Modular plug-in extension enabling cross-dispersed spectroscopy for Large Binocular Telescope

Hyukmo Kang, David Thompson, Al Conrad, Conrad Vogel, Ariel Lamdan, et al.

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 (9 September 2019); doi: 10.1117/12.2528865

Event: SPIE Optical Engineering + Applications, 2019, San Diego, California, United States

Modular plug-in extension enabling cross-dispersed spectroscopy for Large Binocular Telescope

Hyukmo Kang[a], David Thompson[b], Al Conrad[b], Conrad Vogel[b], Ariel Lamdan[a], and Dae Wook Kim[a,b,c]

[a]James C. Wyant College of Optical Sciences, University of Arizona, 1630 E. University Blvd., Tucson, AZ 85721 USA

[b]Large Binocular Telescope Observatory, 933 N. Cherry Ave., Tucson, AZ, 85721 USA

[c]Department of Astronomy, University of Arizona, 933 N. Cherry Ave., Tucson, AZ, 85721 USA

ABSTRACT

The LUCI (LBT Utility Camera in the Infrared) instruments are a pair of near infrared (NIR) imagers and spectrographs for the Large Binocular Telescope (LBT) that include a set of cryogenic exchangeable focal plane masks. Although LUCI covers the NIR zJHK bands at different resolutions with existing gratings, it is not currently possible to get zJHK in a single exposure with a single LUCI which is required for some planetary science programs. To produce a simultaneous zJHK spectrum with a single LUCI, we designed a system consisting of small and simple optical elements to fit within the limited space in the focal plane mask frame to cross-disperse fixed short slits. This system, called MOBIUS (Mask-Oriented Breadboard Implementation for Unscrambling Spectra), consists of a double-folding mirror, a collimating spherical mirror with 180 mm radius of curvature, and a dispersing prism with the rear surface mirror-coated. MOBIUS disperses the input slit perpendicular to the dispersion direction of the gratings in LUCI. The resulting order separation is at least ~2.7 arcsecond, allowing a slit length of up to ~2.3 arcsec without mixing orders at the LUCI image plane. Since MOBIUS would be introduced into the existing light path via the exchangeable slit mask mechanism, no modification to the current LUCI instrument is needed. Eventually, binocular observations combining one of the Multi-Object Double Spectrographs (MODS) with LUCI+MOBIUS at the LBT will provide simultaneous coverage from 0.3 to 2.4 μm for studies of asteroids and other faint solar system bodies.

Keywords: LBT, LUCI, Spectrograph, Cross dispersion, Instrument Design

1. INTRODUCTION

The LUCI (LBT Utility Camera in the Infrared) instruments are a pair of near infrared (0.89 μm to 2.4 μm) imagers and spectrographs for the Large Binocular Telescope (LBT)[1–4] (Fig. 1). LUCI1 and LUCI2 are installed at the front Bent-Gregorian f/15 focal stations of the LBT, and are equipped with a set of cryogenic exchangeable focal plane masks. Both LUCIs provide imaging, long-slit and Multi Object Spectroscopy (MOS) over a 4 square arcminute field of view as well as adaptive optics corrected imaging and spectroscopy over a 30 arcsecond field of view.

Currently, we can use both LUCIs simultaneously to get a spectrum covering the zJHK bands (zJ and HK).[4] We can extend the coverage down to 0.32 μm by running one MODS (The Multi-Object Double Spectrographs)[5] and one LUCI, at the expense of either the zJ or HK bands. It would be of benefit to extend the simultaneous coverage over the full range.

In this paper, we report on our design of a cross-disperser module called MOBIUS (Mask-Oriented Breadboard Implementation for Unscrambling Spectra) to produce a simultaneous zJHK spectrum with a single LUCI as shown in Fig. 2. Requirements for the MOBIUS design included that there would be no modifications to the existing LUCI

Further author information: (Send correspondence to David Thompson)
David Thompson: E-mail: dthompson@lbto.org

Astronomical Optics: Design, Manufacture, and Test of Space and Ground Systems II, edited by Tony B. Hull, Dae Wook Kim, Pascal Hallibert, Proc. of SPIE Vol. 11116, 1111606 · © 2019 SPIE
CCC code: 0277-786X/19/$21 · doi: 10.1117/12.2528865

