Design of a laboratory testbed for external occulters at flight Fresnel numbers

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ABSTRACT

One of the main candidates for creating high-contrast for future Exo-Earth detection is an external occulter or starshade. A starshade blocks the light from the parent star by flying in formation along the line-of-sight from a space telescope. Because of its large size and scale it is impossible to fully test a starshade system on the ground before launch. Instead, we rely on modeling supported by subscale laboratory tests to verify the models. At Princeton, we are designing and building a subscale testbed to verify the suppression and contrast of a starshade at the same Fresnel number as a flight system, and thus mathematically identical to a realistic space mission. Here we present the mechanical design of the testbed and simulations predicting the ultimate contrast performance. We will also present progress in implementation and preliminary results.

Keywords: External Occulters, Starshade, High Contrast Imaging, Exoplanets, Laboratory Scaling

1. INTRODUCTION

Most extra-solar planets are detected by using indirect observation such as the radial velocity method, transit photometry, and microlensing. However, there is increasing interest in the atmospheric composition of extra-solar planets and in the discovery of bio-signatures. This information can only be obtained by direct imaging. The main challenge with the direct observation of Earth-like extra planets is that the planet is $10^{10}$ fainter than the parent star and the angular separation between the parent star and the planet is minimal.

Many approaches have been suggested over the last couple of decades for imaging these planets. One of the main candidates for creating high-contrast for future Earth-like planets detection is an external occulter or starshade. Figure 1 shows the external occulter concept. The occulter is a spacecraft flown along the line-of-sight of a space telescope to suppress starlight and enable high-contrast direct imaging of exoplanets. Several designs have been proposed ranging from flagship-class such as THEIA and the NWO to probe-class such as O3 and NWP. The occulters are typically tens of meters in diameter and the separation from the telescope is of the order of tens of thousands of kilometers.

![Figure 1. Schematic diagram of external occulter mission concept. The occulter is placed along the line-of-sight of a space telescope and target star to suppress starlight and enable high-contrast direct imaging of exoplanets.](image-url)
Optical testing of a full-scale occulter on the ground is impossible because of the long separations. Therefore, laboratory verification of occulter designs is necessary to validate the optical models used to design and predict occulter performance. Laboratory scaled experiments have been ongoing at Princeton for several years\textsuperscript{6,7}. The limitations of the size of our previous laboratory forced a scaled design that was equivalent to a significantly larger space occulter and an extremely large telescope, with a correspondingly much larger inner working angle. This design has an equivalent Fresnel number of 607.3, compared to the typical mission being considered with a Fresnel number of roughly 15. The consequence of this disparity is a highly over-resolved image that can produce very high contrast even in the face of limited suppression in the shadow.

In this paper we describe the design of a testbed at Princeton that allows verification of scaled occulter at flight-like Fresnel numbers whose suppressed shadow is mathematically identical to that of space occulters. In section 2, we describe a sample design operating at a flight Fresnel number and is thus representative of a realistic space mission. In section 3, we present predicted performance of this sample design. This includes the ideal performance absent any manufacturing limitations and errors as well as the best performance to be expected in the presence of laboratory errors. In section 4, we present the mechanical design of the testbed. In section 5, we discuss progress in implementation and our future plan.

2. EXPERIMENTAL DESIGN

Since occulters for any size mission are typically tens of meters across with tens of thousands of kilometers separation, testing them at full scale on the ground is not possible. For an experimental validation, we must scale from space dimension to laboratory size while we maintain the validity of the optical model in which the occulter operates. The optimization process is described in more detail in previous papers\textsuperscript{6-8}. In this chapter we briefly summary the design process. We also introduce our new approach to simultaneously optimize the apodization for the inner occulter and for the outer support ring.

2.1 Occulter Mask Design

An external occulter is an opaque screen designed to minimize the effects of diffraction so that the shadow cast on the pupil of a telescope downstream of the occulter is optimally dark. The procedure for designing the occulter mask is similar to that used previously\textsuperscript{8}. We first design an occulter for space dimensions which we then shrink to laboratory size. We start with the expression for the electric field $E_{occ}$ past an occulter mask with circularly symmetric transmittance profile $A(r)$ with range $[0, 1]$ at a distance $z$ downstream with wavelength $\lambda$, can be written as the Fresnel integral\textsuperscript{9}:

$$E_{occ} = \frac{2\pi}{i\lambda z} \int_{\rho}^{R} e^{-\frac{2\pi i r^2}{\lambda z}} J_0 \left( \frac{2\pi r \rho}{\lambda z} \right) A(r) r dr$$ \hspace{1cm} (1)

where $R$ is the maximal radial extent of the mask, $J_0$ is the zeroth-order Bessel function of the first kind, $\rho$ is the radial distance across the shadow, and $r$ is the radial distance across the occulter mask.

