BATMAN: a DMD-based MOS demonstrator on Galileo telescope

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ABSTRACT

Multi-Object Spectrographs (MOS) are the major instruments for studying primary galaxies and remote and faint objects. Current object selection systems are limited and/or difficult to implement in next generation MOS for space and ground-based telescopes. A promising solution is the use of MOEMS devices such as micromirror arrays which allow the remote control of the multi-slit configuration in real time.

We are developing a Digital Micromirror Device (DMD) - based spectrograph demonstrator called BATMAN. We want to access the largest FOV with the highest contrast. The selected component is a DMD chip from Texas Instruments in 2048 x 1080 mirrors format, with a pitch of 13.68µm. Our optical design is an all-reflective spectrograph design with F/4 on the DMD component.

This demonstrator permits the study of key parameters such as throughput, contrast and ability to remove unwanted sources in the FOV (background, spoiler sources), PSF effect, new observational modes. This study will be conducted in the visible with possible extension in the IR. A breadboard on an optical bench, ROBIN, has been developed for a preliminary determination of these parameters.

The demonstrator on the sky is then of prime importance for characterizing the actual performance of this new family of instruments, as well as investigating the operational procedures on astronomical objects. BATMAN will be placed on the Nasmyth focus of Telescopio Nazionale Galileo (TNG) during next year.

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

1. INTRODUCTION

Multi-object spectroscopy (MOS) is a key technique for large field of view surveys with a high density of objects such as high-z galaxies or stars. MOEMS programmable slit masks could be next-generation devices for selecting objects in future infrared astronomical instrumentation for ground-based and space telescopes. MOS is used extensively to investigate the formation and evolution of galaxies by optimizing the Signal-to-Noise Ratio (SNR): high precision spectra are obtained and the problem of spectral confusion is cancelled, in order to reach fainter limiting fluxes and to maximize the scientific return 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.

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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. MSA has been selected to be the multi-slit device for NIRSpec and is under development at NASA's Goddard Space Flight Center. They use a combination of magnetic effect for shutter actuation, and electrostatic effect for shutter latching in the open position. In Europe an effort is currently under way to develop single-crystalline silicon micromirror arrays for future generation infrared multi-object spectroscopy.[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. For example, a MOEMS-based MOS concept where the programmable slit mask is a MMA is shown in the left-hand side of Fig. 1. In action, the micro-mirrors in the ON position direct the light toward the spectrograph, while the micro-mirrors in the OFF position are directing the light towards a trap.

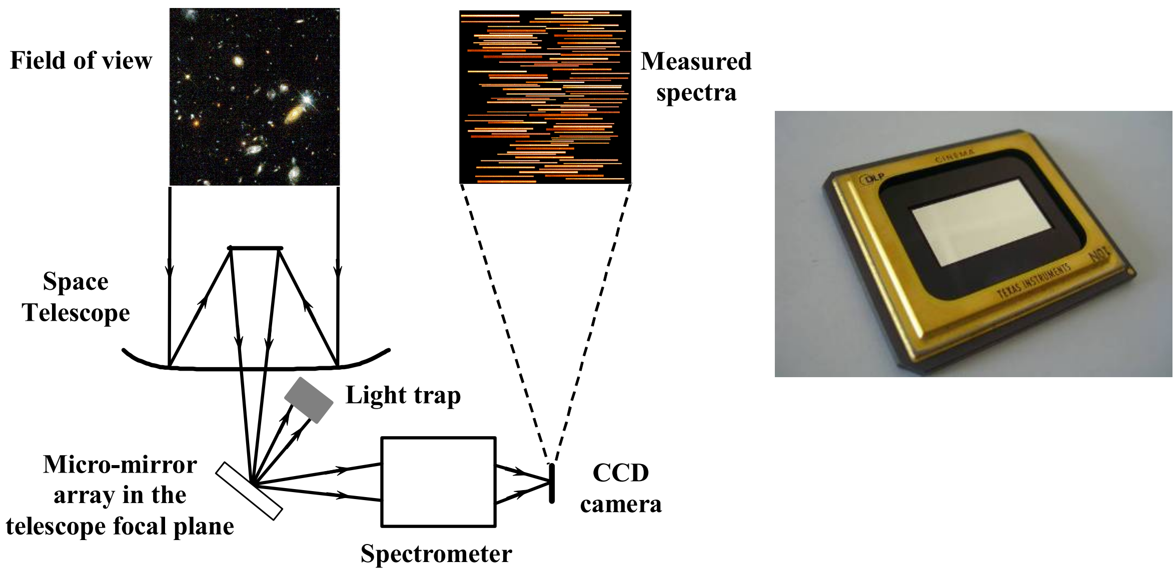

Fig. 1: Principle of a Multi-Object Spectrograph with a Micro-Mirror Array.
DMD chip from Texas Instruments (2048 x 1080 micromirrors).

A Digital Micromirror Device (DMD) from Texas Instruments has been proposed many years ago as device to perform multi-object spectroscopy for astronomical applications [7], but only few of them have really seen the sky [8,9] , due to complex optical layout to feed projected sky areas on the DMD surface, where micro-mirrors can select targets to be sent into a spectrograph. Due to geometric constraints of incoming and outcoming beams hitting the DMD surface, no simple layout can be foreseen, and pretty complex systems have been designed to fully exploit the potentiality of such devices. Some of them have been designed to fly on board of space telescopes [2,10,11] , making use for most of them to very expensive, off-axis aspherical surfaces, to cope with aberrations.