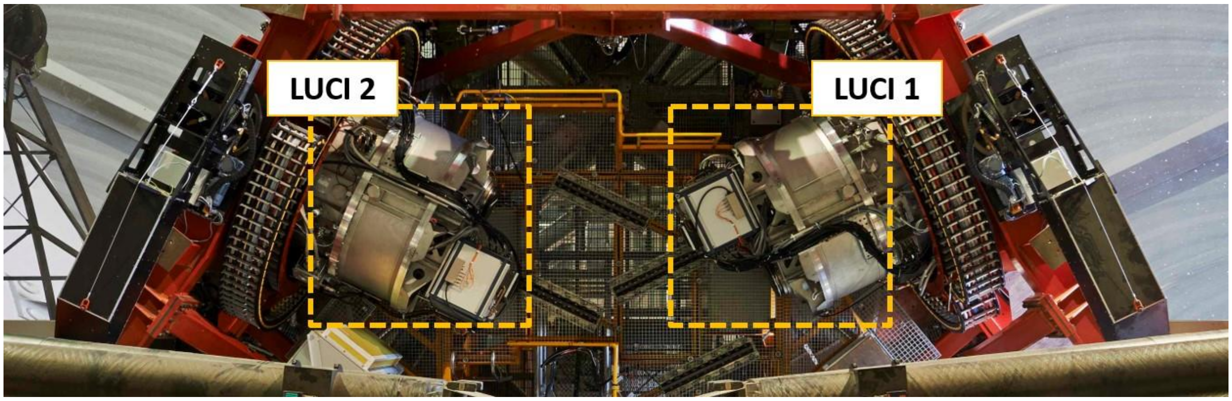

Figure 1. LUCIs on LBT.[6] LUCIs can have same (twinned mode) or different configurations (fraternal twin mode).[4] Also, at the binocular mode of LBT, each side could be configured with different instruments (mixed-mode) such as LUCI and MODS

instruments and that it would not affect the image quality of LUCI. This is achieved by mounting MOBIUS inside of the slit mask frame, located at the telescope focal plane. To demonstrate that the plug-in extension would not degrade performance of LUCI, we compare the spot radius and ensquared energy of each band with and without MOBIUS. By combining this system with MODS through binocular observations, MOBIUS in LUCI provides simultaneous coverage from UV to NIR.[4]

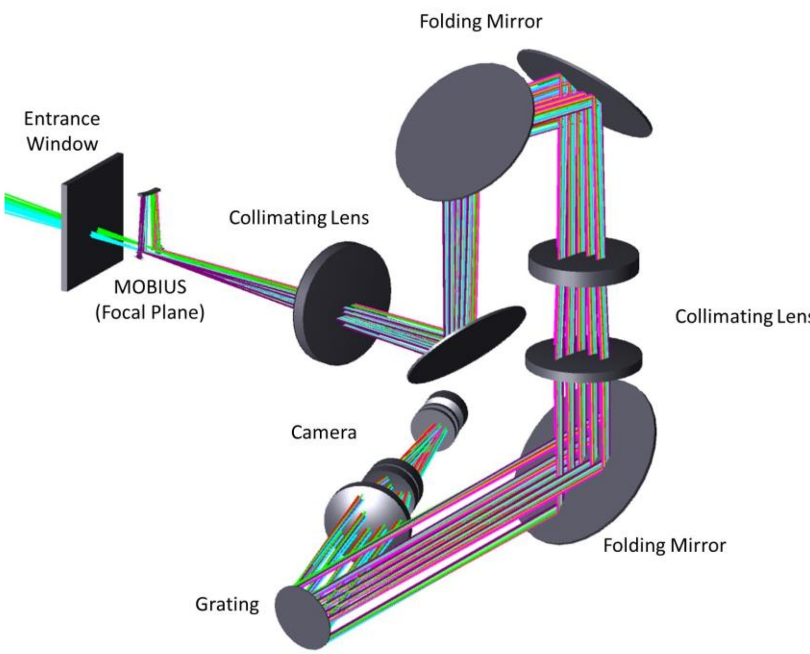

Figure 2. Optical layout shows MOBIUS introduced at the focal plane of LBT. By substituting the traditional slit frame mask with MOBIUS, LUCI is able to produce zJHK spectrum in a single exposure without any modifications in current instrument settings.

2. OPTICAL DESIGN OF MOBIUS

2.1 Concepts

The concept of MOBIUS is a modular cross-dispersing unit that can easily be deployed to and removed from the focal plane in LUCI without any other modifications to the current instrument. This characteristic provides broad band coverage (0.89 μm to 2.4 μm) in a single LUCI subject to scientific objectives with low cost and risk.