One of the most significant challenges in creating a laboratory-scale experiment is eliminating diffraction and specular reflection from mounting supports for the starshade model. This was a significant source of error in past experiments\textsuperscript{10-12}. Our approach to mitigating this diffraction problem is to create a second ring around the outside of the occulter so that the open region is an annulus. We then support the central starshade with the same number of struts as petals to ensure that any diffracted light appears outside the shadow\textsuperscript{13}. This allows us to mount the starshade in a baffling screen with light only passing through the annulus, eliminating both diffraction from the supports and stray light. While this does introduce an outer working angle beyond which there is another shadow with no light, we are able to fully verify the diffraction of the starshade at the critical small separations near the inner working angle by examining the annular suppressed region.

The main difference here is that we now have the ability to simultaneously optimize the apodization for the inner occulter and for the outer ring. This avoids the use of Babinet’s principle and reduces the computing time. As we’ll see, it also results in a higher performing mask. This new optimization finds the ideal apodization (accounting for both the inner and outer radii) via the linear program:
where \( E_{\text{occ}}(\rho; \lambda) \) and \( A(r) \) are given in Eq. 1, \( \sigma \) represents the smoothness condition threshold, \( a \) the extent of the opaque central disk, \( b \) the extent of the outer annulus, and \( 2c \) the suppression performance level sought in the shadow. The formulation is infinite dimensional. We discretize wavelengths in the interval \([\lambda_{\text{min}}, \lambda_{\text{max}}]\), which defines the shadow suppression wavelength band. We also apply midpoint discretization for the radial coordinates, with \( r \) over the range \([0, R]\) and \( \rho \) over the range \([0, \rho_{\text{max}}]\) and use a trapezoidal scheme for numerical integration. The upper radial bound \( \rho_{\text{max}} \) on the shadow in the pupil plane defines the optimized dark hole portion of the shadow.

In Table 1, we list the parameters used in the optimization problem to obtain the apodization profile and corresponding petalized mask shown in Fig. 2(a) for the example suppression constraint of \( 10^{-11} \). The wavelength band \([\lambda_{\text{min}}, \lambda_{\text{max}}]\) is evenly discretized in 20 nm and 25 nm intervals to include the end wavelengths. We use midpoint discretization across the occulter radius \( r \) and across the shadow radius \( \rho \). The outer ring is designed to be twice the radius of the inner occulter, and the inner tips of the outer petals are designed to start at four-fifths of the radial distance. The suppression constraint is introduced across each component of the electric field and thus setting \( c = 5.5 \) corresponds to a shadow intensity suppression of \( 10^{-11} \). The outer ring allows us to use support struts to hold the inner occulter. The struts are accounted for by introducing a multiplicative factor \( b \) on the apodization function to reduce the total transmission. The resulting smooth optimized apodization profile in Fig. 2(a) can be petalized to a binary occulter mask as shown in Fig. 2(b), with the support struts appearing by multiplication with a scale factor \( b = 0.9 \). The binary mask is created from \( N = 16 \) petals that are defined by turning the apodization profile into the edge of the binary mask, with opaque points on the mask belonging to the set \( S^{14} \).
2.2 Laboratory Scaling

In this section, we discuss how space occulters can be scaled to laboratory size while maintaining the validity of the optical model, and describe details of the experimental design. The floor space of the new lab allows for a final propagation distance of 78 m, much larger than the current 10 m\footnote{6,7} and enough to allow operation at flight Fresnel numbers. Figure 3 shows an updated layout for the new experimental testbed. Due to the increased propagation distance in the updated testbed, a full-size enclosure connecting the source and the telescope optical table as used in the current testbed represents a significant structural engineering challenge. A more feasible approach is to connect the two enclosures that contain optical tables at either end via a smaller tunnel of diameter $D$, but this requires careful evaluation of the tunnel sizing\footnote{6,7}. The occulter mask will be placed at a distance $h$ from the artificial source and the camera is located at a distance $z$ from the occulter mask. The total propagation distance available is given by $Z = h + z$.

