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Deployable cryogenic cross-dispersing unit for simultaneous zJHK spectroscopy

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Abstract

A modular cryogenic cross-disperser MOBIUS for the Large Binocular Telescope (LBT) is being developed to produce a simultaneous zJHK spectrum with a single LUCI, the LBT Utility Cameras in the Infrared. Its compact and exchangeable optical design fit within the existing focal plane mask frame of the LUCI spectrograph without any other hardware modifications. This unique deployable system enables a rapid acquisition of data over a wide wavelength range to better understand the unknown objects in the universe.

Keywords Cross-dispersion · Spectroscopy · Large Binocular Telescope · LUCI · MOBIUS

1 Introduction

Most astronomical objects we observe do not change significantly from night to night, or even over months or years. Gathering data over a broad wavelength range, using different telescopes and instruments over a longer period of time would not significantly impact the conclusions drawn from the astronomical data set. However, there are classes of objects where simultaneous spectroscopic observations spanning the visual (i.e., 0.32–1.0 μm) and near infrared (i.e., 1.0–2.4 μm) bands would benefit the science goals. These objects include transient sources like Gamma Ray Bursts, novae, supernovae, and flare stars, where the source in outburst remains bright for a limited amount of time. It also includes solar system objects like asteroids that may present a changing composition as they rotate and requires a broad wavelength coverage to differentiate between the different types [1]. Novel sources of any type could also benefit from the ability to quickly gather data over a wide wavelength range to better understand what it is.

The common way to build an instrument with wide wavelength coverage would be to design it from scratch to take full advantage of the latest technology, as was done with X-Shooter [2] at the ESO VLT (European Southern Observatory Very Large Telescope). However, at the Large Binocular Telescope (LBT) [3], we already had pairs of optical imaging spectrographs MODS (Multi-Object Double Spectrographs [4]) covering 0.32–1.0 μm and infrared imaging spectrographs LUCI (LBT Utility Cameras in the Infrared [5]) covering 0.95–2.4 μm shown in Fig. 1. These instruments have been in normal operation with successful scientific observations for some time [6]. The telescope control software treats the two 8.4 m in diameter telescopes as fully independent, with the two main constraints being that they must remain co-pointed with respect to each other within ~ 80 arcseconds on sky, and that one side cannot affect any ongoing observations on the other side. In addition, LUCI utilizes exchangeable cryogenic focal plane masks for a long-slit multi-object spectroscopy. With the planned addition of a new grating that would enable adaptive-optics

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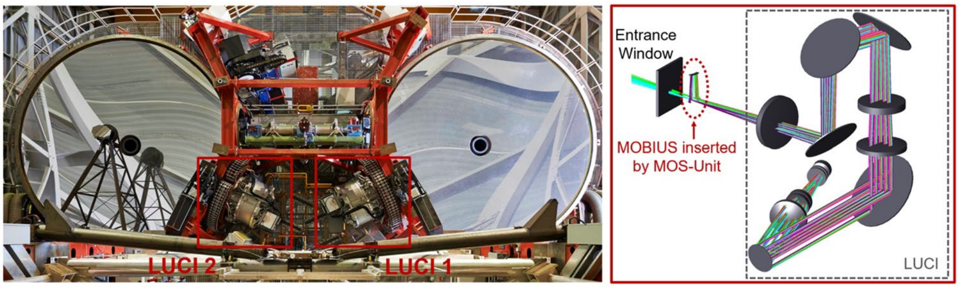

Fig. 1 (left) Two 8.4 m in diameter primary mirrors on the Large Binocular Telescope and the two existing LUCI instruments in the red boxes. (right) Exchangeable cryogenic optical design of MOBIUS between the LUCI instrument (black dashed square) and the entrance window of LBT. MOBIUS is located at the telescope (i.e., the primary, secondary, and tertiary mirrors) focal plane of LBT. By deploying MOBIUS instead of a standard long-slit mask, LUCI produces cross-dispersed zJHK spectrum without any hardware modifications to the current instrument. [7, 8]

spectroscopy, we realized that another configuration of the instrument would allow all four near-IR bands to be observed concurrently if we could achieve a sufficient level of cross-dispersion. The full optical and infrared bands could then be covered simultaneously by pairing one MODS with one LUCI.

