BATMAN: a DMD-based multi-object spectrograph on Galileo telescope

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ABSTRACT

Next-generation infrared astronomical instrumentation for ground-based and space telescopes could be based on MOEMS programmable slit masks for multi-object spectroscopy (MOS). This astronomical technique is used extensively to investigate the formation and evolution of galaxies.
We are developing a 2048x1080 Digital-Micromirror-Device-based (DMD) MOS instrument to be mounted on the Galileo telescope and called BATMAN. 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.
ROBIN, a BATMAN demonstrator, has been designed, realized and integrated. It permits to determine the instrument integration procedure, including optics and mechanics integration, alignment procedure and optical quality. First images and spectra have been obtained and measured: 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. Observation strategies are studied and demonstrated for the scientific optimization strategy over the whole FOV.
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. This instrument will be placed on the Telescopio Nazionale Galileo mid-2015.

Key words: multi-object spectrograph, micromirror array, astronomical instrumentation, on-sky demonstrator, MOEMS.

1. INTRODUCTION

In future infrared astronomical instrumentation for ground-based and space telescopes. Multi-Object Spectroscopy (MOS) is a key technique for large field of view surveys. MOS is used extensively to investigate astronomical objects 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. MOEMS programmable slit masks could be next-generation devices for selecting objects. 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.

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MOEMS devices such as micromirror arrays (MMA) [1, 2, 3] or micro-shutter arrays (MSA) [4] are promising solutions. 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. BATMAN will be placed on the Nasmyth focus of Telescopio Nazionale Galileo (TNG) during next year. ROBIN, a BATMAN demonstrator, has been designed, realized and integrated; measured images and spectra will be presented and analyzed.

2. 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]

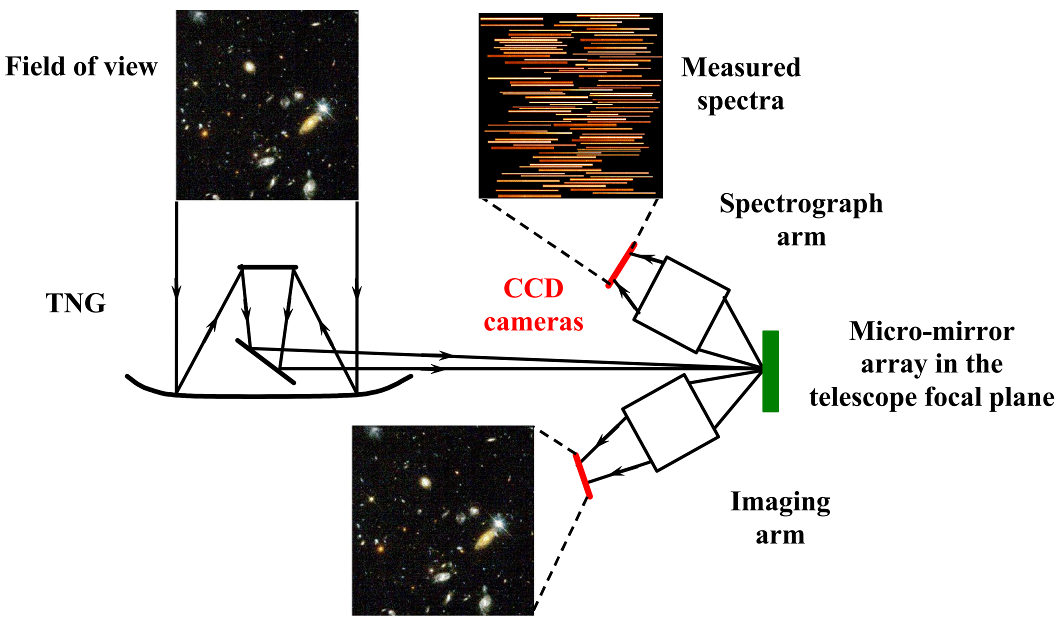

Fig. 1: Principle of BATMAN spectro-imager

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	3.6 m
Field of view	6.8 arcmin x 3.6 arcmin
Focal ratio	F/4 on DMD (with 2048 – 1080 micro-mirrors) Plate scale = 0.2 arcsec per micromirror
Beams on DMD	incoming light at normal incidence out-coming light at 24° DMD orientation at 45°
Wavelength range	400 - 800 nm
Spectral resolution	R=560 for 1arcsec object (typical slit size)
Two arms instrument	one spectroscopic channel and one imaging channel
Detectors	Two 2k x 4k CCDs

Table 1: Baseline of BATMAN

2.1 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.

2.2 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 500-2000 according to the slit size (five to one micro-mirrors).

