PROCEEDINGS OF SPIE

SPIEDigitalLibrary.org/conference-proceedings-of-spie

BATMAN @ TNG: instrument integration and performance

Zamkotsian, Frederic, Lanzoni, Patrick, Tchoubaklian, Nicolas, Ramarijaona, Harald, Moschetti, Manuele, et al.

Frederic Zamkotsian, Patrick Lanzoni, Nicolas Tchoubaklian, Harald Ramarijaona, Manuele Moschetti, Marco Riva, Marc Jaquet, Paolo Spano, William Bon, Mathieu Vachey, Luciano Nicastro, Emilio Molinari, Rosario Cosentino, Adriano Ghedina, Manuel Gonzalez, Walter Boschin, Paolo Di Marcantonio, Igor Coretti, Roberto Cirami, Filippo Zerbi, Luca Valenziano, "BATMAN @ TNG: instrument integration and performance," Proc. SPIE 10702, Ground-based and Airborne Instrumentation for Astronomy VII, 107025P (6 July 2018); doi: 10.1117/12.2315222

Event: SPIE Astronomical Telescopes + Instrumentation, 2018, Austin, Texas, United States

BATMAN @ TNG:
Instrument integration and performance

Frederic Zamkotsian[1], Patrick Lanzoni[1], Nicolas Tchoubaklian[1], Harald Ramarijaona[1], Manuele Moschetti[2], Marco Riva[2], Marc Jaquet[1], Paolo Spano[2], William Bon[1], Mathieu Vachey[1], Luciano Nicastro[3], Emilio Molinari[4], Rosario Cosentino[4], Adriano Ghedina[4], Manuel Gonzalez[4], Walter Boschin[4], Paolo Di Marcantonio[5], Igor Coretti[5], Roberto Cirami[5], Filippo Zerbi[2], Luca Valenziano[3]

[1] Aix Marseille Universite, CNRS, LAM (Laboratoire d'Astrophysique de Marseille) UMR 7326, 38 rue F. Joliot Curie, 13388 Marseille Cedex 13, France,
[2] INAF Osservatorio Astronomico di Brera, Via Bianchi 46, I-23807 Merate (Lc), Italy,
[3] INAF/IASF Bologna, via P. Gobetti 101, I-40129 Bologna, Italy,
[4] INAF-Telescopio Nazionale Galileo, Rambla J. A. Fernandez Perez 7, 38712 San Jose de Brena Baja, Spain,
[5] INAF-OAT, Osservatorio Astronomico di Trieste, Via G.B. Tiepolo 11, I-34143 Trieste, Italy

e-mail address: frederic.zamkotsian@lam.fr

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). 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, in galaxies formation and evolution, in stellar physics and in solar system small bodies characterization.
We are developing a 2048 x 1080 Digital-Micromirror-Device-based (DMD) MOS instrument to be mounted on the 3.6m Telescopio Nazionale Galileo (TNG) and called BATMAN. A two-arm instrument has been designed for providing in parallel imaging and spectroscopic capabilities. BATMAN will be mounted on the folded Nasmyth platform of TNG. Thanks to its compact design, high throughput is expected. The two arms with F/4 on the DMD are mounted on a common bench, and an upper bench supports the detectors thanks to two independent hexapods. The stiffness of the instrument is guaranteed thanks to a box architecture linking both benches. The volume of BATMAN is 1.4x1.2x0.75 m^3, with a total mass of 400kg. Mounting of all sub-systems has been done and integration of the individual arms is under way.
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 new operational procedures on astronomical objects (combining MOS and IFU modes, different spatial and spectral resolutions in the same FOV, absolute (spectro-) photometry by combining imaging and spectroscopy in the same instrument, automatic detection of transients …).
This instrument will be placed at TNG by beginning-2019.

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

1. INTRODUCTION

Multi-Object Spectroscopy (MOS) is used extensively to investigate astronomical objects in large field of view surveys MOS is a key technique for 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, in galaxies formation and evolution, in stellar physics and in solar system small bodies characterization. Major telescopes around the world are equipped with

Ground-based and Airborne Instrumentation for Astronomy VII, edited by Christopher J. Evans, Luc Simard, Hideki Takami,
Proc. of SPIE Vol. 10702, 107025P · © 2018 SPIE · CCC code: 0277-786X/18/$18 · doi: 10.1117/12.2315222

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) will use a programmable multi-slit mask. MOEMS programmable slit masks would 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.
MOEMS devices such as micromirror arrays (MMA) [1, 2, 3] or micro-shutter arrays (MSA) [4] are promising solutions. MMAs are designed for generating reflective 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 the integration and the preliminary performances of a DMD-based spectrograph called BATMAN; this instrument includes 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.