To get more than 2 millions independent micromirrors, the only available component is a DMD chip from Texas Instruments that features 2048 x 1080 mirrors and a 13.68µm pixel pitch (right-hand side of Fig. 1). Typical operational parameters are room temperature, atmospheric pressure and mirrors switching thousands of times in a second, while for MOS application in IR, the device should work in vacuum, at low temperature, and each MOS exposure lasts between 400s and 1500s, with mirrors held in one state (either ON or OFF) during the exposure.

This paper has been originated by EUCLID-NIS studies and ESA technical assessment of a DMD chip for space application in particular. [12] The Laboratoire d'Astrophysique de Marseille (LAM) has over several years developed different tools for the modeling and the characterization of MOEMS-based slit masks, especially during the design studies on JWST-NIRSpec. [13,14]

We are presenting in this paper a DMD-based spectrograph called BATMAN, including two arms, one spectroscopic channel and one imaging channel. A breadboard on an optical bench, ROBIN, has been developed and is presented for a preliminary determination of BATMAN performances. If this demonstrator is successful, next step will be BATMAN placed on the Telescopio Nazionale Galileo. [15]

2. DMD AS 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.** [12]

In order to evaluate the capability of a DMD device to select objects in a field of view, we have developed a dedicated test set-up, demonstrating the concept of a DMD-based MOS spectrograph. From a field of view simulator, objects could be selected with the DMD device. Then, device performances have been measured and object selection procedure evaluated. An optical characterization test setup has been developed at LAM and one of the key parameters, the contrast has been measured, revealing a value as high as 2250. [15]

3. BATMAN CONCEPT

BATMAN, the DMD-based spectrograph instrument is scheduled to be mounted on the Telescopio Nazionale Galileo 3.6-m telescope, at the Nasmyth focus. This instrument includes two arms working in parallel: one spectroscopic channel and one imaging channel (Fig. 2).

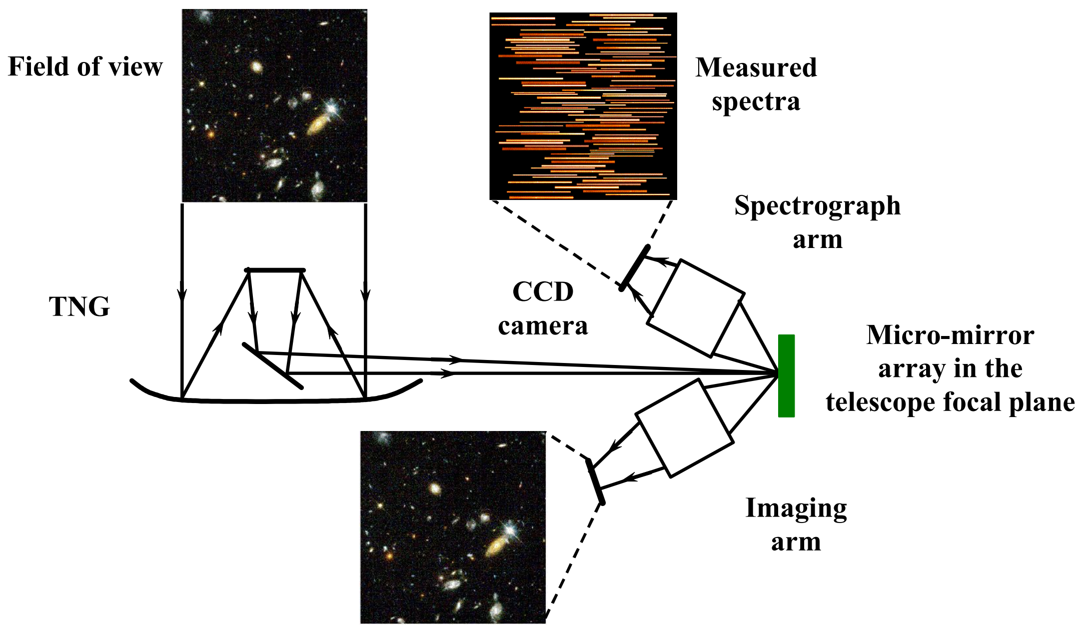

Fig. 2: Principle of BATMAN instrument to be mounted on the Telescopio Nazionale Galileo 3.6-m telescope.

Our goal is to make a robust and efficient instrument on a 4m-class telescope: this is a challenge. 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.

Moreover, some space and weight constraints went from the available telescope focal plane, a folded F/11 Nasmyth focus. 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] That system was designed with a much longer focal ratio (F/8), starting from an Offner relay system, where the secondary convex mirror was substituted with a convex grating. Here, we reduced the focal ratio by a 2x factor, thus improving the field of view by a 4x factor.

BATMAN concept is shown in Fig. 3: from the F/11 telescope focus, a fore-optics is used to reduce the F-number down to F/4 on the DMD; two arms are fed by the DMD, the imaging channel and the spectroscopic channel, both based on the same optical design. The overall design is folded in order to fit the Galileo Nasmyth interface. A calibration unit will be inserted in the fore-optics path.