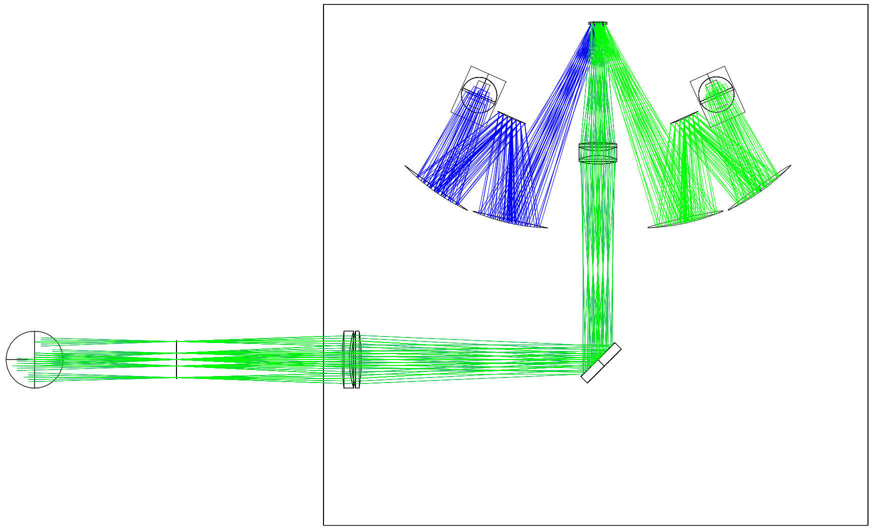

Fig. 2: Optical layout of BATMAN. Light coming from the telescope is split by the DMD into 2 arms, a spectrograph arm and an imaging arm (both are Offner relays).

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, as shown in Fig. 3. Typical monochromatic spot diameters are <0.3 arcsec over the whole FOV for wavelengths between 400nm and 800nm; in Fig. 7, boxes are 1 x 1 arcsec wide. Simulated spectra (400nm – 800 nm) on the detector are shown in Fig. 4.

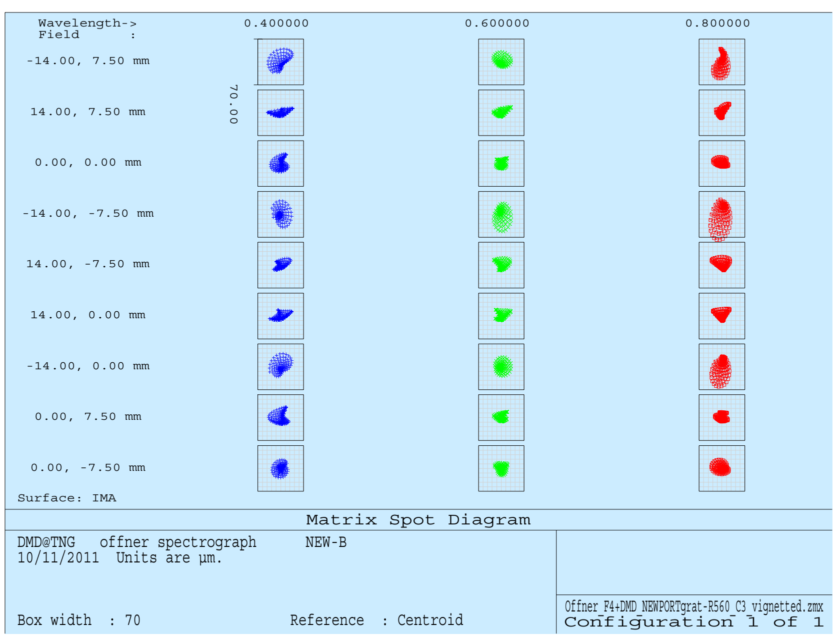

Fig. 3: Spectroscopic channel spot diagrams. Boxes are 1 x 1 arcsec wide.
Different wavelengths and field of views are given, covering the whole DMD active surface.

