Final Report

Phase I Study

HOMES
Holographic Method for Exoplanet Spectroscopy

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Introduction

The search for habitable exoplanets in the "neighborhood," that is within 10 parsecs (pc), invites new observational techniques, because telescopes available today have significant limitations. For example, gravitational micro-lensing is a deep field method that has little or no utility within 10 pc. Photometry of transits reduces the availability of exoplanets to a probability of approximately a 1%, and fewer than 1 out of 100 earth twins would ever be seen. For the 1% of exoplanets seen in transit, spectra of albedos cannot be taken. Even more limiting, Doppler shift studies are indirect and cannot characterize exoplanets other than by their orbits and masses through stellar radial velocity (RV). Moreover, RV by Doppler shift cannot detect planets in orbits on a plane perpendicular to our line of sight. Astrometry can be used to measure stellar orbital wobble for those exoplanetary systems in the plane perpendicular to our line of sight, as was contemplated for the cancelled NASA SIM mission[1] and rests now with ESA's GAIA[2]. In either case, the exoplanets detected by stellar RV or astrometry would not be directly observed, so the assumption that the three phases of water could exist does not answer a key question of habitability. Is there water on the exoplanet? Moreover, the discovery of water on an exoplanet in the habitable zone, exciting though it would be, is insufficient to determine just how habitable the exoplanet might possibly be. Like Goldilocks' porridge - there are many other ingredients beyond water alone in a life-sustaining soup.

We propose a new species of optical telescope that has as one of its capabilities the high resolution spectrographic characterization of exoplanets on stars within 10 pc of the observatory. To achieve this performance specification, we propose to break with convention by taking advantage of an optical technology unknown until relatively recent times: the hologram. In this *Report* we show how holograms used in primary and secondary can extract spectrograms from exoplanets at distances reaching 33 light years from our solar system. We describe a notional space telescope using these novel optics that could make its observations in a space deployment scenario.

Direct observation of an exoplanet presents a special set of difficulties in telescope performance. The angular resolution required to directly resolve inner exoplanets is in the tens of milliarcseconds (mas). Sensitivity to flux must be to 30th magnitude or fainter. The parent star must be attenuated by a factor of 10^{10} in the visible, 10^{8} in the infrared so that star glare does not overwhelm the albedo of exoplanets residing at a very narrow angular separation in a telescope's field-of-view. Identifying habitable exoplanets also presumes spectrographic capabilities that can indicate a match between the exoplanet's albedo and expected signatures like water, oxygen, hydrocarbons and other organics.

The maxim of "bigger is better" applies to astronomical telescopes because resolution and sensitivity are proportional respectively to primary objective aperture and area. Due to practical limitations imposed by space deployment, smaller telescopes are under study; but the parameter of size applies as much as ever. A G-class star would produce enough flux for an Earth twin albedo at 10 pc from our observatory to reflect 0.5 photon/m^2 per sec over a 10% bandwidth at visible wavelengths.[3] By that metric, if one could park the Keck at the second Lagrange point, it would be hit with 30 to 50 photons per second from the earth-like exoplanet. It is not unreasonable, therefore, to specify 10 meter or larger collectors for this assignment. Even with a 10 m primary, the angular resolution of a

segmented mirror like the Keck is limited to approximately 40 milliarcseconds. A 16 to 50 meter primary would be preferable for directly resolving exoplanets like an earth twin. These diameters have been characterized by others.[4]

One means to mitigate the cost of a large primary is to limit the aperture of one of the two areal dimensions. This carries the penalty that planets on the short side of the aperture cannot be seen immediately and may go unseen unless the telescope is rotated 90° or there is a matched pair. If a planetary system is known to exist, the asymmetry does not preclude direct imaging over a portion of an orbit. This is the approach we have selected from our notional Holographic Optical Method for Exoplanet Spectroscopy or HOMES.

In the case of our proposed dispersive primary objective, a secondary spectrograph serves much as a secondary lens did in the original telescopes of the seventeenth century. The secondary spectrograph in HOMES must operate with at high resolving power in order to detect exoplanets. The échelle spectrograph has been the most widely adopted astronomical spectrograph for resolving the highest resolution and might be called the “gold standard" for performance. The échelle uses a method of cross dispersion that disambiguates overlapping high-order spectra and displays an array of sub-spectra that are far broader in aggregate than the free spectral range of any one order alone. Resolving powers above 100,000 have been achieved by this method. [5 & 6]

In this Phase I project, we have investigated a novel double dispersion configuration that might possibly achieve performance levels comparable to the échelle. It does not employ high-order plane grating diffraction to magnify the dispersed radiation as an échelle does. Instead it uses holograms which operate in the first-order. This type of disperser has a broad free spectral range and can accommodate dispersion over a wide spectrum in a single order. Instead of using dual dispersion to disambiguate, it uses a second dispersion by diffraction to magnify.

