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

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International Conference on Space Optics — ICSO 2014, edited by Zoran Sodnik, Nikos Karafolas, Bruno Cugny, Proc. of SPIE Vol. 10563, 105634N · © 2014 ESA and CNES
CCC code: 0277-786X/17/$18 · doi: 10.1117/12.2304262

BATMAN FLIES: A COMPACT SPECTRO-IMAGER FOR SPACE OBSERVATION

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INTRODUCTION

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. 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) [5,6]. 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. To get more than 2 millions independent micromirrors, the only available component is a Digital Micromirror Device (DMD) chip from Texas Instruments (TI) that features 2048 x 1080 mirrors and a 13.68µm pixel pitch. DMDs have been tested in space environment (-40°C, vacuum, radiations) by LAM and no showstopper has been revealed [7].
We are presenting in this paper a DMD-based spectrograph called BATMAN, including two arms, one spectroscopic channel and one imaging channel. This instrument is designed for getting breakthrough results in several science cases, from high-z galaxies to nearby galaxies and Trans-Neptunian Objects of Kuiper Belt.

INSTRUMENTATION

A. BATMAN concept

BATMAN is a compact spectro-imager with two arms in parallel: a spectroscopic channel and an imaging channel. Both arms are fed by using the two DMD mirrors stable positions (Fig. 1) [8].

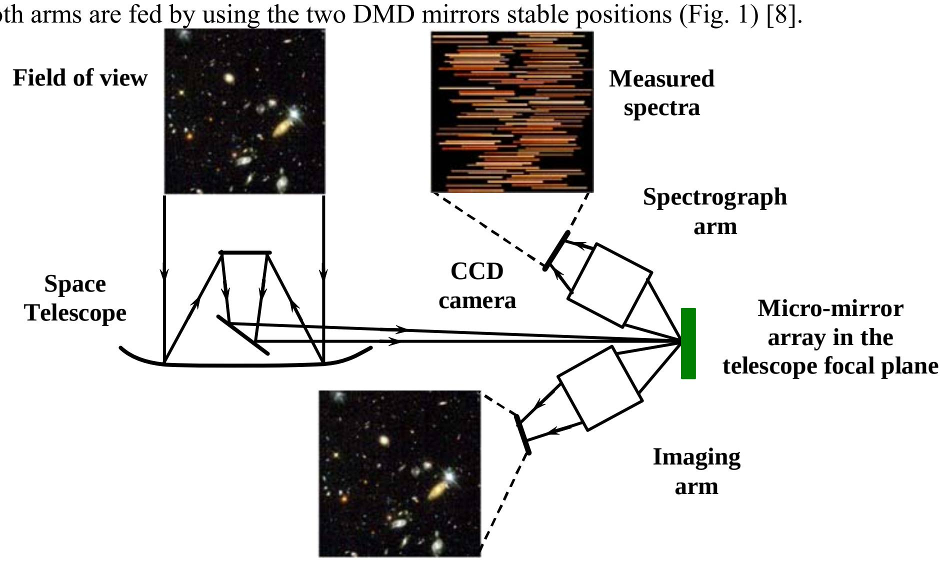


Fig. 1. Principle of BATMAN spectro-imager

Our goal is to make a robust and efficient instrument for a space mission. Selecting a good starting point was really important. Previous works have been based onto smaller DMD chip areas and larger focal ratios, covering relatively smaller field of view. Here we concentrated to meet larger areas, still with simple optical layouts. 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) both spectroscopy and imaging modes could be available, using the two ON/OFF state mode of micromirrors;
(d) all optical components should lie in plane, for easy integration and alignment;
(e) 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 [2]. BATMAN baseline is resumed in Table 1.

Primary mirror diameter	1 m
Obscuration	10 %
Objects selector	DMD with 2048 – 1080 micro-mirrors
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

B. Slit generator

Digital Micromirror Devices (DMD) from Texas Instruments could act as objects 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** [7]**.**

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 [6]. On a longer time scale, these arrays could be used in BATMAN concept.