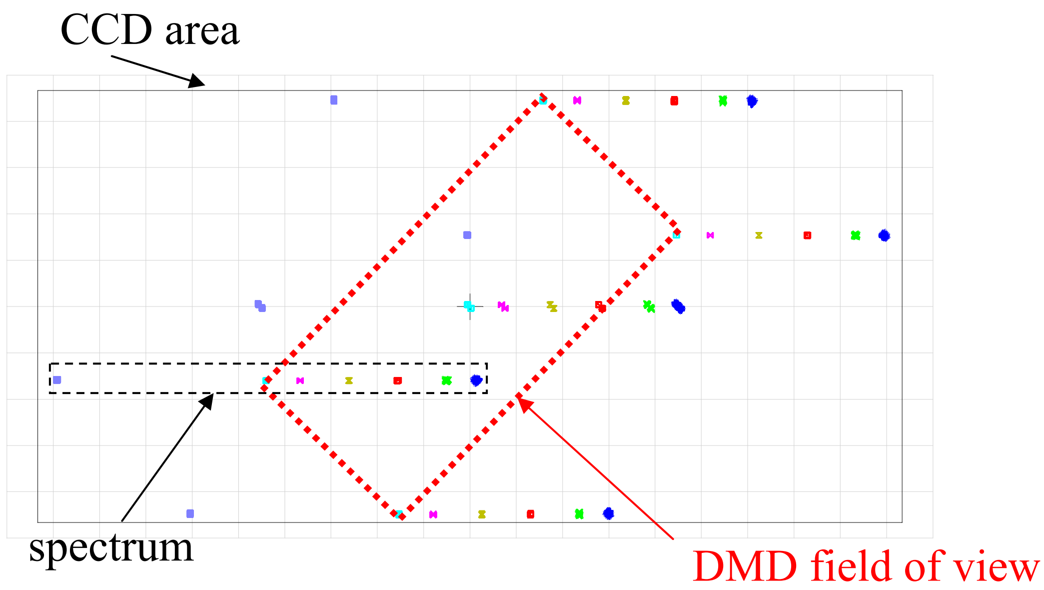

Fig. 4: Spectroscopic channel; simulated spectra on the detector.

2.3 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 (Fig. 5). Two hexapods attach the detectors to their bench for an individual alignment of the dewars. The main bench supports 2 arms: the entrance beam is adapted by the fore optics and is split by the DMD into 2 arms, a spectrograph arm and an imaging arm.

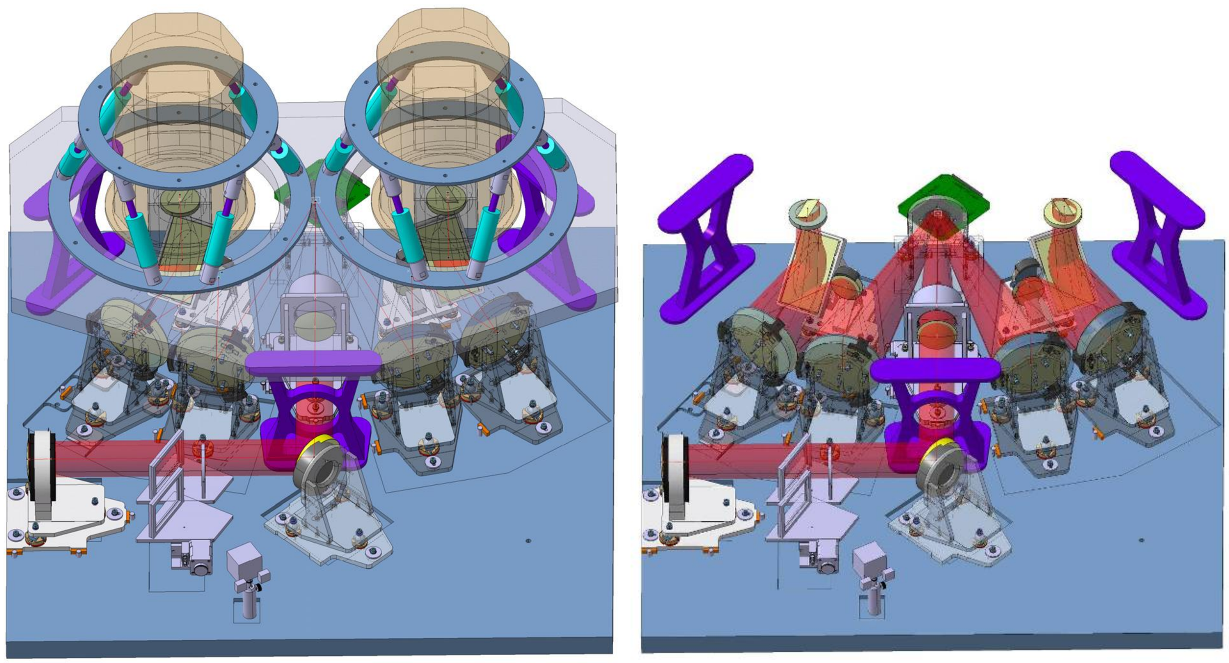

Fig. 5: BATMAN opto-mechanical design: overall view and detailed view of the main bench (dewar bench removed)

Two 2kx4k science grade detectors will be provided, integrated, tested and managed by TNG. A cover around the instrument will protect it from any straylight sources. Electronics boxes as well as computers will be located on instrument sides. The volume of the instrument is: 1100 x 1100 x 770 mm^3.