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]

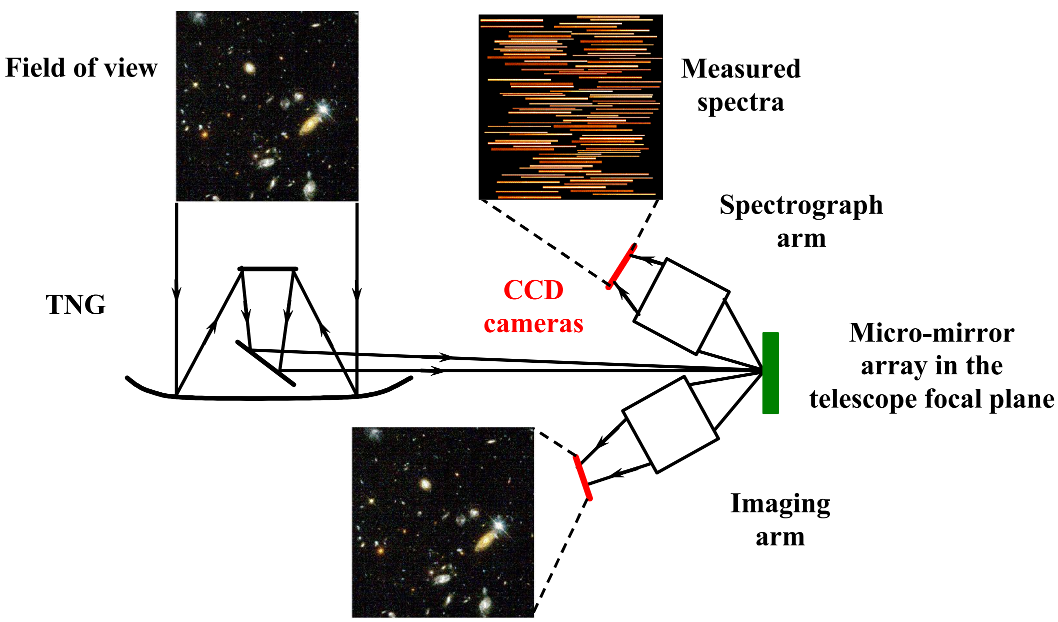

Fig. 1: Principle of BATMAN spectro-imager

Our goal is to make a robust and efficient instrument. 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).

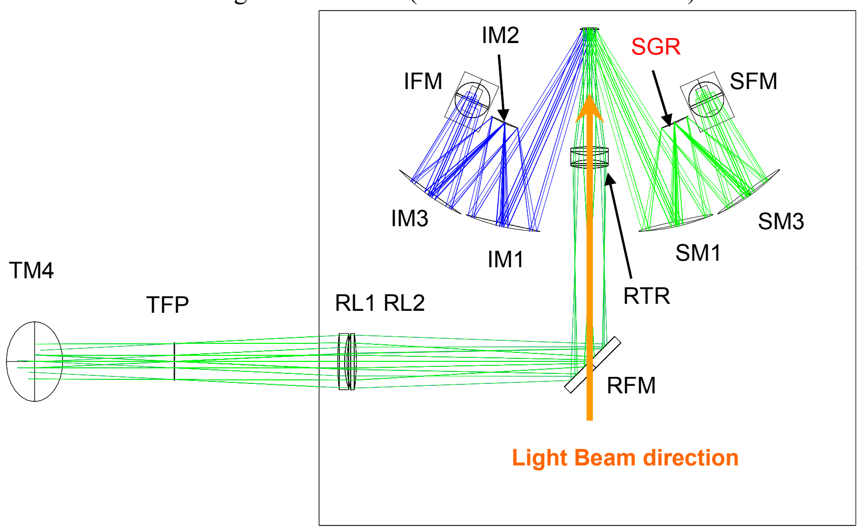

Fig. 2: Optical layout of BATMAN. Light coming from the telescope is split by the DMD into 2 arms, a spectrograph arm and an imaging arm (both are Offner relays).

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. Typical monochromatic spot diameters are <0.3 arcsec over the whole FOV for wavelengths between 400nm and 800nm. Simulated spectra (400nm – 800 nm) on the detector are shown in Fig. 3.

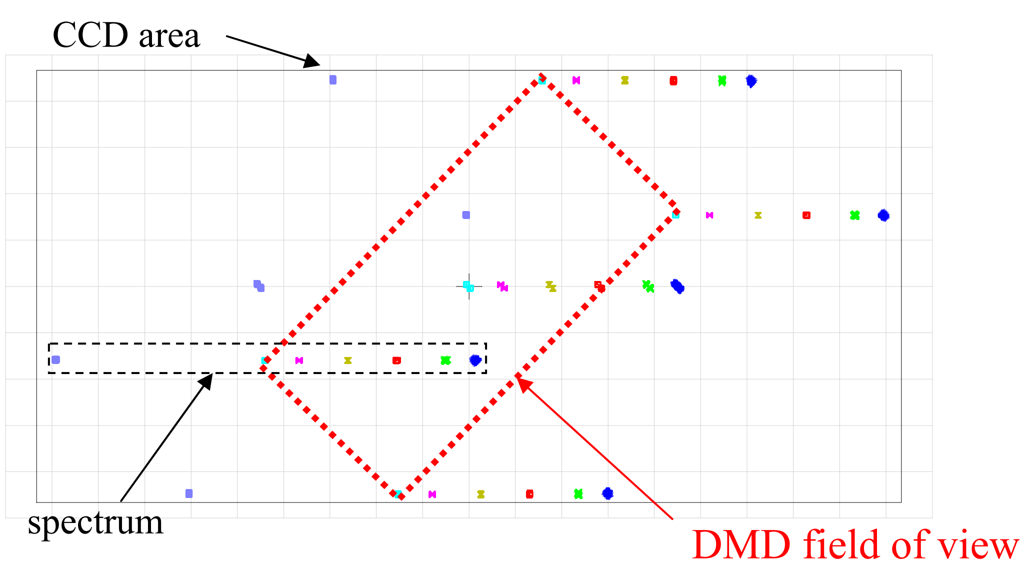

Fig. 3: Spectroscopic channel; simulated spectra on the detector.