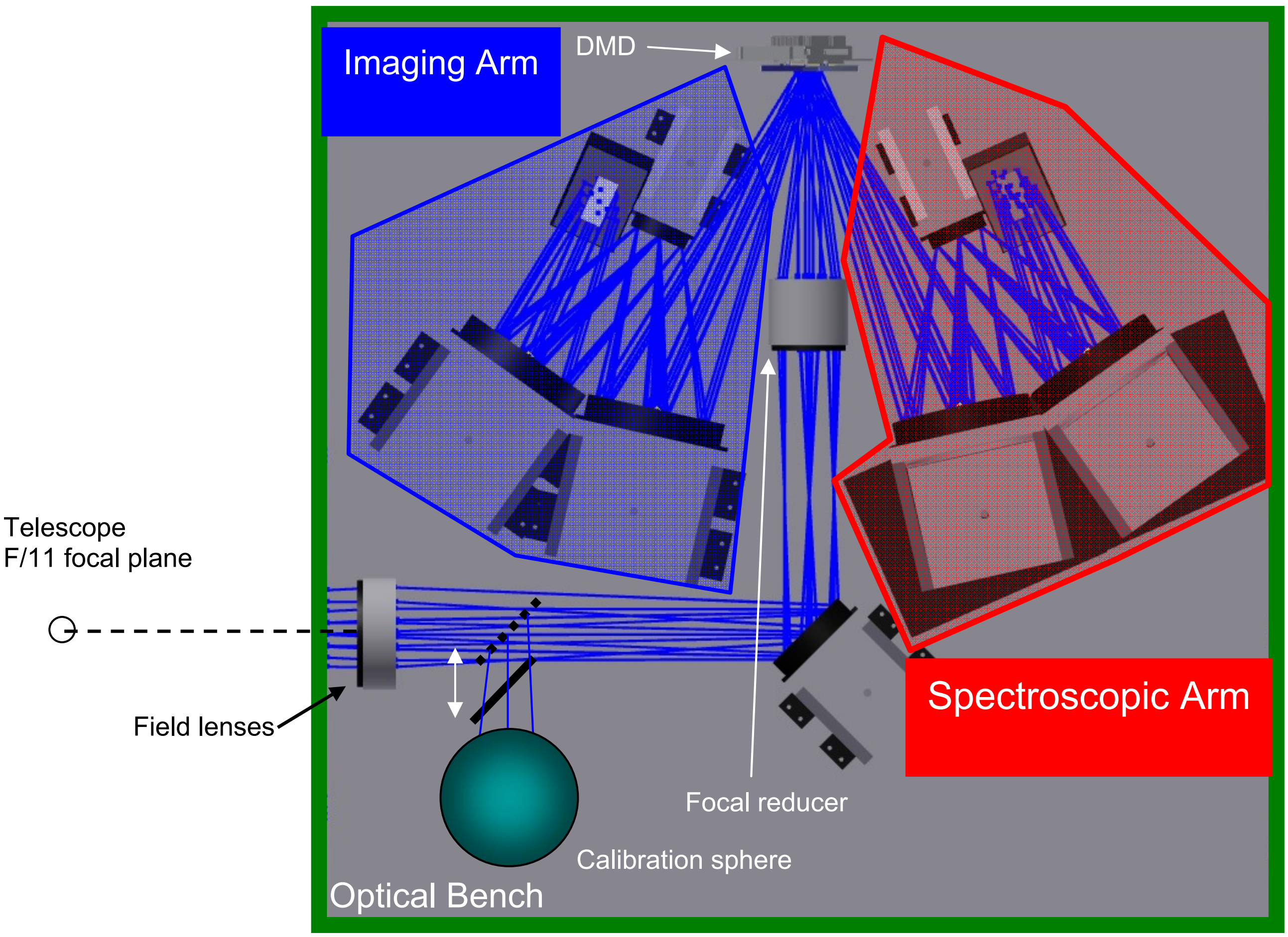

Fig. 3: BATMAN concept including an imaging arm and a spectroscopic arm.

BATMAN baseline is resumed in Table 1.

Field of view	6.8 arcmin x 3.6 arcmin
Focal ratio	F/4 on DMD (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 DMD-based spectrograph on Galileo telescope

4. 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. 4). BATMAN is based on a double Offner relay system with a 1:1 magnification between the DMD pixels and the detector pixels, thanks to their quasi identical sizes: 13.68 µm for the DMD pixels (pitch) and 13.5µm for 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.

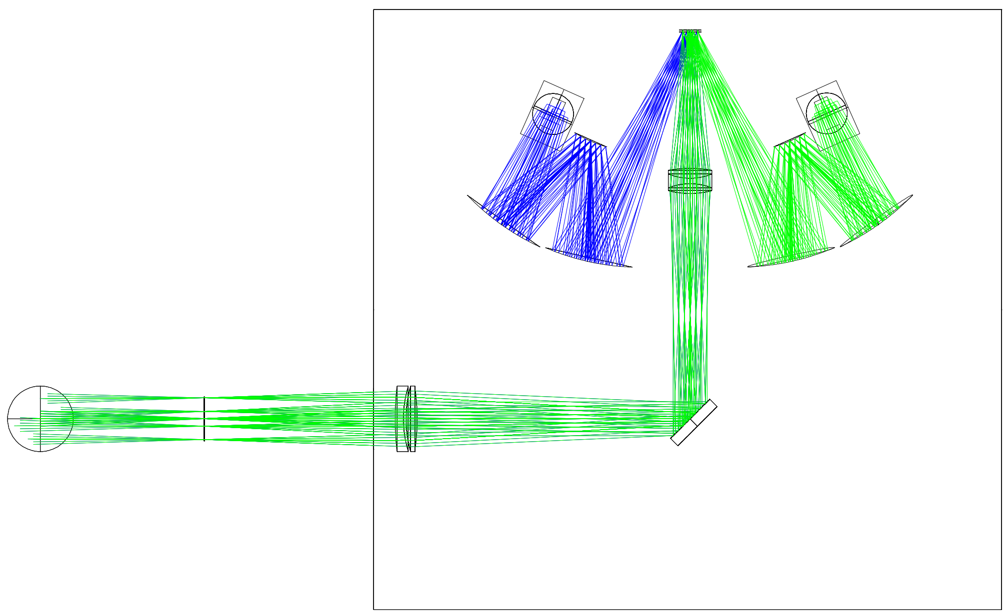

Fig. 4: Optical layout of BATMAN. Light coming from the telescope is adapted in F-number thanks to the fore-optics and reach the DMD with a F/4 beam, and is split by the DMD into 2 arms, a spectrograph arm and an imaging arm (both are Offner relays).

