, Ecole Polytechnique Federale de Lausanne (EPFL) and CSEM 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 this MMA were determined from previous simulation results and measurements. 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.

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. 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. Prototypes of MMA with 2048 individually addressable micromirrors (64 x 32 mirrors) have been successfully realized (Fig. 3) [5,6].

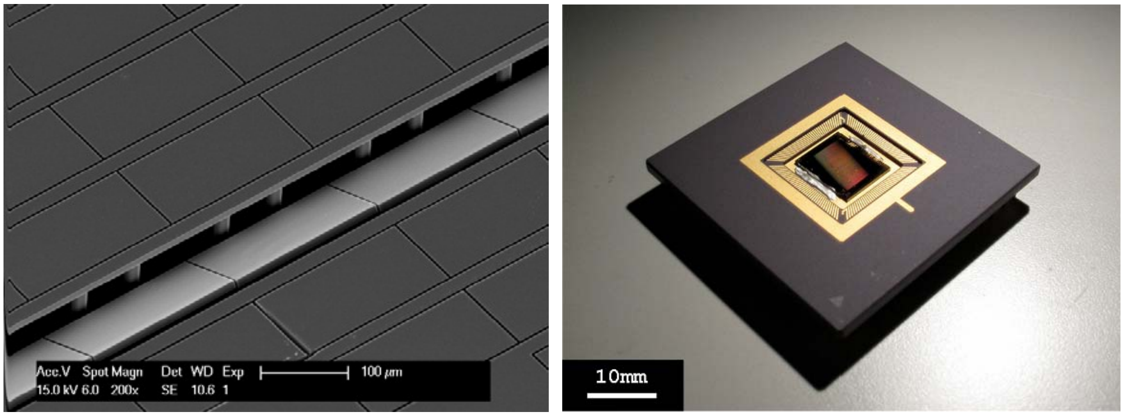

Fig. 3. 64 x 32 micromirror array (a) Close view of 100 x 200 μm^2 micromirrors
(b) Mounted MMA in a Pin Grid Array (PGA)

MMA have been tested at LAM on bench set-ups dedicated to the characterization of MOEMS devices. 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, see Fig. 3a). Our locking mechanism is designed in order to ensure this goal and a performance of a few arc-minutes angle difference has been obtained. The fill factor was 83% 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 2 x 2 sub-part of a MMA of 32 x 64 micromirrors was actuated successfully. The contrast of a micromirror was characterized on a dedicated optical bench at LAM: a contrast ratio of 1000:1 was obtained.

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. 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. This is especially important on the mirrors themselves: they are covered by a thin gold layer, gold having a different CTE than silicon.

The micromirrors could be successfully actuated before, during and after cryogenic cooling at 162K. We could measure the surface quality of the gold coated micromirrors at room temperature and at 162 K without large deformation difference. **A 9.8nm PTV surface deformation was measured at 293K, increasing up to 27.2nm PTV at 162K. When coming back at room temperature, we measured again the mirror surface deformation and obtained a value of 9.9nm PTV, identical to the value measured before cooling of the array**. The deformation is due to the CTE mismatch between the thick silicon micromirror and the thin gold coating layer on top. However, the surface deformation stays within the limit of 50 nm.

III. BATMAN and ROBIN, towards an end-to-end demonstrator

BATMAN flies is based on the background developed by the consortium since 2010, engaged in ROBIN and BATMAN projects.

Mission pathfinder: ROBIN, a BATMAN demonstrator

Before developing BATMAN, we have built a demonstrator named ROBIN, for characterizing the actual performance of this new family of instruments, as well as investigating the operational procedures on astronomical objects. The design of the demonstrator is identical to the instrument design for being fully representative, with a global reduced size, on mirrors as well as on the grating. The general mechanical design of ROBIN consists of a main optical bench supporting 2 arms: a spectrograph arm and an imaging arm. The detectors are located on both sides of the bench. Opto-mechanical design is shown in Fig. 4.

ROBIN has been integrated and aligned (Fig. 4b). The optical beam is entering from the top center; the DMD is located at the bottom center and both arms are fed, on the right hand side is the imaging arm and on the left hand side is the spectroscopic arm. Both arms are fully identical except the convex mirror being replaced by the convex grating in the spectroscopic arm. Images and spectra are recorded by two CCD cameras located on both sides (left and right).