For that purpose, MOBIUS would be built into one of the exchangeable slit mask frames that are stored and handled by the MOS unit.[7] Then the MOBIUS-integrated mask frame would be placed in the focal plane of the LBT, and disperse the image of the slit perpendicular to the dispersion direction of the higher resolution gratings in LUCI. These concepts require that MOBIUS preserves the optical properties of the incident beam (e.g. position of focal plane, f-number, chief ray angle) and the image quality at the detector plane of LUCI. Additionally, the cross-dispersed distance between orders should be large enough to secure the required slit length while avoiding overlap. The current design of MOBIUS is optimized for the N3.75 camera with the G040 grating, so the minimum dispersion distance between orders should be larger than 1 mm to achieve the required slit length of 2 arcseconds or more. Lastly, two identical cross-disperser modules will be built into a single mask frame side by side, allowing for sky-subtraction by dithering between source and sky positions.

Figure 3 shows the schematic concept of MOBIUS. The incident beam from the LBT reflects off the side of a triangle pick-off mirror towards the inside of the mask frame. It is then collimated via a spherical mirror before entering the dispersing prism. The prism has a mirror-coated rear surface and is tilted to cause retroreflection. These processes happen in the plane of the slit mask, and the dispersed beam returns to the pick-off mirror. At this point, the beam hits the other side of triangle, and is directed into LUCI. As long as the ray angles and focal plane of the MOBIUS dispersed beams nominally match that of the initial LBT beam, the condition being that no rays are vingetted, the LUCI detector will see four spectra, each corresponding to a different NIR band. Therefore, MOBIUS can provide broad band coverage without any adjustments to the current instrument.

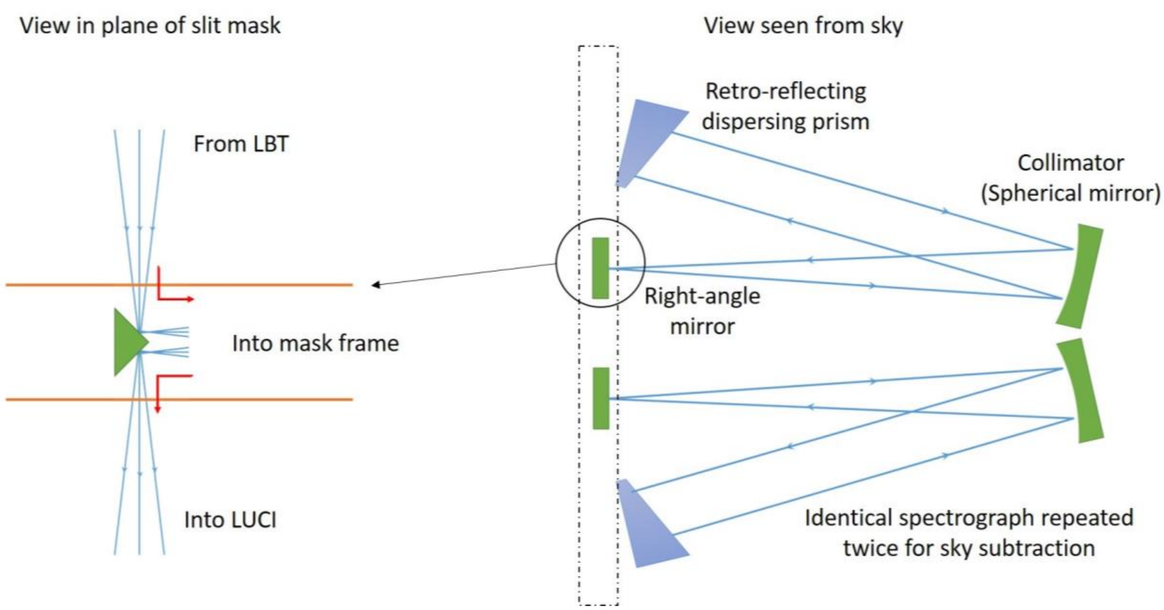

Figure 3. Schematic figure of MOBIUS a modular cross-disperser for LUCI. The right-angle mirror is inserted near the focal point of LBT to deflect the incoming beam from the LBT into the mask frame. Inside of the frame mask the beam is collimated and dispersed, then it is returned to the previous light path. Through this process, the input beam is cross dispersed before the higher dispersion grating in LUCI.