C. BATMAN optical design

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. 2). 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 224mm radius of curvature with about 200 l/mm line density, leading to a spectral resolution of 500-1000 according to the slit size (one or two micro-mirrors).

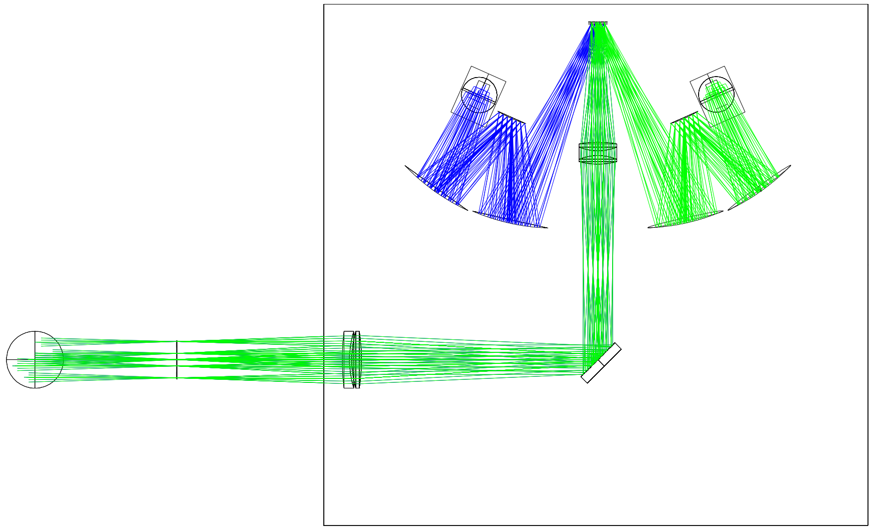


Fig. 2. Principle of BATMAN spectro-imager :
Optical layout of BATMAN. Light coming from the telescope is split by the DMD into 2 arms, a spectrograph arm and an imaging arm (both are Offner relays).

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. 3.

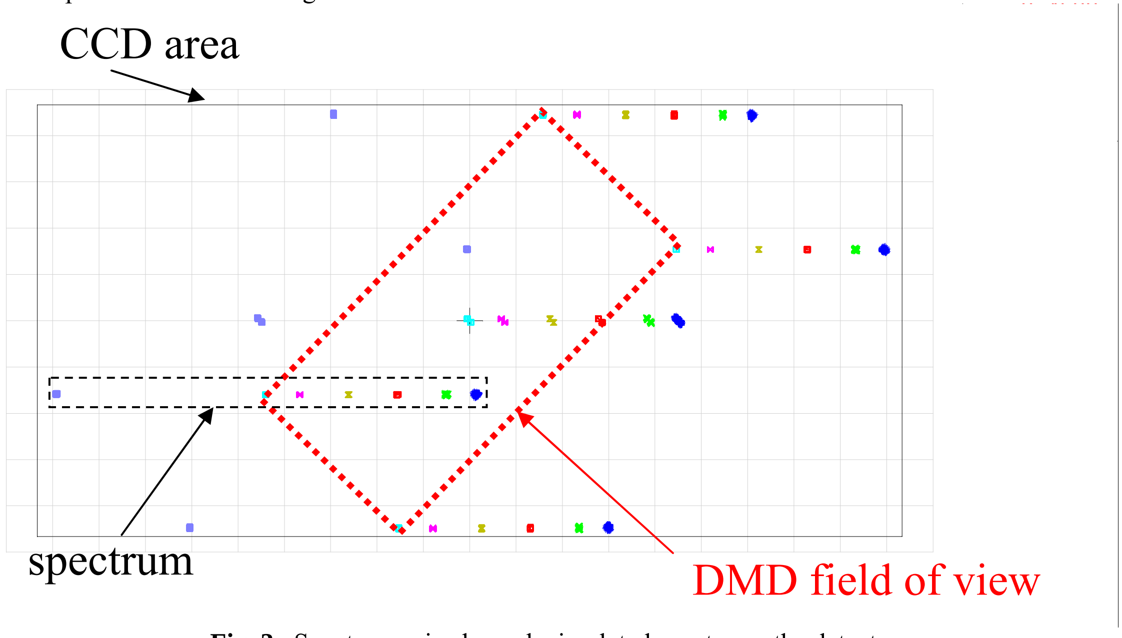


Fig. 3. Spectroscopic channel; simulated spectra on the detector.

