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Marcos A. Esparza, Heejoo Choi, Dae Wook Kim, "Alignment of Multi-Order Diffractive Engineered (MODE) lens segments using the Kinematically-Engaged Yoke System," Proc. SPIE 11487, Optical Manufacturing and Testing XIII, 114870V (20 August 2020); doi: 10.1117/12.2569442

Event: SPIE Optical Engineering + Applications, 2020, Online Only

Alignment of Multi-Order Diffractive Engineered (MODE) lens segments using the Kinematically-Engaged Yoke System

Marcos A. Esparza[a], Heejoo Choi[a,b], and Dae Wook Kim[a,b,c,*]

[a]James C. Wyant College of Optical Sciences, The Univ. of Arizona, Tucson, AZ, 85721, USA
[b]Large Binocular Telescope Observatory, 933 N. Cherry Ave., Tucson, AZ, 85721 USA
[c]Department of Astronomy and Steward Observatory, University of Arizona, Tucson, AZ, 85721, USA

ABSTRACT

With the continued development of multi-order diffractive engineered (MODE) lenses that consist of both multi-order diffractive surfaces and a diffractive Fresnel lens surface, it is becoming more realistic that these components may be used as an ultralight large aperture primary for space telescopes. As conceptual designs for these large primaries push the size limits of optics manufactured by compression molding, it becomes necessary to make a segmented MODE lens primary rather than a monolithic one. We use the Kinematically-Engaged Yoke System (KEYS) to align the segments of a 0.24-m, PMMA, monochromatic, MODE-like lens (having no diffractive Fresnel lens features). The KEYS alignment system consists of modified ultra-fine alignment screws with ball bearings on the end that kinematically engage with the step-like features of the MODE lens surface (similar to a Fresnel lens) to constrain the segments in 5 degrees of freedom, leaving rotation about the optical axis unconstrained. The alignment of the segments is verified using multiple methods including a scanning white light interferometer and deflectometry. Such an alignment system has the capability of fixing the segments together in order to bond them with adhesive while aligned. These tests offer a proof of concept for a system that can be used for an eventual 0.24-m, compression molded, glass, segmented MODE lens.

Keywords: alignment, metrology, multi-segmented optics, MODE lens, optomechanics, kinematic constraint, flexures

1. INTRODUCTION

Astronomical discovery using optical instruments drives those making telescopes to design observatories with larger and larger apertures in order to increase resolution and see further into the universe. For space and ground based observatories, a mirror-based aperture is often used as they are inherently achromatic and more lightweight than lenses of similar optical power. Currently, the observatory with the largest aperture is the Large Binocular Telescope with two 8.4-m mirror segments that make up an aperture of 22.5-m. Telescopes in construction or develop such as the Giant Magellan Telescope and the European Extremely Large Telescope with the former made up of seven 8.4-m segments making and aperture of 24.5-m and the latter made up of 798 1.5-m segments making up an aperture of 39-m. This is in contrast to the largest lens used in a telescopes which is a 1-m lens used at the Yerkes observatory (built in 1897).[1] Even if lens used in telescopes that are being developed are counted, the largest lens is 1.6-m in diameter and is used in the camera for the Vera C. Rubin Observatory (also referred to as the Large Synoptic Survey Telescope) which itself uses a 8.4-m mirror for its primary optical collector.[2] However, mirrors require precise surface figuring, typically on the order of 0.01λ. This becomes more difficult when large apertures are divided into segments as each segment also need to aligned precisely with each other. The multi-order diffractive engineered (MODE) lens is a novel optical element that is significantly thinner and more lightweight than typical lenses of the same diameter and optical power, yet if broken up into segments, has looser tolerances than those of mirror segments.[3]

*letter2dwk@hotmail.com

Optical Manufacturing and Testing XIII, edited by Dae Wook Kim, Rolf Rascher,
Proc. of SPIE Vol. 11487, 114870V · © 2020 SPIE · CCC code:
0277-786X/20/$21 · doi: 10.1117/12.2569442

These alignment tolerances are on the order of micrometers rather as opposed to nanometer-scale tolerances that are expected with mirror segments. The MODE lens allows for the design and development of telescopes with larger apertures without the worry of needing nanometer-precision alignment mechanisms. Successful development of the MODE lens and enabling technologies (manufacturing, alignment, and bonding) opens up new astronomical opportunities such as the Nautilus mission concept which proposes the use of 8.4-m MODE lenses used in a space-based observatory.[4]

One of the enabling technologies that must be developed is a new mechanisms and alignment system that can prove that a MODE lens can be divided into segments and aligned within its required tolerances. To utilize other advantages of the MODE lens such as its unobscured aperture, the assembly procedure proposed in this paper requires the lens segments to be aligned, bonded together and mounted along the circumference of the lens. In this paper, we present the design and testing of the Kinematically-Engaged Yoked System (KEYS) which is used in the alignment step of this assembly process.