It is reasonable to investigate holographic gratings for dispersion. Échelle gratings are typically ruled on the mechanical engines available since Rowland in the 19th century, but relatively recently holography has provided an alternative means of grating production which is better suited to forming groove pitches shorter than visible wavelengths themselves. This type of grating is called a Diffractive Optical Element (DOE) when it is a plane grating and a Holographic Optical Element (HOE) when curved rules of variable pitch are created by holographic methods These groove geometries are difficult or impossible to manufacture on ruling engines and open up new possibilities in diffraction grating fabrication through the use of coherent radiation or micro-lithography.

There are ample reasons to develop new spectrographs not only in astronomy but throughout the many disciplines that rely on spectrographic analysis. Our investigation into a new type of telescope may have applications in other sciences than astronomy. It is closely related to a 3D microscope we have developed on a separate track [7], and recently we have also used some of the technology being investigated under our NIAC grant in a commercial area - computer/human user interfaces.[8] HOMES is a project that could have relevance in technologies beyond astronomy. That said, HOMES is a telescope designed specifically with exoplanet detection and characterization in mind. The architecture may also prove useful in other areas of astronomical observation, but here we present the concept in the specific context of exoplanet discovery inside of our solar "neighborhood."

1. Motivation

It is good to detect exoplanets but not good enough. Characterization is by spectroscopy. The more accurately spectral signatures are recorded, the better the science. Yet modern telescopes have the same fundamental designs as telescopes of the seventeenth century, and those were invented in complete ignorance of spectral signatures. Centuries ago it seemed sufficient to observe the spatial positions of planetary objects and catalog their relative motions. The nineteenth century spectrograph revolutionized the science but not the basic telescope. Since spectral signatures are requisite, our motivation is to investigate revolutionary telescope designs with a goal to take spectrographs of exoplanet albedos.

a. Apertures

The size of the primary objective is a measurement of a telescope's performance, because the primary objective determines both resolving power and sensitivity. The adage goes, "Bigger is better." Growing mirror size is not easy. Over the twentieth century, the trend has been to double the size of the primary over twice the lead time per step, Figure 1.

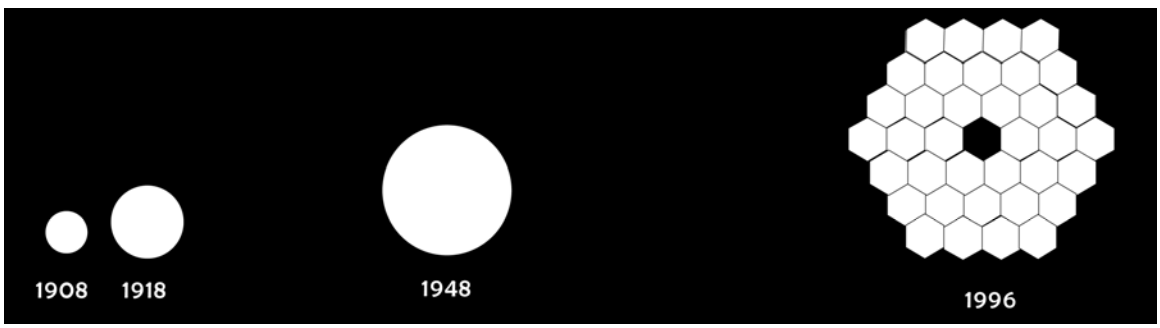


Fig. 1 Mirrors: each doubling in diameter has taken twice as long as the prior iteration.

In 2002, proponents for an acceleration in the development of giant mirror telescopes convened in Hawaii at the biennial SPIE conference on Astronomical Telescopes and Instrumentation to announce a quantum leap from ten meter up to 100 meter diameters for ground telescopes.[9] The resolving power of such primaries would meet the challenge of isolating exoplanets within the 50 mas inner working angle (IWA) between a parent star and a planet in the habitable zone. The unlikelihood of producing such apertures were anticipated by J.M. Beckers who summarized in a final oral statement at the conclusion of the 2002 conference.[10] Beckers asked the conferees if the pursuit of huge mirror diameters was blinded by the ambitions of the proponents rather than reasonable expectations of how telescopes actually work. His warning was well founded, and the goals for extremely large ground telescopes have since been scaled back.

Yet, the need to grow the size of primary objectives is real enough. Lyon and Clampin[11] show, that with our stellar "neighborhood" of 20 pc a Hubble size mirror would require integration periods of months to detect an earth twin to a S/N 5. If the mirror was 64 times larger, the requisite integration period would drop to a day. Such a mirror would be 16 meters in diameter. Can NASA make a space telescope primary objective of this size? To do so would be to stretch the possible.

b. Areal mass

Even with honey comb ribs to lighten their mass, glass parabolic mirrors are massive. An 8.4 meter glass blank for a single mirror in the Giant Magellan (GMT) weighs more than 19 tons. It has seven of them. The mass of the platform including mirrors is 1,100 metric tons, and GMT must pivot dynamically with the rotation of the earth to maintain pointing accuracy equal to its resolving power. The problem only grows more vexing with the goal of launching large apertures into space. As a rule of thumb, an assembled areal mass of 1 kg/m^2 is a reasonable target for space telescopes in the 10 to 100 m aperture class.[12] If the mass of glass exceeds this limit, then another substrate must be found. The James Webb Space Telescope (JWST) has a 6.5 m mirror made of beryllium, but this results in an areal mass of 22 kg/m^2 and 40 kg/m^2 when assembled. Membrane mirrors that have the requisite areal mass do not hold to the surface figure needed for visible wavelengths.