2.3 BATMAN opto-mechanical design

BATMAN will be mounted at TNG Nasmyth focus on a folded platform. This focus does not implement a derotator mechanism, leading to a rotating instrument with a non-invariant g-vector during the exposure. We are then putting a strong constraint on the stiffness of the instrument: **the image/spectrum must not move by more than 2 detector pixels (27µm) on both detectors, while the instrument is rotating by 90°**. The overall view of BATMAN mounted at TNG telescope is given in Fig. 4.

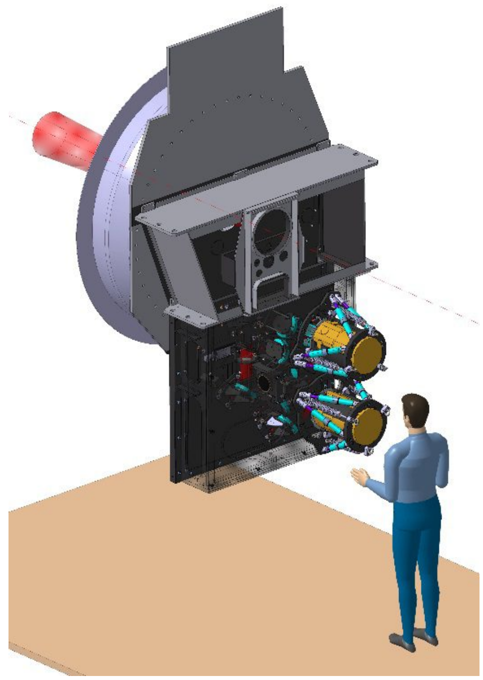

Fig. 4: BATMAN overall mechanical design, mounted at TNG folded Nasmyth focus.

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.

Two 2kx4k science grade detectors are 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: 1400 x 1200 x 770 mm^3. The estimated weight is 400kg.

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). The main bench is lightweighted.

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.

A full-instrument Finite Element Model (FEM) has been developed in order to calculate the deformation of the overall instrument during an observation run. As BATMAN will be mounted on the folded Nasmyth platform of TNG and then rotate during observation, the design has been optimized in order to minimize the deformation of instrument, and fulfil the < 2 detector pixels shift requirement. FEM is done under different gravity vector orientation for simulating extreme instrument locations, and deformations of the main bench as well as translation/rotation of each detector are calculated.
Displacements are calculated along the 3 orthogonal axis and **all values are below the requirement of < 2 pixel detectors (27 µm).** [9]

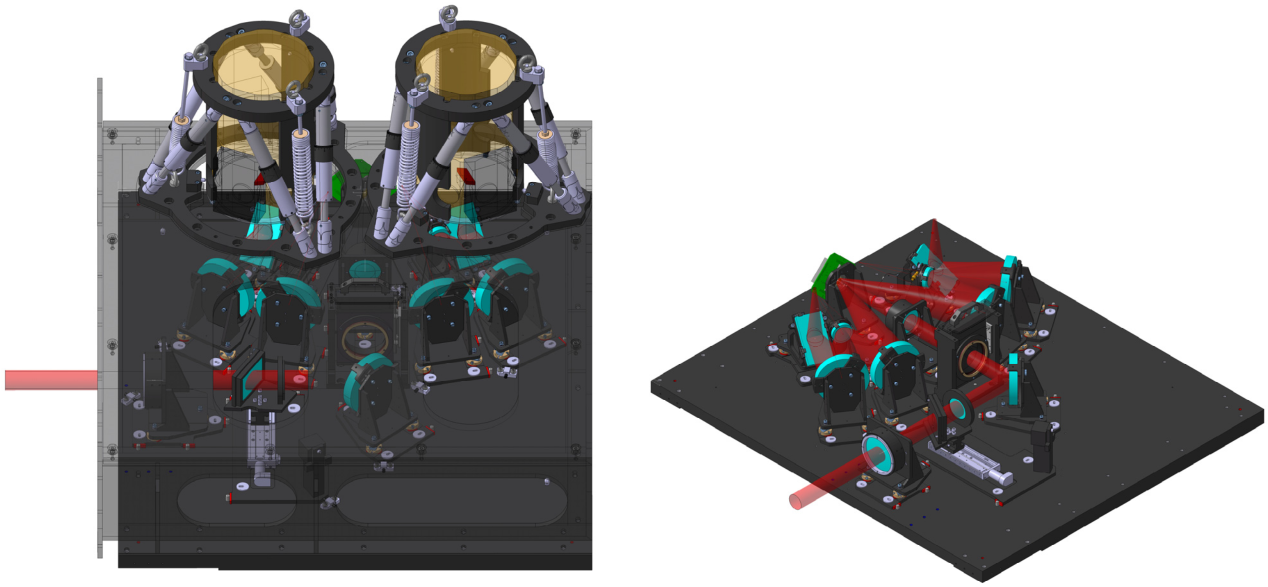

Fig. 5: BATMAN opto-mechanical design: overall view and detailed view of the main bench (dewar bench removed)

Note that most of the time, the exposure duration is not that long for the instrument to rotate widely, at most a few degrees; then, the detector displacement may stay in the range of few microns. This shift could be calibrated and chased, thanks to the imaging arm providing shorter exposures in comparison with the spectroscopy arm.

