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Manufacture of 8.4 m segments for the GMT primary mirror

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ABSTRACT

The Richard F. Caris Mirror Lab at the University of Arizona continues production of 8.4 m lightweight honeycomb segments for the primary mirror of the Giant Magellan Telescope. GMT will have a center segment surrounded by six off-axis segments, plus an additional off-axis segment to allow continuous operation as segments are removed for coating. The second off-axis segment was completed and accepted in 2019. We are currently polishing the optical surface of off-axis Segment 3. We have completed work on the rear surfaces of Segment 4, the center segment, and off-axis Segment 5. We are assembling the mold for off-axis Segment 6 with the spin-casting scheduled for March 2021.

Keywords: Giant Magellan Telescope, telescopes, optical fabrication, optical testing, off-axis, aspheres

1. INTRODUCTION

Not quite 100 years ago, Edwin Hubble used the new 100 inch Hooker Telescope at Mt. Wilson, the world's largest, to make two discoveries that revolutionized our understanding of the Universe. Hubble's identification of a Cepheid variable star in the Andromeda Nebula, in 1923, definitively established that the Universe extends far beyond the Milky Way. By 1930 Hubble's determination of distances to galaxies had expanded the Universe by more than a factor of 1000 in distance, and Hubble was able to combine his distances with redshifts measured by Slipher and Humason to demonstrate the expansion of the Universe.[1]

Hubble made these discoveries within a dozen years of commissioning of the Hooker Telescope, which had 2.8 times the collecting area of the 60 inch telescope at Mt. Wilson but little or no improvement in angular resolution, limited by seeing. Today, construction is underway for a new generation of telescopes that are roughly twice the diameter of existing telescopes and bring at least the same improvement in sensitivity that Hubble was able to exploit. What's more, with adaptive optics becoming routine at infrared wavelengths and gradually moving to visible wavelengths, the new telescopes will also have much better angular resolution. They are among the first telescopes to have adaptive optics built into the basic design and to anticipate diffraction-limited performance in many observing modes. The combined improvements in sensitivity and resolution are unprecedented. Dramatic discoveries are unpredictable, but we shouldn't be surprised to see some drama in the next two decades.

The 25 m GMT[2],[3] is one of this new generation of telescopes. Its primary mirror consists of seven 8.4 m lightweight honeycomb mirrors, setting GMT apart from the Thirty Meter Telescope[4] with 492 1.4 m segments and the European Southern Observatory's 39 m ELT[5] with 798 1.4 m segments. The honeycomb design provides the stiffest and lightest large mirrors ever made, minimizing deflections due to gravity and wind. The use of 8.4 m segments guarantees a smooth wavefront over large fractions of the aperture and, together with the segmented adaptive secondary mirror, simplifies alignment and phasing of the telescope. The primary mirror segments are being made at the Richard F. Caris Mirror Lab at the University of Arizona. The first two off-axis segments are finished and Segments 3-6 are in different stages of manufacture. Segments are numbered in order of casting; Segment 4 is the center segment.

The six identical off-axis segments present significant challenges in fabrication and optical testing. Each segment has 13 mm p-v aspheric departure, primarily astigmatism. Among other challenges, the interferometric test has a 3-element off-axis null corrector that includes a 3.75 m curved mirror and has overall dimensions exceeding 8 m.[6],[7] To mitigate the risk of a mistake in the interferometric test, we have multiple independent measurements of critical parameters including radius of curvature, off-axis geometry and low-order aberrations (astigmatism, coma, trefoil and spherical aberration). These tests are housed in a 28 m vibration-isolated test tower.

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2. STATUS OF SEGMENT PRODUCTION

Completion of the first off-axis segment in 2012 represented a major technology demonstration for the GMT. The next challenge was to improve the production rate to match the telescope schedule. We made a number of improvements in methods and equipment for fabrication and testing during and after the manufacture of Segment 1.[8],[9] These improvements led to much more efficient figuring of Segment 2, which we polished in less than half the calendar time of Segment 1. We have continued to adjust the process based on the experience with Segment 2. Figuring of Segment 3 is proceeding at a good pace in spite of limitations related to Covid, and the production schedule is now consistent with the telescope project timeline.