We first scale the design from space separation to laboratory separation by maintaining a constant Fresnel number as before. We designate the propagation distance for the space design as $z_{\text{space}}$. Then we scale to a new propagation distance $z$ corresponding to lab dimensions by introducing a scaling factor $s = (z_{\text{space}}/z)^{1/2}$. The new radius of the mask becomes $R' = R/s$. Thus, for the case of a direct spatial scaling with a plane wave input beam, the maximal mask size is achieved by increasing the separation distance $z$ available in the laboratory. For a set total distance available $Z$, the source would be set to the minimum distance necessary to achieve a collimated beam and this would in turn maximize $z$. The finite size of the input collimated beam, however, can result in significant variation from the idealized infinite-extent planar input beam which can dominate the performance of the diffractive shadow. This effect is the likely limit on the performance of another occulter testbed\footnote{10,12}. Additionally, any collimating optics used introduce wavefront errors that cannot be eliminated. Occulter performance is highly susceptible to phase errors at the occulter plane.

To mitigate the diffractive effects related to a finite width collimated input beam, we design the testbed to operate with a diverging input beam. As with the current testbed we scale the design to account for a diverging input beam at the same separation distance by maintaining equivalent Fresnel numbers. For an occulter with a collimated input beam increasing the separation distance to the camera increases the mask size; however, for a diverging beam, setting the mask at a smaller distance $h$ from the source results in a larger divergence and we must shrink the occulter mask’s radius by a factor $\gamma = (1 + z/h)^{1/2}$ such that $R'' = R'/\gamma$ compared to the equivalent collimated mask $R'$ at the same separation distance $z$. We also enlarge the radial dimension across the shadow by a factor of $\gamma$ such that $\rho'' = \rho'/\gamma$. We can show mathematically that the maximal occulter radius occurs at $z = h$. The maximum occurs when $z = h = 39$ m as expected.
In Table 2, we summarize the scaling of the occulter parameters. We first show the parameters of the designed occulter at space dimensions then scale these parameters to the laboratory. We assume a total distance of 78 m is available and optimally set the divergence to maximize the size of the occulter mask, which assumes a 39 m distance from the source to the mask and a 39 m propagation distance past the mask. The intermediate scaling for the collimated case assumes a 39 m distance scaling for comparison purposes. In the final column, we show the resulting scaled parameters after application of the beam divergence. Scaling for a diverging beam results in shrinking the occulter mask while increasing the size of the shadow. We correspondingly increase the size of the aperture to still correspond to a 4 m space telescope. However, we expect that we will experiment with different aperture sizes to, among other things, find the optimal size to remain in the shadow during the long integrations.

2.3 Beam Propagation model

To validate the models, we design subscale experiments which obey the same scalar field relationship. One of the challenges of such a laboratory experiment is scaling the starshade/telescope system by many orders of magnitude while maintaining meaningful results. This is achieved by introducing a scale factor constant $s$ such that the dimensionless Fresnel numbers appearing in the diffraction integral remain constant. This guarantees that the mathematical, integral representation of the diffraction past the starshade is identical for both the full-scale and lab-size geometries. We start with the expression for the electric field $E_{occ}$ past an occulter mask in Eq. (1). We then make the substitutions $\rho' = \rho/s$, $\gamma' = \gamma/s$, $A'(\gamma') = A(s\gamma)$, and $z' = z/s^2$, $R' = R/s$, $E_{occ}(\rho') = E_{occ}(s\rho)$.

$$E_{occ}'(\rho') = \frac{2\pi}{i\lambda z'} \int_0^\infty e^{\frac{2\pi i\rho'}{\lambda z'}} J_0\left(\frac{2\pi \rho'}{\lambda z'}\right) A'(r') r' dr'$$

(4)
which is functionally identical to the unscaled expression. The resulting scaling is quadratic along the separation direction and linear in the transverse directions, allowing us to scale a space occulter to lab size. It is worth noting that under this scaling, the geometry does change so the inner working angle that we would expect from space increases in the laboratory substantially. However, the mathematical descriptions of the lab and space versions are identical. The scaling approach is thus an effective means of demonstrating that the scalar theory and resulting mathematical description is valid.