2 MOBIUS (mask-oriented breadboard implementation for unscrambling spectra)

An exchangeable modular cross-disperser MOBIUS is being developed to produce a simultaneous zJHK spectrum with a single LUCI in LBT. A key design boundary condition for MOBIUS is that there would be no modifications to the existing LUCI instrument hardware [7, 8]. This unique requirement is achieved by designing MOBIUS to fit inside a LUCI slit mask frame and using the MOS (Multi-Object Spectrograph) robot to deploy it in the telescope focal plane as if it is the nominal MOS long-slit mask depicted in the red dotted circle of Fig. 1 (right). With a 0.25 arcsecond wide slit and LUCI's rapid guide and collimation mode, MOBIUS will produce spectra with a spectral resolution of $R \sim 1800$ using only one LUCI covering all four near-IR bands concurrently. The available MOBIUS slit length of each of the two spectrographs is limited to ~ 2.3 arcseconds. This is driven by the limited space available for the collimated beam in the mask frame as well as the maximum dispersion power of the single Strontium Titanate ($SrTiO_3$) prism used in each spectrograph design [9].

3 Exchangeable cryogenic optical design of MOBIUS

The detailed optical design of MOBIUS including two twin mini-spectrographs to provide sky subtraction by dithering is presented in Fig. 2 (left) [7, 8]. Because MOBIUS needs to fit within the pre-defined volume (i.e., 150 × 150 × 12 mm), the maximum size of optical components is limited by the

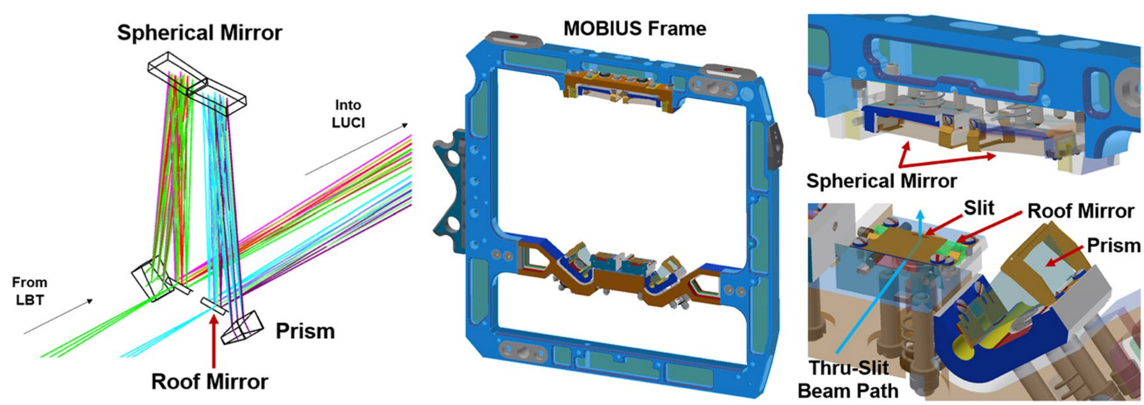

Fig. 2 (left) Optical path through MOBIUS with two spectrograph units located side by side for sky subtraction by dithering. (middle) The MOBIUS optical components mounted on a frame interchangeable with the original slit masks in the MOS-Unit. (right) Zoom-in view of the opto-mechanical mounts allowing a precision integration and alignment of the MOBIUS optics. [7]

nominal long-slit mask frame size shown in Fig. 2 (middle). Also, as another critical design requirement, the total mass of MOBIUS unit must be no more than 20 g over that of a standard long-slit mask frame (i.e., 308 g) so it can be safely handled by the existing MOS-unit robot. Finally, it must survive and maintain its optical quality and alignment when cooled to the cryogenic temperatures (~77 K), which is the operational environment of LUCI.