Figure 1 shows Segment 3 being polished with a 40 cm pitch lap. We use laps of different sizes, shapes and construction, but all are driven in an orbital motion. Figure control is achieved by varying the dwell as a function of position on the mirror. The stiffer pitch laps provide passive smoothing of structure on scales smaller than the lap, but are subject to misfit due to the large curvature variations across the mirror surface. We design the laps and polishing strokes so that plate flexure and pitch flow accommodate these curvature changes.

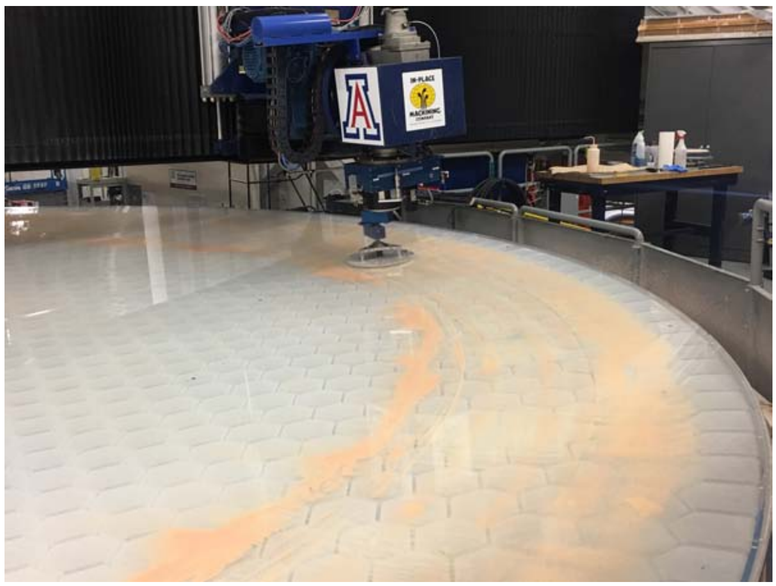

Figure 1. GMT Segment 3 being polished with a 40 cm pitch lap on an orbital polisher.

We cast Segments 2 and 3 in 2012 and 2013. Segment 2 was finished in 2018 with acceptance tests completed in 2019. We project completion of Segment 3 in mid-2021. The long interval between casting and finishing these two segments included fabrication of the 8.4 m combined primary and tertiary mirrors for the Large Synoptic Survey Telescope[10], generating the 6.5 m primary mirror for the Tokyo Atacama Observatory, and major upgrades to our 8.4 m generating and polishing machines.

Figure 2 shows the results of the fabrication process for Segments 1 and 2. The plots show the surface error after we simulate the active optics correction that will be made at the telescope. Both segments meet the accuracy requirements, which are specified in terms of the wavefront structure function, giving allowed error as a function of spatial scale. Segment 2 is somewhat more accurate in mid-scale structure. More significantly, the fine grinding and polishing operations took less than half the time for Segment 2.

Segment 4, the center segment, was cast in 2015 and Segment 5 in 2017. We have completed work on the rear surfaces of both segments, including bonding the 165 loadspreaders that form the interface between the mirror and its support system. Figure 3 shows Segment 5 shortly after the furnace was opened following the spin-casting, and Figure 4 shows Segment 5 after bonding of the loadspreaders.

