Physical barriers to Imaging & Spectroscopy of Terrestrial Exoplanets

J. B. Breckinridge
California Institute of Technology, Pasadena, CA. and
James C. Wyant College of Optical Sciences U of Az, Tucson, AZ.
C. Lillie
Lillie Consulting, LLC Playa del Rey, CA.

Abstract

This white paper reviews the physical and cost barriers to imaging and spectroscopy of terrestrial exoplanets using space and ground telescope Lyot coronagraphs. We review the physical optics aspects of diffraction, scattered light, image formation, and polarization that projects and STDT's have ignored in order to obtain optimistic estimates of achievable static contrast. The dimensions of cost and reliability are considered for space telescope systems.

Background

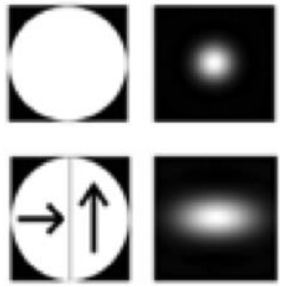
Physics of the interaction of light and matter currently limit imaging and spectroscopy of terrestrial exoplanets. An optical system corrected for geometric path difference errors is a necessary but not sufficient condition for the perfect image formation needed to directly image terrestrial exoplanets. Geometric (trigonometric) path difference errors are controlled using adaptive optics (tip-tilt & wavefront), active metrology and precision pointing. However, image quality is also determined by several physical optics factors: diffraction, polarization, partial coherence, and chromatism all of which degrade image quality and are not corrected through the control of geometric path difference by adaptive optics. The source of physical optics errors lies in the opto-mechanical packaging of optical elements, masks, stops and the thin film coatings needed to obtain high system transmittance. Optical radiation from stars and their planets is incoherent. Astronomers model this radiation as scalar. However, when propagating through a telescope/instrument incoherent becomes partially polarized and exoplanet contrast depends on the material properties of mirrors, coatings, filters and their physical layout within the system.

Current models ignore important aspects of physical optics predict contrasts in the 10^{-9} to 10^{-11} range. Astronomers are developing science observing programs that assume contrasts in the 10^{-9} to 10^{-11} can be achieved with current technology and modeling tools and architectures. These contrasts will be impossible to achieve without employing new tools of physical optics and modern understanding of the interaction of light and matter.

Image formation in Partially Polarized Light

The vector-wave (polarization) aspect of light plays 2 major roles in exoplanet coronagraphy. One is the application of polarimetry to extract scientific information of value about the physical nature of the source and the other is telescope/instrument induced polarization effects on system transmittance, image quality and coronagraph instrument contrast[1],[2],[3],[4].

A thought experiment using linear orthogonal polarizers and a telescope shows the role of vector waves in image formation and the effects of polarization on contrast. Figure 1 shows the effects of adding unwanted polarizers to an optical system: Top left shows an open, unmasked exit pupil of a telescope with zero geometric wavefront error. Top right shows the shape of the PSF recorded with the pupil on the top left. Bottom left shows the same telescope pupil as that shown in the upper left, but now with two linear polarizers over the top, each aligned orthogonal to the other. In the lower left of Fig 1, we see that horizontally polarized light is admitted to the left-hand side of the pupil and vertically polarized light is admitted to the right-hand side of the pupil. The bottom right shows the PSF recorded using the pupil on the bottom left. Note that with no polarizer (top of Fig 1) the angular resolution is not position-angle dependent, however, with the polarizers (bottom of Fig) the angular resolution is position angle dependent. Astronomers define position angle as the rotation angle in the plane of the sky, or in this case the plane of object space. That is, the upper right in Figure 1 shows that the angular resolution is the same in all directions from the axis, whereas the lower right in Figure 1 the angular resolution is not the same in all directions from the system axis. Angular resolution in the vertical direction exceeds that in the horizontal direction for the PSF shown in the lower right.



1.

Figure 1 PSF's shown for a telescope with zero geometric wavefront aberration without (upper) and with (lower) polarizers. Note that the shape of the PSF changes and thus shape of the mask needed to attenuate the radiation changes.