The optics will be mounted in dedicated mounts with pins and shims, and could be aligned along all degrees of freedom with 10 to 20µm-range 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 BK7 or silica). The main bench is light weighted.

A calibration unit is placed along the path, in the fore-optics, between the two lens-groups. An integrating sphere with several lamps will shine the instrument thanks to a sliding mirror entering the optical path during the calibration exposures.

Currently, a Finite Element Modeling (FEM) is under way in order to calculate the deformation of the overall instrument during an observation run. BATMAN will be mounted on the folded Nasmyth platform of TNG and then rotate during observation. FEM is done under different gravity vector orientation for simulating extreme instrument locations, and deformation of the main bench as well as translation/rotation of each detector are calculated. If the shift exceeded one pixel size, instrument mechanics will be revisited and adapted. Bench(es) architecture(s) will be then finalized before issuing drawings for instrument realization.

2.4 BATMAN: system architecture

The Control Software Architecture of BATMAN at the TNG is developed at Osservatorio Astronomico di Trieste. It address both the low-level part, which is responsible to control the vital part of the spectrograph (i.e. motorized functions, sensors, lamps) and the high-level part, which coordinates the activities to perform an astronomical observation; it will also address the interface with the TNG database, with the local archive, the DMD machine and the CCDs workstations. Startup and observer GUI, as well as engineering GUI have been developed. Other relevant parts of the overall software architecture are the data reduction software (DRS) managed by INAF/IASF Bologna, the detector control software (DCS) managed by TNG and the internals of the archive managed by INAF/IASF Bologna. The DMD@TNG control software and Data Handling System (DHS) compose what we call the "*Observation Manager*" and have been described previously. [9]

2.5 BATMAN: on-sky demonstration

BATMAN is already under construction. Many parts have been already realized or are under way (Fig. 6).

Fig. 6: BATMAN parts under way

On-going work concerns:

- Optics: fore-optics lenses have been delivered and will be mounted in their barrels; convex mirror and grating have been delivered; mirrors are under realization.
- Opto-mechanics: a first mirror mount has been produced and integrated; alignment precision will be tested. M4 telescope mirror mount has been realized. Fore-optics barrels have been designed and are under realization.
- Detectors: two dewars are currently available for housing the two science-grade detectors (2k x 4k CCD, pixel: 13.5µm). The tilted mechanical structures supporting the CCDs inside the dewars have been designed and are under realization. Full assembly is scheduled by the end of this year.
- Calibration Unit: optical and mechanical designs have been completed and parts are under realization. Lamps, fibers, integrating spheres and shutter have been delivered.
- Electronic architecture: the main blocks have been designed and will be managed for the DMD by LAM, the detectors by TNG, the calibration unit by Obs. Merate. This work is under Obs. Trieste responsibility.
- Software: see previous paragraph.

Instrument abilities are wide, including variable spatial bin and variable spectral resolution, as well as any combination of the above modes over the whole FOV. MOS and IFU (scanning slit) are available. Any slit mask configuration could be produced, i.e. any shape, including long slit, and a real time reconfiguration ability. These new features allow new observation strategies for optimizing the recorded scientific data over the FOV, following an optimized strategy on each object. For example, MOS and IFU combination any time and anywhere in the FOV are possible.

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 our French-Italian collaboration, this instrument will be placed on the Telescopio Nazionale Galileo 3.6-m telescope, at the Nasmyth focus, by mid-2015.

2.6 BATMAN flies

"BATMAN flies" is the space version of BATMAN [10]: a compact spectro-imager based on MOEMS for generating reconfigurable slit masks, and feeding two arms in parallel. The FOV is 25 x 12 $arcmin^2$ for a 1m telescope, in infrared (0.85–1.7µm) and 500-1000 spectral resolution.

Unique science cases for Space Observation are reachable with this deep spectroscopic multi-survey 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. [7] ROBIN, BATMAN demonstrator, has been built and delivers already images and spectra in parallel, allowing us to validate all expected performances (see paragraph 3). And BATMAN is scheduled to be mounted for an on-sky demonstration in the coming year on Telescopio Nazionale Galileo 3.6-m telescope.

And then, hopefully, BATMAN will fly.

3. 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.

3.1 ROBIN design and integration

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. 7 (a).