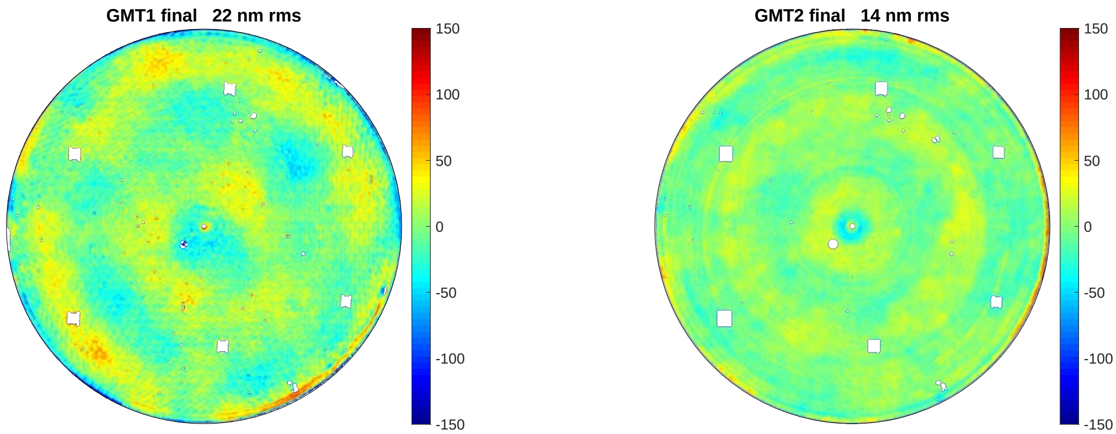

Figure 2. Finished surfaces of GMT Segments 1 and 2. Plots show surface error in nm, after simulated active optics correction using segment alignment and 27 bending modes. These corrections use a small fraction of the available motion and actuator force range.

Figure 3. Measurement of the thickness of the facesheet after the spin-casting of GMT Segment 5. Photo by Ray Bertram, University of Arizona.

We are currently assembling the mold for off-axis Segment 6 with the spin-casting scheduled for March 2021. We have purchased 20 tons of Ohara Corporation's E6 borosilicate glass for Segment 7.

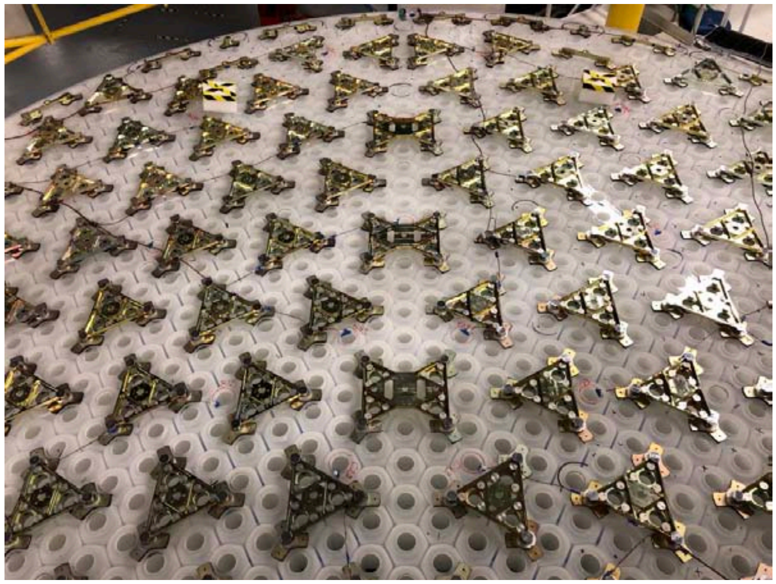

Figure 4. Rear surface of Segment 5 showing some of the 165 loadspreaders. In the telescope, each loadspreader is the interface to a 3-axis (axial + 2 lateral) pneumatic actuator.

3. VALIDATION OF OPTICAL TESTS

The test systems for GMT segments are large and complex, and have tight alignment tolerances. Sensitivities to alignment errors are much greater for the off-axis segments than for comparable axisymmetric mirrors. In addition, in order to form a single 25 m near-parabolic primary mirror, the segments require essentially identical radii of curvature after an active-optics correction. The limited range of active correction then implies that each segment's radius must be controlled to about 0.5 mm, just over one part in 10^4, during manufacture. In addition to radius of curvature, low-order aberrations through spherical are sensitive to alignment errors in the tests and are therefore most vulnerable to a mistake in any one test. While we can show on paper that each test meets its accuracy requirements, the only way to have sufficient confidence in the accuracy of the finished mirror is to have independent measurements of all critical parameters and to require agreement among multiple tests. This agreement guarantees that the mirror surface can be corrected with active optics in the telescope to eliminate low-order errors and leave only mid-scale and small-scale errors of about 20 nm rms. The independent tests are listed below.