c. Surface figure

The propagation of a wave front focused by a mirror achieves its diffraction limit when the surface is perfect. In practice, parabolic mirrors are polished to tolerances in the sub-wavelength regime. The mirrors of the GMT are polished nominally to 0.05 λ/D. The segmented design must retain inter-mirror registration over the span of nearly 27 meters in a dynamic mountaintop setting with changing temperatures and heavy wind loads. JWST is configured with active optics for its beryllium mirrors. It has always been assumed that there are no alternatives to mirror magnifiers and a perfect surface figure was required to make a perfect telescope. Lenses were previously the only known alternative primary objectives, but they are as intolerant of figure error and also suffer from chromatic aberration which led to their demise. If surface figure is a limiting parameter for reflection and refraction, does the same limitation apply to diffraction?

d. Pupil diffraction

It cannot be fully appreciated until mirrors are operated at their performance limits, but the “spiders” that hold the secondary mirror along with any similar interstitial structures perturb a wavefront on its way to the image plane of the telescope. In an image of the star nearest to us, Figure 2, one can see spikes that have a certain celestial magic.[13] However, these aesthetically pleasing artifacts are aberrations. In recent years off-axis mirrors, partial or half parabolas with unobstructed pupils, have become a more common design specification.[14] Interestingly, diffraction is intrinsically an off-axis phenomenon.

Fig. 2 Hubble image of Proxima Centauri. Its planetary region, indicated by a black dot, cannot be resolved inside the diffraction limit.

e. High contrast imaging

Exoplanets in the "neighborhood" of our solar system, within 10 pc or 33 light years, are among the faintest objects ever observed, comparable to the galaxies in the Hubble "Deep Field" survey,[15] approximately 30th magnitude. Neighborhood inner exoplanets are within a few hundredths of an arc second of their parent stars which are up to one billion times brighter than the exoplanets they illuminate. The combination of a narrow angle of separation and the extremely high contrast between parent and exoplanet presents a challenge for coronagraphs originally created for observation of the sun from earth. While progress is reported in the pursuit of a full set of features needed to null or occlude the star and distinguish exoplanetary objects in orbit nearby [16] the limitations imposed by mirror primaries in diameter (especially in space deployment) and the contrast ratio of 10^{10} have resulted in simulations exhibiting many limitations. These include coarse resolution, false positives, speckle and narrow spectral bandwidth.

f. Spectra

To find an exoplanet in an orbit falling within the "Goldilocks" zone - not too hot and not too cold for the liquid phase of water - does not mean there is water on the exoplanet. Water has a spectral signature that must be acquired to be determinative. The "pale blue marble" of earth's reflected light in its albedo does hint at an earth twin spectrum, but what science wants is far more detailed. Exoplanet spectroscopy requires division of available photons into wavelength bands which could lead to light starvation at narrow bands. Moreover, even with water present, life signatures are far more complex. Because of the precision required, spectra of exoplanets will require telescopes with huge collection areas large enough to capture enough scarce exoplanet photons to allow for the division of wavelengths needed for detailed albedo analysis.

Present thinking on exoplanet coronagraphy is to limit bandwidth of acquired starlight so that a destructive null can be obtained to mask its light and reveal the faint planet light. Notwithstanding that a mirror is the most effective achromatic primary objective, bandwidths are being quite deliberately narrowed and most energy thrown away to get at the elusive exoplanetary images. The choice is not optimal for characterizing the albedos of the exoplanets. The question to address is whether the primary could possibly divert selected bands across the spectrum so that nothing is lost while the secondary coronagraphs do their work.

After the coronagraph, the spectrograph makes the characterization. Spectrographs, like mirror primaries in the centuries before them, have changed little in basic concept since their inception. The most notable change has been the échelle cross-disperser which uses low frequency plane gratings and their resulting high-orders followed by a perpendicular prism to create two dimensional spectral distributions at the highest resolutions. These échelle spectrographs are double dispersers with a resulting loss of efficiency and are not being contemplated in present exoplanet telescope designs. However, their high resolution or something of equivalent resolving power is called for if the characterization of directly observed exoplanets will include key signatures.

2. Innovation

To satisfy the demanding criteria for exoplanet spectrographic telescopes, solutions may be found in unusual designs made possible through recent innovations in optics. Optical holography has matured over half a century to the point where diffraction can be considered for the astronomical collection and focusing of electromagnetic periodic waves. Unlike reflection, diffraction is dispersive and lends itself to spectroscopy. This potential for an architectural shift by using a disperser as the primary is not without historical precedent. A type of slitless spectrograph based on a primary objective plane grating was introduced in the nineteenth century.[17] However, it was always understood that there were significant limitations when the diffraction grating is the first element.[18] A primary objective grating (POG) telescope suffers from coarse resolution and metamers, that is, overlapping spectra from proximate objects.[19] We propose here for the first time an alternative architecture using a secondary disperser to overcome these endemic limitations that previously restricted POG development.