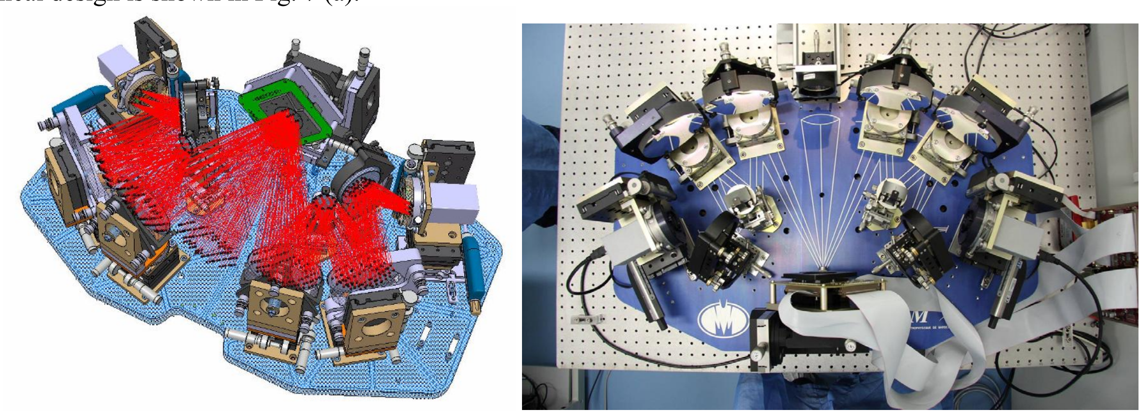

Fig. 7: (a) 3D general design view of ROBIN (in red, beam propagation in the demonstrator); (b) integrated ROBIN picture

ROBIN has been integrated and aligned (Fig. 7 (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).

In Fig. 8, a general view of ROBIN mounted on an optical bench in LAM clean-room facility. Input beams, including field of view simulator and spectral sources (spectral lamps and lasers) are also shown.

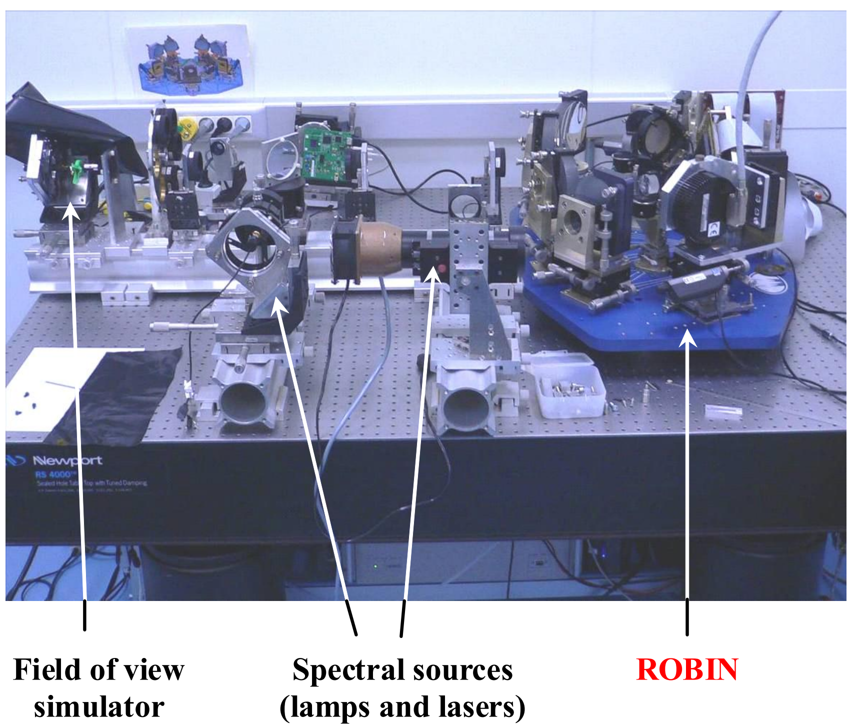

Fig. 8: ROBIN mounted on an optical bench in LAM clean-room facility. Input beams are also shown.

3.2 ROBIN images

First images have been measured. In the imaging arm, typical slit mask patterns used during the space evaluation of the DMDs [7] are recorded (Fig. 9); the optical quality is good enough for imaging each individual micromirror (13.68µm pitch) within whole FOV. Measured values are in agreement with the calculated values (paragraph 2.2 and Fig. 3).