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 parts 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. [10]

2.5 BATMAN new observational modes

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. A space version of this instrument, *BATMAN flies*, has also been studied with specific science cases in the IR wavelength band. [11]

Thanks to our French-Italian collaboration, BATMAN will be placed on the Telescopio Nazionale Galileo 3.6-m telescope, at the Nasmyth focus, by beginning 2019.

3. BUILDING BATMAN

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

On-going work concerns:

- Optics: fore-optics lenses have been delivered, mounted in their barrels and alignment has been measured; convex mirror and grating have been delivered; all mirrors have been delivered and tested.
- Opto-mechanics: all mirrors and the grating are mounted; they have been tested. M4 telescope mirror has been realized, mounted and tested. Fore-optics mounts have been completed and lenses integrated. Hexapods have been designed, realized, delivered and tested.
- 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 realized. Full assembly of both detectors has been completed and vacuum tested.
- Calibration Unit: optical and mechanical designs have been completed and parts have been realized. Lamps, fibers, integrating spheres and shutter have been delivered. Integration will be done shortly.
- Electronic architecture: the main blocks have been designed and will be managed for the DMD by LAM, the detectors by TNG. This work is under Obs. Trieste responsibility for the general design and implementation.
- Software: see previous paragraph 2.4.

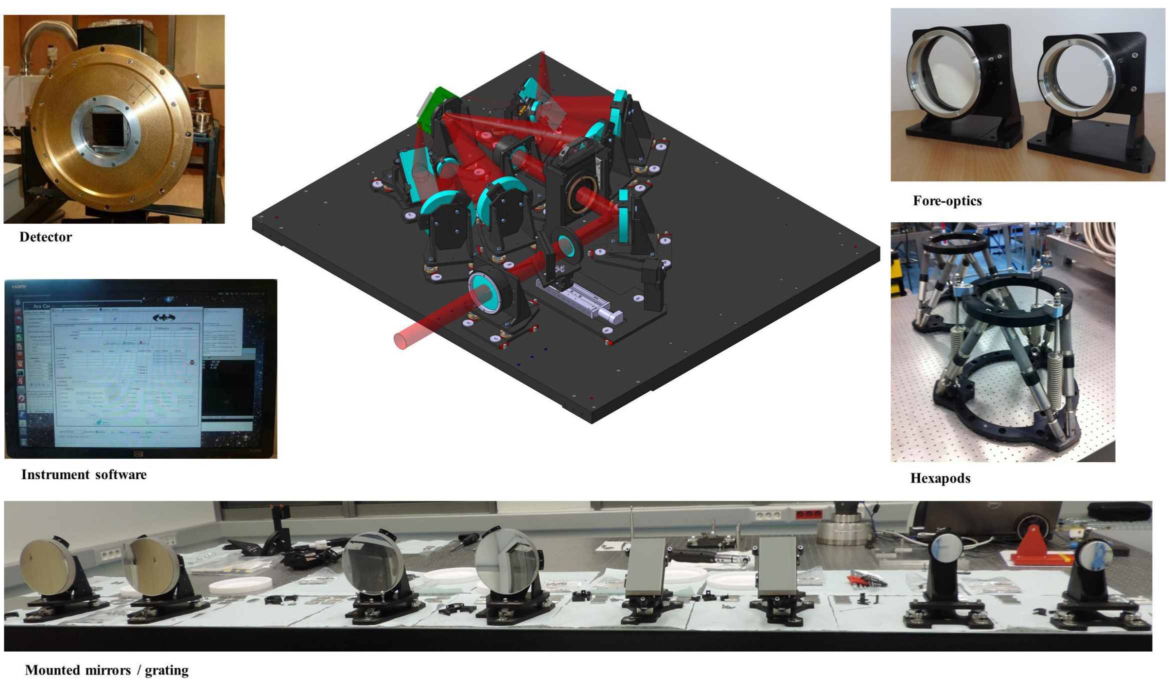

Fig. 6: Building BATMAN is under way

3.1 BATMAN optics

Optical design of BATMAN is based on a robust concept, minimizing the aberrations (see paragraph 2.2), and including only flat and spherical surfaces on all elements.
The optical elements suite is composed by:

- fore-optics: 2 lenses group, one doublet and one triplet, plus one folding mirror
- mirrors: 4 concave (+1 spare), 2 folding rectangular mirrors, M4 circular mirror of the telescope, 1 convex
- grating: 1 convex

All optical elements included in BATMAN have been delivered and tested; all of them are already mounted. The fore-optics lenses have been delivered, mounted in their barrels and alignment has been measured; all mirrors as well as convex mirror and convex grating have been delivered, mounted and tested.