Moreover, we further report here on our study of primary objective dispersive optics to show how they can be effectively used to focus radiation by varying the pitch and the geometry of grating lines. Spectrometers with holographic optical element (HOE) diffraction gratings of variable pitch that focus dispersed radiation have been studied and reported. [20] These have features of concave gratings which have three dimensional shaped surfaces that can form spectrograms after a slit without ancillary optics. In a similar way, an HOE grating requires no ancillary reflection or refractive surfaces.

Taking the HOE spectrometer a further step allows us to contemplate using it not simply in the secondary but as the primary itself. There is no precedent for such an architecture in astronomical telescopes. Our study suggests that an avenue for an entirely new species of astronomical telescope will be found by using HOE primary and secondary optics, and we further disclose dispersive methods to overcome vexing issues with coronagraphy.

a. Specification

The motivation for improving telescope performance to acquire spectra from exoplanet albedos leads us to propose a set of challenging and unprecedented specifications that would make the acquisition possible:

- Collection area > 500 m^2
- Aperture > 50 m
- Coronagraph extinction in broad band visible light > 10^{10}
- Inner working angle < 50 mas (0.5 AU @ 10 pc)
- Outer working angle > 1 arcsecond (or nearest neighboring star)
- Highly relaxed figure tolerance < 100 λ/L where L is grating length
- Arial Mass Primary Objective < 1 kg/sq m^2 (space deployment)
- Off-axis optical path without interstitial diffractive surfaces

To these performance specifications we add the requirement that the telescope package achieve solar orbit at L2 using a standard heavy lifter such as the Atlas V carrying a payload of 8,000 kg with a fairing shroud of diameter no greater than 5 meters.

b. HOE

A holographic optical element can be made at the intersection of a plane wave and a spherical wave originating from a common coherent monochromatic source. In playback the HOE exhibits a lens' or a mirror's capability to focus. A plane wave incident upon the HOE at the recording wavelength will focus at precisely the distance and angle of the recording spherical wave object beam. To the eye it would appear that a virtual point at that wavelength floats in front of or behind the HOE. A real image of the point is also present, and it can be detected by an area array sensor placed at the focal point.

An important distinction between HOEs and focusing mirrors is that the position of a reconstructed point is highly wavelength-dependent. At the wavelength used to record the HOE, the reconstruction takes places at the angle and focal distance from the HOE as the original spherical wave's source, but all other wavelengths focus elsewhere. Images resulting from playback of an HOE in broad band illumination are highly chromatic. Multiple illumination sources (the sky) compound the problem of chromatic aberration by introducing a plurality of overlapping spectra.

Chromatic dispersion issues aside, HOEs do have an important feature applicable to space telescopes not previously available in telescope primary objectives. HOEs are nominally flat and can reside on flat gossamer membrane substrates of a minimal areal mass that is highly desirable for space deployment of large collectors. In addition, they can be mass replicated from master HOEs or computer printing through lithography.

The benefit of low areal mass and the capacity to focus are exploited in proposed MOIRE solar and earth observatories that use anti-hole photon sieve variants of a Fresnel Zone Plate (FZP) in an on-axis configuration of an HOE.[21] The FZP is not efficient, and the anti-hole photon sieve may even be less so, but the proposed solar and terrestrial targets are bright. Although chromatic aberration is significant, wavelength determines focal length, and the problem is somewhat less noticeable at the focal plane for any one wavelength. A sharp bandpass filter at a selected wavelength can be used to disambiguate overlapping images. The FZP earth observation platform is slated for geosynchronous earth orbit insertion where large apertures are desirable. The flat membrane primary can be stowed in the delivery vehicle in a folded "origami" geometry. Apertures of 10 to 20 meters are contemplated by project leaders.[22]

An FZP could produce hyperspectral imagery one wavelength at a time over an operation cycle that sampled many focal plane adjustments, but the juxtaposition of each wavelength at its own focal plane does not recommend it for practical spectroscopy of extended objects. Much as Dennis Gabor's original holography concept and its eponymous Gabor Zone Plate (GZP) superimposes the object and reference beams that form the GZP, there is a problem sorting out different wavelengths when all share a common axis. In addition to this problem, the on-axis approach which imitates a conventional mirror telescope brings with it the embedded diffractive surfaces of the spider struts holding the secondary optics. These both limit the throughput of signal and add their diffraction image to the energy distribution at the image plane.

As Leith and Upatnieks [23] demonstrated in 1962 over a decade after Gabor's seminal 1949 publication naming holography [24] arranging the reference and the object wavefronts at different angles relative to the recording hologram plane provides considerable benefits in playback. Now the illumination source does not occlude the line of sight on the image.