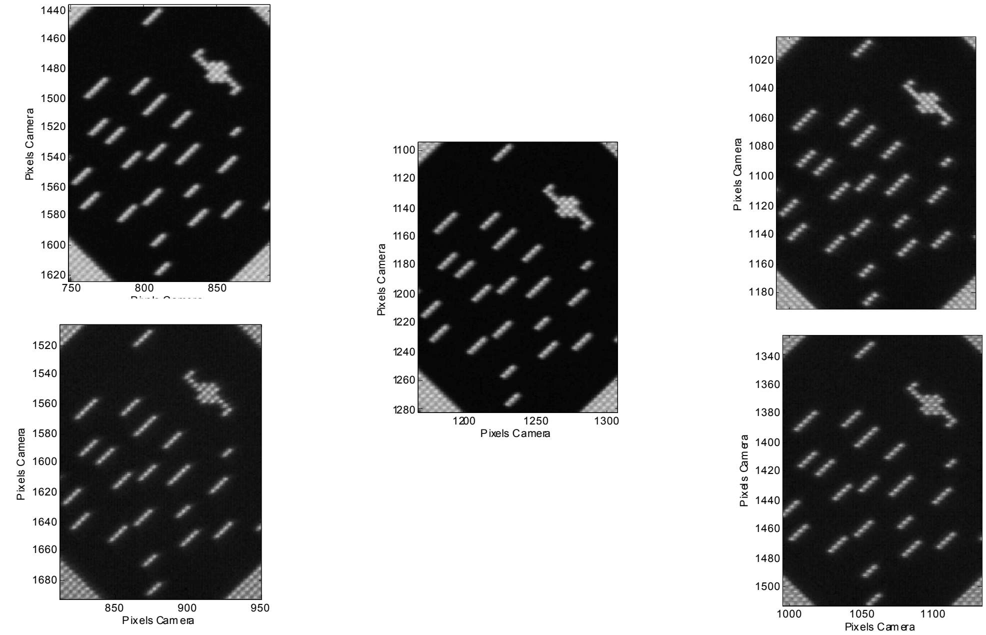

Fig. 9: ROBIN image quality at the center and at the edges of the FOV; individual micromirrors (13.68µm pitch) are resolved.

3.3 Slit configuration

A DMD pattern manager has been developed in order to generate any slit mask pattern from a list of objects. [11] Length and width of each slit are tunable as well as its orientation. Hardware and software were developed by Visitech (a Norwegian company) and LAM for driving the DMD boards. The software is developed in Matlab for driving the DMD chip by a computer. The DMD driver electronics consists of a formatter board and a DMD board. The general architecture of the system is described elsewhere. [7] In Fig. 10 are shown typical slits with 5x15 micromirrors (2 orientations, vertical and at 45°) and a single micromirror slit (13µm) recorded with the camera in the imaging arm. Upper line is displayed as seen by the imaging arm (slits are dark), lower line is displayed as seen by the spectroscopic arm (slits are bright). Note the very good optical quality of the demonstrator as single micromirrors are resolved.

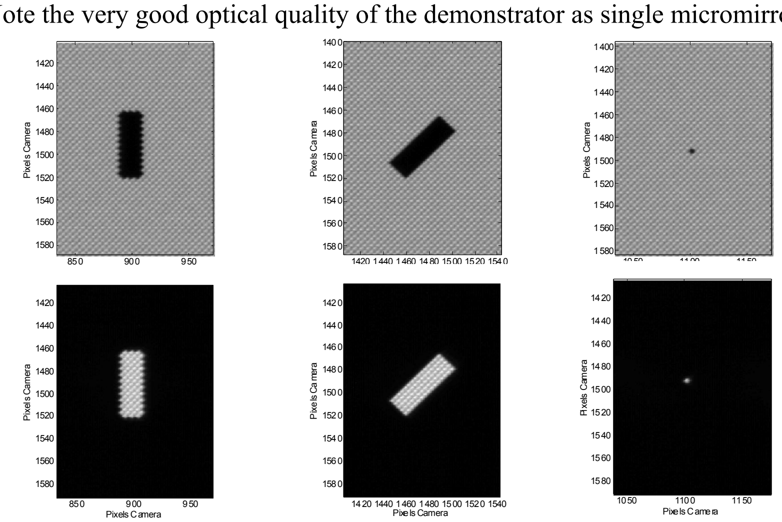

Fig. 10: ROBIN slits; typical slits with 5x15 micromirrors (2 orientations, vertical and at 45°) and a single micromirror slit (13µm). Upper line as seen by the imaging arm (slits are dark), lower line as seen by the spectroscopic arm (slits are bright).