D. BATMAN opto-mechanical design

The general 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 housings (Fig. 4).

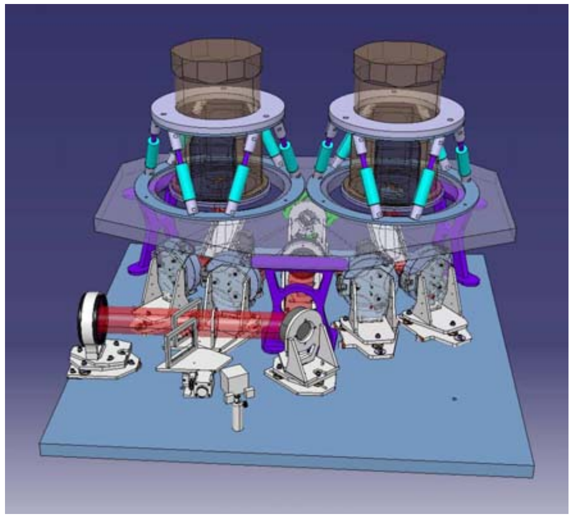
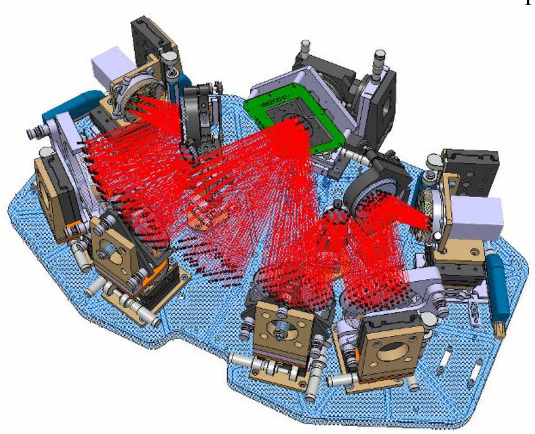


Fig. 4. BATMAN opto-mechanical design.

E. 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. 5 (a).



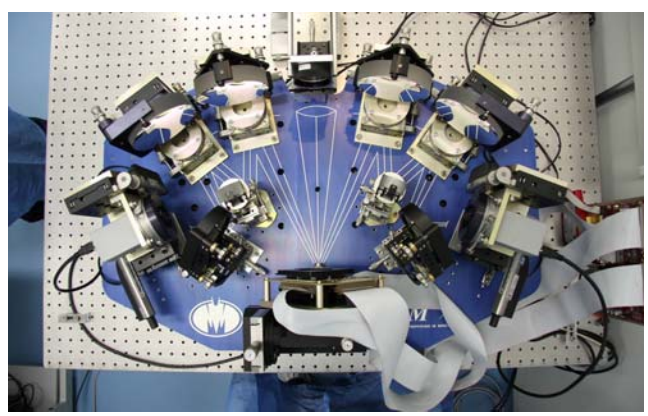


Fig. 5. (a) 3D general design view of ROBIN (in red, beam propagation in the demonstrator); (b) integrated ROBIN picture

ROBIN has been integrated and aligned (Fig. 5 (b)). 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).

First images and spectra have been obtained and measured. In the imaging arm, typical slit mask patterns are recorded (Fig. 6a); 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. 6b).

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.