The twin sets of MOBIUS optical components include two folding (i.e., right-angle) roof mirrors made of Zerodur with gold coating (i.e., 100 nm thickness Au), two spherical collimator/camera mirrors (180 mm radius of curvature) made of aluminum-coated Zerodur, and two dispersing prisms made of $SrTiO_3$ with a silver coating on the back-side surface of prism and anti-reflective coating on the front side surface.

The roof mirror is located near the telescope focal point of the LBT. It folds the incident beam into the MOBIUS mask plane and directs it through the entrance slit and toward the spherical collimating mirror. The roof mirror's shape is a mirror coated right-angle prism, so the outer surfaces are employed for reflection. The dispersed beam is retroreflected inside MOBIUS, so the input and output beams are nearly parallel to each other as shown in Fig. 2 (left). Thus, the apex angle of the pick-off roof mirror is designed to be 90° to preserve the ray angles before and after MOBIUS [10].

The spherical mirror collimates the input beam and directs it to the $SrTiO_3$ dispersing prism as shown in Fig. 2 (left). The apex angle of the dispersion prism is 19° and the prism is used in a double-pass configuration using retroreflection by the back surface silver coating.

The dispersed beam from the prism heads back toward the spherical mirror and is re-focused near the other side of the roof mirror that diverts the light into LUCI for the second dispersion using the grating. As a result, the input beam from the LBT is pre-dispersed via MOBIUS in the orthogonal direction of the LUCI grating dispersion. At the final science camera focal plane detector, a cross-dispersed spectrum covering the full zJHK bands is acquired [10].

4 Cryogenic MOBIUS integration, thermal test, and performance

4.1 MOBIUS engineering unit assembly and optical alignment

MOBIUS engineering unit was successfully assembled and optically aligned as shown in Fig. 3 (top-left) [7, 10]. It was optically aligned and tested at room temperatures using an incandescent light source followed by f/15 LBT input beam emulator. The focused beam footprint with and without MOBIUS was measured and compared as shown in Fig. 3

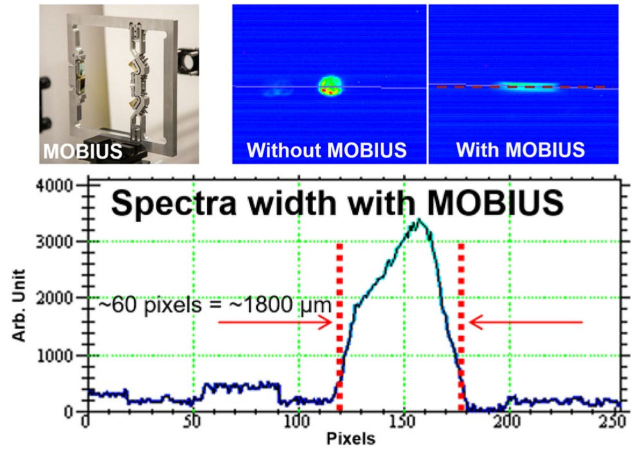

Fig. 3 (top-left) Assembled MOBIUS engineering unit including the optical components and test frame (not light-weighted). (top-right) Measured beam footprint of the f/15 LBT-like beam focal spot with and without MOBIUS. The red dashed line represents the spectra profile analysis line. (bottom) The measured pre-dispersed spectra profile from the MOBIUS engineering unit with the f/15 incandescent light source. The length of measured spectra profile of 1800 µm was limited by the measurement bandwidth of the InGaAs detector that was used for the lab tests. [7]

(top-right). Also, the width of the pre-dispersed beam footprint was measured and confirmed its performance along the profile (red dashed line in Fig. 3). The measured ~1800 µm spectra width matched the expected optical simulation value using raytracing software.