The Leith-Upatneiks configuration is also applicable when a primary objective of a telescope is an HOE. Playback off-axis removes diffraction artifacts, increases playback efficiency, and moves focal planes at different wavelengths into non-overlapping positions for each source. A sharp bandpass filter at any of these locations limits image formation to selected wavelengths. To the side are images of the same source. Given multiple sensors, each in the appropriate position with the appropriate bandpass filter, the collection of images in aggregate would be hyperspectral. The configuration is a GZP on the "half shell," that is, the light is coming from the center of the GZP to receivers configured to one side of the central axis. This opens up the capability of receiving all the light in all the wavelengths focused by the primary objective. This is the configuration we are investigating for HOMES - Holographic Optical Method for Exoplanet Spectroscopy.

c. Architecture

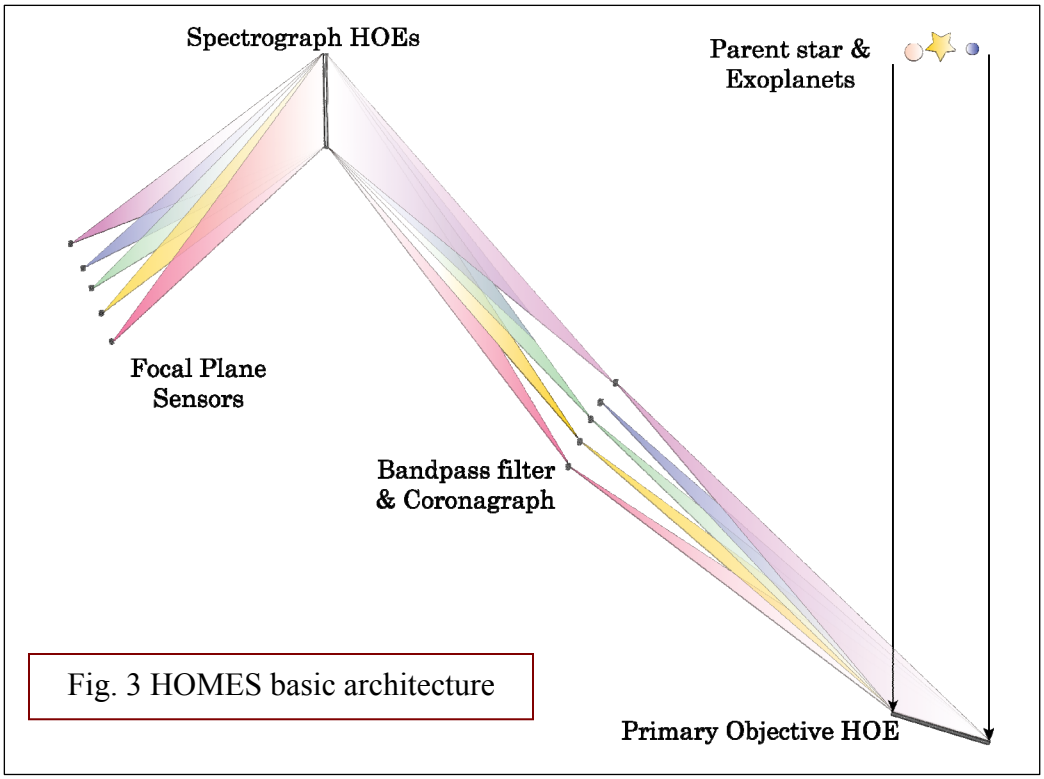


Fig. 3 HOMES basic architecture

The structural subsections we address in HOMES, Figure 3, are those needed to collect the light from an exoplanetary system, those needed to remove competing stars and the parent star, those that separate the images of the planets to take their spectra, and finally the sensors that record the data. We present the instrument in a free flying formation, although that is not strictly a requirement for this instrument to function. We use formation flying to illustrate the relative location of the components.

Plane waves from exoplanetary system are collected by a Primary Objective HOE. Images of the system appear in discrete wavelength bands and can be filtered to remove other stars and the parent star. A spectrograph then spreads the narrow band signal to produce a separate image of each planet at the focal plane sensors. The Zemax [25] computer program generated the model, Figure 4, was made to corroborate a set of first principles. This model of a hologram was made at λ=500 nm. The HOE model has a length of 50 meters and a width of 10 meters.

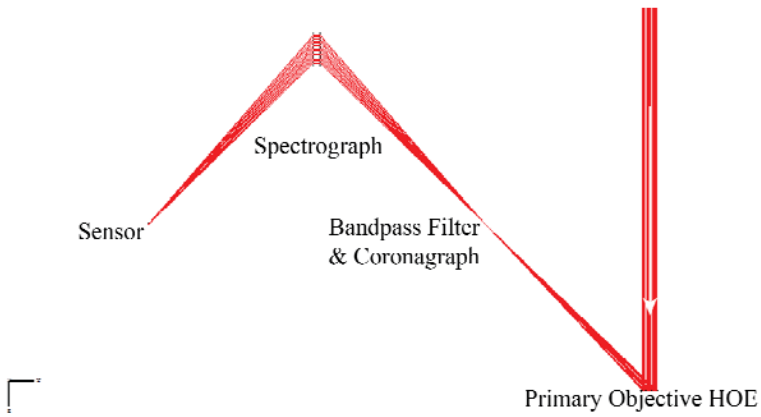


Fig. 4 Zemax model of principal holographic elements

d. Primary Objective

The HOE we would use is a chirped frequency holographic grating that can focus a plane wave down to a point. The HOE is aspirational. Nothing like it has ever been manufactured, although deceptively it can be modeled by a few keystrokes and general unit selections in Zemax wherein the HOE is presumed to have a perfect chirp over some 50 meters. Assuming it physically existed, the HOE plane would be oriented toward the plane waves coming from the target so that the star is directly overhead. This allows the primary objective to present its largest surface area, capture the most flux and focus at the most wavelengths. The aperture will also be at its greatest, and spectral bandwidth will be at a maximum.

