Lawrence Livermore, Ball Aerospace and Technologies Corporation, and NeXolve Corporation are preparing diffractive membrane optics for the Membrane Optic Imager Real-Time Exploitation (MOIRE) project.

Developing Lightweight Optics for Space

A general rule for telescopes is that bigger is better. Improving our ability to view dim and distant objects, or see finer details on nearer objects, requires a telescope with better resolution and more light-gathering power, which generally means a bigger aperture. With no atmospheric distortion to affect the resolution of large-aperture space-based telescopes, the sky is the limit. Scientists are only restricted by the practicalities of device fabrication and transportation. Because the materials must be transported to space at great cost and effort, strict limits are imposed on the size and weight of the telescope optics, structures, and other components.

When the National Aeronautics and Space Administration's next-generation James Webb Space Telescope is launched in 2018, it will have a segmented aperture with a diameter of 6.5 meters—seven times the light-collecting area of the Hubble Space Telescope. As early as 1996, though, Lawrence Livermore physicist Rod Hyde was working on a design that would take advantage of the Laboratory's expertise in optics design and fabrication to put a much larger telescope—with a 20-meter-diameter aperture—into space. (See *S&TR*, March 2003, pp. 12–18.) To make this possible, Hyde and his colleagues seemingly took a step backward in telescope technology.

High-performance telescopes such as Hubble and the future Webb typically are reflective telescopes, meaning their primary optical element is a curved mirror. In contrast, a transmissive telescope consists of a long tube with a lens (rather than a mirror) at one end to collect and focus light and an eyepiece at the other through which to look. Optics for transmissive telescopes are significantly less sensitive to surface imperfections than mirrors, but standard transmissive lenses are far too heavy for transporting to space. Pairing transmissive telescope technology with diffractive optics—a notable manufacturing strength for the Laboratory—would allow researchers to lighten the launch load.

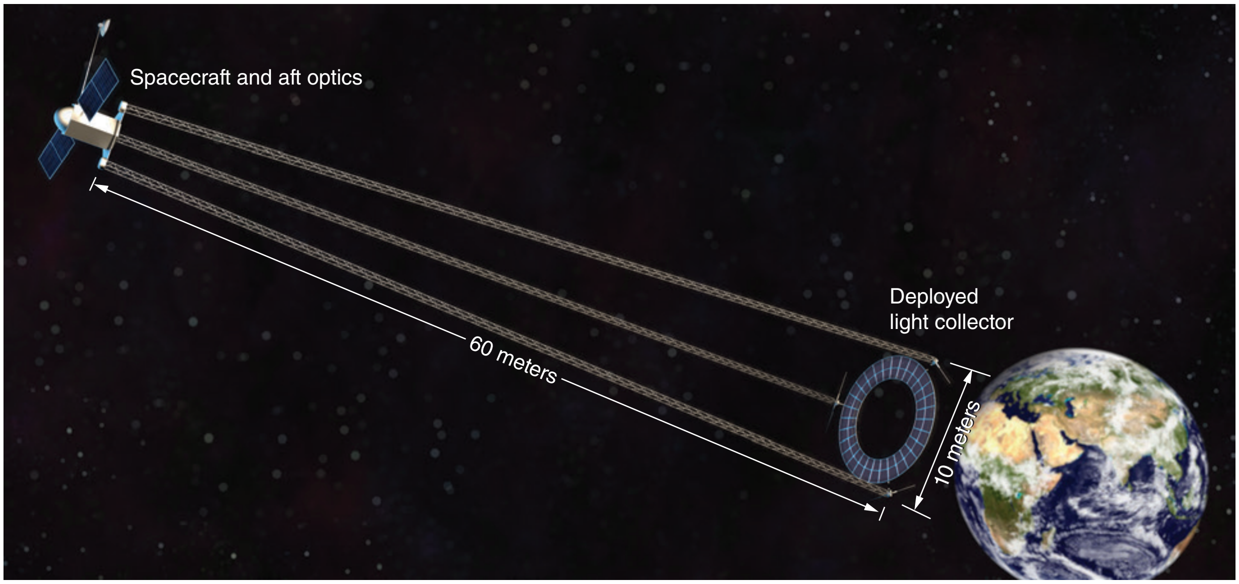
Transmissive diffractive optics, also called Fresnel lenses, are patterned on one surface, with features often too small to be visible to the naked eye. These tiny, patterned features are tailored to bend light of particular wavelengths. (See *S&TR*, September 1995, pp. 24–33.) The height of these surface features is on the order of the wavelength of light. Because light is focused by the surface features and not by refraction of bulk glass, diffractive lenses can be made far thinner and lighter than standard lenses. The disadvantage of diffractive optics–based telescopes is their extremely limited bandwidth. A diffractive light collector focuses the various wavelengths of light at different points in space, severely limiting the light signal at the focal plane. Fortunately, incorporating a second, inverse diffractive lens with a pattern carefully matched to the light collector corrects these focusing aberrations and provides enough photons at the focal plane for imaging.