4.2 Light-weighted MOBIUS assembly for LBT commissioning

The commissioning-ready MOBIUS is designed to match a standard LUCI slit mask (for both volume and weight) so that it can be handled using the existing MOS-unit. The total weight must not exceed 328 g including the optical components and metallic opto-mechanical support structures. The dispersion optics and optical alignment stages embedded in MOBIUS add mass to the general LUCI long-slit mask, such that the complete assembly weighed 399 g (~71 g overweight) in the engineering unit design as calculated by the 3-d mechanical design program. While the opto-mechanical parts were left unmodified the outer frame and aluminum structure parts were significantly optimized for removal of unnecessary volume and weight from the engineering unit.

The light-weighted MOBIUS design drawings and the final assembly are shown in Fig. 4. The red pockets outline in the left and middle panels are the optimized zones that were cut out for light-weighting. The depth of most pockets is 3.8 mm, and the total thickness of the MOBIUS frame is 10 mm, leaving an I-beam cross-section on the frame to maintain its structural stiffness. After a few revisions of

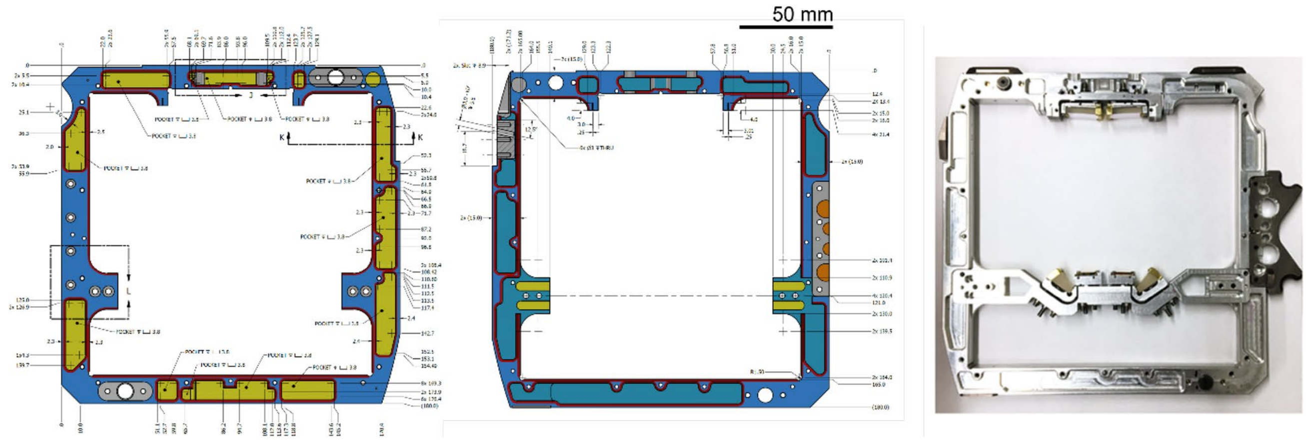

Fig. 4 Light-weighted cryogenic MOBIUS full frame drawings of the (left) back face and (middle) front face. The red color zone indicates the optimized light-weighting cut out areas creating I-beam cross sections for structural stiffness. (right) The light-weighted cryogenic MOBIUS frame before installing its black masks blocking stray lights from the telescope

adjusting the cutting pockets, we successfully reduced the total weight to 326 g in the modeling software. The as-built weight of the fully assembled and light-weighted cryogenic MOBIUS assembly is 325 g, leaving about 3 g of margin from the maximum weight limitation value that can be safely handled by the MOS-unit.