3.3 ROBIN spectra

A slit mask with typical slits with 5x15 micromirrors and a single micromirror slit is displayed on the DMD. In the spectroscopic arm, spectra are recorded (Fig. 11). **For the 1 micromirror slit (mirror size 13.68 µm), the spectrum is displayed on 1.5 detector pixels (detector pixel size 8.3µm), demonstrating that the 1:1 Offner relay type spectrograph is perfectly aligned. The spectrum is on 1.5 detector pixels height over the whole 450-650nm wavelength range; the length of the spectrum is over 500 detector pixels.**

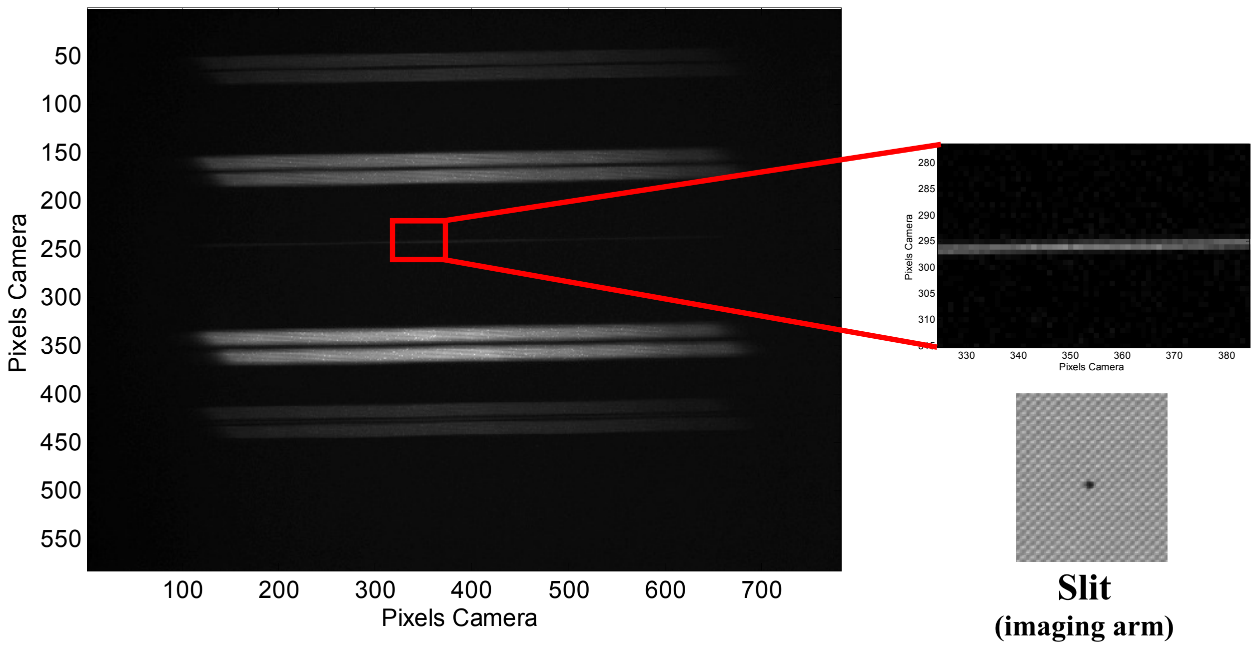

Fig. 11: Spectra in the spectral channel, including a single micromirror slit; close view of the spectrum generated by the one-micromirror slit, and the corresponding slit image recorded with the imaging arm.

3.4 ROBIN spectral resolution

The spectral resolution is linked to the size of the input slit and the optical quality of the spectrograph. In the previous paragraphs, we have demonstrated the optimal optical quality of the instrument, by showing resolved images and spectra for one micromirror slits. Then, by moving from the typical slit width of 5 micromirrors down to one micromirror, we might reveal spectral lines finest features. For this purpose, we choose as an input light source a HgCdZn lamp with many emission lines, including a 2 nm wavelength separation in a spectral doublet (576.96 nm and 579.07nm).

In Fig. 12 are shown several spectral profiles recorded with ROBIN spectroscopic arm for a variable width slit: the 2 nm spectral lamp doublet (HgCdZn) is unresolved for 5 micromirrors wide slit, still unresolved for a 3 micromirrors wide slit and resolved for 2 and 1 micromirrors wide slits. Spectra (as recorded by the spectroscopic camera) for 5 micromirrors wide slit and 1 micromirror wide slit are also displayed at the top and the bottom of Fig. 12, clearly showing the variable resolution of the spectrograph with respect to the slit size.

3.5 ROBIN instrument abilities

We have also 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. Results will be presented elsewhere.