2. OPTO-MECHANICAL DESIGN OF KEYS

The KEYS alignment mechanism was developed using a segmented MODE-like lens (no diffractive Fresnel lens surface on the back of the lens) made of diamond-turned PMMA and 0.24-m in diameter as seen in Fig 1. The lens is divided into one central segment and 8 wedge segments.

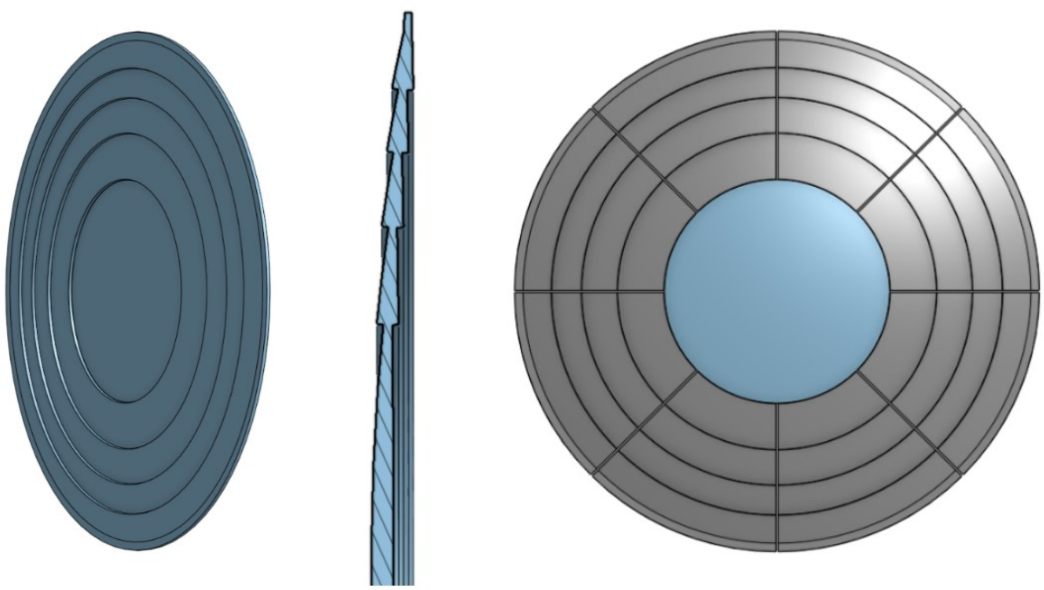

Figure 1. (left) A views of a 3D model of the prototype MODE-like lens before it was segmented, (center) a cross-section view showing the blaze profile of the MODE-like lens and (right) a top view showing how the MODE lens is segmented.

The KEYS alignment mechanism utilizes the step features of the blaze profile of the MOD (Multi-Order Diffractive) surface of the MODE lens in order to kinematically engage the lens segments. Each wedge segment is constrained and adjustable in five degrees of freedom with the rotation about the optical axis left unconstrained. Three of the degrees of freedom (tip, tilt, and piston) are controlled using ultra-fine thread adjustment screws that move parallel to the optical axis at different points on the wedge segment. As seen in Fig 2, two setscrews on the outermost blaze step contact the lens segment at two points while the set screw closer to the optical axis only contacts the segment at one point. This is a total of five points of contact and five degrees of freedom that are kinematically constrained.