- The interferometric test, or principal test, measures the full aperture on all spatial scales down to its 10 mm sampling, as well as radius of curvature.[6],[7] It uses a large null corrector—comprising a 3.75 m spherical mirror, a 0.76 m sphere, and a computer-generated hologram—to shape the test wavefront to match the ideal off-axis surface with its 13 mm p-v aspheric departure.
- The scanning pentaprism test is the main independent verification of off-axis geometry and large-scale figure.[11]-[13] It synthesizes a star test by illuminating the segment with a narrow collimated beam parallel to the telescope's optical axis and scanning the beam across the segment in multiple cuts. A detector at the telescope's prime focus measures the motion of the focused spot, which is proportional to the slope error on the segment. We use the slope data to determine the radius of curvature, astigmatism, coma, trefoil and spherical aberration.
- The Laser Tracker Plus (LT+) system is a scan of the full surface with a laser tracker, with stability references to eliminate the effects of rigid-body motion.[14],[15] LT+ works with a ground or polished surface. It is accurate to about 1 μm rms surface (including all aberrations) and 0.4 mm in radius of curvature.

A fourth test, the Software Configurable Optical Test System (SCOTS), is a deflectometry system that measures slopes over the full aperture with high spatial resolution and dynamic range.[16],[17] The slopes are integrated to give a full surface measurement with high accuracy for periods up to 2-3 m. SCOTS is especially valuable in early stages of polishing because it can measure a much larger range of slope error than the interferometer. It is less sensitive to large-scale structure with small slope errors, so is not used to validate the measurement of radius of curvature and low-order aberrations.

The final measurements of Segment 1 in 2012 showed agreement among the tests, within the expected uncertainties.[18] Prior to polishing and measuring Segment 2, we verified the accuracy of the test systems by re-measuring Segment 1 in 2017.[9] These measurements showed good agreement with the 2012 acceptance tests and good agreement among the three tests. Finally, the acceptance tests for Segment 2 in 2019 gave good agreement among the three tests. Figure 5 shows the results of the Segment 2 acceptance tests for radius of curvature and astigmatism. Uncertainties in astigmatism are much larger than for a symmetric mirror because of the high sensitivity to alignment, but astigmatism is easily corrected with active optics (bending the mirror), so these uncertainties are well within the acceptable limits.

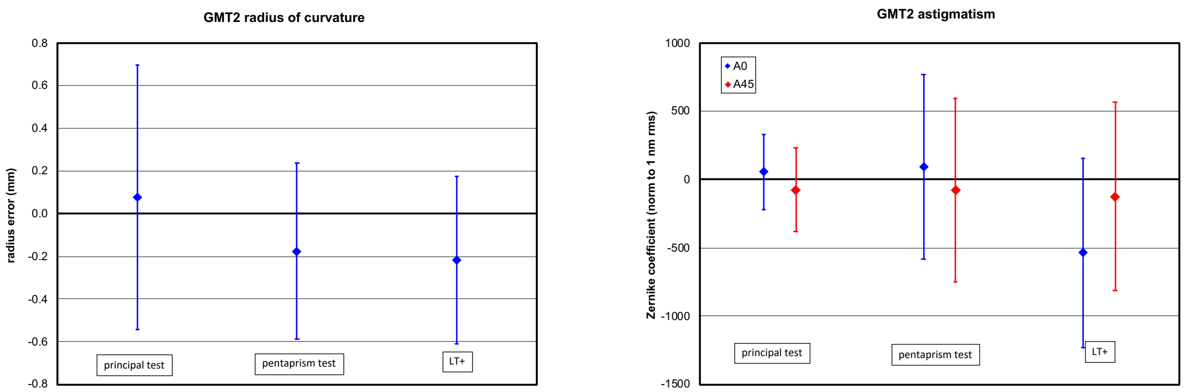

Figure 5. Measurements of radius of curvature and two components of astigmatism with three independent tests, as part of the acceptance tests of GMT Segment 2. Error bars represent 2-σ uncertainties. The nominal radius of the parent is 36 m. For all 3 tests the radius is determined from a distance measurement and the Zernike focus aberration.

4. SPIN-CASTING OF SEGMENT 6

The spin-casting process has been described in [19] and [20], and can be viewed in a video at https://mirrorlab.arizona.edu/content/gmt-giant-magellan-telescope. Almost all aspects are unchanged since the first 8.4 m LBT mirror was cast in 1997.

The mold consists of a tub of silicon carbide cement, wrapped with Inconel steel bands to support its cylindrical wall, and lined with ceramic fiber. For a GMT off-axis segment, the cavities in the honeycomb mirror are formed by 1681 ceramic fiber boxes (Figure 6). Each box is bolted to the floor of the mold with silicon carbide hardware and a ceramic fiber spacer to hold the box 30 mm above the floor. The ceramic fiber (from Rex Materials, machined to final dimensions at the Mirror Lab) does not interact chemically with the glass, so it can be separated from the glass safely after the casting. The tops of the boxes follow the optical surface so the finished mirror will have a uniform facesheet, 28 mm thick. This means all 1681 boxes are unique, but the shapes have mirror symmetry across an axis that runs through the center of the parent surface.