2.2 Optical Design

The components of MOBIUS are simple: a double folding mirror, a spherical mirror, and a dispersing prism. The double folding mirror is made of Zerodur and is shaped like a right-angle prism. This is located near the focal point of LBT to deflect the incident beam into the slit mask frame.

The collimator, a Zerodur spherical mirror with 180 mm radius of curvature, is located at the focal length of the spherical mirror from the focal point of the LBT, and tilted so the collimated beam does not hit the right-angle mirror. Typically an off-axis parabolic (OAP) mirror is used as a collimator, but we adopted a spherical mirror because with the slow f/15 beam from the telescope there is no significant difference in the Strehl's ratio between an OAP and a spherical mirror. Furthermore, the use of a spherical mirror is advantageous in fabrication and alignment.

The dispersion prism is made of Strontium Titanate ($SrTiO_3$). Strontium Titanate is a material transmissive in the operating temperature and wavelengths.[8] The apex angle of the prism is 19°, and it is tilted to cause retroreflection at the rear surface that is mirror-coated. The dispersed beam from the prism is returned to the other side of the right-angle mirror, and propagates into LUCI. As a consequence, the minimum separation of order by MOBIUS is ~1.6 mm at the focal plane of the LBT.

The optical design of a unit of MOBIUS is shown in Fig. 4(a). Fig. 4(b) shows the overall layout of MOBIUS with two identical mini spectrographs are located side by side to provide sky subtraction by dithering.

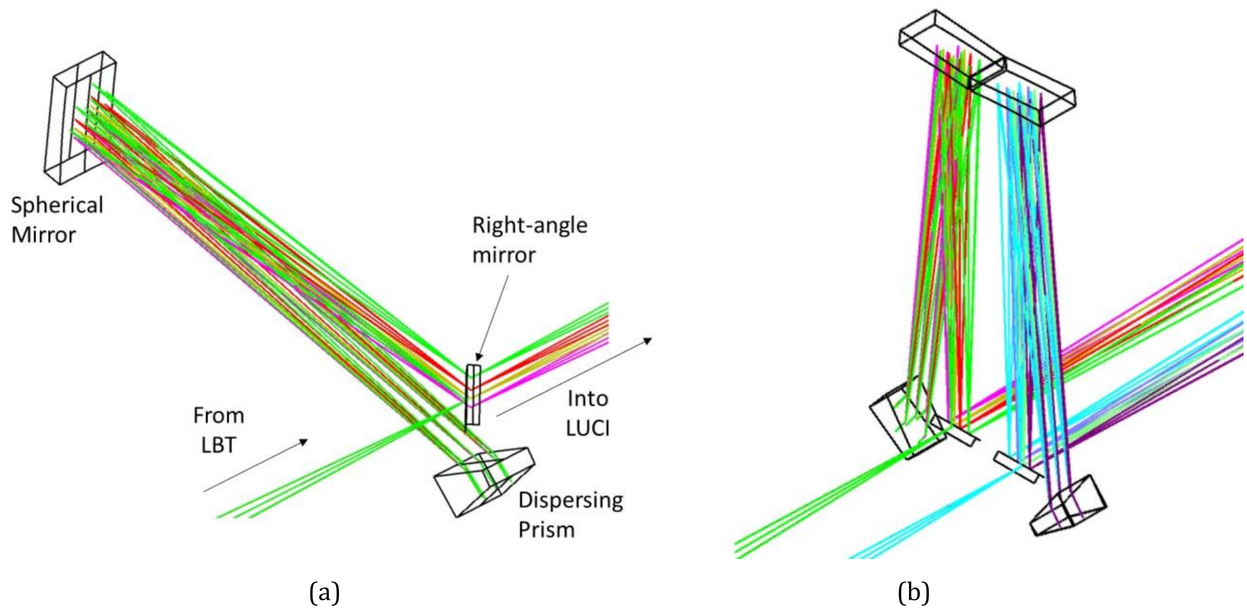

Figure 4. Optical layouts of MOBIUS. (a) shows an unit of MOBIUS. and (b) shows the overall layout of MOBIUS with two identical spectrograph units located side by side. For the sky subtraction by dithering, we flipped one unit to allow placement of the two entrance slits as close as possible.