The radial position of the wedge is controlled by moving the two outer setscrews per wedge radially. This is done using folded flexures[5] that the outer setscrews are mounted on. This is seen in Fig 3 which shows the base plate of the KEYS system on which the folded flexures are cut into. Using folded flexures allows for much simpler manufacturing as most the adjustment modules could be made out of one monolithic part mostly machined using water-jetting. The base plate was made out of 7075 aluminum in order to use an easily manufacturable material with a high strength to stiffness ratio which is beneficial for compliant mechanisms such as folded flexures.[6]

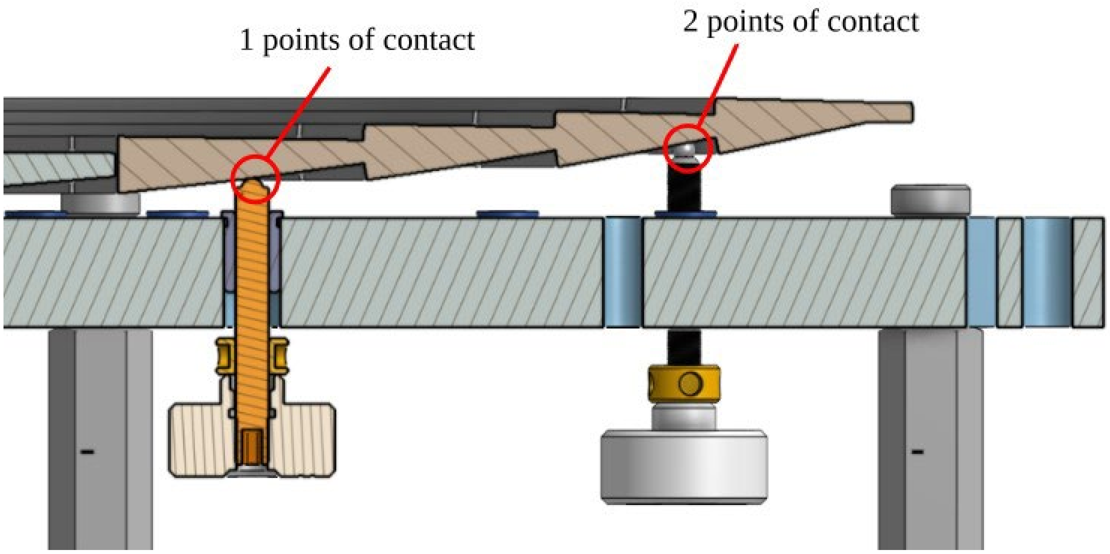

Figure 2. A section view of a 3D model of the KEYS system showing where the ball-ends of the set-screws contact the MODE-like lens segment. Note that the outer set of two setscrew ball-ends (one of which is not shown) contacts the lens at two points and the inner setscrew contacts it at one point

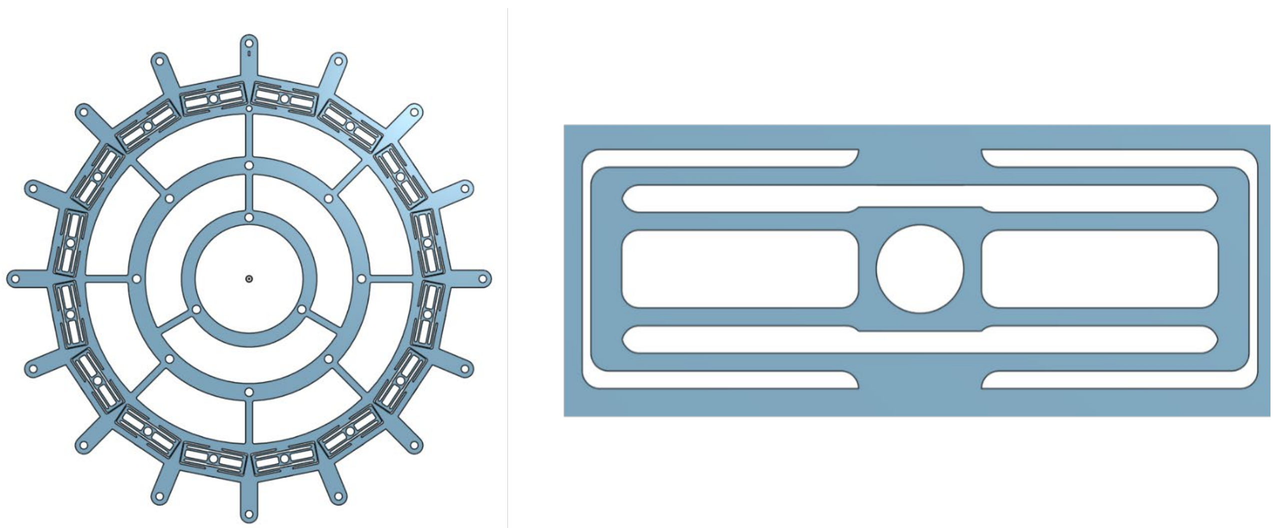

Figure 3. (left) The base plate of the KEYS system with 16 folded flexure elements (two per wedge lens segment) that move the outer setscrews radially and (right) a close up view of a single folded flexure.