To minimize the potential for error from diffraction and aberrations of imperfect optics, we also change the geometry to use a diverging beam. This avoids introducing aberrations from collimating optics that would corrupt the wavefront impinging on the starshade mask. This is done by introducing a scaling factor $\gamma > 1$ applied as a change of variables $r'' = r'/\gamma$, $\rho'' = \gamma \rho'$, and $z'' = z'$.

\[
E_{\text{occ}}^\gamma (\rho') = \frac{2 \pi \mathcal{R}^2}{i \lambda z'} \int_0^r e^{i \pi \rho' (r^2 + \rho'^2)} J_0 \left( \frac{2 \pi \rho'}{\lambda z'} \right) A'(r') r' dr' \tag{5}
\]

3. PREDICTED PERFORMANCE

3.1 Ideal one-dimensional simulation

In this section, we describe the performance of the ideal optimized occulter apodization profiles with perfectly symmetric realizations. We calculate the performance of the laboratory mask under scaled conditions corresponding to a diverging input beam. In section 2.1 we described the linear program and optimization parameters used to design the occulter apodization profile. To evaluate the electric field downstream from the inner occulter, we use the one-dimensional Fresnel diffraction integral including the Jacobi-Anger expansion with the series summation of the first twenty non-zero Bessel terms (setting $K = 20$ and $N = 16$) and re-write the integral as follows

\[
E_{\text{in}} (\rho, \phi) = \frac{2 \pi}{i \lambda z} \int_0^R E_{\text{in}} (r) e^{\frac{2 \pi i r}{\lambda z}} J_0 \left( \frac{2 \pi \rho}{\lambda z} \right) A(r) r dr + \sum_{k=1}^N \frac{4 \pi \cos (k \pi \phi)}{i \lambda z} \int_0^R E_{\text{in}} (r) e^{\frac{2 \pi i r}{\lambda z}} J_{kN} \left( \frac{2 \pi \rho}{\lambda z} \right) \sin (k \pi A(r)) \frac{r}{k \pi} dr
\]

The physical dimensions for the optical propagation are listed for the diverging scale column in Table 2. The wavelength is set at 633 nm to match the monochromatic HeNe laser used for the experimental laboratory.

The simulation results are shown in Fig. 4. The suppression-calibrated shadow intensity at the pupil plane is shown in Fig. 4(a), the contrast calibrated point spread function at the image plane is shown in Fig. 4(b), and the stretched image of the Fig. 4(b) is shown in Fig. 4(c). The azimuthal average curve for the suppression is shown in Fig. 4(d) and for the contrast in Fig. 4(e). The solid red line in Fig. 4(d) indicates the extent of the aperture for the diverging beam and solid red lines in Fig. 4(e) indicate the annular working region. The resulting mean suppression over a 4-m telescope centered in the occulter shadow is $10^{-11}$, and the resulting mean contrast over a 4-m telescope centered in the occulter shadow is $10^{-13.4}$.

Suppression is measured at the pupil plane with light allowed to impinge directly on the detector. Suppression is the ratio between the flux in the mask’s shadow and the flux without the mask. Contrast is measured at the image plane with a camera focused on the point source, and is the ratio between the flux at each pixel in the image formed when the mask is in place and the flux of the peak pixel of the PSF without a mask.

Measuring both suppression and contrast is useful as it allows for verification of the consistency of the results. Contrast measurements can indicate the limitations of the suppression performance of the occulter mask, as the source of any stray light can be directly observed. Suppression measurement describes the performance of the occulter directly and is decoupled from the telescope.
Figure 4. Effect on performance of ideal mask under diverging input beam laboratory conditions: (a) Suppression at the laboratory pupil plane for a diverging input beam. (b) Contrast at the laboratory image plane for a diverging input beam. (c) Stretched image of contrast at the laboratory image plane. (d) Azimuthal average suppression across pupil plane. The solid red line indicates the extent of the aperture at the shadow, with a mean suppression across this aperture of $10^{-11}$. (e) Azimuthal average contrast across image plane with a diverging input beam. Solid red lines indicate the annular working region of the annulus. Mean contrast over the annular region for the diverging beam cases is $10^{-13.4}$.

3.2 Error included two-dimensional simulation

The simulated performance of the occulter mask in previous section assumed a perfect realization using sixteen petals. For a proper assessment of laboratory performance it is necessary to simulate the suppression and contrast of a realizable mask with expected errors in the manufacture of the mask.