4.1 Fore optics

The F/11 input beam is shaped thanks to a fore-optics based on a fully refractive relay system designed to match the spectrograph focal ratio (F/4), covering visible wavelengths from 400 to 800 nm. It is based on five all-spherical lenses into two groups with a telecentric design; all glasses are standard (Fig. 5). The 8 arcmin in diameter field-of-view exhibits a maximum vignetting of 40% at 4 arcmin off-axis. The DMD plate scale is 68 µm/arcsec, or 0.2 arcsec/DMD-micromirror. The image quality is ~0.8 arcsec, typical spot diameter in the FOV.

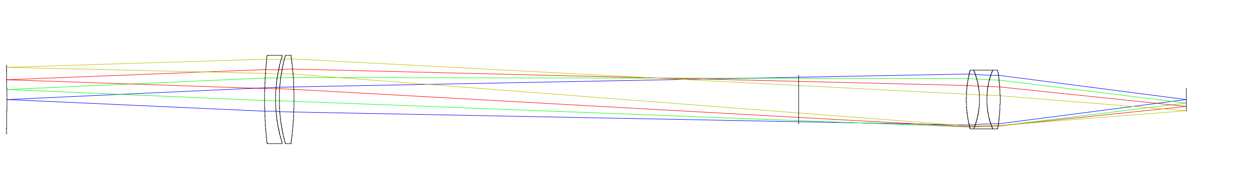

Fig. 5: Optical layout of BATMAN fore-optics.

4.2 Spectroscopic channel

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 (Fig. 6). Indeed, spherical mirrors belong to the same mother mirror, sharing the same radius and center of curvature. One mirror only could be used instead of two separate ones, helping the alignment of the system. However, mechanical and operational constraints can lead to split these two mirrors. We have preferred two identical spherical mirrors with a diameter of 160mm and a radius of curvature of 438mm.

The most critical component of the system is the convex grating, due to complex manufacturing and tight alignment tolerances. Many developments have been done in the last decade to produce such devices and implement them into hyperspectral imaging. A Richardson (Newport group) grating has been chosen from their available list of gratings, leading to a component with 282.7 l/mm line density and 224mm radius of curvature.

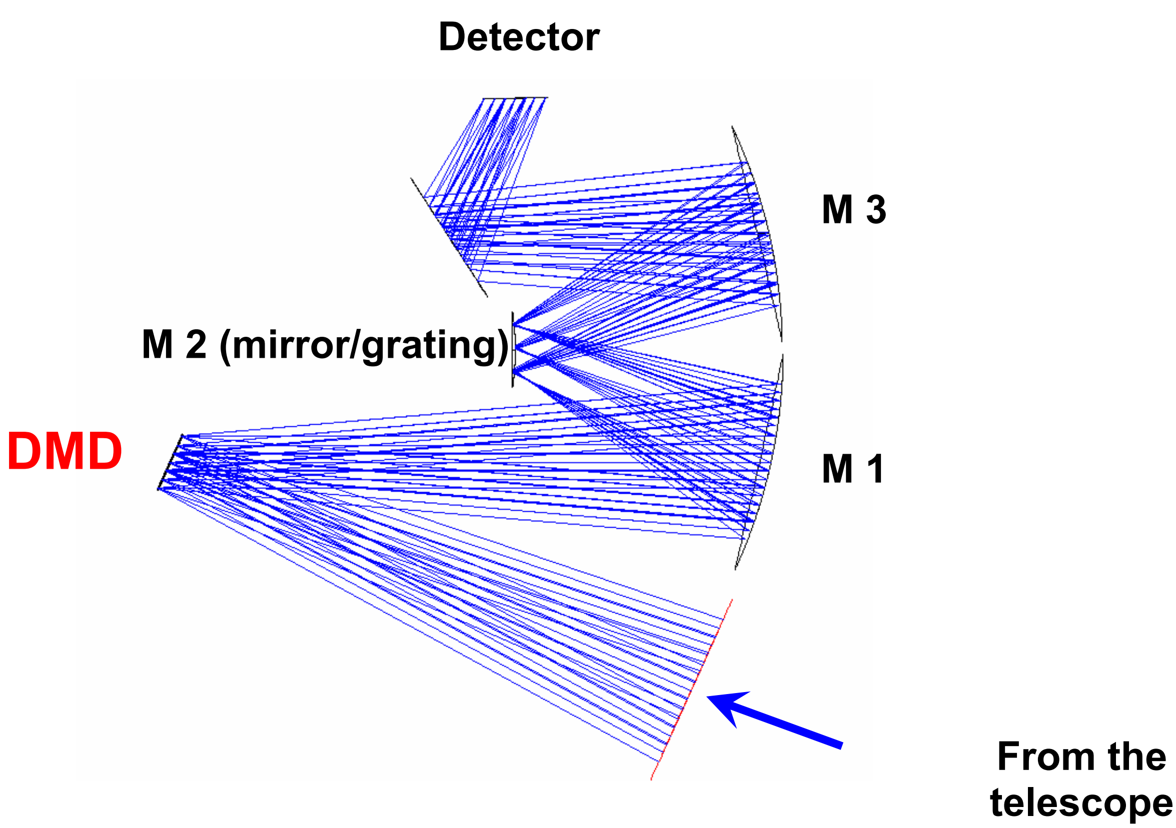

Fig. 6: Optical layout of the DMD-spectrograph/imaging arm. Light coming from the telescope enters from center.

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. 7. 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. 8.

