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Kinematically engaged yoke system for segmented lens-based space telescope integration and testing

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Abstract. One of the most profound and philosophically captivating foci of modern astronomy is the study of Earth-like exoplanets in the search for life in the Universe. The paradigm-shifting investigation described here calls for a new type of scalable space telescope that redefines the available light-collecting area in space. The Nautilus Space Observatory, enabled by multiple-order diffractive optics (the MODE lens), is ushering in the advent of large space telescope lenses designed to search for biosignatures on a thousand exo-earths. The Kinematically Engaged Yoke System (KEYS) was developed to align a segmented version of the MODE lens. A technology demonstration prototype of KEYS was built and tested using scanning white light interferometry and deflectometry. A deflectometry system was also developed to monitor the closed-loop alignment of the segmented MODE lens during its UV (i.e., Ultraviolet) curing.

Keywords: KEYS, Nautilus, MODE Lens, Alignment, Space Telescope.

1 Nautilus searching a thousand Earths

Nautilus, named after J. Verne's submarine [1], is a revolutionary telescope concept (Fig. 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 the 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.

The science goal of Nautilus is to investigate more than 1000 habitable-zone, Earth-sized exoplanets through transit studies to determine their atmospheric diversity and the occurrence rate of atmospheric biosignatures at a distance 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 observatory 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.

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

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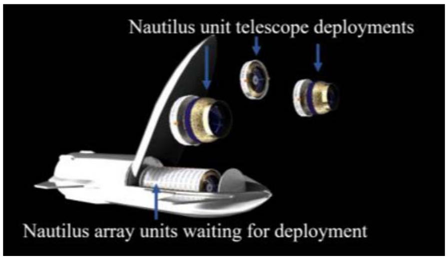

Fig. 1. Rendering of the Nautilus fleet consisting of multiple unit telescope array during the space deployment phase.

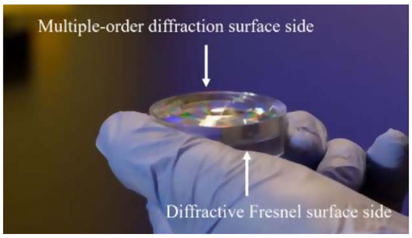

Fig. 2. MODE lens consisting of two engineered optical surfaces, a multiple-order diffraction surface and a diffractive Fresnel surface balancing and compensating chromatic aberrations from refraction and diffraction.

errors and metrology noise with a plastic 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 Scalable optical design and fabrication

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.

The Nautilus unit telescope is packaged in a compact disk-like form factor 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.

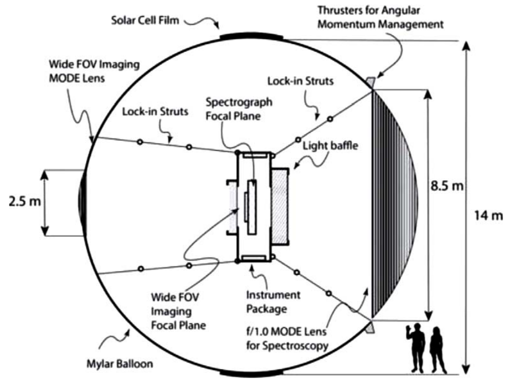

Fig. 3. Nautilus unit telescope concept using 8.5 m MODE lens (on the right side) and 2.5 m MODE lens (on the left side). The 8.5 m MODE lens size is limited by the rocket fairing size. The optional 2.5 m aperture provides parallel imaging capabilities with a wide field of view, optimized for exoplanet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

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.

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 glass molded MODE lens segment was successfully fabricated as shown in Figure 5. This multi-parameter fabrication process chain optimization with cost modelling is reported to show the scalability of the Nautilus architecture [5].

4 Kinematically Engaged Yoke System

One efficient solution enabling very large MODE lenses (e.g., 8.5 m diameter) is fabricating multiple MODE segments and bonding them together. The Kinematically Engaged Yoke System (KEYS) was developed to align these MODE lens segments before bonding. Prototypes of KEYS are currently being developed for a 240 mm diameter MODE lens with nine segments (one center segment and eight ring segments).

4.1 Kinematic opto-mechanical design

The KEYS alignment mechanism uses the inherent step feature of the front MODE lens surface to kinematically engage with the lens segment using ball bearings bonded to adjustment screws. As depicted in Figure 6, each ring segment contacts three balls, two balls along an outer radius contact the lens segment at two points, and one ball

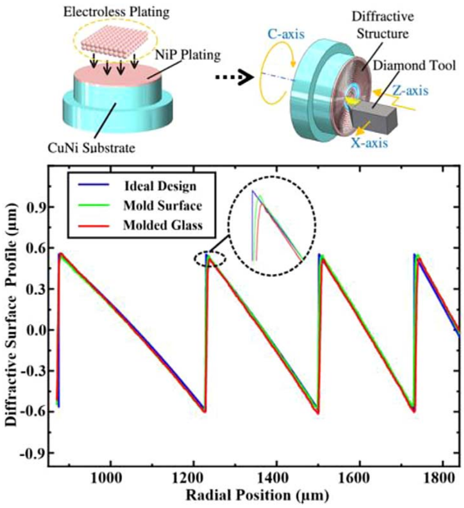

Fig. 4. (top) Schematic diamond turning process of the MODE lens' diffractive Fresnel surface mold. (bottom) Diffractive Fresnel surface profile comparison between the design, the diamond turned mold, and the molded glass surface [4].