The mold is pre-heated twice, once with the silicon carbide tub and steel bands, and once after installing the ceramic fiber pieces, in order to stabilize its dimensions. The glass—Ohara E6 low-expansion borosilicate—is then placed on top of the mold (Figure 7). For a GMT segment, 17,500 kg of glass is placed on the mold; grinding will reduce the mass of the finished mirror to about 16,000 kg. The E6 glass is extremely uniform in expansion coefficient, which essentially eliminates distortion due to the change from lab temperature to operating temperature. A significant advantage for our process is that Ohara delivers the glass as blocks broken out of a set of one-ton melts. All surfaces are pristine fracture surfaces which melt together seamlessly in the honeycomb mold, leaving no trace of the original blocks.

The mold is enclosed in a furnace with electric coil heaters in the floor, walls and ceiling. It is heated over a few days to 1165°C, where the glass has the consistency of cold honey. In a few hours the glass flows down the 12 mm gaps between boxes to form the ribs of the honeycomb mirror, and under the boxes to form the flat backplate. The furnace starts spinning before the glass starts to soften at 900°C and continues to spin until the glass is completely solid again. Spinning produces a symmetric parabolic surface. The rotation rate of 5 rpm gives roughly the best-fitting paraboloid with $R = 37$ m. The off-axis optical surface, with its 13 mm p-v astigmatism, will be produced by diamond generating, which also removes several mm of excess glass.

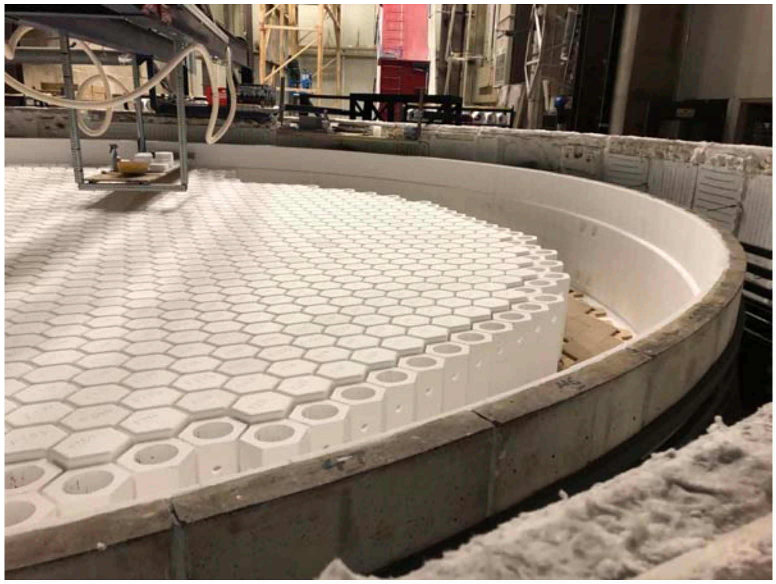

Figure 6. Nearly completed mold for casting GMT Segment 6.