Since MOBIUS needs to fit within a limited space (150 x 150 x 12 mm), the maximum width of optical elements is limited by the thickness of the slit mask frame (Fig. 5). Also, additional weight of the slit frame should be less than 20 grams so that the MOBIUS can be safely handled by the MOS-unit and focal plane unit of LUCI.

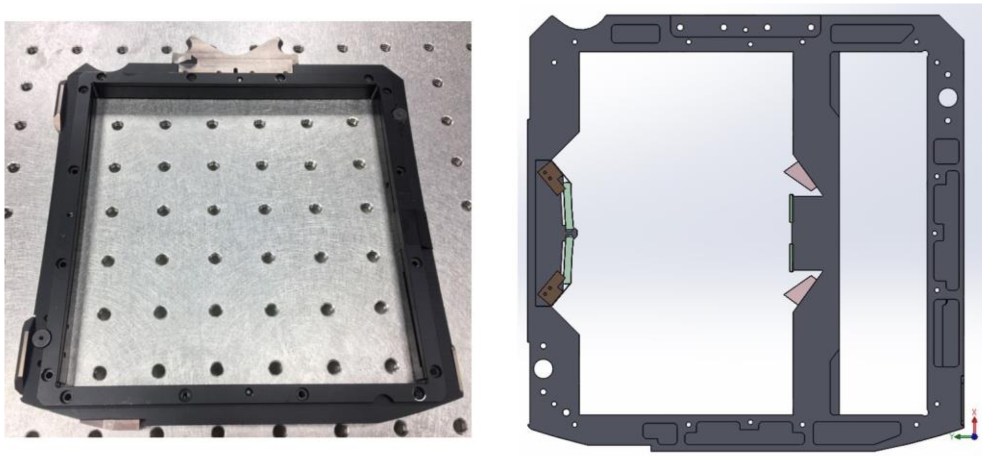

Figure 5. Slit frame of LUCI (left) and estimated 3D modelling of MOBIUS built in the frame (right). To compensate the additional weights of MOBIUS, light weighting features are included in the frame.

3. RESULT AND PERFORMANCE

Figure 6 shows how MOBIUS works with LUCI. Without MOBIUS (Fig. 6(a)), the footprint of different orders are dispersed in a line and overlapped such that they are indistinguishable. MOBIUS generates perpendicular dispersion that gives spectra without overlap (Fig. 6(b)). Because we put two mini cross dispersers, there are two sets of zJHK spectra, one for the target the other for sky subtraction. The configuration with N3.75 camera and G040 grating allows a slit length up to ~2.3 arcsecond at the LUCI image plane without mixing orders.

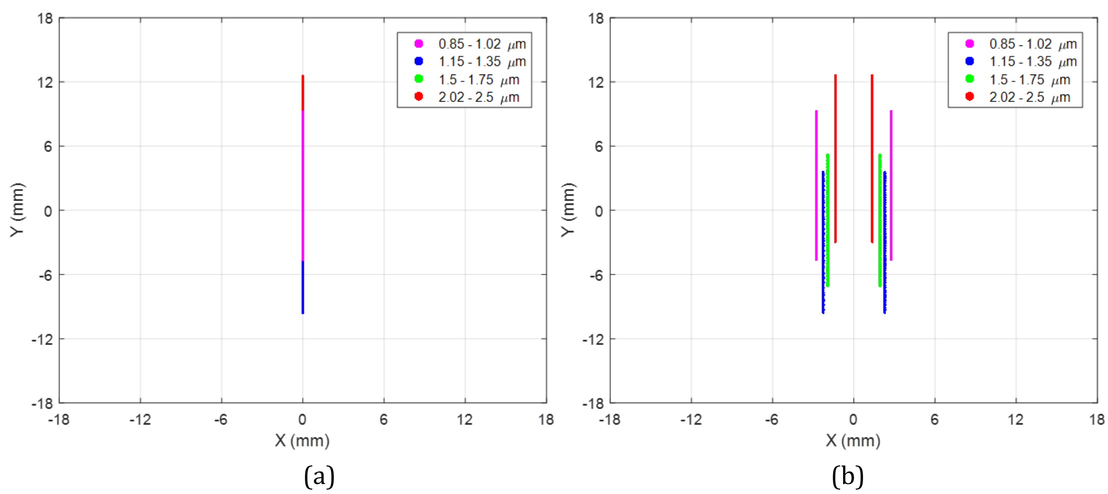

Figure 6. Footprint diagram at the detector when observing (a) only using LUCI and (b) LUCI with MOBIUS. With MOBIUS, spectra of each order are not overlapped. MOBIUS allows slit length up to ~2.3 arcsecond.