Fig. 5. Glass molded MODE lens ring segment using low transition temperature Ohara L-BSL7 glass.

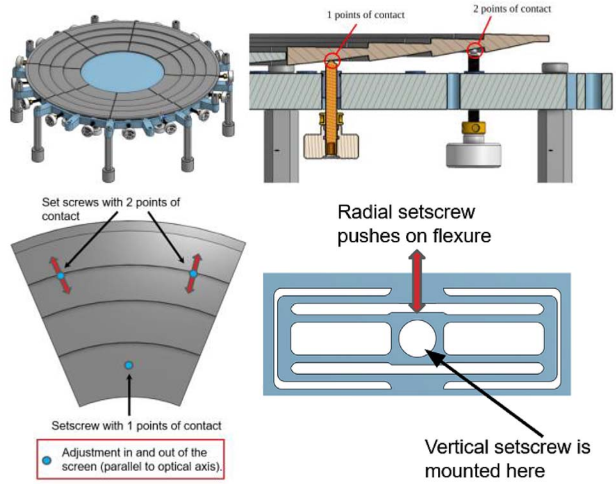

Fig. 6. 3D model of KEYS with kinematic opto-mechanical design details and flexure model [6].

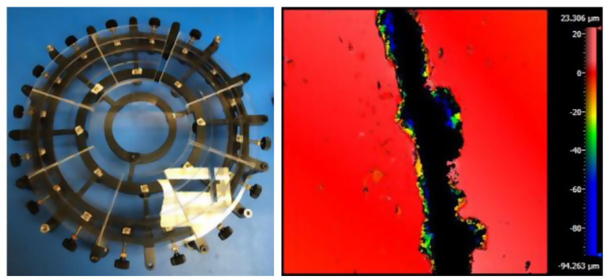

Fig. 7. (left) Fully assembled KEYS prototype and (right) SWLI results after fine alignment of the lens segments with the adjustment setscrews. After fine alignment, the height difference at the gap is within 20 μm (without relative tip/tilt between the two segments) [6].

along an inner radius contacts the lens segment at one point. This provides the lens segment with five degrees of constraint, leaving rotation of the lens segment about the MODE lens optical axis unconstrained (as it is an axially symmetric optics). To adjust the position and orientation of the lens segment during alignment; tip, tilt, and piston are adjusted using the adjustment screws that move parallel to the optical axis. Adjustment within the transverse plane is controlled using adjustment screws that push onto flexures to which the outer tip/tilt/piston adjustment screws are attached. The lens segment is then preloaded against the ball bearings using spring plungers or magnets [6].

4.2 KEYS technology demonstration prototype

The KEYS prototype (in Fig. 7) alignment mechanism was built out of waterjet aluminium plates. The flexure was designed to kinematically constrain the adjustment structures. The spring plungers that are used for preloading were mounted on another aluminium plate that was fixed above the ring lens segment. The precision alignment capabilities of this prototype were tested using a scanning white light interferometer (SWLI) and a deflectometry system. The SWLI was used to determine how well cophased two ring segments of the lens could be. As seen in Figure 7 (right), the KEYS was able to align two ring segments to within 20 μm, which is within the necessary tolerances of performance for this lens. The deflectometry system was used to measure the resolution of adjustment of the KEYS. As seen in Figure 8, the segments were successfully adjusted with a resolution of 0.006°.

5 Integration and testing of MODE lens

5.1 Closed-loop UV curing

After the optical alignment of the MODE lens segments on the optical testbed using interferometry, it will be necessary to monitor the alignment of the MODE lens segments on the KEYS during the bonding process and have a closed-loop adjustment system to correct misalignments that may occur. UV curing adhesive between the MODE segments is the bonding method. (Note: Laser welding is another option that can be used to join the segments.)