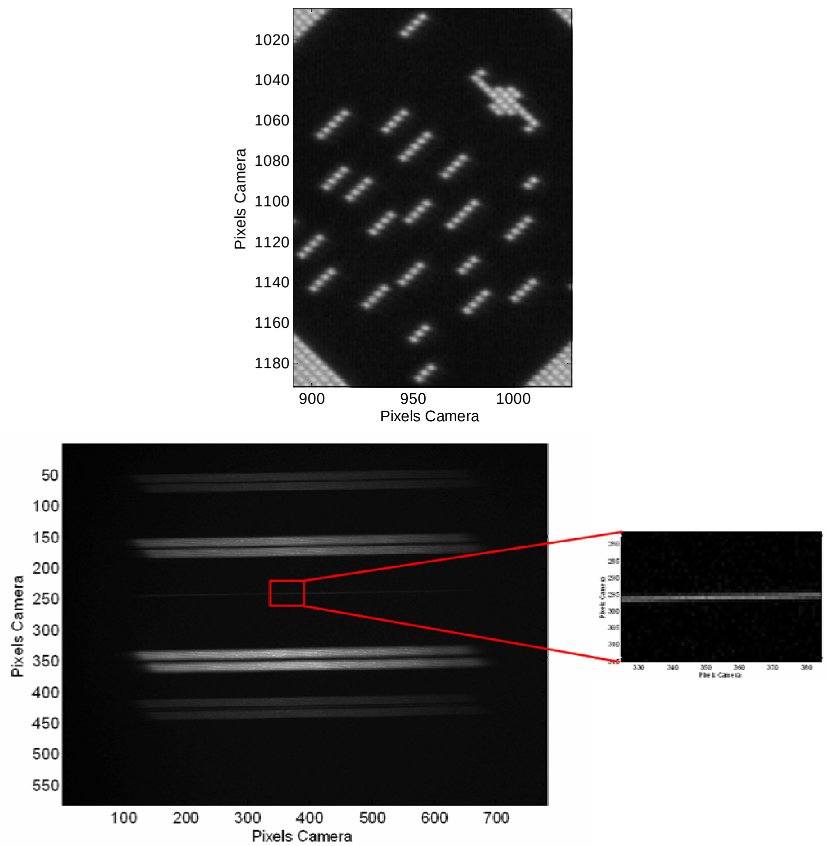


Fig. 6. (a) Image of a typical slit mask in the imaging channel; (b) spectra in the spectral channel, including a single micromirror slit (close view of the spectrum generated by the one-micromirror slit)

F. BATMAN on-sky demonstration

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 [8]. 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 mid-2015.

SCIENCE CASES

Our proposal 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 Space Observation 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).

Our science cases as well as preliminary simulations have been developed and presented elsewhere [9].

In this paper, we develop one specific case, *a performance comparison between BATMAN and EUCLID deep survey*.

The EUCLID mission is tuned to survey a huge area of the sky. The near infrared spectroscopy is optimized to detect a maximum of emission line galaxies up to redshift 2. The instrument is based on slitless spectroscopy which allows to observe all the sources in the field of view but the slitless spectroscopy have a very high sky background and the spectra of neighbour sources could overlap. The observation strategy and the data analysis must take into account some decontamination methods. The EUCLID deep survey will combine 40 observations of the same fields to ensure a sensitivity up to 5e-17 erg/s/cm² on 40deg² and a very efficient decontamination of the spectra crowding.

To compare the BATMAN and EUCLID spectroscopy, we simulated a Emission Line Galaxy from a model of a COSMOS galaxy [10]. This galaxy is at redshift 2.5 and at magnitude H 24. The flux in the OII line is 1.0e-16 erg/s/cm². For the BATMAN simulation we used the same instrument model than in the proposal. We made a EUCLID-like instrument model using the EUCLID definition study [11]. The image simulation for both instruments is based on the aXeSIM software [12]. For the BATMAN simulation, we simulate the shortest version of the observation strategy, 50 exposures of 3600s. For the EUCLID-like simulation, we simulate a deep survey with 40 exposures of 560s as defined in the reference document. We performed a very simple extraction (not optimal) and we binned the 2D spectra of each exposure to reconstruct the 1D spectra.