The sky provides a plurality of sources, one of which is the target planetary system and its parent star. The superimposed spectra of all stars create overlapping images, but they are out of focus and displaced in wavelength from the target star. In Figure 5 we show how this appears in Zemax when two sources are

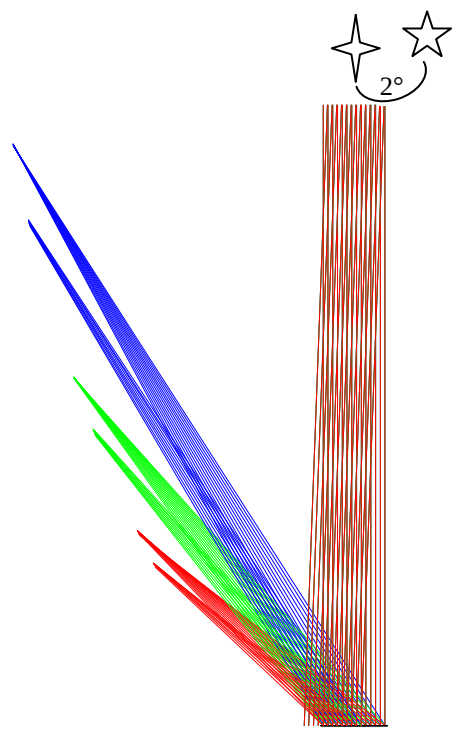


Fig. 5 Comparison of two sources subtending angular separations of 2° on HOE at respective λ = 400, 500 and 600 nm

compared, one being the target perpendicular to the plane of the HOE and the other being off-axis by 2°. Of course, there are innumerable other stars to be dealt with, but the in showing one pair in Figure 5 we illustrate how for any source outside a narrow angular displacement, the HOE will disperse a different set of wavelengths to other foci of the HOE. We will completely eliminate these competing images coming from other stars at the next component in the optical train, the bandpass filter (see Section e below).

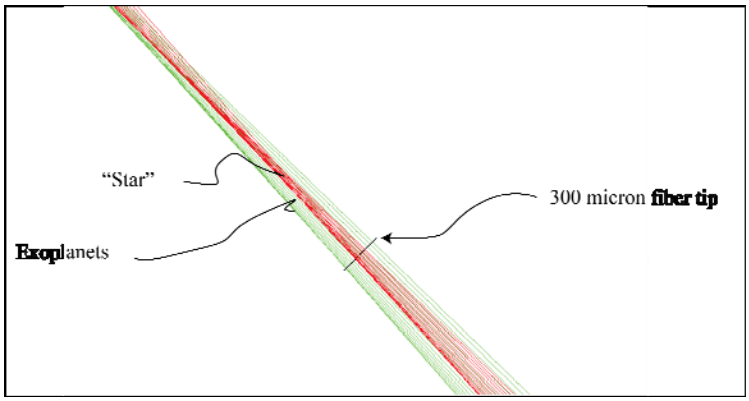


Fig. 6 An HOE focal point where the exoplanetary system outer working angle spans 300 mas and inner working angle is 10 mas.

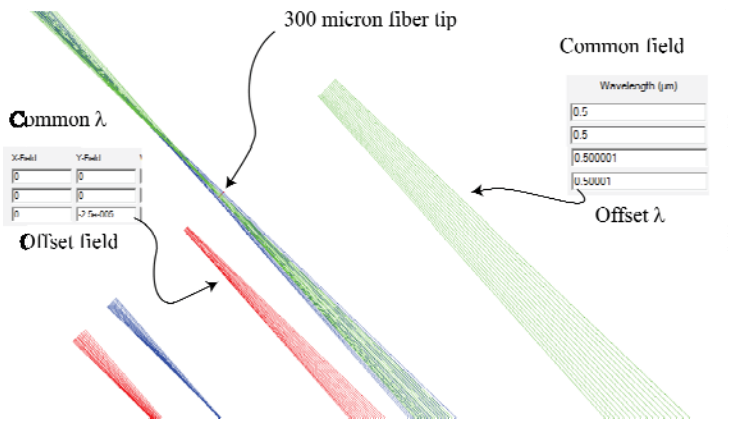


Fig. 7 Offsets between a fiber capturing one image of an exoplanetary system and other images at other bands.