Fig. 7: 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.

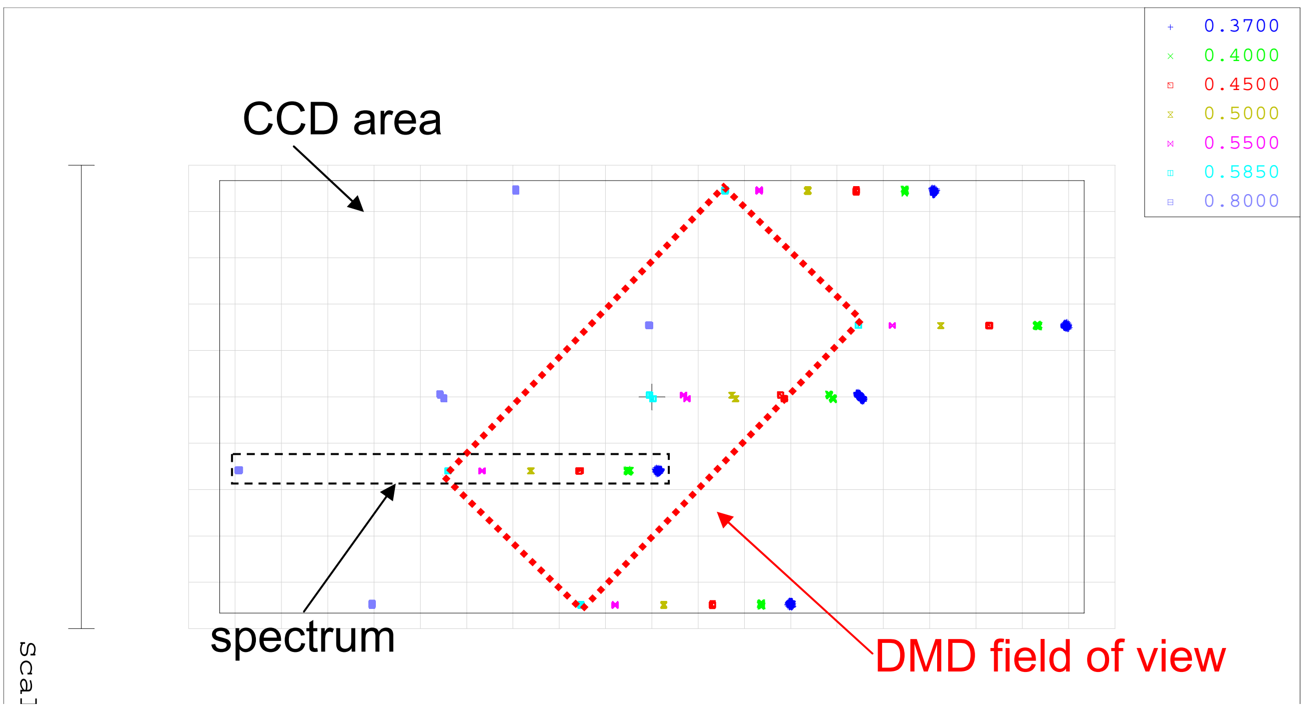

Fig. 8: Spectroscopic channel; simulated spectra (400nm – 800 nm) on the detector.

4.3 Imaging channel

An imaging channel has been added, being a copy of the spectroscopic channel when the grating is exchanged with a spherical convex mirror with the same radius of curvature (Fig. 6). The two channels can easily share the same plane, to make the optomechanical arrangement easier. Delivered image quality onto the detector is high enough to not degrade spatial resolution and is identical to the spot diagrams shown in Fig. 7: typical monochromatic spot diameters are <0.3 arcsec over the whole FOV for wavelengths between 400nm and 800nm.

5. 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 dewars (Fig. 9). This 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. The detectors are located on top of the bench. 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 10µm-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 zerodur 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.

The complete opto-mechanical design will be detailed elsewhere.

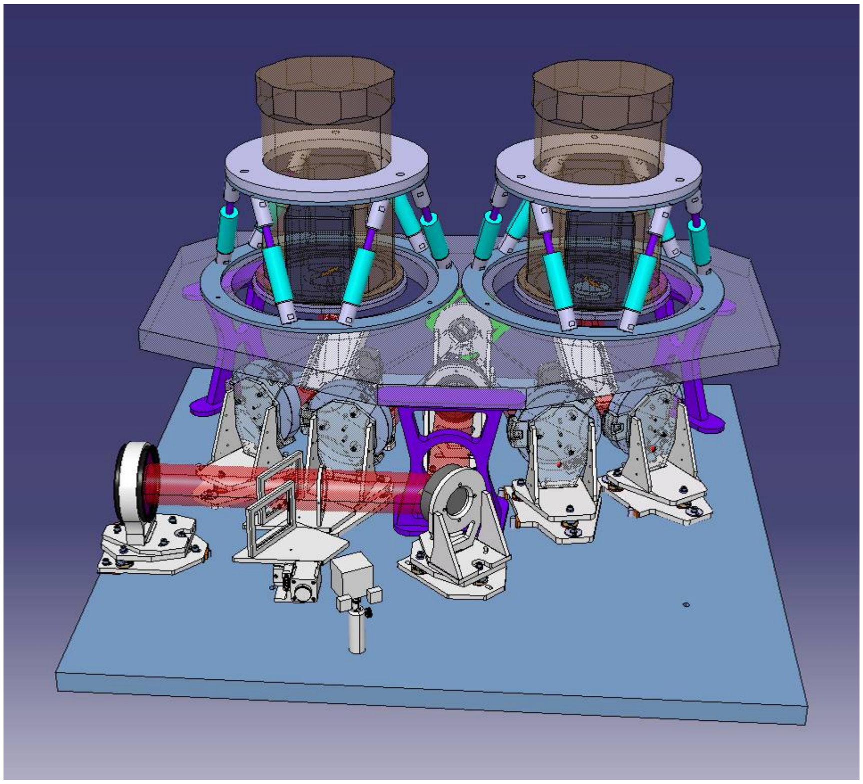

Fig. 9: BATMAN opto-mechanical design.