The lens segments sit on the ball-end setscrews as shown in Fig 4. The setscrews that adjust the radial position by pushing on the folded flexures can also be seen here. The assembled KEYS system is also shown in Fig 4. A top plate is added to mount spring plungers which apply a preload to the lens segments so that it remains in contact with the ball-end setscrews.

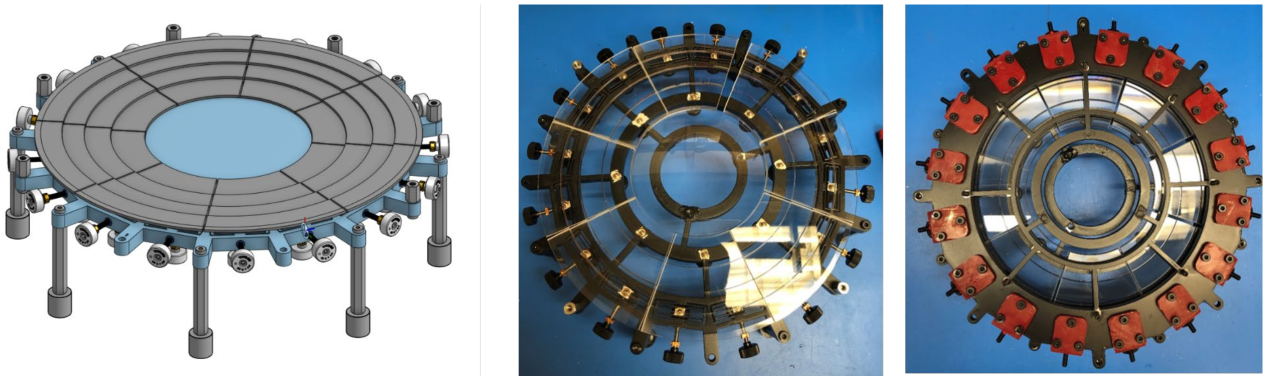

Figure 4. (left) A 3D model of the assembled KEYS system mounting the MODE segments without the top plate, (center) the assembled KEYS system without the top plate and (right) the assembly with the top plate. The top plate on which spring plungers are mounted for preloading the lens segments.

3. PROTOTYPE MODE SEGMENTS ALIGNMENT WITH KEYS

The initial alignment capability of the KEYS system was tested using a scanning white light interferometer (SWLI) and deflectometry. These tests show that the KEYS system can adjust the wedge segments within the tolerances needed for cophasing which is 25 μm between each segment and that the KEYS system has enough resolution to adjust the lens segments within the tolerances needed for tip/tilt which are 0.030°. For the SWLI test, a Zygo NewView was used to measure the height and angle difference at the gap of two segments after adjustment. The SWLI was used to measure and the further adjust the alignment in order co-phase all the segments. However, as can be seen in Fig 5, the top plate of the KEYS system makes it difficult to make measurements in all but a few locations on the optic.