Fitting a 20-meter-diameter sheet of glass, no matter how thin, into a rocket was infeasible, so Laboratory researchers designed a segmented lens that could be neatly folded for transport and then opened on arrival in orbit. With funding from the Laboratory Directed Research and Development Program and the Defense Advanced Research Projects Agency (DARPA), they built a 5-meter primary lens called Eyeglass to test how well the components folded, unfolded, and assembled. Livermore's diffractive optics group, led by optics engineer Jerry Britten, fabricated the precision meter-scale diffractive optics segments that the design required. The prototype, completed in 2002, generated interest. However, perceived risk and budget constraints prevented a large-scale follow-on, and the project was dormant for nearly a decade.

A New, More Flexible Eyeglass

In 2010, DARPA held a design competition to demonstrate technology for a video imaging system in geosynchronous Earth orbit. The DARPA project, Membrane Optic Imager Real-Time Exploitation (MOIRE), called for a large-aperture transmissive diffractive optical space telescope that could image an area greater than 100 square kilometers with a video update rate of at least one frame per second. Ball Aerospace and Technologies Corporation, together with the Laboratory and NeXolve Corporation, was selected by DARPA to prepare a design for MOIRE that would demonstrate the manufacturability of a light-collecting lens, the structures to hold the optics tight and flat, and the additional optical elements needed to turn a diffraction-based optic into a wide-bandwidth imaging device. Lawrence Livermore's area of responsibility is diffractive optics fabrication.

In many ways, MOIRE is a direct successor to Eyeglass. Perhaps the most significant differences between the two efforts are in the optical material and manufacturing techniques. Glass



Upon arrival in orbit, the MOIRE spacecraft would deploy solar arrays, unfold the telescope tube, and then unfurl a micrometer-thin, diffractive optic membrane to form a massive segmented light collection lens (not to scale). (Rendering by Ryan Chen.)

offers excellent optical properties, but concerns about the launch survivability of large, thin glass plates, along with a desire to minimize weight, drove researchers to select a lightweight, packable, flexible membrane material for MOIRE optics. The NeXolve-created polyimide membrane is virtually weightless and a mere 20 micrometers thick, with a near-zero coefficient of thermal expansion. Significant temperature fluctuations in space would cause materials with high coefficients of thermal expansion to stretch significantly and thereby distort images.

A transmissive telescope typically requires vastly greater distances for focusing than reflective telescopes. Eyeglass designers initially intended to put the light-collecting lens into orbit several kilometers from the eyepiece and other electronic components. However, launching two spacecrafts and keeping them precisely aligned with one another would have introduced additional complexity and risk.

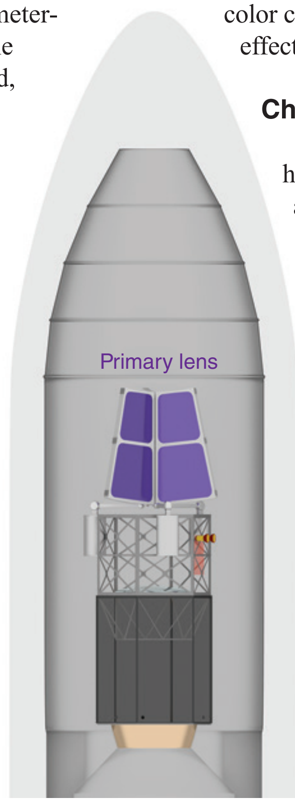
A change to the manufacturing process allowed the MOIRE team to shrink the length of the telescope. Says Britten, "With Eyeglass, we used a wet-etching process and were limited to approximately 10-micrometer-wide optical surface features. With an ion mill, we can now create high-fidelity, submicrometer features on meter-scale optics." Using equipment and techniques developed to create large diffraction gratings for the National Ignition Facility and its Advanced Radiographic Capability (see *S&TR*, December 2011, pp. 12–15), the diffractive optics group was able to shorten the required focal length for a 10-meter-diameter telescope to about 60 meters. Furthermore, the MOIRE team's design calls for a single-launch payload, significantly reducing both risk and transport costs.