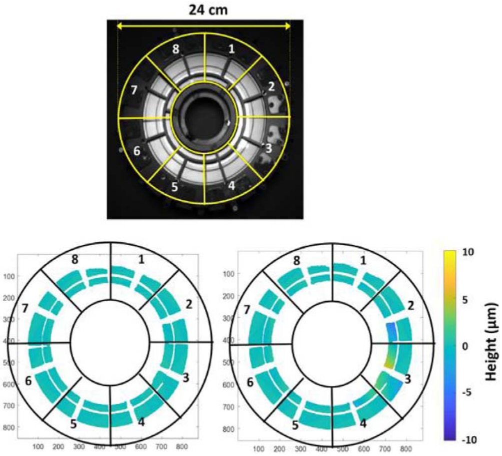

Fig. 8. The real data from the deflectometry metrology system. (top) Live view from the deflectometry camera. (bottom-left) All eight segments are well-aligned against initial co-phasing status. The black line represents the actual size of the single segment. (bottom-right) Successfully detection of segment 3 being drifted from the reference position by tilting angle of 0.006°. (Note: X and Y axis units are in pixels.) [6].

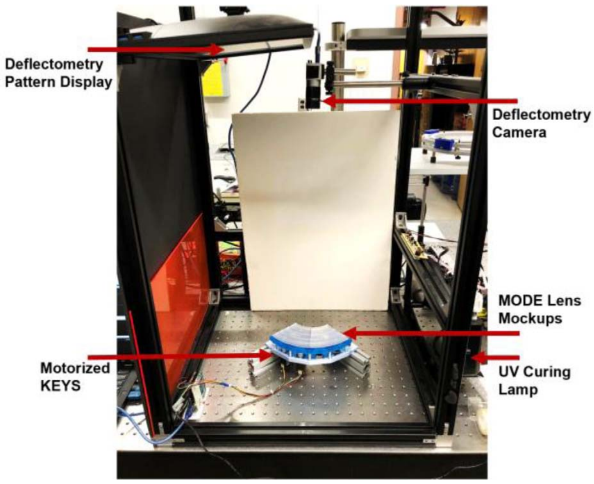

Fig. 9. Closed-loop UV curing set-up with KEYS supporting the two MODE lens segment mockups. The deflectometry system provides the in-situ alignment feedback to control the KEYS [7].

The deflectometry system was used to test the closed-loop feedback capabilities to guide the KEYS adjustment for this in-situ correction capability.

A two-ring-segment KEYS system with motorized tip/tilt/piston adjustment screws was built and tested using this deflectometry monitoring and closed-loop adjustment system. In this irreversible UV bonding experimental setup, 3D printed models of the segments were used as a mockup and a glass slide was fixed on the top of each to emulate the specular reflection of the actual MODE lens. The closed-loop UV curing configuration utilizing KEYS and a deflectometry monitoring system is shown in Figure 9.

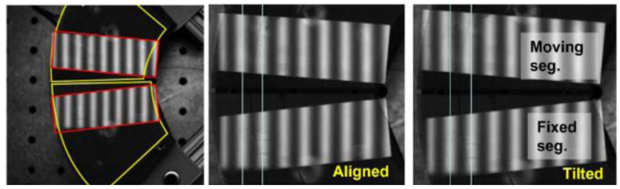

Fig. 10. The acquired deflectometry pattern images. (left) The yellow boundary indicated the 3D printed mockups MODE segments. The attached slide glass provides a strong return signal representing the actual MODE lens surface case. The upper segment is mounted on a motorized KEYS support and the lower one is mounted on a manual adjustment support. (middle) The KEYS system was used to align the segments and saved the raw fringe image as a reference. (right) An intentional perturbation was applied to the upper segment and the misaligned was clearly detected by the shift of the pattern, which is processed by the deflectometry phase calculation [7].

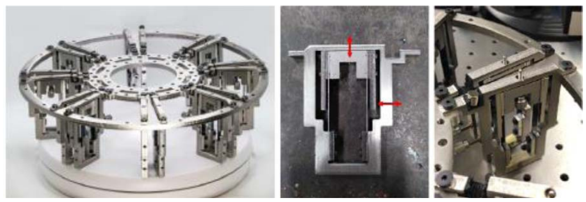

Fig. 11. (left) The high optical throughput KEYS prototype, (middle) Newly updated flexure module with red arrows showing the degrees of adjustment per flexure module, (right) Two flexure modules on the prototype with adjusters installed [8].

Deflectometry was used due to its large dynamic range combined with high precision slope measurement capability.

The measured deflectometry fringe patterns reflected off the glass slides placed on top of the lens segments are presented in Figure 10. The movement of these fringes during UV bonding process are used to calculate necessary adjustments that need to be made by KEYS to correct for misalignments that may occur during the bonding process. In the future, these off-axis wedge segments will be aligned in reference to the center segment, which is a circular segment that will be fixed in place.

A newer KEYS prototype has been designed and built with a new flexure design and magnetic preloading mechanism, as shown in Figure 11. This new prototype has a more open aperture (i.e., higher optical throughput) and will allow for efficient optical alignment and testing of the MODE lens assembly [8].

6 Conclusion

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. The KEYS prototype successfully demonstrated its capability to align the segmented

MODE lens system for the telescope integration and testing process.

Conflict of interest

The authors declare no conflict of interest.

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