We give the physical optics explanation for this phenomenon. Orthogonally polarized white light does not interfere to create an image. In Fig 1, the lower left image of the exit pupil the polarized radiation from the left portion of the exit pupil does not interfere with the orthogonally polarized radiation from the right portion of the exit pupil. Therefore, the PSF is elongated in the horizontal direction. In this case the PSF is the scalar sum (linear superposition) of two images of a "D" shaped aperture, not the vector sum across the circular aperture shown in the upper right panel in Fig 1. The inner working angle is larger in the horizontal direction than it is for the vertical direction. This means that a coronagraph mask positioned at the image plane that is designed using scalar theory and applied to a system with polarization aberrations would leak large amounts of light around the occulting mask to flood the coronagraph and block light from exoplanets. Unless taken into consideration, this may reduce exoplanet yield to the level of uselessness.

Although this is a rather dramatic example and no one would intentionally place orthogonal linear polarizers over their telescope pupil, this shows that any source of polarization change across the exit pupil will result in distortion of the PSF at some level and result in light leakage around those occulting masks designed using scalar theory only.

Detailed analyses have been performed for HabEx and LUVOIR assuming perfectly reflecting isotropic mirror surfaces. However, distortions to the electromagnetic field incident onto the Lyot mask are introduced by form birefringence within the highly reflecting primary mirror coating and polarization is also introduced by the use of dichroics to separate bandwidths. These wavefront distortions reduce contrast by factors of 100 to 1,000 to make terrestrial exoplanet imaging and characterization impossible without a serious program in polarization mitigation.

Scalar diffraction[5]

Today, large astronomical telescopes (JWST, ELT and TMT) use primary mirrors that are segmented or mosaiced using hexagonal mirrors. These hexagonal segments of the primary mirror impress three diffraction gratings across the primary aperture which diffract light across the image plane to mask exoplanets at certain position angles and separations.

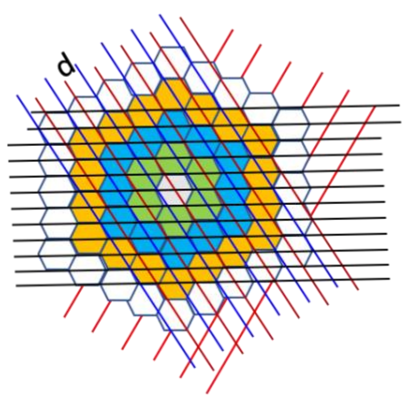


Figure 2 Four ring hexagonally segmented primary mirror showing the 3 diffraction gratings with ruling separation of d

each rotated 60-degrees relative to the other across the aperture.

Where are the exoplanets in the field and do the diffraction orders from the gratings across the primary mask these planets is an important question. Assume that we are looking to image and spectroscopically examine earth twins between 10 and 80 parsecs. The angular resolution between the exoplanet and its star then varies between 12.5 and 100 milli-arc-second. If we assume we want to place the earth-twin at the 3rd Airy diffraction ring (for 500-nm), then the aperture size ranges between 3.7 meters and 29.7 meters. Figure 3 below shows a sketch of the point spread function or image plane irradiance distribution at the image plane for diffraction orders n=0, 1, and 2.

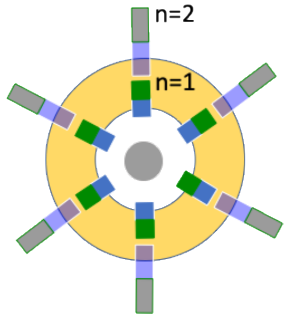


Figure 3 The point spread function or image plane irradiance pattern produced by the aperture pattern from the hexagonally segmented primary mirror shown in Figure 2. Six low dispersion spectra of the star appear at diffraction order # 1 and diffraction order # 2. The length of the spectra correspond to optical bandwidth between 450 and 550 nm. Note the Lyot mask will block the zero-order for the on-axis star image, but will not block the diffraction orders: n=1 or n=2 or n>2. The irradiance in the diffracted orders will be about 10^{-6} of the central star intensity.

Segmenting the primary mirror followed by deployment to create a "filled" aperture is a necessary feature of large ground or space telescopes. It is the gaps between the hexagonal mirrors that cause unwanted diffraction. But segmenting or partitioning the aperture into arrays of hexagonal mirrors is not required. Using geometric patterns other than hexagons lets us control diffraction and optimize the system for the characterization of exoplanets.