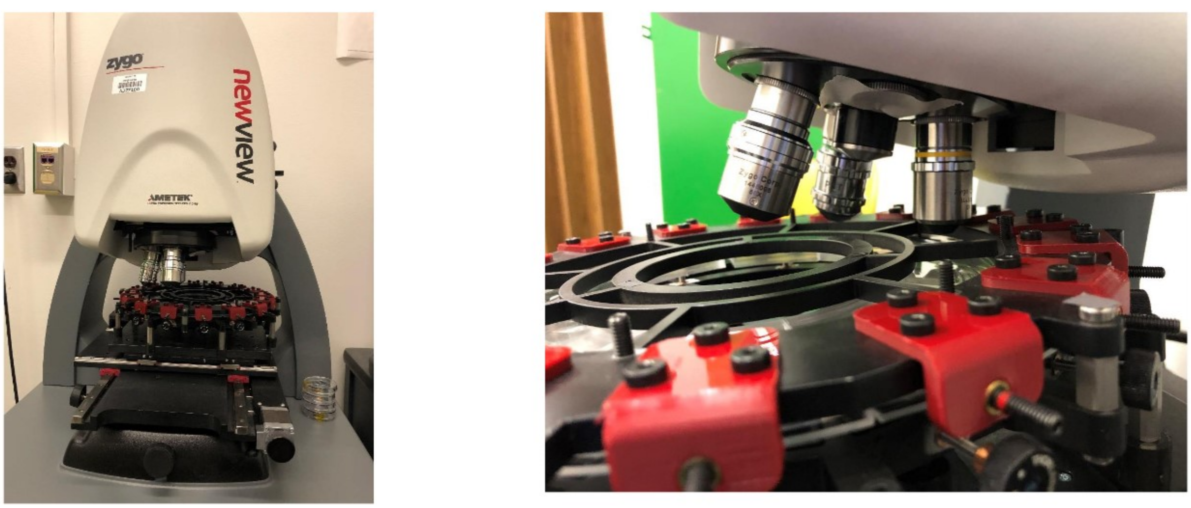

Figure 5. The KEYS system under the Zygo scanning white light interferometer.

Despite this difficulty, some initial measurements and validation could be done. The MODE lens segments were placed inside the KEYS system and the surface figure measurement was taken. The lens segments were then aligned as well as they could be in this current setup and another surface figure measurement was taken. The results are shown in Fig 6 and it is clear that after fine alignment, the height difference at the gap is within 20 μm which is within our cophasing tolerances (25 μm). Further improvements in the measurement and alignment setup will allow for easier alignment and very likely better alignment.

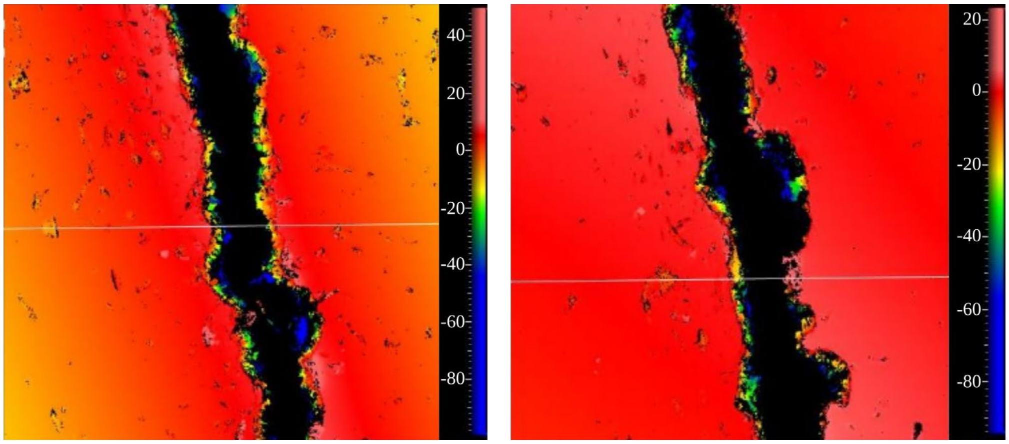

Figure 6. (left) The SWLI results after the lens segments immediately after they were placed inside the KEYS system and (right) SWLI results after fine alignment of the lens segments with the adjustment setscrews. It is clear that after fine alignment, the height difference at the gap is within 20 μm (without relative tip/tilt between the two segments) which is within our cophasing tolerances (25 μm).

Measurements using deflectometry were also performed as this measurement method has a wider field of view that could capture the full MODE lens and has a larger dynamic range.,[7,8] As can be seen in Fig. 7, the deflectometry setup consists of the KEYS system, a screen showing a sinusoidal pattern that modulates and a camera the captures the reflection off the MODE lens. There is significantly more room in this measurement setup to allow for manual adjustment for the setscrews and all the wedge segments can be measured simultaneously. While this deflectometry system cannot directly measure the cophasing between segments, the deflectometry system measures the slope angle of the segment compared to a previous orientation. This allows us to determine the resolution that the KEYS system is capable of for the tip/tilt measurements and adjustments. This setup will also be useful for monitoring a bonding procedure to fix the segments together once they are aligned. In the future software can be written to determine the cophasing between segments based on current hardware and measurements.