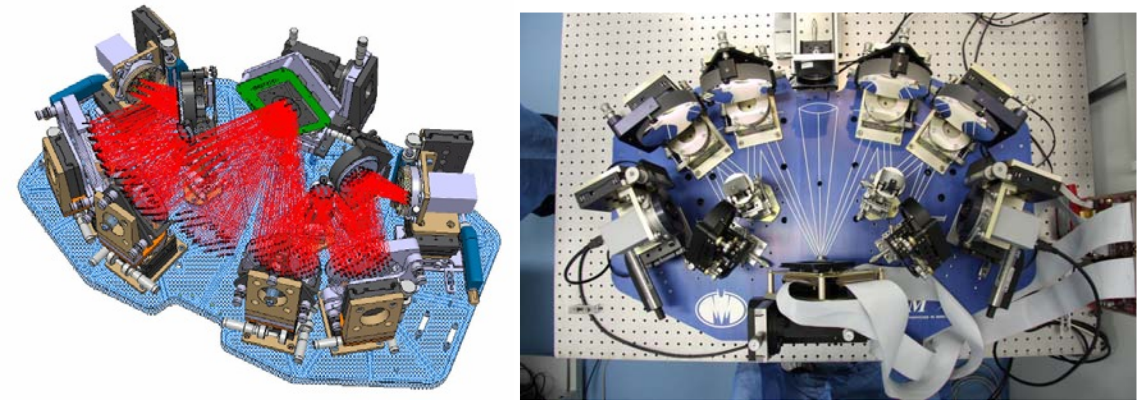

Fig. 4. (a) 3D general design view of ROBIN (in red, beam propagation in the demonstrator);
(b) integrated ROBIN picture

First images and spectra have been obtained and measured. In the imaging arm, typical slit mask patterns are recorded (Fig. 5a); the optical quality is good enough for imaging each individual micromirror. In the spectroscopic arm, typical spot diameters are within 1.5 detector pixels, and spectra generated by one micro-mirror slits are displayed with this optical quality over the whole visible wavelength range (Fig. 5b).

We have tested successfully the instrument abilities in terms of variable spatial bin and variable spectral resolution, and any combination of the above modes over the whole FOV; in particular, MOS and IFU-like (scanning slit) modes have been studied, with any slit mask configurations (any shape, including long slit) as well as real time reconfiguration.

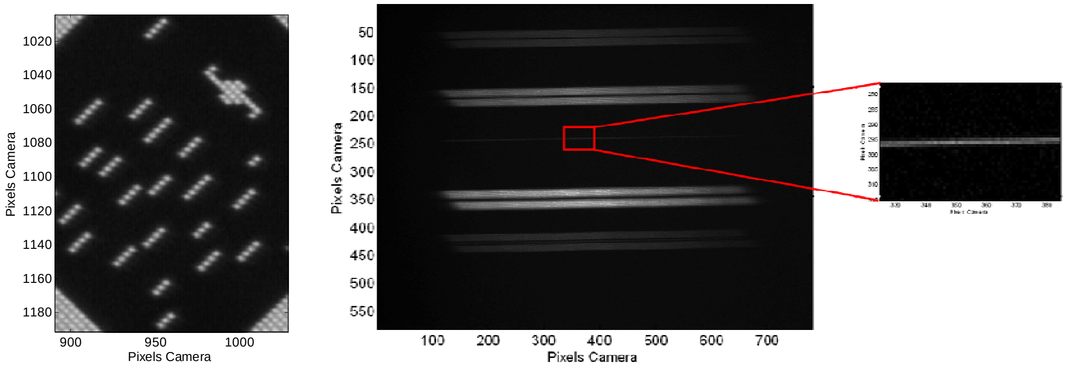

Fig. 5. (a) Image of a typical slit mask in the imaging channel; (b) spectra in the spectral channel, including a single micromirror slit (close view of the spectrum generated by the one-micromirror slit)

BATMAN: on-sky demonstration

BATMAN is a 2048x1080 Digital-Micromirror-Device-based (DMD) MOS instrument to be mounted on the 3.6m Galileo telescope (Fig. 6a). A two-arm instrument has been designed for providing in parallel imaging and spectroscopic capabilities. The field of view (FOV) is 6.8 arcmin x 3.6 arcmin with a plate scale of 0.2 arcsec per micromirror. The wavelength range is in the visible and the spectral resolution is R=560 for 1 arcsec object (typical slit size). The two arms will have 2k x 4k CCD detectors. This general design is identical to the concept shown in the first paragraph (Fig. 1). The mechanical design of BATMAN consists of a main optical bench supporting all optical elements except the detectors mounted on a second bench over the first one and attached to the main bench thanks to two hexapods for an individual alignment of the detector dewars (Fig. 6b).

Building BATMAN is under way, with all optics delivered and tested and some other major instrument parts delivered and tested (hexapods, fore-optics, detectors …). Remaining opto-mechanical parts are ordered and integration and alignment of the instrument is scheduled during spring 2017 [8]. BATMAN on the sky is of prime importance for characterizing the actual performance of this new family of MOS instruments, as well as investigating the operational procedures on astronomical objects. Thanks to a French-Italian collaboration, this instrument will be placed on the Telescopio Nazionale Galileo 3.6-m telescope, at the Nasmyth focus, by 2017.