The mirrors suite has been manufactured by Winlight Optics and all delivered components are within the requirements. The surface quality is measured and exhibit values better than the requirement ($\lambda/4$), ranging from 41 to 84nm Peak-to-Valley. A typical surface aberration map is shown in Fig. 7 for the concave spherical mirror #1, with piston, tilt and power removed: the PTV aberration is 41 nm. The roughness is well controlled for all mirrors in the range of 0.6nm rms. [9]

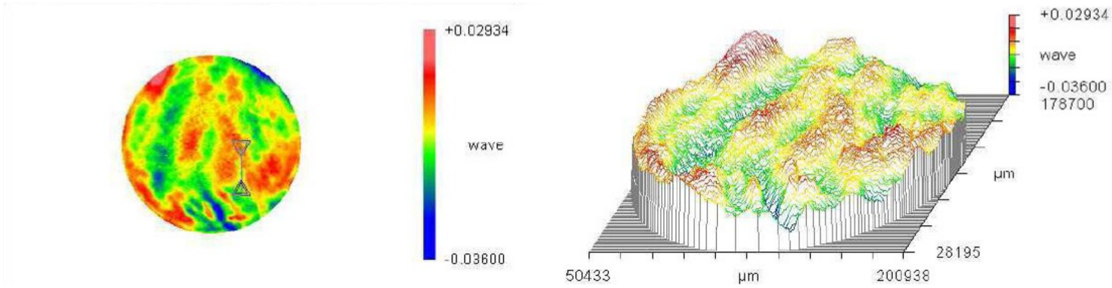

Fig. 7: BATMAN concave mirror #1 surface quality (41nm PTV). Piston, tilt and power removed.

All mirrors are coated with protected silver made by Optics Balzers. The reflectivity is exceeding 95% for the 400-465nm range, above 98% in the 465 – 700 nm range and finally, greater than 97% for the 700 – 800 nm range. [9]

The fore-optics doublet and triplet have been provided, aligned and glued in their barrels. Then, they have been integrated on the brackets (Fig. 8) allowing proper alignment on the bench with the positioning/repositioning system described in paragraph 3.3.


Fig. 8: BATMAN fore-optics lenses (doublet and triplet), mounted and aligned in their barrels.

3.2 BATMAN convex blazed grating

The compact Offner-type spectrograph design contains a low density convex grating to disperse light. For optimization of the spectrograph efficiency, this convex grating must be blazed at the right angle for maximizing the light in the first order of diffraction. An efficient convex blazed grating has been developed in collaboration with Centre Suisse d'Electronique et de Microtechnologies (CSEM) in Switzerland.

A blazed reflective grating has been designed with a period of 3300 nm and a blaze angle of 5.1°, and fabricated onto and into convex substrates with 225 mm radius of curvature and a footprint diameter of 63.5 mm. The blaze is optimized for the center wavelength of 580 nm within the spectral range of 400 – 800 nm. The master of the blazed grating structure has been originated on a flat substrate starting from a rectangular grating with a period of 3300 nm. The rectangular grating was UV replicated twice using Sol-Gel material and subsequently converted into a blazed shape by angular Ar ion etching. Two approaches have been studied to transfer the blazed grating from a flat surface onto a convex substrate.In the first approach, a flexible stamp was generated by UV replication of the blazed grating, utilizing a flexible nanoimprint material. The flexible stamp was used to emboss Sol-Gel spin-coated on the convex substrate. In this approach the final component is a convex substrate with a Sol-Gel layer carrying the grating structure. In the second approach, nanoimprint material is used as a masking layer for Reactive Ion Etching of the convex substrate. With this approach, the final component is a convex quartz substrate with the grating structure etched into the volume. The monolithic approach is perfectly suited for space environment. The two approaches are successful and two gratings have been fabricated and coated with protected silver. The final figure exhibit a 7° blaze angle for the grating onto the substrate, while the grating into the substrate is even closer to the requirement with a 5.7° blaze angle over the whole surface (Fig. 9). **The 5.7° blaze angle convex grating will be integrated in BATMAN.**

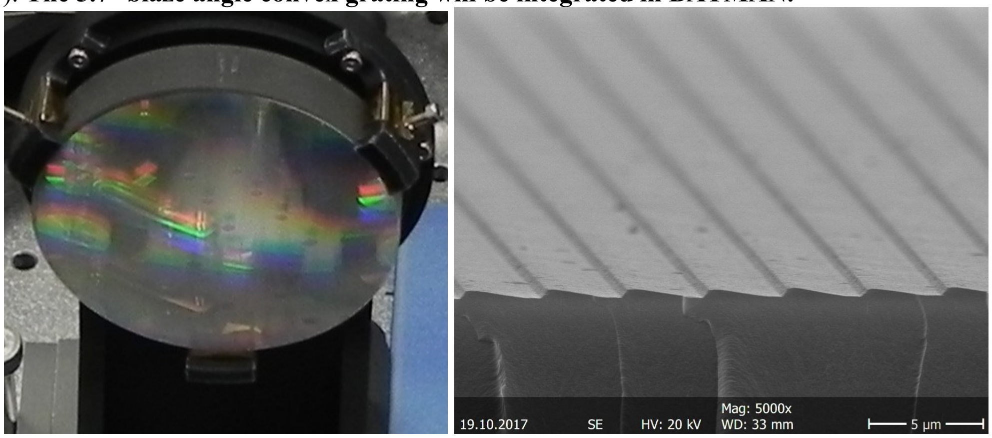

Fig. 9: BATMAN convex blazed grating mounted in its barrel; scanning electron microscope view of the grating surface

We demonstrated the successful realization of a blazed grating on convex surfaces for next generation compact and highly efficient spectrographs. Performance characterization is on-going, and a high efficiency on the 1st diffraction order is expected, more than doubling the efficiency of a non-blazed grating. [12]
This new type of non planar reflective gratings will be the key component for future high throughput spectrographs in future ground-based instruments as well as space missions.