Delivering Precision Optics

The word *moiré* refers to an interference pattern, such as one used during the fabrication of diffractive optics. It is an appropriate name for a project where diffractive optics are central to success. The process for creating each of MOIRE's diffractive optical segments is complex and takes several weeks because of the sheer size of the optics.

Pattern transfer begins with fabricating a master pattern in chrome on glass. A membrane surface is then covered uniformly with a photosensitive coating, and the master pattern is placed similar to a stencil over the membrane. When the photosensitive coating is exposed, a pattern is created in the coating. Finally, the pattern is transferred permanently into the membrane using an ion-beam etcher, and the coating is stripped off. The result is a membrane surface that is patterned with precisely spaced grooves of uniform depth.

Working with Ball and NeXolve, Britten's group has manufactured optics for two phases of the multiyear MOIRE project. Membranes were supplied by NeXolve and printed and etched at the Laboratory. For the first phase of delivery, completed in mid-2011, the diffractive optics experts created a sample 80-centimeter-diameter off-axis circular diffractive optical element with 4-micrometer-wide features that will serve as one segment in the giant light-collecting lens. Britten's group and the team at Ball tested the accuracy and precision of the master pattern and pattern transfer with promising results. Diffraction efficiency was measured at better than 30 percent, approaching the approximate 35-percent theoretical maximum efficiency for the design. This performance established confidence in the MOIRE team's ability to fabricate precision large-scale membrane optics. For the Laboratory's contribution to Phase 2, to be completed in early 2013, team members have significantly scaled up optics production. They will deliver six 80-centimeter-diameter trapezoidal optics that comprise one-eighth of the ring-shaped primary lens, several spare optics, and the smaller optical components at the "back end" of the telescope—diffractive color correctors that turn a transmissive telescope into an effective imaging device.

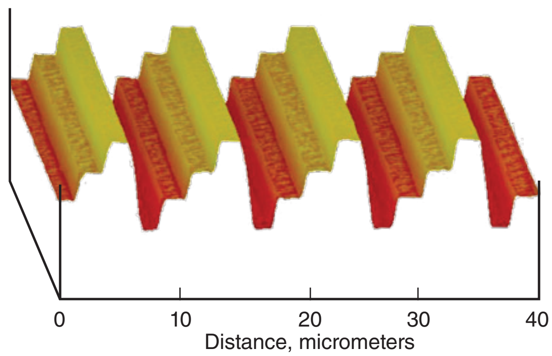


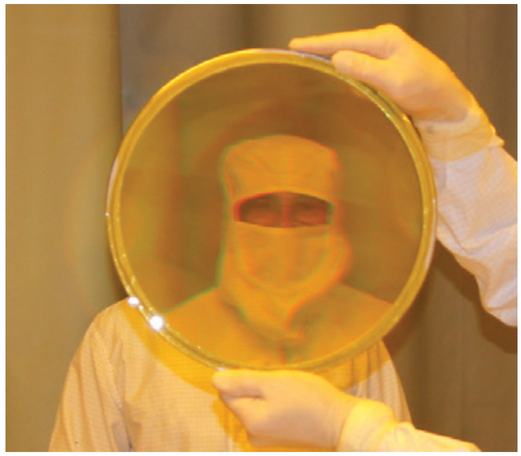
Lightweight, flexible, packable optics and other telescope components are essential for the launch to geosynchronous orbit. The MOIRE primary lens at the top of the rocket is designed to fold similar to an umbrella for launch and transport.