The same displacement phenomenon is also used to differentiate the exoplanets in the system from their parent star and from each other. The exoplanets focus to a common point but appear at slightly different wavelengths. Consider the Zemax model shown in Figure 6 which shows one focal point at a 300 μm fiber tip. Wavelengths associated with exoplanets would share the same fiber with their parent star and fall within a band spanning 0.001 nm. We can see from this model in Figure 7 that other images of the exoplanetary system, while present, will appear at different wavelength bands and different focal lengths. Adjacent fibers that are not shown would capture other spectrographic images and contribute to the overall flux collection.

We are looking for exoplanets that are being segregated by their wavelength, not by their position at a specific angle relative to other exoplanets or their parent star. The concept is quite different from prior telescopes and needs to be understood for this distinction from earlier telescope paradigms. In a reflective primary telescope images are taken from angular displacement. Angular resolving power is the critical measure of resolution. In the present instance where an entire exoplanetary system appears at exactly the same angle but with each object at slightly different wavelength, bringing a narrow band of wavelengths to a common focus may require compensation by a refractive element. Our

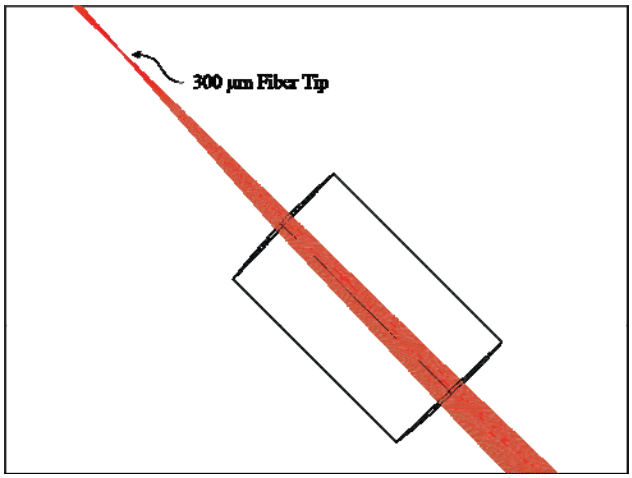


Fig 8 The refractive correction needed to produce a common focus for the narrow band of wavelengths across an exoplanetary system.

strategy is that dispersion of wavelengths by refraction (where shorter wavelengths are more highly dispersed) is in the opposite wavelength order of diffraction (where longer waves are more highly dispersed). A method to exploit the reciprocal is described in our prior publication on dispersive primary telescopes. [26] In the present model we have introduced a thick lens, Figure 8, that is capable of compensating for the loss of focus of objects over the presumed angular spread an the resulting wavelength band that covers an exoplanetary system within 10 pcs.

e. Bandpass Filter and Coronagraph

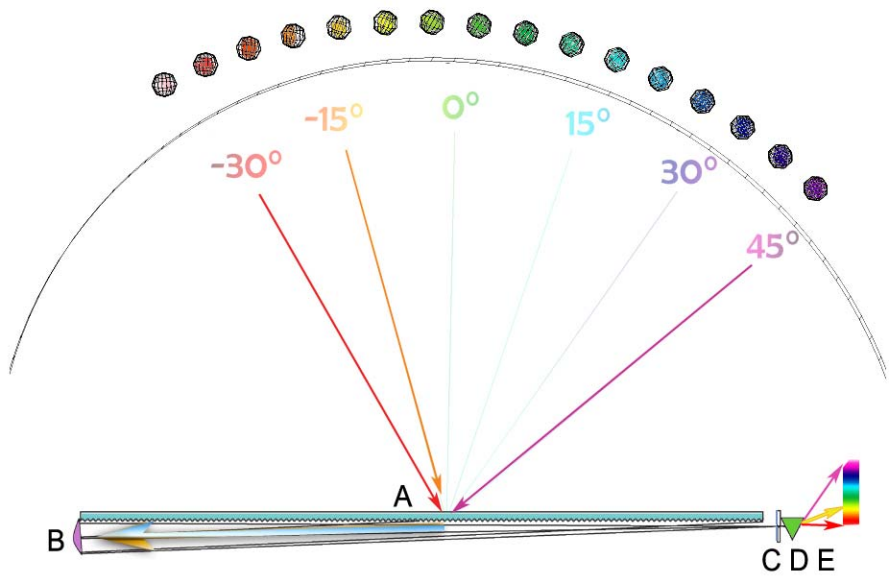


Fig. 9 The MOST: Plane waves incident upon POG **A** are diffracted at grazing exodus to parabolic mirror **B** which focuses them onto slit **C** where prism **D** disperses them into a spectrum **E** where any wavelength can be correlated to an angle of incidence.

We propose a coronagraph that resembles a spectrograph. It derives from The MOST, The Multiple Object Spectrographic Telescope, which incorporates a primary objective grating, Figure 9. In the telescope of Figure 9, plane waves from the sky striking a grating are diffracted into a focusing mirror which is aimed at the slit of a spectrometer. One wavelength is focused for each source object. We have shown in a NIAC *Report* [27] that in

the first diffraction order such primary objective gratings can resolve narrow wavelength bands and correlate them with angles of incidence.