3.3 BATMAN opto-mechanics

Mirror mounts have been produced and integrated. A specific positioning/repositioning system has been developed in order to ease the alignment process: spheres in cones on one side (upper plate) and V in V-grooves on the other side (lower plate), on a 120° basis are used for maintaining the mirror mount in the same position while the shims located under this system and on both side of the whole mount could be adjusted properly, for translating and rotating the mount within the six degrees of freedom. The optics alignment is obtained with pins and shims along X and Y mechanical axis; along Z axis, and for tip, tilt and rotation around the optical axis, shims are used under the repositioning mount. Shims are adjusted by 10µm precision. This mirror mount has been tested in horizontal and vertical positions in order to verify the high stiffness of the system: total shift of the center of the dummy mirror is below the 10µm precision of our Faro arm mechanical measurement tool. [9]
The mirror is glued from the back on its mount by 3 pads. The thickness of the glue is about 100µm. Two mounted concave mirrors are shown in Fig. 10. Mirrors figures measured by interferometry before and after gluing are identical.

Fig. 10: BATMAN mirror mounted on their supports (glued from the back on 3 pads)

In the instrument design, the hexapods are devoted to the alignment of the detectors along the 6 degrees of freedom with an accuracy better than 10µm. They are also devoted to detector refocusing when BATMAN is in operation. This refocusing mechanism compensates mainly the Aluminium bench dimensions variation due to temperature change in the telescope dome: the temperature shift between winter / summer observations may reach 20°C. We have developed our specific manually reconfigurable hexapod with screw motion of ± 10 mm along the 6 arms for fulfilling our requirements. Note that the hexapods will be mounted horizontal when operational on the telescope (Fig. 4). Then, the gravity vector will change during the exposure time, leading to compressive and tensile forces in each hexapod arm. In order to get rid of the mechanical loose, we have decided to preload the hexapods by using 3 springs located at 120° and linking the two rings of the device. [9]

M4 telescope mirror mount has been realized. Fore-optics mounts have been completed and lenses integrated (see previous paragraph, Fig. 8).

Benches architectures (main optical bench, instrument "box" and top bench receiving the hexapods + detectors, see Fig. 5) has been finalized, and final drawings have been issued for full instrument realization.

3.4 BATMAN detectors

Two dewars are currently available for housing the two science-grade detectors (2k x 4k CCD, pixel: 13.5µm). The optimal design of each arm is based on an Offner relay; as the input FOV is a tilted plane due to the DMD feature (each micro-mirror tilts out of the array plane by ± 12°), this specific optical behaviour leads to a 24° tilted focal plane at the Offner relay output, i.e. a tilted detector plane. The tilt angle of the detector is 24° with respect to the optical chief ray reaching the detector. It has been decided to tilt the CCD inside the dewar instead of tilting the whole dewar in the instrument. The tilted mechanical structures supporting the CCDs inside the dewars have been designed and realized (Fig. 11a). The detector is thermally decoupled from the surroundings by an insulator plate, and cooled down by a cold finger located behind it and linked with the liquid nitrogen tank of the dewar.

Full assembly of both detectors has been completed as shown in Fig. 11b. The CCD is precisely located inside the dewar. The front flange is closed with a large window in order to avoid vignetting of the optical beam arriving on the detector plane. Two electronics boxes (black boxes in Fig. 11b) are directly mounted on the dewar. Vacuum has been tested successfully on the mounted detectors.

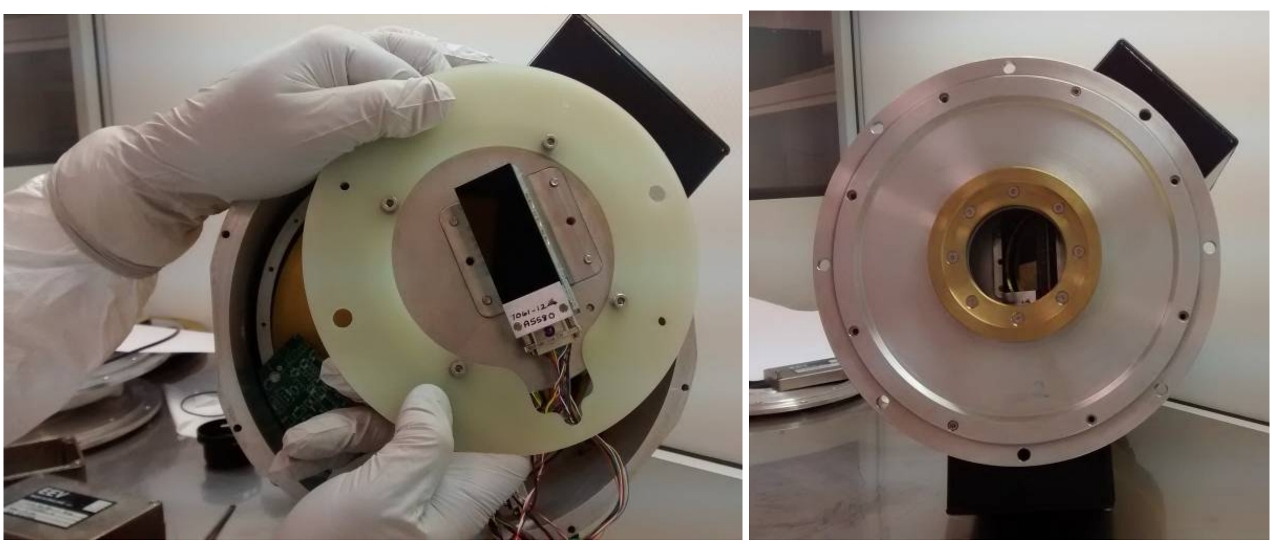

Fig. 11: BATMAN detectors mounted: (a) with detail on the tilted CCD plane mounted in the dewar, and (b) with the flange closed.