To do so we follow the same procedure as for our previous mask to model various feature accuracies. We generate a two-dimensional mask model with $n \times n$ samples and allow the pixels to take on "gray" values (less than 1 but greater than 0) at the petal edges. These gray values are computed via a $g \times g$ anti-aliasing subgrid at each edge pixel. A mask model with $(n, g)$ and with radius $R$ will therefore be representative of the resulting feature size given by $\delta R = 2R/n/g$. This feature size of points along the edges represents the accuracy of the polygons used in the CAD model supplied to the Jet Propulsion Laboratory's Microdevices Lab (MDL) for manufacture. We perform two-dimensional optical propagations with different feature accuracies and compare the results. After that, we see monotonic worsening of performance from the ideal case as the feature size is increased. Based on conversations with MDL, we expect that 0.25 μm feature size is the smallest achievable resolution in the mask manufacturing process and is therefore likely the indicator of the best possible performance. The performance at 0.25 μm is worse than the ideal design but still satisfies our target suppression.

This analysis considered only symmetric edge feature accuracies defined by the regular polygons used in the shape definition. These deterministic models are symmetric, except for small quantization errors arising from translation of a sixteen-fold circularly symmetric pattern to a rectangular grid, and therefore represent an optimistic bound on performance. We also consider the effect on performance due to the loss of symmetry that arises from random perturbations at the mask edges that model manufacturing defects. We see that with increasing edge perturbations there is increased diffraction along the occulter edges thus degrading performance. Based on conversations with MDL we believe that we can reasonably expect the random edge perturbations to be less than 0.5 μm.
In addition to the mask manufacturing errors described above, there are several laboratory tolerances that need to be accounted for in making contrast prediction, or that need to be controlled to appropriate levels to maintain our goal of \(10^{-9}\) suppression\(^6,7\). We simulate a misaligned input beam across the occulter mask by displacing the optical axis of the pinhole from the occulter plane to detector plane. From the simulation results we find a small amount of light leakage at the inner ring of the occulter mask due to misalignment of the input beam. When the misalignment is less than 2 mm the effect on contrast is negligible.

Next, we introduce pure phase aberrations across the pinhole plane by generating a two-dimensional aberrated matrix at this position with a given spectral density. We characterize the error by its rms value found by averaging over the matrix. Because of the spatial filtering effect of the pinhole, high-frequency phase aberrations from the optics are filtered out. Therefore, even large aberrations on the order of \(\lambda/10\) or greater have a small effect on the performance metrics. The results suggest that the pinhole filters aberrations induced by the upstream optical surfaces very well.

To model the loss of symmetry due to a mask tilt, a rotation and in-plane projection can be applied to the occulter mask. We simulate mask tilt by shrinking the mask along the x-axis while maintaining the mask apodization information at each pixel. This model only consider the amplitude effect of the mask tilt. The result is that the performance of the mask will be degraded when the mask tilt is larger than 1 deg.

Figure 5 shows the resulting suppression and contrast of all of the above errors combined on the mask with the selected target suppression and contrast. Table 3 shows the selected values for each of the errors. For these values we find that we can still expect a predicted suppression of better than \(10^{-9}\) and the corresponding contrast. All of the values in the table we can reasonably expect to achieve in the laboratory, giving confidence in our milestone value.

Figure 5. Performance of the laboratory mask using combined error analysis (a) Worst case suppression map (b) Worst case contrast map (c) Suppression profile with 50 runs Monte Carlo simulation (d) Contrast profile with 50 runs Monte Carlo simulation
Table 3. Summary of realistic error parameters for simulation of laboratory environment.