6. SYSTEM DESIGN

The Control Software Architecture of BATMAN at the TNG is developed at Osservatorio Astronomico di Trieste. It will focus on the design of the control software both for the low-level part, which will be responsible to control the vital part of the spectrograph (i.e. motorized functions, sensors, lamps) and for the high-level part, which will coordinate the activities to perform an astronomical observation; it will also address the I/f with the TNG database, with the local archive, the DMD machine and the CCDs workstations. 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. [15]

As for the DMD, we are developing a DMD pattern manager in order to generate any slit mask pattern from a list of objects. 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 hardware is controlled by a RS-232 serial link and a DVI port is used for loading an image onto the DMD. 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. [12] There is a notable difference that separates this system from other DMD board designs; the control signals of the reset drivers are fed through an FPGA. This enables driving the DMD into zones, each zone being driven with a different pattern and refresh rate. The pattern could be then held as long as required by the exposure time. Simulation of several spectra on spectrograph detector is shown in Fig. 10.

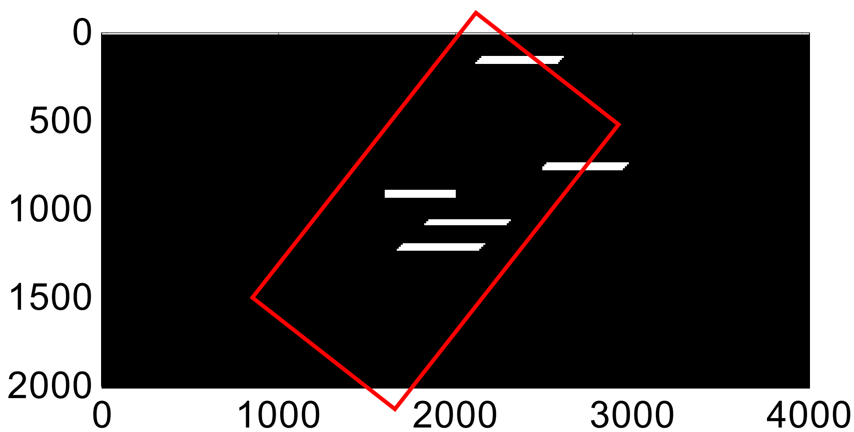

Fig. 10: Simulation of short spectra on spectrograph detector. Footprint of the DMD chip is superimposed in red color.

7. ROBIN: A BATMAN DEMONSTRATOR

Before developing our MOS instrument, we are building 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.

7.1 Optical design

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. ROBIN optical design as well as its foreseen performances have been presented previously. [16]

The input beam is shaped thanks to a relay optics based on a fully refractive relay system designed to match the spectrograph focal ratio (F/4), covering visible wavelengths from 400 to 800 nm. It is based on off-the-shelf lenses. Due to the wide FOV covered by the DMD, we will cover it only partially and we add moving stages on the input beam optical system in order to address the full FOV sequentially.

A spectrograph layout identical to BATMAN 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 (Fig. 6). 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, for a spectral resolution twice shorter than BATMAN value.

This makes the system simple and efficient, not suffering 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 <0.3 arcsec over the whole FOV for wavelengths between 400nm and 800nm, comparable to the spot diagrams obtained for BATMAN. [16] An imaging channel has been added, being a copy of the spectroscopic channel when the grating is exchanged with a spherical convex mirror with the same radius of curvature; optical performances are identical to the spectroscopic channel. Simulated spectra (400nm – 800 nm) on the detector are shown in Fig. 11. They are shorter than BATMAN spectra (Fig. 8)

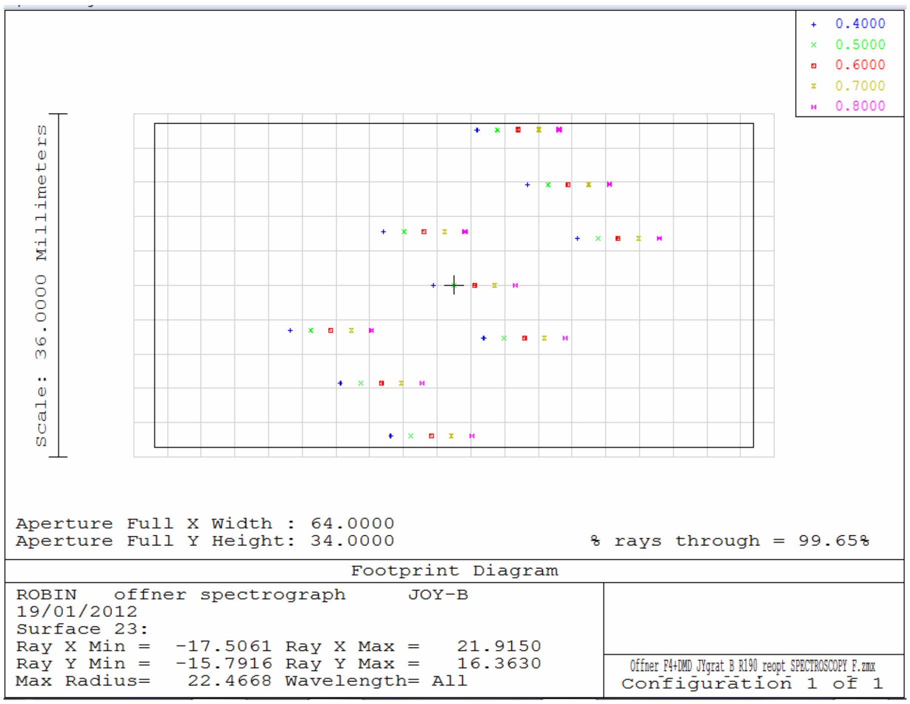

Fig. 11: ROBIN spectroscopic channel; simulated spectra (400nm – 800 nm) on the detector.

