Nautilus: The advent of large lens-based space telescopes

Daewook Kim[1,2,*], *Tom D.* Milster[1,^], and *Dániel* Apai[2,3,Γ]

[1]James C. Wyant College of Optical Sciences, The University of Arizona, Tucson, AZ 85721, USA
[2]Department of Astronomy and Steward Observatory, The University of Arizona, Tucson, AZ 85721, USA
[3]Lunar and Planetary Laboratory, The University of Arizona, Tucson, AZ 85721, USA

Abstract. One of the most profound and philosophically captivating foci of modern astronomy is studies of Earth-like exoplanets in search of life in the Universe. The paradigm-shifting investigation described here calls for a new type of space telescope that redefines the available light-collecting area in space, far beyond what is currently possible with the 6.5 m diameter James Webb Space Telescope. The Nautilus Space Observatory, which is enabled by multiple-order diffractive optics, is ushering in the advent of large space telescope lenses designed to search for biosignatures on a thousand exo-earths.

1 Nautilus searching a thousand Earths

Nautilus, named after J. Verne's submarine [1], is a revolutionary telescope concept (Figure 1) that replaces the traditional reflective primary telescope mirrors with multiple-order diffractive engineered (MODE) material lens technology [2], offering a scalable and resilient solution for astronomical space telescopes. Its robust optical performance against optical errors/misalignments and fabrication by glass molding process enables significantly lower cost of fabrication, integration-and-testing, assembly, and launch compared to modern reflecting telescopes, which require extremely precise co-phasing and alignment for wavefront control.

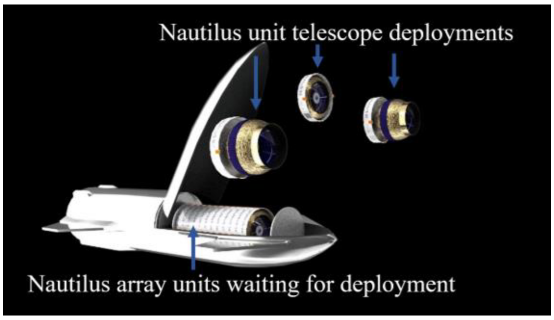

Fig. 1. Rendering of Nautilus fleet consisting of multiple unit telescope array during the space deployment phase.

The science goal of Nautilus is to investigate more than 1,000 habitable-zone, Earth-sized exoplanets through transit studies to determine their atmospheric diversity and the occurrence rate of atmospheric biosignatures at a distance of up to 300 pc. [1] A scalable and resilient fleet of multiple Nautilus space telescopes can find, observe, and provide spectra of deeper and fainter exoplanets than any other concept described to date. This statistically meaningful sample of worlds achieves ~2-3 orders of magnitude increase over the direct imaging or exoplanet transit telescope concepts currently envisioned for the next several decades.

2 Ultralightweight large space lenses

A multiple-order diffractive engineered (MODE) lens has been developed [2], in which chromatic focal length variation exhibits both refractive and diffractive characteristics in balance. This hybrid optical component shown in Figure 2 achieves a high Strehl ratio (i.e., diffraction-limited imaging) performance over a wide range of f/# (i.e., focal length and aperture size) design space.

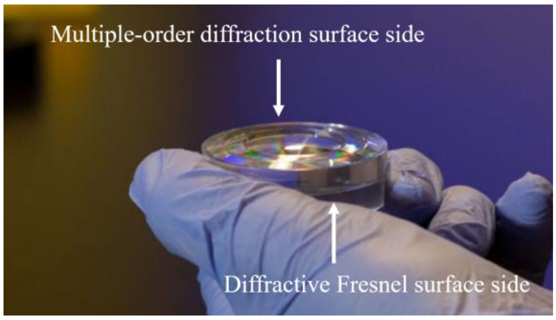

Fig. 2. MODE lens consisting of two engineered optical surfaces, a multiple-order diffraction surface and a diffractive Fresnel surface balancing and compensating chromatic aberrations from refraction and diffraction.

A prototype MODE lens was designed and fabricated for the astronomical R-band wavelength range (i.e., 589 − 727 nm). The measured focal length as a function of wavelength accurately matched design values. Also, an infinite conjugate optical imaging test successfully demonstrated ~2× full-width-half-maximum spot size compared to the ideal Airy disk size despite of all the manufacturing errors and metrology noise with a plastic

Corresponding authors: * dkim@optics.arizona.edu, ^ Milster@optics.arizona.edu, Γ apai@arizona.edu

primary lens. Unlike a traditional refractive-only lens, MODE lens technology does not scale thickness as the diameter increases. Thus, large aperture, ultralightweight lens-based space telescopes are enabled.

3 Nautilus Optical Engineering

3.1 Optical design configurations

The Nautilus Observatory consists of many individual unit telescopes in an incoherent array. No precision formation flight is needed. Each unit telescope design can be configured in a one- or two-MODE lens configuration [1, 3] utilizing different MODE lens aperture sizes. The two-MODE-lens configuration is shown in Figure 3.