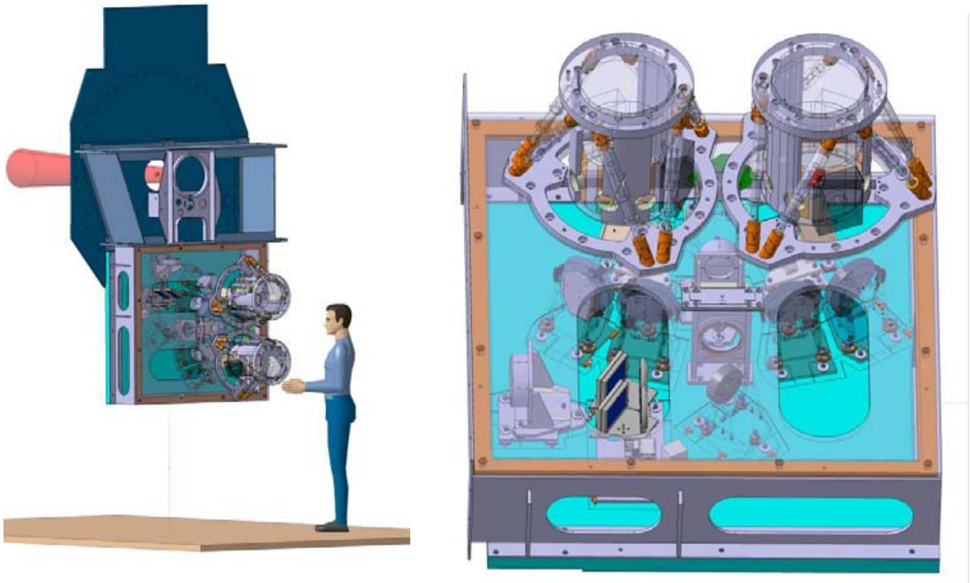

Fig. 6. 3D general design view of BATMAN (a) mounted on the TNG telescope; (b) the instrument

CONCLUSION

BATMAN flies, a new concept using the MOEMS breakthrough technology has been proposed for Earth Observation, Universe Observation and Planet Exploration. BATMAN flies will provide unprecedented versatile, programmable, optimized in mass, volume and cost, and efficient spectro-imagers for space missions. Thanks to our previous developments, pathfinders are already under development, including ROBIN, a lab demonstrator and BATMAN, an on-sky demonstrator, scheduled to be mounted on the TNG 3.6m telescope by next year. **And then, hopefully, BATMAN will fly.**

REFERENCES

[1] R. Burg, P.Y. Bely, B. Woodruff, J. MacKenty, M. Stiavelli, S. Casertano, C. McCreight and A. Hoffman, "Yardstick integrated science instrument module concept for NGST", in *Proceedings of the SPIE conference on Space Telescope and Instruments V*, SPIE **3356**, 98-105, Kona, Hawaii, (1998)

[2] F. Zamkotsian, K. Dohlen, D. Burgarella, V. Buat, "Aspects of MMA for MOS: optical modeling and surface characterization, spectrograph optical design", in *Proceedings of the NASA conference on "NGST Science and Technology Exposition"*, ASP Conf. Ser. **207**, 218-224, Hyannis, USA, (1999)

[3] M. Robberto, A. Cimatti, A. Jacobsen, F. Zamkotsian, F. M. Zerbi, "Applications of DMDs for Astrophysical Research", in *Proceedings of the SPIE conference on MOEMS 2009*, Proc. SPIE **7210**, San Jose, USA, (2009)

[4] M. J. Li; A. D. Brown; A. S. Kutyrev; H. S. Moseley; V. Mikula, " JWST microshutter array system and beyond", Proc. SPIE **7594**, San Francisco, USA (2010)

[5] S. Waldis, F. Zamkotsian, P. Lanzoni, W. Noell, N. de Rooij, "Micromirrors for multiobject spectroscopy: optical and cryogenic characterization", in *Proceedings of the SPIE conference on MOEMS 2008*, Proc. SPIE **6887**, San Jose, USA (2008)

[6] M. Canonica, F. Zamkotsian, P. Lanzoni, W. Noell, N. de Rooij, “The two-dimensional array of 2048 tilting micromirrors for astronomical spectroscopy,” Journal of Micromechanics and Microengineering, 23 055009, (2013)

[7] 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)

[8] Frederic Zamkotsian, Harald Ramarijaona, Manuele Moschetti, Patrick Lanzoni, Marco Riva, Nicolas Tchoubaklian, Marc Jaquet, Paolo Spano, William Bon, Romain Alata, Luciano Nicastro, Emilio Molinari, Rosario Cosentino, Adriano Ghedina, Manuel Gonzalez, Walter Boschin, Paolo Di Marcantonio, Igor Coretti, Roberto Cirami, Filippo Zerbi, Luca Valenziano, "Building BATMAN: a new generation spectro-imager on TNG telescope ", in Proceedings of the SPIE conference on Astronomical Instrumentation 2016, Proc. SPIE **9908**, Edinburgh, United Kingdom, (2016)