7.2 Opto-mechanical design

The general mechanical design of ROBIN consists of a main optical bench supported by three legs and mounted on a damped table (Fig. 12). This bench supports 2 arms: the entrance beam is adapted by the fore optic (not shown in Fig. 12) and is split by the DMD into 2 arms, a spectrograph arm and an imaging arm. The detectors are located on both sides of the bench. A cover around the demonstrator will protect it from any straylight sources. Electronics boxes as well as computers will be located on a separate table.

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 each detector in both arms, in order to address the full FOV sequentially.

Optical performances as well as alignment tolerances will be measured. The alignment and test procedures will then be used on BATMAN to be mounted on the telescope.

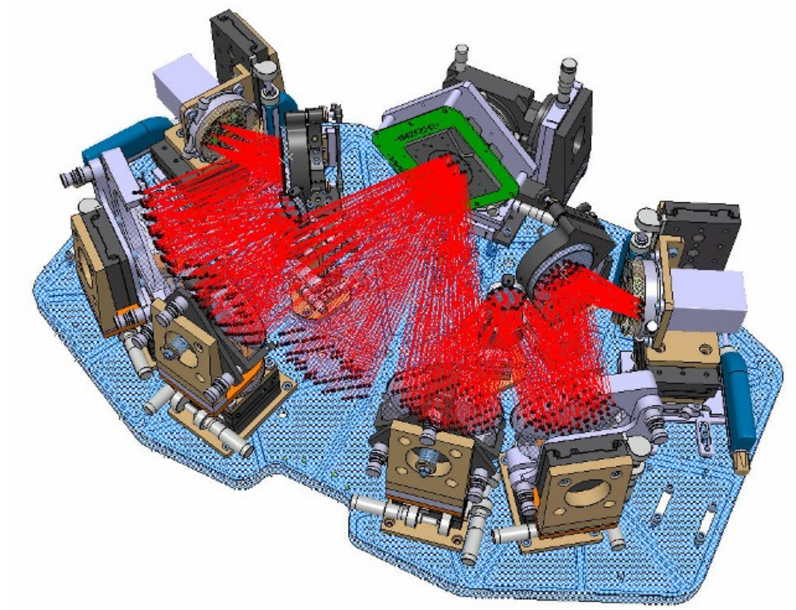

Fig. 12: 3D general design view of ROBIN, the BATMAN demonstrator (in red, beam propagation in the demonstrator)

7.3 ROBIN in action

ROBIN has been integrated and aligned (Fig. 13). 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). The grey ribbons at the bottom of the pictures consist of 300 wires for controlling the DMD. Optical path scheme is etched on the bench.

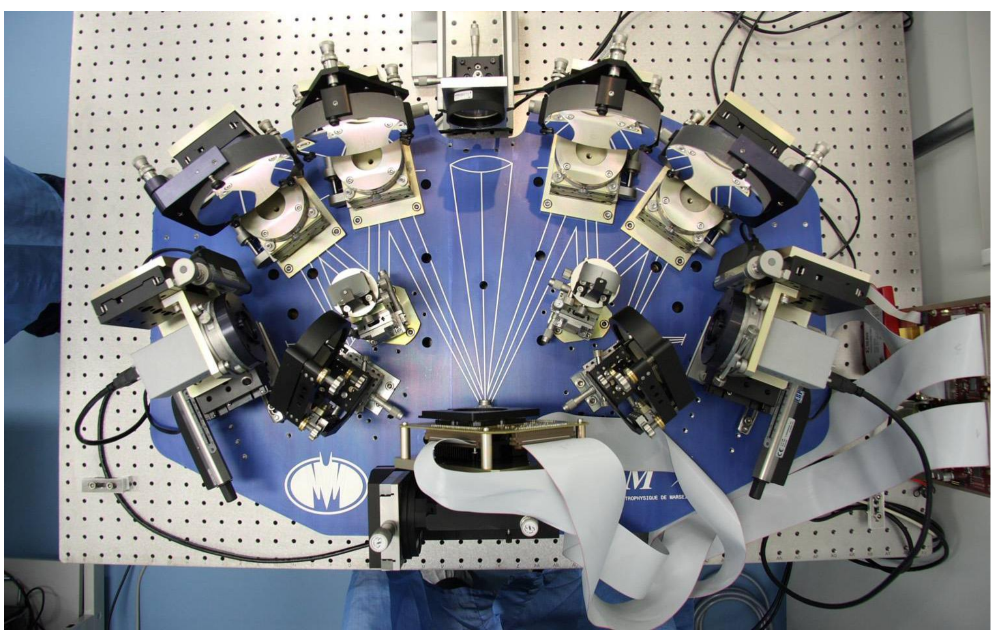

Fig. 13: ROBIN is the BATMAN demonstrator

First images and first spectra have been recorded (Fig. 14). A serial of slits, 5 micromirrors wide and 15 micromirrors long are set on the DMD: in the imaging arm, they appear in black as the light located on these slits is sent towards the spectrograph; in the spectroscopic arm, the slits generate spectra for each of them, and all spectra are aligned on the detector, due to the dispersion orientation of the grating. The incoming beam has been limited to the 450 – 650 nm range in order to fit the limited size of the detector. A profile of the spectra is presented in Fig. 15 with calibration sources located at 454nm, 546nm and 650nm.