As a plug-in extension for LUCI, it is important not to degrade the image quality after introducing MOBIUS. To verify that the image quality remains the same, we compared the *rms* spot radius at the focal plane of the LBT and at the focal plane that is formed after MOBIUS (Fig 7). The radius of *rms* spot size has increased in every band after MOBIUS is introduced, however, it is still equivalent to the size of the Airy's disk. We also compare the ensquared energy at the LUCI detector (Fig. 8). The greatest difference in half width distance for 90% fraction energy is at K band, which is about 2 μm. Considering the pixel size of the detector is 18 μm,[6] and the seeing disk delivered by the telescope is >2 pixels on the N3.75 camera, MOBIUS would not be a limitation to the delivered image quality. These results show that the MOBIUS can expand wavelength coverage of LUCI with little penalty.

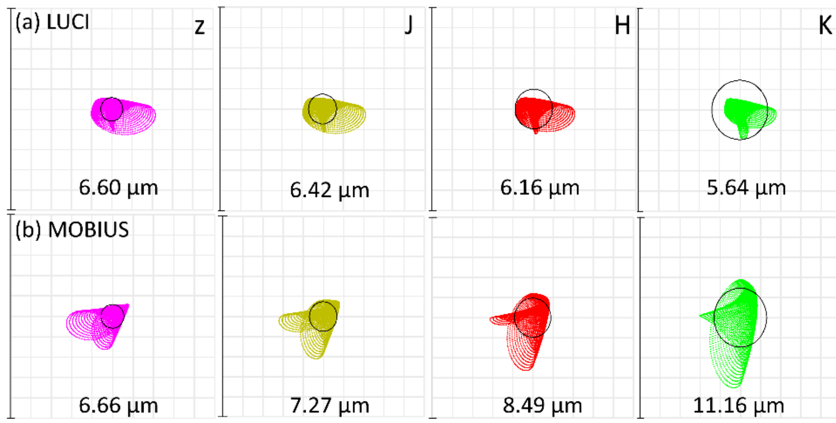

Figure 7. Spot diagrams at the focal plane of LBT when (a) LUCI only and (b) LUCI+MOBIUS is applied. The numbers in figure represent the rms spot radius of each spot diagram. Although the rms spot radius is slightly increased after the MOBIUS, it is still nearly the size of Airy's disk. Also, considering the smallest expected FWHM at the focal plane delivered from the telescope is 150 µm or 0.25 arcsecond, the image quality is dominated by the atmospheric seeing.