In order to block the stray lights except for the two slit beam paths of MOBIUS, one-side blackened LUCI mask has been also designed, cut, folded, and inserted in the MOBIUS frame as shown in Fig. 5. Its light-weighted retainers around the outer edge and strategic interlocking of the three mask pieces hold the three-dimensional mask (surrounding the MOBIUS optics without causing light vignetting) firmly in place. The blackened side shown in Fig. 5 (left) faces into LUCI to reduce scattered light toward the science instrument. The other side of the mask shown in Fig. 5 (right) shows the two open apertures (in red dotted circle) used to pass the science beam entering the twin slits of the MOBIUS indicated in Fig. 2 (right). The size of open apertures should be wide enough not to block beam from LBT while not too big to cause stray lights. Since the position of open apertures is about 5 mm

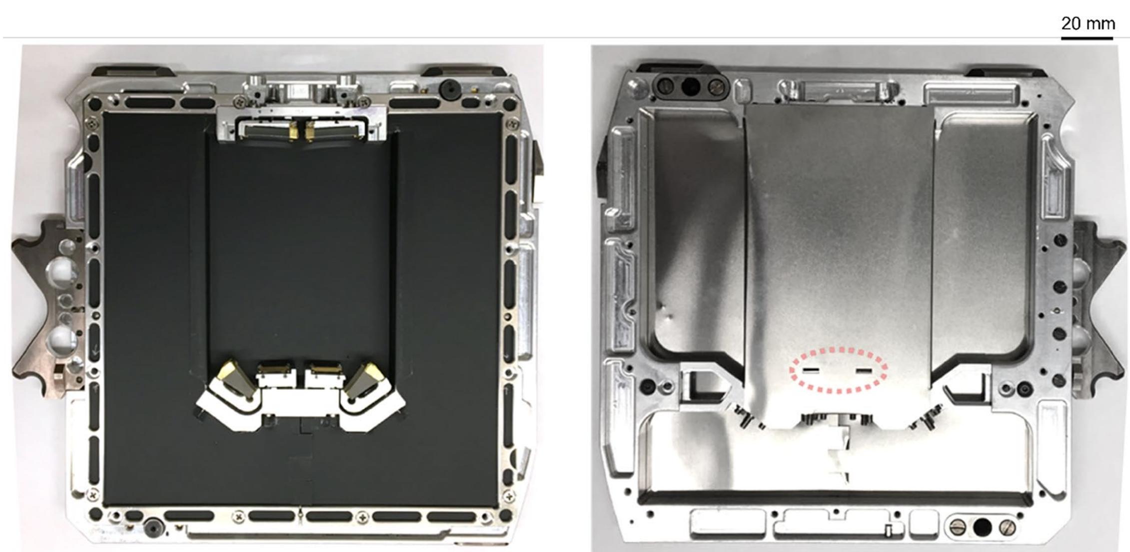

Fig. 5 The fully assembled commissioning-ready light-weighted MOBIUS unit with the stray light mask blocking unwanted lights from the sky. The black side photo (left) faces into LUCI, helping to prevent scattered light. The bare steel side (right) faces the LBT. The two open apertures (inside red dotted circle) allow the nearly focused telescope beam in to the twin MOBIUS slits located near the roof mirrors as shown in Fig. 2 (right)