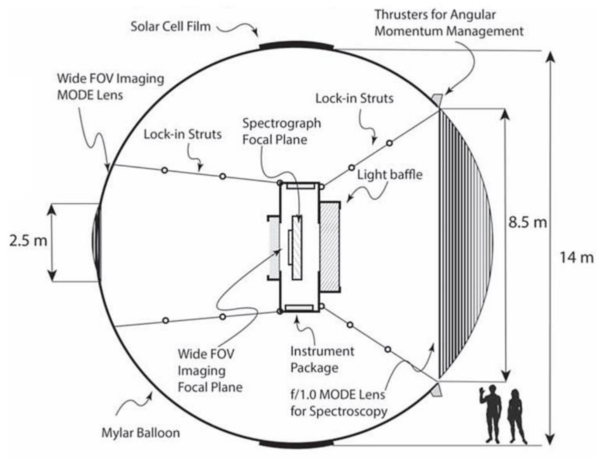

Fig. 3. Nautilus unit telescope concept using 8.5 m MODE lens (on the right side) and 2.5 m MODE lens (on the left side). The 8.5 m MODE lens size is limited by the rocket fairing size. The optional 2.5 m aperture provides parallel imaging capabilities with a wide field of view, optimized for exoplanet transit search or surveys. [1]

The Nautilus unit telescope is packaged in a compact disk-like formfactor and deployed once they are in space, as shown in Figure 1. Once in orbit, a gas canister inflates a Mylar (or any other membrane material) balloon acting mostly as a simple thermal shield and light baffle, and deploys the instrument package along with the MODE lenses. Lock-in linkage struts provide mechanical stability and longevity of the telescope, as shown in Figure 3.

3.2 MODE lens fabrication via glass molding

MODE lenses are fabricated using a diamond-turned mold in a precision glass molding process. The optimal MODE lens manufacturing process going through molding temperatures of ~550°C has been tested and refined via selection of proper mold material, compatible mold fabrication, precision glass molding phase, and stability of the mold itself.

For optimal mold machining and release, as illustrated in Figure 4(top), nickel phosphorous (NiP) plating is applied to the copper-nickel C71500 (CuNi) mold substrate, which has a similar coefficient of thermal expansion (CTE) to the NiP plating.

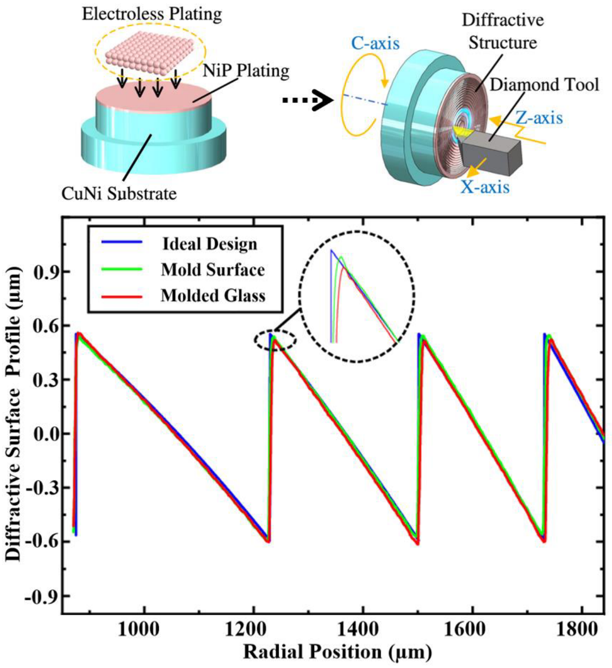

Fig. 4. (top) Schematic diamond turning process of the MODE lens' diffractive Fresnel surface mold. (bottom) Diffractive Fresnel surface profile comparison between the design, the diamond turned mold, and the molded glass surface. [4]

The diffractive Fresnel surface molding capability was demonstrated in terms of surface micro roughness and diffractive optical surface profile accuracy, as presented in Figure 4(bottom). The measured surface roughness values over multiple regions show superb smoothness of Sa = 2 nm. Also, as shown in Figure 4(bottom), the molded diffractive Fresnel surface is accurately molded with <0.05 μm error between the glass and mold. [4] The multi-parameter fabrication process chain optimization with cost modelling is reported to show the scalability of the Nautilus architecture. [5]

4 Conclusions

A very large aperture MODE lens for astronomical space telescopes is ushering in the era of large lens-based space telescopes that provide unprecedented photon collection efficiency in order to probe deep into space for surveying exoplanets for biosignatures.

References

1. D. Apai, et al., The Astronomical Journal, 158:83 (21pp) (2019).
2. T. Milster, et al., Appl. Opt. **59**, 7900-7906 (2020).
3. "Future of Astronomy," *Sky & Telescope*, November Issue, 32-33 (2021).
4. Y. Zhang, et al., Opt. Lett. **45**, 6438-6441 (2020).
5. M. Dupuis, et al., J. Astron. Telesc. Instrum. Syst. 8(2) 027001 (2022).