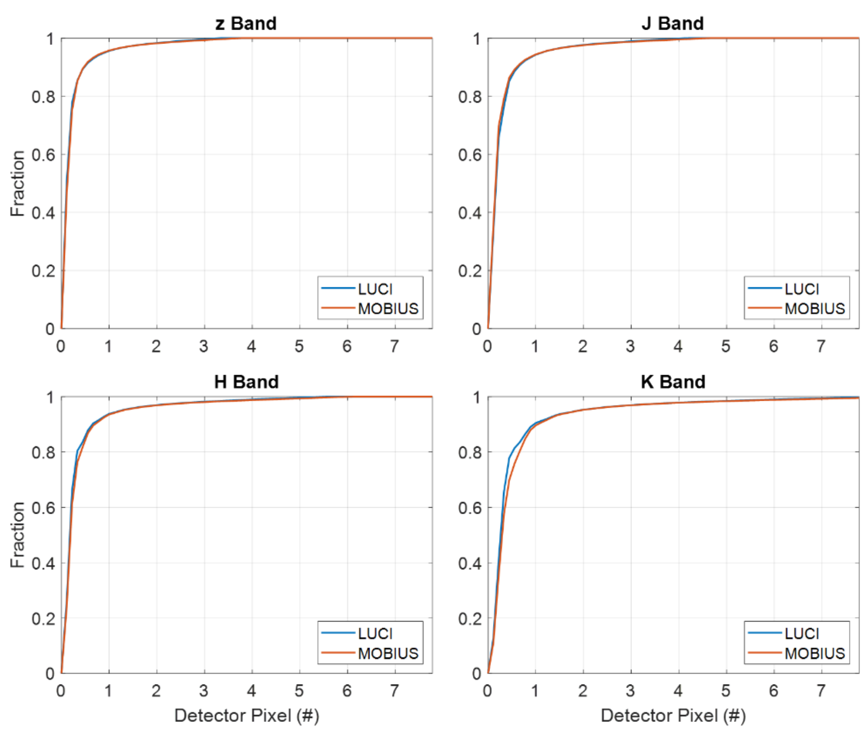

Figure 8. Ensquared energy comparison between LUCI and LUCI with MOBIUS. The difference in half width distance between LUCI and MOBIUS for 90% fraction energy is less than a pixel (on detector). Considering the seeing disk is >2 pixels or 0.25 arcsecond, this difference is insignificant.

4. CONCLUSION

We presented a slit mask based cross disperser expansion module which enables existing spectroscopic instruments to cover broad bands in a single exposure. Since MOBIUS utilizes the current mask frame and hardware, it is not required to modify the current instrument set up. MOBIUS provides simultaneous and continuous spectrum from 0.89 μm to 2.4 μm, while at most generating negligible variation in optical performance. Binocular observations with one MODS and one MOBIUS-equipped LUCI is expected to provide simultaneous coverage from UV to NIR.

ACKNOWLEDGEMENT

We also want to thank the people who contributed to the editing and reviewing of the manuscript. A special thank you goes to John Kam who helped edit and gave feedback on the article.

REFERENCES

[1] Seifert, W., Appenzeller, I., Baumeister, H., Bizenberger, P., Bomans, D., Dettmar, R.-J., Grimm, B., Herbst, T., Hofmann, R., Juette, M., Laun, W., Lehmitz, M., Lemke, R., Lenzen, R., Mandel, H., Polsterer, K., Rohloff, R.-R., Schuetze, A., Seltmann, A., Thatte, N. A., Weiser, P., and Xu, W., "LUCIFER: a MultiMode NIR Instrument for the LBT," in [*Instrum. Des. Perform. Opt. Ground-based Telesc.*], *Proc. SPIE* **4841**, 962 (2003).

[2] Mandel, H., Seifert, W., Hofmann, R., Ju¨tte, M., Lenzen, R., Ageorges, N., Bomans, D., Buschkamp, P., Dettmar, R.-J., Feiz, C., Gemperlein, H., Germeroth, A., Geuer, L., Heidt, J., Knierim, V., Laun, W., Lehmitz, M., Mall, U., Mu¨ller, P., Naranjo, V., Polsterer, K., Quirrenbach, A., Sch¨affner, L., Schwind, F., Weiser, P., and Weisz, H., "LUCIFER status report: summer 2008," **7014**, 70143S (2008).

[3] Hill, J. M., Ashby, D. S., Brynnel, J. G., Christou, J. C., Little, J. K., Summers, D. M., Veillet, C., and Wagner, R. M., "The large binocular telescope: binocular all the time," in [*Ground-based Airborne Telesc. V*], *Proc. SPIE* **9145**, 914502 (2014).

[4] 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**, 1070205 (2018).

[5] Pogge, R. W., Atwood, B., Brewer, D. F., Byard, P. L., Derwent, M. A., Gonzalez, R., Martini, P., Mason, J. A., O'Brien, T. P., Osmer, P. S., Pappalardo, D. P., Steinbrecher, D. P., Teiga, E. J., and Zhelem, R., "The multi-object double spectrographs for the large binocular telescope," in [*Ground-based and Airborne Instrumentation for Astronomy III*], *Proc. SPIE* **7735**, 77350A (2010).

[6] Heidt, J. and Thompson, D., "LUCI User Manual." September 7, 2016 https://sites.google.com/a/lbto.org/luci/documents-and-links.

[7] Buschkamp, P., Hofmann, R., Gemperlein, H., Polsterer, K., Ageorges, N., Eisenhauer, F., Lederer, R., Honsberg, M., Haug, M., Eibl, J., et al., "The lucifer mos: a full cryogenic mask handling unit for a nearinfrared multi-object spectrograph," in [*Ground-based and Airborne Instrumentation for Astronomy III*], *Proc. SPIE* **7735**, 773579 (2010).

[8] Dore, P., De Marzi, G., and Paolone, A., "Refractive indices of SrTiO3 in the infrared region," *Int. J. Infrared Millimeter Waves* **18**, 125–138 (1997).