Challenges and Enhancements

While membrane optics are lightweight and flexible, handling and etching a pattern in the surface of a material analogous to household plastic wrap has posed significant challenges throughout the project. The material may undergo almost no thermal expansion, but it does have a large moisture expansion coefficient, meaning that it expands and contracts substantially as humidity levels change. This behavior can distort the diffraction pattern or shift the built-in alignment fiducials that match up the lens segments.

Fortunately, an effort is under way to quantify and anticipate membrane behavior. The group has noted, for instance, that the photoresist-coating process consistently causes the material to stretch and sag. Understanding this effect will allow the diffractive optics group to compensate for it in the master pattern or correct for it through adaptive optics—in effect, to create a corrective lens for the telescope. The researchers are also experimenting with optimal methods of mounting the membrane and maintaining





(left) Three-dimensional atomic force microscopy (AFM) is used to image the surface of a four-level glass master optic. The vertical scale (690 nanometers high) and sidewall slope is exaggerated by software and the AFM tip width, respectively. (right) With a four-level etched membrane pattern, light is diffracted in one direction, producing a single offset image of optics engineer Jerry Britten.

tension to improve smoothness and radial uniformity throughout the manufacturing process.

The diffractive optics group, in conjunction with NeXolve, has also engaged in a more ambitious research effort. The researchers want to improve imaging quality by changing the diffraction feature shape of the primary light collector and thereby increase light transmission and reduce background noise. This risk-reduction demonstration, performed in addition to the Phase 1 and 2 optics delivery, has entailed switching from a two-level pattern, which splits most of the light into two paths, to a four-level stepped pattern, which concentrates the light into the imaging path while simultaneously reducing stray light, thus increasing the signal-to-noise ratio of the telescope. Patterning multiple levels of features requires two rounds of masking and etching with submicrometer accuracy, a process deemed virtually impossible to perform on an unstable membrane surface. Instead, the partners decided to fabricate a membrane with the complex pattern built into it from the start.

Preliminary testing with NeXolve confirmed the feasibility of the idea, and the equipment used to write the chrome mask pattern was upgraded so it could generate the more complex features. The Laboratory's diffractive optics group then proceeded to fabricate a glass master optic patterned with the four-level stepped structure. Using the master, NeXolve created replica membranes with the negative of this pattern formed in the surface during manufacturing. The first round of membranes has demonstrated impressive performance and confirmed that the Livermore and NeXolve team can produce sophisticated multilevel patterns at the requisite scale. Diffraction efficiency has risen from 35 to 55 percent, and background noise from stray light has been cut from 30 percent to less than 1 percent.

MOIRE Takes Flight

Phase 2 of MOIRE culminates in April 2013 with an integrated demonstration of a partial 5-meter-diameter ground-based telescope. If this demonstration achieves its goals, launch and deployment of a 10-meter-diameter telescope with more efficient diffractive optics in geosynchronous orbit could follow. That telescope would weigh an astonishing seven times less than a reflective telescope of the same size. While more work must be done before MOIRE reaches the skies, Lawrence Livermore's optics fabrication expertise has helped to successfully demonstrate that a large diffractive membrane optic can be used as a building block for developing a lightweight, segmented-aperture telescope. Laboratory investment in optics research and manufacturing infrastructure made as part of National Ignition Facility construction has confirmed its value yet again with the MOIRE effort.

If MOIRE is successful, other lightweight transmissive space telescopes are likely to follow, with scientific, defense, or even communications missions. Although MOIRE is a telescope that will look down at Earth rather than at distant stars, the principles are the same for both. The eventual goal for MOIRE, like Eyeglass before it, is a space telescope with a 20-meter-diameter lens. With a space telescope of that size, astronomers could observe weather patterns on Saturn with 100-kilometer resolution or planetary nebula 600 light years away with 1-astronomical-unit resolution. For a project that not long ago looked to be relegated to the annals of astronomical engineering history, the future is looking bright.

—Rose Hansen

Key Words: Defense Advanced Research Projects Agency (DARPA), diffractive optics, Eyeglass, Fresnel lens, James Webb Space Telescope, membrane optics, Membrane Optic Imager Real-Time Exploitation (MOIRE) project, space telescope.

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