Figure 7. The deflectometry measurement system consisting of the KEYS (bottom), a screen with modulated sinusoidal pattern image (upper left) and a camera (upper center) to capture the reflection off the MODE lens segment surface.

Fig 8 shows the results of the initial segment orientation and the results after one of the segments is slightly perturbed using one of the tip/tilt adjustment screws.[9] We were able to adjust and measure a tilted angle of 0.006°. This successfully demonstrated resolution is less than the required tolerance on our tip/tilt orientation (i.e., 0.030°), so the KEYS system has sufficient resolution necessary to adjust them within the tolerances.

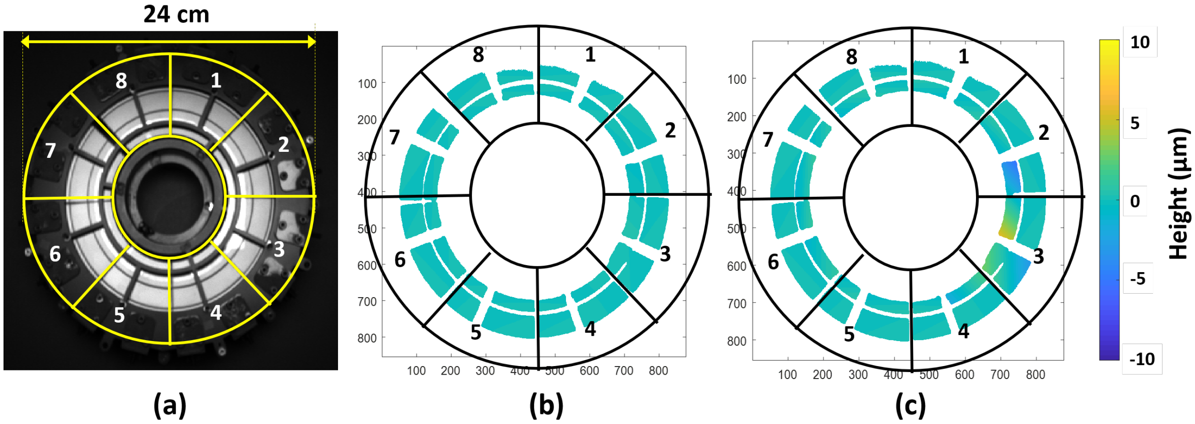

Figure 8. The real data from the metrology system (a) Live view from the camera. (b) All segments are well-aligned against initial co-phasing status. The black line represents the actual size of the single segment. Due to the obstacle of KEYS, it measures the opened area only but it is large enough to examine the misalignment. (c) Segment 3 drifted from the reference position and the measured tilting angle is 0.006°. (Note: The X and Y axis units of (b) and (c) are in pixels.) [9]

4. CONCLUSION AND FUTURE WORK

Initial testing of the KEYS system is very promising. Using the KEYS system allows us to kinematically constrain the wedge segments of the MODE lens and precisely adjust its position based on measurements using a scanning white light interferometer and deflectometry. The two design concepts of (1) using ball-end setscrews to kinematically constrain the segments and (2) the folded flexure to radial adjust the position of the wedge segments will likely be maintained through future iterations of the KEYS system. However, improvements can be made such as developing a method to apply preload to the lens segments without the need for a top plate. This will allow for measurement of the whole surface of the MODE lens and make measurements with the scanning white light interferometer more feasible. The folded flexures could also be moved further out radially to allow for a more open aperture. This will make optical tests (such as a star test) easier to perform. Lastly, the center segment (non-wedge) segment will be mounted in place using a removeable adhesive so that the wedge segments can be aligned relative to it using the KEYS system before all the segments are bonded together.

ACKNOWLEDGMENTS

The authors would like to acknowledge the Gordon and Betty Moore Foundation for their financial support of the development of the MODE lens and it's enabling technologies. Special thanks go to Ariel Lamdan for his assistance in the assembly of the KEYS system and the deflectometry measurement system, Tom Milster and Young-sik Kim for their assistant with concepts related to the MODE lens and the rest of our peers in Large Optics Fabrication Testing (LOFT) group who provide helpful insights and morale support every day.

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