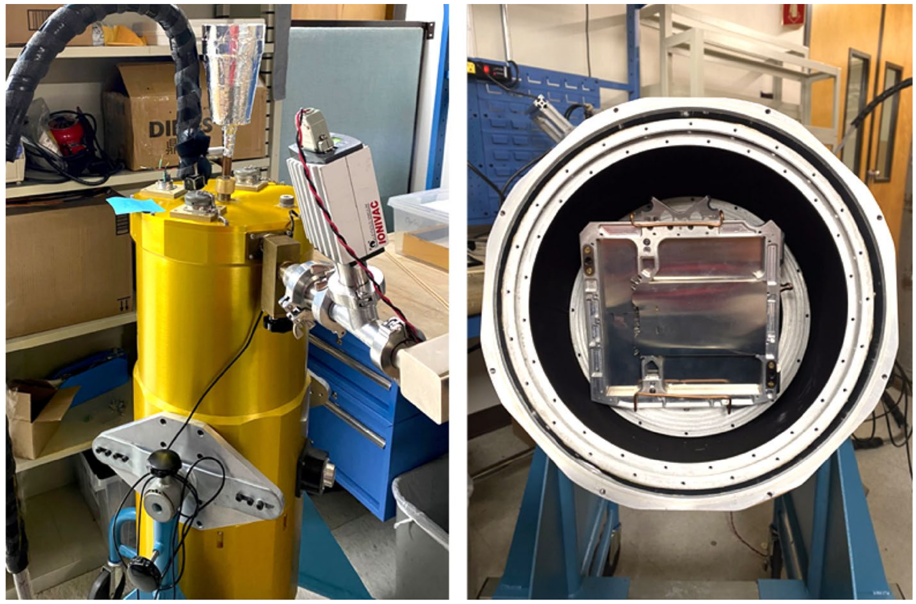

Fig. 6 (left) The cryogenic dewar for MOBIUS thermal cycling test using liquid nitrogen (for ~ 77 K cooling). (right) The final cryogenic MOBIUS unit installed inside the dewar. The MOBIUS unit is securely suspended by a copper wire cage that is bolted to the cold plate during the thermal tests in the dewar

away from the telescope focal point along with the beam path, the aperture size should be at least 0.3 mm larger than the slit size considering the f/# of the input beam. With some margin, we set the aperture size as 6 × 1 mm. The entrance slit (i.e., focal plane slit mask) is located after the open aperture and the roof mirror as shown in Fig. 2 (right).

4.3 Cryogenic thermal-cycling test and optical performance

The cryogenic thermal cycling tests were performed to check that MOBIUS maintains its optical alignment through a cool-down and warm-up cycle, that nothing breaks, and that the many adjustment screws in the assembly do not loosen to ensure the safe use in LUCI. For the cryogenic test, the fully assembled and aligned commissioning-ready MOBIUS frame was placed inside a test dewar (shown in Fig. 6) which is vacuum-pumped and then cooled with liquid nitrogen down to ~ 77 K (i.e., the operating temperature of LUCI). After the cool-down phase, the MOBIUS frame was warmed back to room temperature for the optical alignment status check.

After the cryogenic thermal cycling, without any re-adjustment of the initial alignment, the overall length of the spectra and distribution profile of the two pre-dispersed spectra were maintained for both twin configurations as presented in Fig. 7. This is the final confirmation test for the official commissioning of the MOBIUS for LUCI on LBT. As the cryogenic test dewar had no external windows the practical optical adjustment and calibration of MOBIUS will be performed using LUCI's actual on-sky measurement data.

5 Conclusions

The light-weighted cryogenic MOBIUS unit enabling cross-dispersion capability for LUCI on LBT has been successfully designed, assembled, and tested for its operational environment. Because MOBIUS maintains the identical form-factor of the standard long-slit mask frames handled by the robotic MOS system, it does not require any hardware modification to the current instrument. Its unique optical configuration enables simultaneous zJHK spectroscopy of the target object in a single exposure. Paired with one MODS (Multi-Object Double Spectrograph) in LBT's binocular observing mode, astronomers can obtain spectra from the UV atmospheric cut-on wavelength at 0.32 μm to 2.4 μm wavelength in the NIR. This simultaneity over a broad range of wavelength offers invaluable scientific opportunities to investigate and study the transient phenomena, from rotating asteroids in our own solar system to gamma ray bursts, or potentially interesting astronomical objects from time-domain observations where the source is otherwise unknown.