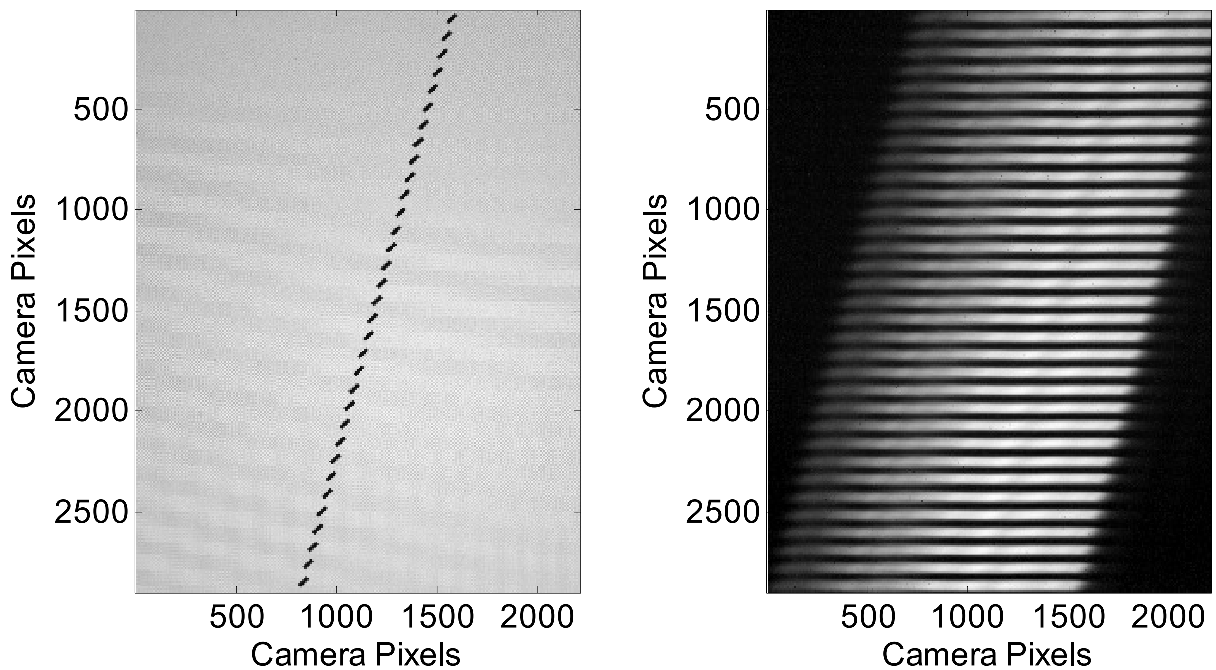

Fig. 14: Image of the slit mask in the imaging channel and the corresponding spectra in the spectral channel

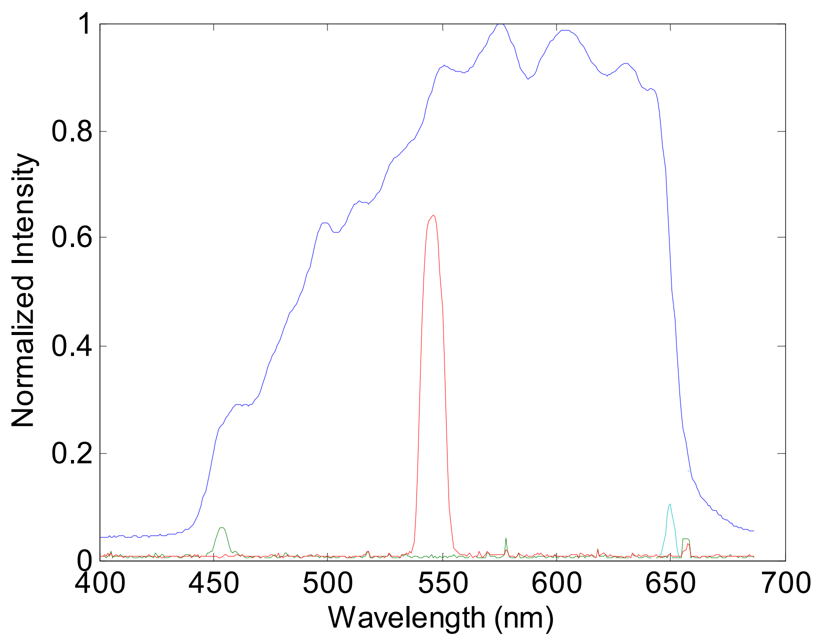

Fig. 15: Profile of a spectrum with calibration sources located at 454nm, 546nm and 650nm.

8. CONCLUSION

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 propose to develop a DMD-based 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 two arms with an F-ratio of F/4 on the DMD are mounted on a common bench. Very good optical quality on the DMD and the detectors has been reached. The opto-mechanical design is based on a main bench for the optics and an upper bench for the detectors, their alignment is made with two independent hexapods. Detailed opto-mechanical design is under way.

ROBIN, a BATMAN demonstrator, will permit to determine the instrument integration procedure, including optics and mechanics integration, alignment procedure and optical quality measurement. We will also test 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 will be studied, with any slit mask configurations (any shape, including long slit) as well as real time reconfiguration. Finally observation strategies will be studied and demonstrated for the scientific optimization strategy over the whole FOV. ROBIN has been designed, realized and integrated. First images and spectra have been obtained. Full characterization and use of the demonstrator is scheduled for the coming months.

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 during next year, in 2013.

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