Figure 7 compares the input spectrum, the simulation of BATMAN observation and our EUCLID-like simulation. The BATMAN spectrum is at very high signal to noise ratio and allow a very deep analysis of the galaxy properties. We can clearly identify two emission lines. The EUCLID spectra allow clearly to detect and measure the OII line but the fainter lines and the continuum are in the noise fluctuations. This example illustrates that the two instruments and the two missions goal are very different. The EUCLID mission is optimized to survey a very large part of the sky and to study the statistical properties of the universe. **The BATMAN proposition will study fainter sources on a restricted area compared to EUCLID.**

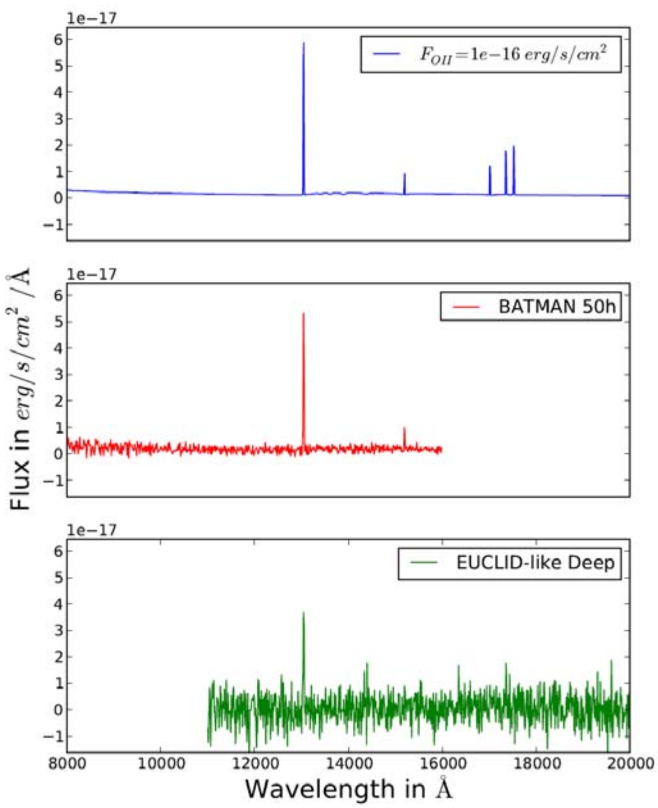


Fig. 7. Comparison of BATMAN and EUCLID-deep survey
The spectrum, in blue, at the top, is the input spectra of the simulation. This is a spectrum from COSMOS galaxy [10] at redshift at z=2.5, magnitude H 24 and with a flux the OII line of 1e-16erg/s/cm2. The red spectrum is the expected observation with BATMAN with 50 exposures of 1h.The green spectrum, at the bottom, is the expected observation with a EUCLID-like deep survey.

Figure 8 shows the simulation of a Lyman Break Galaxy from the composite spectrum of Shapley et al. [13]. We redshifted this rest-frame spectrum at z=7 and we scaled it in order to have a flux in the Lyman alpha line of 1.0e-18 erg/s/cm² and a magnitude H of 26. The spectra in red are the simulation result in four cases, 50, 100, 200 and 400 exposures of 1h. Even if the extraction was not performed in an optimal way, we see that below 200h of observation the identification of the galaxy would be difficult. The 200h of integration, allow to measure the Ly alpha line and by the way the redshift. To access to the continuum analysis, 400h of integration are required.