4. BATMAN INTEGRATION

BATMAN integration has started by assembling all sub-systems on a Newport damped table in order to review both the integration procedure as well as a first performance evaluation.

4.1 BATMAN mounting

The integrated channel is shown in Fig. 12, following the optical design presented in Fig. 2: the light source is located on the top left of the picture (outside the picture), simulating the beam coming from the telescope; then the fore-optics is constituted by a doublet, a 45° folding mirror and a triplet; the beam reaches the DMD, on the right hand side of the picture, before entering the spectroscopic channel, i.e. the Offner relay, M1 is a concave collimating mirror, G2/M2 the convex grating / respectively the convex mirror, M3 the concave "camera" mirror for focusing the spectra/images on the detector. This detector is not the Science camera, but an alignment CCD.

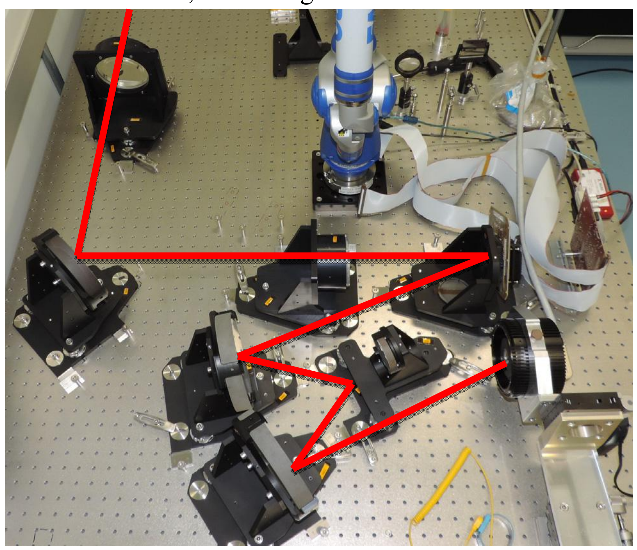

Fig. 12: BATMAN integration of one channel (beam direction represented by the red line, from input (top of the image) to the detector (bottom))

This channel is integrated, aligned and optimized as a spectroscopic arm with the convex grating. For evaluating the image quality in the imaging arm, the alignment has been slightly modified to place the mirror in M2 and refocus the detector accordingly. Spectra/image quality is discussed in the following paragraphs.

4.2 Image quality

When mounted in the imaging configuration, several patterns have been applied to characterize the image quality. The bottom right part of the DMD FOV is shown in Fig. 13, featuring the LAM characterization pattern. [7]

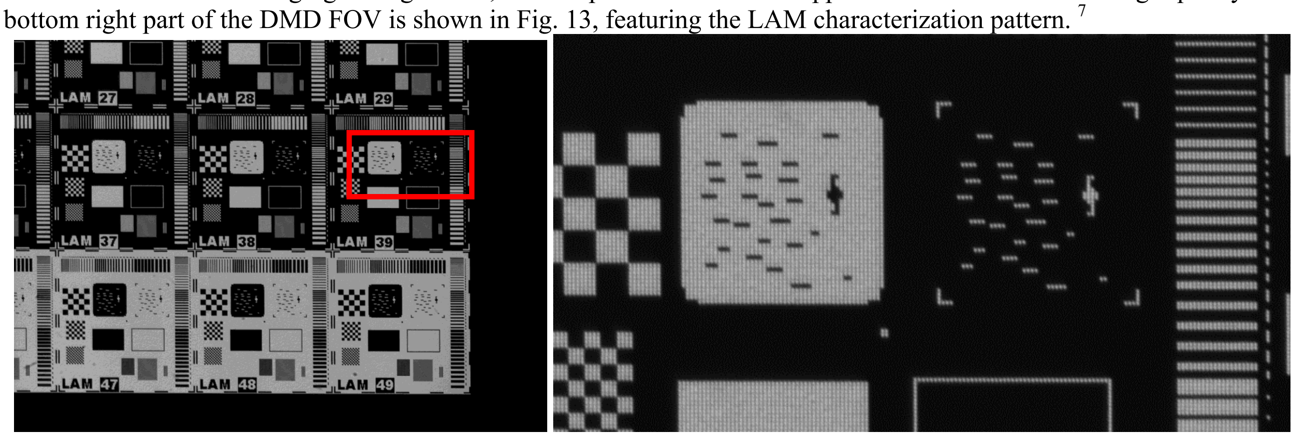

Fig. 13: BATMAN imaging quality; left: small part of the DMD surface with the LAM characterization pattern (description in 7); right: a magnified view of the red square zone, the individual micromirrors are clearly visible.

In the magnified image, individual micromirrors are clearly visible as expected from the optical design, where the image quality might permit revealing individual micromirrors. When scrolling over the whole FOV, the image quality is good and uniform. **This result shows that our procedure for aligning in the optimal position each optical component in BATMAN is validated.**

4.3 Slit configuration

A DMD pattern manager has been developed in order to generate any slit mask pattern from a list of objects. [13] 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. 13 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). Images all over the FOV have been obtained, featuring typical slit mask patterns used during the space evaluation of the DMDs. [7] They show a uniform and high image quality, as single micro-mirrors are resolved.