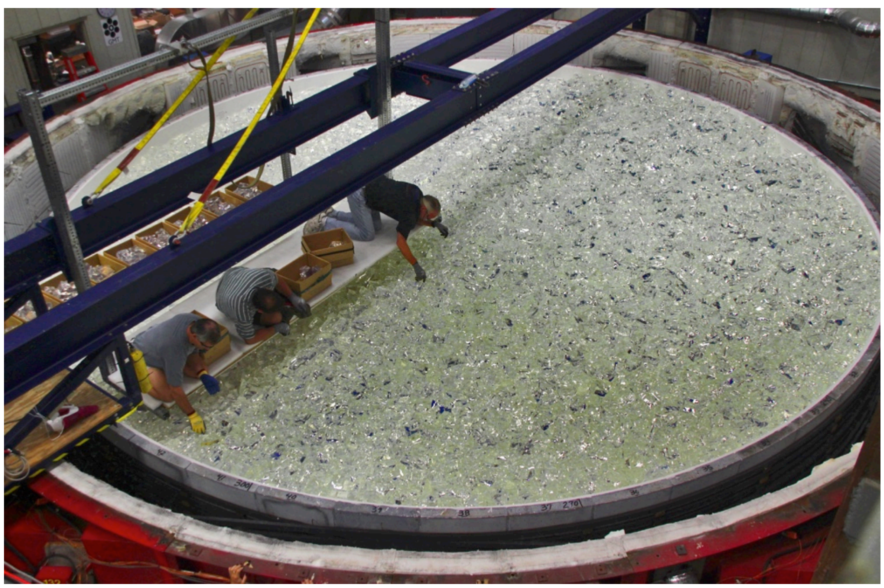

Figure 7. Placement of Ohara E6 glass blocks on the mold for GMT Segment 3. Photo by Ray Bertram, Steward Observatory.

The mirror cools and anneals for 85 days. The cooling rate is only 3 K/day through the annealing range, 530-450°C, in order to minimize the temperature gradients that will become density gradients with stress after the mirror reaches uniform temperature. Once the mirror cools to lab temperature, we remove the furnace in pieces and remove the mold's outer tub wall. At this point we can inspect the mirror's front facesheet and outer wall, but inspection of the internal structure has to wait until the floor of the mold and the ceramic fiber boxes are removed from inside the honeycomb.

To gain access to the back of the mirror for removal of the mold, we lift the mirror with a steel frame and turn it into a vertical plane. Most of the silicon carbide floor tiles and all of the ceramic fiber boxes are still attached, nearly doubling the weight supported. The lifting frame bonds to the mirror's front surface with compliant adhesive on 36 disks (Figure 8). The silicon carbide floor pieces and associated hardware are removed first. This leaves a 90 mm hole in the backplate at the center of each honeycomb cell. We insert high-pressure water nozzles through these holes to break up the ceramic fiber and wash it out of the mirror. (The same holes are used to ventilate the mirror in operation at the telescope.) At this point we have a lightweight glass structure with the desired mechanical and thermal properties.

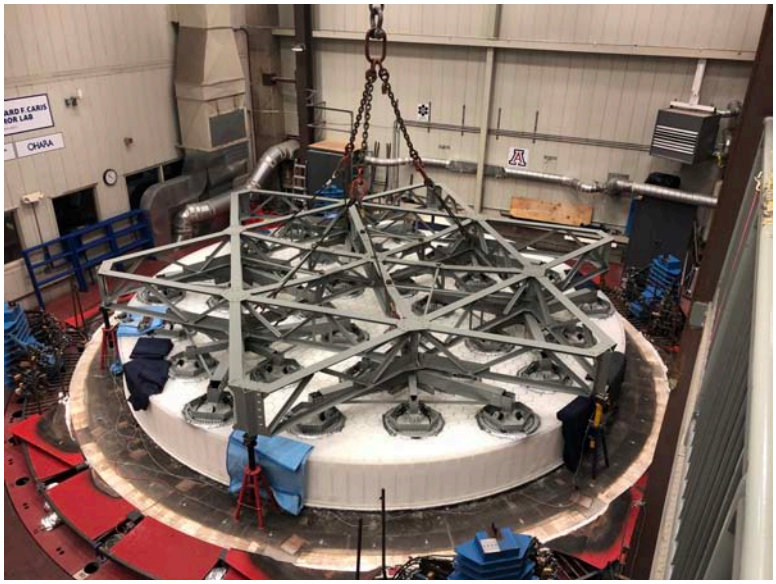

Figure 8. GMT Segment 5 prepared for the lift off of the furnace hearth following the spin-casting. The lifting fixture is bonded to the front surface with compliant adhesive applied to 36 disks.

5. CONCLUSION

The Mirror Lab continues a vigorous program to produce primary mirror segments for GMT. The first two off-axis segments are finished and four more segments are in various stages of manufacture. Recent achievements include the successful casting of Segment 5 in 2017 and completion of Segment 2 in 2018. Upgrades to the generating and polishing systems have resulted in greatly improved polishing convergence for Segments 2 and 3. We are preparing to cast Segment 6 in March 2021. We anticipate completion of the remaining segments on a schedule consistent with the telescope project timeline.

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