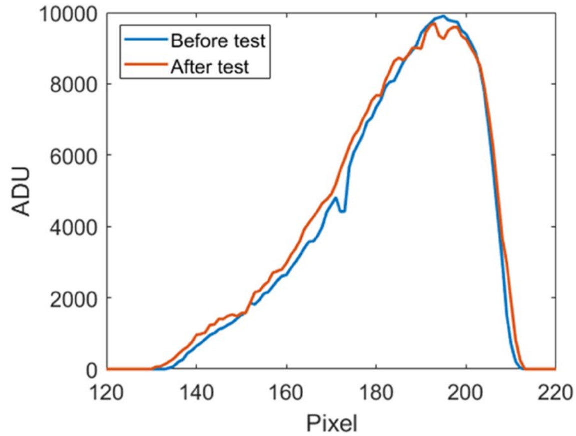

Fig. 7 (left) Measured spectrum profile from one of the twin MOBIUS beam paths before and after the thermal cycling and (right) the other side spectrum. The spectrum profiles are mirror-symmetric as the MOBIUS twin spectrographs are also mirror-symmetric as shown in Fig. 2 (left). The measured arbitrary digital unit (ADU) spectrum profiles of the before-thermal cycling test (blue lines) and the after-thermal cycling test (red lines) are nearly identical for both sides of the MOBIUS spectrographs confirming the optical alignment of MOBIUS frame and its performance are successfully kept after the thermal cycling test

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Data availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

References

1. V. Reddy, T. L. Dunn, C. A. Thomas, et al.: Mineralogy and surface composition of asteroids. Asteroids IV (2867) (2015).
2. Vernet et al.: X-shooter, the new wide band intermediate resolution spectrograph at the ESO Very Large Telescope. 2011, A&A, 536A, 105.
3. Hill, J.M., Ashby, D.S., Brynnel, J.G., et al.: "The large binocular telescope: binocular all the time" in ground-based airborne telesc V. Proc. SPIE **9145**, 9145 (2014)
4. Pogge, R.W., Atwood, B., Brewer, D.F., et al.: "The multi-object double spectrographs for the large binocular telescope", in ground-based and airborne instrumentation for astronomy III. Proc. SPIE **7735**, 77350A (2010)
5. Seifert, W., Ageorges, N., Lehmitz, M., Buschkamp, P., Knierim, V., Polsterer, K., Germeroth, A.: Results of LUCIFER1 commissioning. Proc. SPIE **7735**, 292 (2010)
6. Rothberg, B., Kuhn, O., Edwards, M., Hill, J., Thompson, D., Veillet, C., Wagner, R. M., and Power, J.:Current status of the facility instruments at the Large Binocular telescope Observatory. In: [Ground-based Airborne Instrum. Astron. VII]. Proc. SPIE 10702, 10702 (2018).
7. Daewook Kim, Hyukmo Kang, Jim Wiese, Heejoo Choi, Al Conrad, and David Thompson.: "Modular Cross-Dispersion Spectrometer MOBIUS for Large Binocular Telescope". CLEO-PR/ISOM/ODF Japan OThA1B-02 (2022).
8. Hyukmo Kang, David Thompson, Al Conrad, Conrad Vogel, Ariel Lamdan, Dae Wook Kim.: "Modular plug-in extension enabling cross-dispersed spectroscopy for large binocular telescope." Proc. SPIE 11116. Astronomical optics: design, manufacture, and test of space and ground systems II, 1111606 (2019); https://doi.org/10.1117/12.2528865
9. Dore, P., De Marzi, G., Paolone, A.: Refractive indices of $SrTiO_3$ in the infrared region. Int. J. Infrared Millimeter Waves **18**, 125–138 (1997)
10. Kang, H., Thompson, D., Conrad, Al., Wiese, J., Choi, H., Reddy, V., Kim, D.: Plug-in cross-dispersing module for the Large binocular telescopeapos;s infrared spectrograph large binocular telescope utility camera in the infrared. J. Astron. Telesc. Instrum. Syst. **8**(4), 045003 (2022). https://doi.org/10.1117/1.JATIS.8.4.045003

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