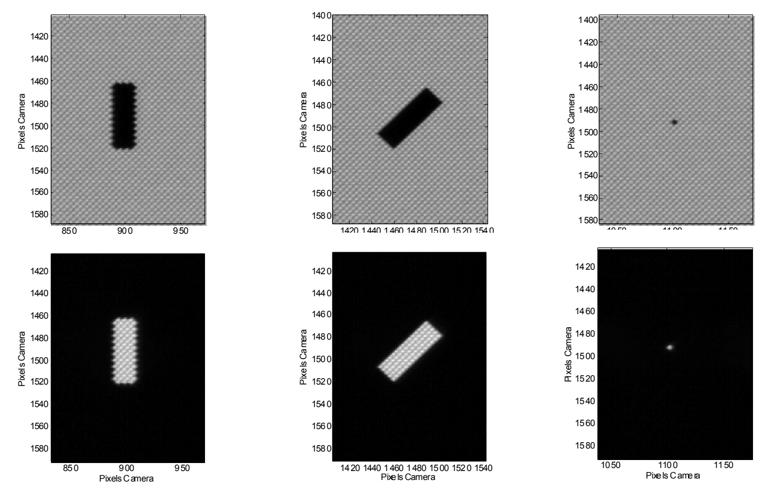

Fig. 13: ROBIN slits; typical slits with 5x15 micromirrors (2 orientations, vertical and at 45°) and a single micromirror slit (13µm). Upper line as seen by the imaging arm (slits are dark), lower line as seen by the spectroscopic arm (slits are bright).

4.4 BATMAN 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. 14). **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 well aligned. The spectrum is on 1.5 detector pixels height over the whole displayed wavelength range.**

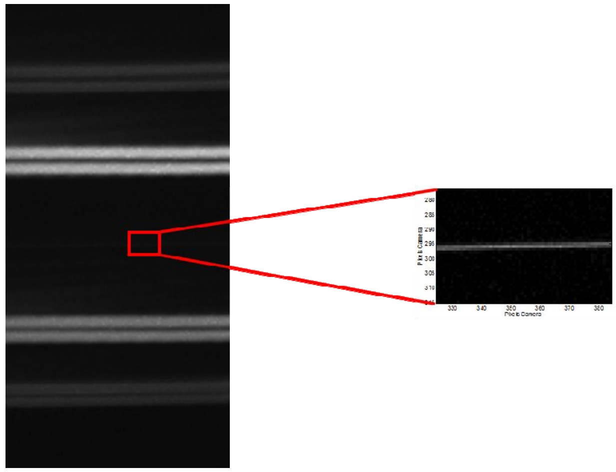

Fig. 14: Spectra in the spectral channel, including a single micromirror slit; close view of the spectrum generated by the one-micromirror slit (the corresponding slit image recorded with the imaging arm is in Fig. 13).

5. CONCLUSION

In order to investigate the formation and evolution of galaxies, next-generation infrared astronomical instrumentation for ground-based and space telescopes will 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. Building BATMAN is under way, with all optics delivered, mounted 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 the year 2018.

Instrument integration is on-going, and preliminary instrument performance has been measured: both imaging and spectra quality have been successfully optimized to the expected level.

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 by beginning 2019.

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, 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)

[10] F. Zamkotsian, P. Spano, L. Martin, M. Riva, P. Lanzoni, F. Zerbi, L. Valenziano, L. Nicastro, "DMD-based MOS demonstrator on Galileo telescope," in Proceedings of the SPIE conference on Astronomical Instrumentation 2010, Proc. SPIE **7735**, San Diego, USA, (2010)

[11] F. Zamkotsian, O. Ilbert, J. Zoubian, A. Delsanti, S. Boissier, A. Lancon, " BATMAN flies: a compact spectro-imager for space observation," in Proceedings of the SPIE conference on Astronomical Instrumentation 2014, Proc. SPIE **9143**, Montreal, Canada, (2014)

[12] Frederic Zamkotsian, Igor Zhurminsky, Patrick Lanzoni, Nicolas Tchoubaklian, Christian Schneider, Sören Fricke, Marc Schnieper, Fabian Lütolf, "Convex blazed gratings for high throughput spectrographs," in Proceedings of the SPIE conference on Astronomical Instrumentation 2018, Proc. SPIE **10706**, Austin, USA, (2018)

[13] F. Zamkotsian, P. Spano, P. Lanzoni, W. Bon, M. Riva, L. Nicastro, E. Molinari, P. Di Marcantonio, F. Zerbi, L. Valenziano, " DMD-based Multi-Object Spectrograph on Galileo telescope", Proceedings of the SPIE conference on MOEMS 2013, Proc. SPIE **8618**, San Francisco, USA, (2013)

[14] Frederic Zamkotsian, Paolo Spano, Patrick Lanzoni, Harald Ramarijaona, Manuele Moschetti, Marco Riva, William Bon, Luciano Nicastro, Emilio Molinari, Rosario Cosentino, Adriano Ghedina, Manuel Gonzalez, Paolo Di Marcantonio, Igor Coretti, Roberto Cirami, Filippo Zerbi, Luca Valenziano, "BATMAN: a DMD-based Multi-Object Spectrograph on Galileo telescope" in Proceedings of the SPIE conference on Astronomical Instrumentation 2014, Proc. SPIE **9147**, Montréal, Canada, (2014)