This is shown in Figure 4 below which shows how a "pinwheel" segmentation pattern provides a point symmetric point spread function which gives the same maximum detection and characterization sensitivity at all position angles when compared to the hex segmentation diffraction pattern. The PSF's are calculated for monochromatic light at 500-nm wavelength. In the upper left we see the hex segment pattern for a 10-meter LUVOIR. In the center we see the image plane energy distribution in a 1-arcsec x 1 arcsec region centered on the system axis that shows the 6-fold symmetry exoplanet diffraction-mask discussed in Figure 3. To maximize starlight suppression for an aperture comprised of hex mirrors, requires a Lyot mask whose shape is matched to the 6-fold symmetry exoplanet diffraction-mask. The upper right shows a plot of Log_{10} irradiance as a function of radius in arc sec. for 0 (solid red) and 30 (dashed black) degrees azimuth angles.

The 10-m aperture at the lower left is comprised of segments arrayed in a "pinwheel" pattern. In the lower center we see point spread function for the pinwheel aperture energy distribution in a 1-arcsec x 1 arcsec region centered on the system axis and in the lower right we see a plot of Log_{10} irradiance as a function of radius in arc sec. for all azimuth angles. The VV6 and other high transmittance Lyot stops are optimized for point symmetric PSF's,

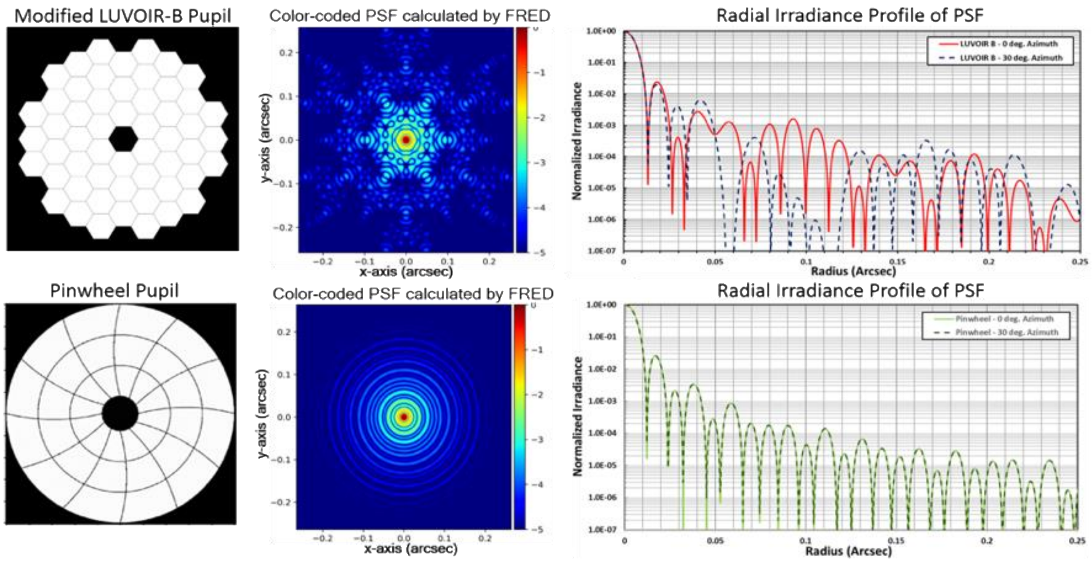


Figure 4. Image plane irradiance distributions (column 2 and 3) are shows for hexagonal tessellated and "pinwheel" tessellated 10-meter apertures.

By segmenting the primary using regular hexagon mirrors, astronomers have created diffraction gratings across the primary that diffract starlight into the region where we expect to see very faint terrestrial exoplanets. Two solutions are apparent to solve this problem: 1. Employ complex sophisticated A/O active masks adding complexity, unwanted absorption and mission risk. Or 2. Invent a passive segment architecture that will not create the unwanted diffraction, increase transmittance and decrease mission risk.

Scattered light

It is well known that optical systems exhibit narrow angle or "specular" scattered light to "fill" in the first dark ring of the Airy diffraction pattern with incoherent scattered light to add background noise to the exoplanet detection and characterization problem. To control this source of scattered light requires an understanding of the interaction of light and matter that has not yet been applied to the development high performance terrestrial exoplanets[5].

Conclusions

Resources are needed to develop innovative, creative ways to design optical systems for the characterization of terrestrial exoplanets. Without these analyses astronomers will not be able to afford the cost of building terrestrial exoplanet characterization systems. We can fine tune the E&M field from the fore-optics by optimizing the hardware configuration and impedance matching that field to the Lyot filter to maximize the starlight suppression and maximize system transmittance. Resources are required to perform this interactively between modeling and experiment. The authors have shown that the cost of adding an optical surface to a billion dollar class telescope system approached $100 M[6]. Single surfaces need to be developed that to perform multiple functions.

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