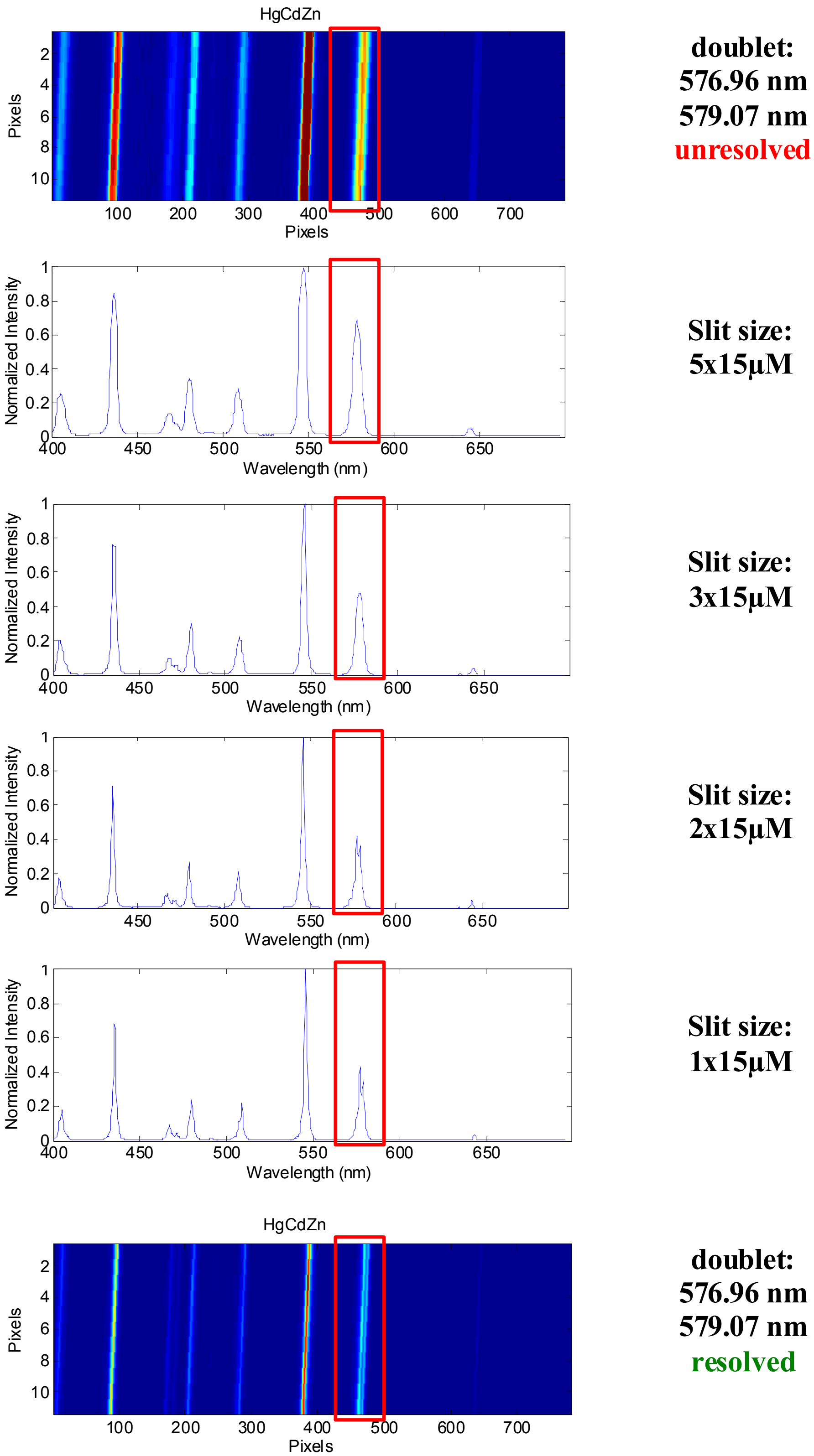

Fig. 12: ROBIN spectral resolution: 2 nm spectral lamp doublet (HgCdZn) unresolved for 5 micromirrors (µM) wide slit and resolved for 2 µM wide slit.

4. CONCLUSION

In order to investigate the formation and evolution of galaxies, next-generation infrared astronomical instrumentation for ground-based and space telescopes could be based on MOEMS programmable slit masks for multi-object spectroscopy.

BATMAN is a 2048x1080 Digital-Micromirror-Device-based (DMD) MOS instrument to be mounted on the 3.6m Galileo telescope. 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.

ROBIN, a BATMAN demonstrator, has been designed, realized and integrated. It permits to determine the instrument integration procedure, including optics and mechanics integration, alignment procedure and optical quality. First images and spectra have been obtained and measured: 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. Observation strategies are studied and demonstrated for the scientific optimization strategy over the whole FOV.

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