<table>
<thead>
<tr>
<th>Error Parameter</th>
<th>Budget</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature Accuracy</td>
<td>0.25 μm</td>
</tr>
<tr>
<td>Edge Perturbation</td>
<td>0.5 μm</td>
</tr>
<tr>
<td>Diagonal Beam Misalignment</td>
<td>2 mm</td>
</tr>
<tr>
<td>Optical Aberrations</td>
<td>60 nm</td>
</tr>
<tr>
<td>Mask Tilt</td>
<td>1 deg</td>
</tr>
</tbody>
</table>

The remaining source of error will be wavefront variations due to air motion and density inhomogeneities in the tubes. The laboratory enclosure will be operating at room temperature in a non-stabilized environment. As such, it is possible for temperature gradients to develop, which may result in atmospheric effects due to variations in refractive index across the propagation direction. Straightforward analyses using simple power law wavefront error shows that the suppression and contrast are extremely sensitive to wavefront aberrations. Wavefront error with an rms as small as 0.1 nm can result in a loss of suppression beyond \(10^{-9}\). However, the system is also sensitive to the spatial scales assumed. Further modeling is necessary to understand the response to turbulent and laminar air motion. Careful modeling of the experiment is required to reliably predict the air motion and resulting wavefront aberrations. These will be performed in order to ensure our models match our eventual measurements. In addition, we plan to perform wavefront measurements directly on a representative tube segment in a similar environment to bound the wavefront error problem.

4. EXPERIMENT DESIGN

4.1 Enclosure Design

The new laboratory facility will be located in an 80 m long hallway in the basement of the Frick Chemistry building on Princeton University's campus. The location is climate-controlled with minimal foot traffic. The basement location provides a stable environment for the optical tables.

The facility will be composed of a long, enclosed tube with three stations, one for the laser and pinhole, one midway for the starshade mask, and one at the end for the camera. This is different from the current facility where the entire experiment is enclosed. Figure 6 shows a schematic diagram of the layout. Simulations show that a tube diameter of 1 m or greater is adequate for diffraction effects not to affect the shadow at the \(10^{-9}\) suppression level. The tube is made up of 2 m length and 1 m diameter. They are standard ductwork tubes made from spiral-wound Galvanneal sheet joined by Galvanneal Accuflanges and light-tight Neoprene gaskets. The flanges double as baffling along the length of the tube. The interior of the tube is painted matte black with a very low reflectivity paint. 13 possible paint combinations were selected based on specifications and spectrophotometer reflectance tests were performed at JPL to choose the best paint. Figure 7(a) shows a schematic of a tube segment. The tubes will be supported along their length by support saddles from simple 80/20 suspensions. Figure 7(b) shows a first mounted tube.

We will use workstation enclosures for the laser, mask, and camera. The enclosures are semi-custom versions of Newport's standard LTE-44-4 (4' x 4' x 4') light-tight enclosure. The standard hardboard panels are being replaced with sturdy low-reflectance matte black acrylic panels. The tube opening will be custom machined and rigidly attached to the tube flanges. The enclosures sit on semicustom 4' x 4' version of Newport's RS2000 research grade table.

4.2 Stray light analysis

The diverging optical beam can propagate from one end of tunnel to the other. Due to the finite size of the experimental enclosure and reflectivity of black paint, the final performance can be affected by the stray light from the tunnel. Figure 8 shows a schematic diagram of scattering within the enclosure. We refer to source to mask region as the input tunnel and downstream from the mask as the exit tunnel. We will set baffles around the occulter mask extending to the enclosure. Therefore most of the light will be blocked at this position. The black line shows the case of no reflection which is an ideal circumstance of the experiment. The blue line represents a first reflection in the input tunnel that reaches the pupil plane through the mask. The red line indicates a first reflection at the input tunnel and a second reflection at the exit.
tunnel. These rays uniformly distribute to the pupil plane. Figure 9 shows the effect of these stray light without any baffles inside the tunnel except at the occulter mask position. When the reflectivity of paint is greater than 1%, these stray light can degrade the occulter performance. Our candidate paint has a reflectivity of 5%. We have to set additional baffles to block these rays. We find one solution that 0.8 m diameter baffle at every 2 m tube block most of the stray light. We are modifying the baffle design accordingly.

Figure 6. Schematic layout of the new lab facility.

Figure 7. (a) Schematic diagram of tube segment. (b) First mounted tube.

Figure 8. Schematic diagram of light reflection inside tunnel.
5. CONCLUDING REMARKS

As can be seen in this paper, the analysis and design of the laboratory scaled mask at flight Fresnel numbers is largely completed and indicates promising performance in suppression and contrast. The final modeling step is to add to the two-dimensional simulations other laboratory errors as for our previous mask, including wavefront aberrations to represent air motion inside the tunnel. We also examine the performance degradation introduced by the finite size of the enclosure and reflectivity of black paint. Construction has already begun and we expect first light in mid-December.

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