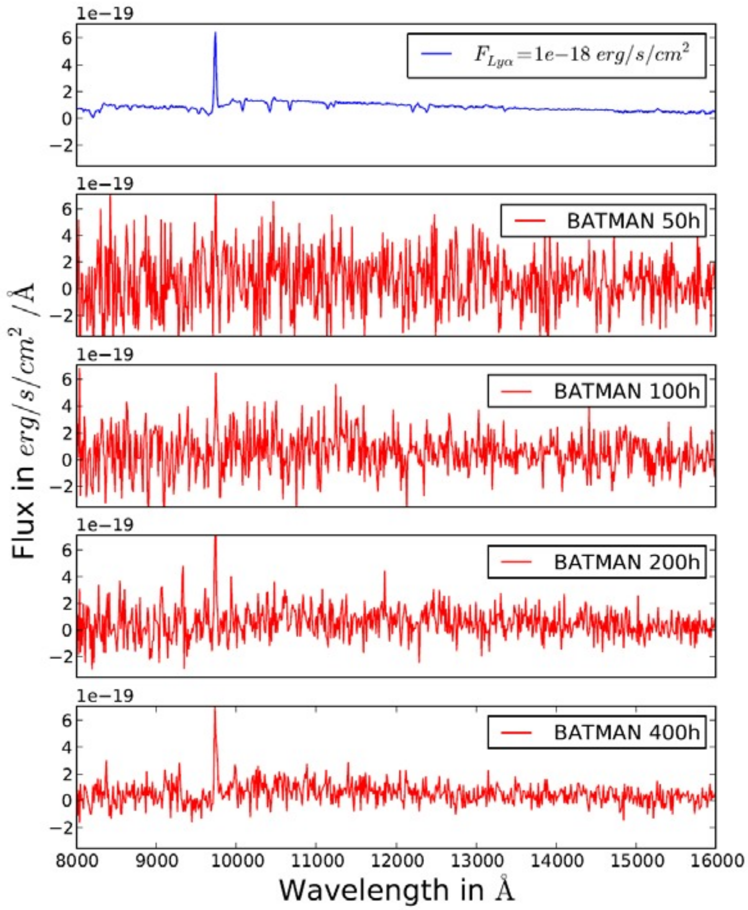


Fig. 8. Simulation of a Lyman Break Galaxy observation with BATMAN
The spectrum, in blue, at the top, is the input spectra of the simulation. It is a composite spectrum from Shapley et al. [13], redshifted at z=7 and scale in order to have 1e-18erg/s/cm2 in the Ly alpha line and a continuum at magnitude 26 in H band. The others spectra, in red, are the expected observations with BATMAN with 4 exposure times, 50h, 100h, 200h and 400h.

CONCLUSION

Our proposal 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 Space Observation 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).

Pathfinder towards BATMAN 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. 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. Finally, BATMAN is scheduled to be mounted for an on-sky demonstration in the coming year on a ground-based 4m-class telescope.

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, Paolo Spano, William Bon, Marco Riva, Patrick Lanzoni, Luciano Nicastro, Emilio Molinari, Rosario Cosentino, Adriano Ghedina, Manuel Gonzalez, Paolo Di Marcantonio, Igor Coretti, Roberto Cirami, Marco Manetta, Filippo Zerbi, Daniela Tresoldi, Luca Valenziano, "BATMAN: a DMD‒based MOS demonstrator on Galileo telescope ", in *Proceedings of the SPIE conference on Astronomical Instrumentation 2012*, Proc. SPIE **8446**, Amsterdam, Netherlands, (2012)
[9] Frederic Zamkotsian, Olivier Ilbert, Julien Zoubian, Audrey Delsanti, Samuel Boissier, Ariane Lancon, " BATMAN flies: a compact spectro-imager for space observation ", *in Proceedings of the SPIE conference on Astronomical Instrumentation 2014*, Proc. SPIE **9143**, Montréal, Canada, (2014)
[10] Ilbert, O., Salvato, M., Le Floc'h, E., et al., "Galaxy Stellar Mass Assembly Between 0.2 < z < 2 from the S-COSMOS Survey", ApJ, 709, 644, (2010)
[11] Laureijs, R. et al., "Euclid Definition Study Report", arXiv1110.3193L, (2011)
[12] Kümmel, M., Albrecht, R., Fosbury, R.F., et al., "PHLAG: Pipeline for Hubble Legacy Archive Grism Data", Astronomical Data Analysis Software and Systems XVI, 376, 245, (2007)
[13] Shapley, A.E., Steidel, C.C., Pettini, M., Adelberger, K.L., "Rest-Frame Ultraviolet Spectra of z~3 Lyman Break Galaxies", ApJ, 588, 65, (2003)