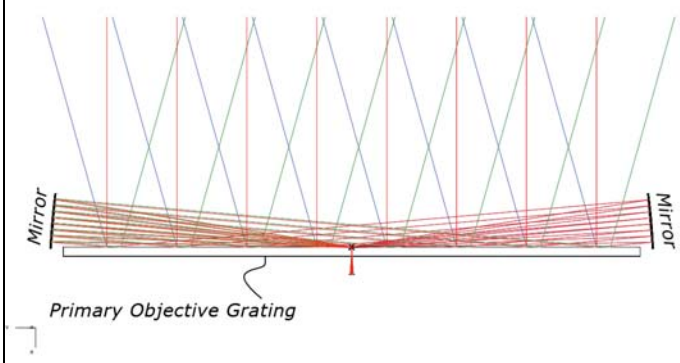


Fig. 10 Dual parabolas focused to a common point

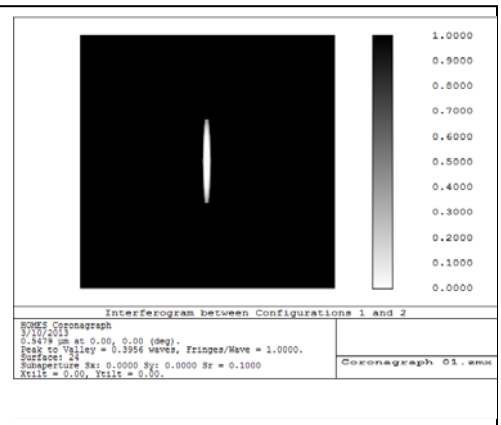


Fig. 11 Interferogram of Fig. 8

The POG of Figure 9 is a primary objective plane grating, and it can be configured with sinusoidal blaze so that the first-order disperses with equal energy in both directions. When that happens as in Figure 10, there can be a common intersection of two foci which can be configured to perform as an interferometer. Imagine that the same plane wave of the same wavelength is incident upon the POG at equal and opposite angles or that the star is at the zenith. At the central combiner, the two wavefronts can be spatially adjusted to form an interferometric null as per Figure 11. The null occurs at the center of the star.

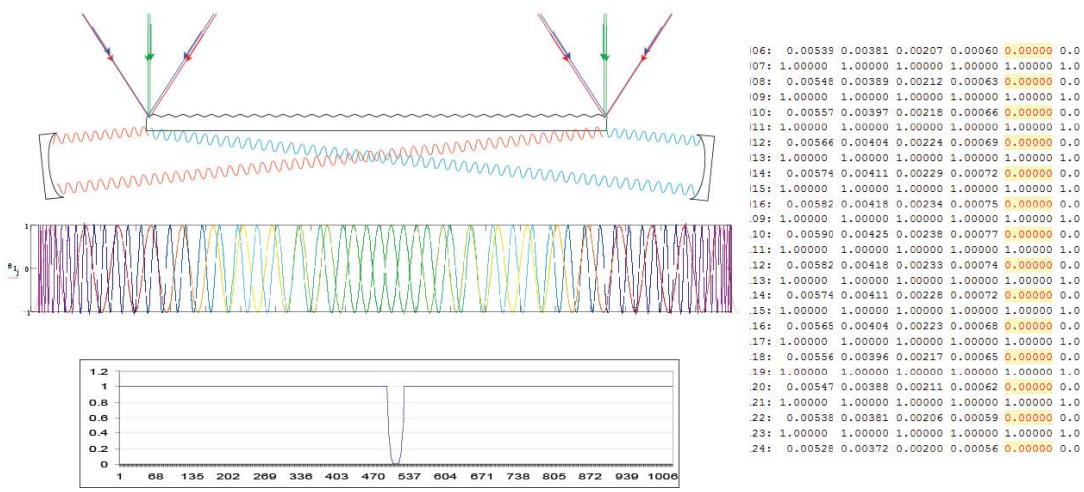


Fig. 12 Spectral interferometer serves as a coronagraph to null a central wavelength. Two equal and opposite spectra share a common wavelength that is out of phase with itself and the combiner forms a singularity of flux zero at the common wavelength. A listing of relative intensity levels on the right hand side are shown in the graph below.

The null of Figure 11 has no side lobes - a highly desirable feature for a nulling interferometric coronagraph. The reason there is only one lobe, as illustrated in Figure 12, is that the destructive interference can be seen to take place over an extremely narrow wavelength band where equal and opposite spectral lines are superimposed. The center of the node can be adjusted depending on a sub-wavelength offset of the mirror pair.

As illustrated in Figures 10-12 where two parabolic mirrors are used, the interference is presumed to be between plane waves positioned in equal and opposite sides of the plane grating. If an elliptical mirror is used, Figure 13, then the spectral interferometer can be fiber-fed in the near-field. Although it focuses for sources in the near-field, the elliptical figure of the reflector pair in Figure 13 does not match the wavefront perfectly. Plane grating dispersion appears to lack a common focal point. To design this interferometer, perhaps two aconic mirrors are needed. Nonetheless the operative principle that there can be a singularity is suggested by the interferogram made with the pair of elliptical mirrors of Figure 13. The band of destructive interference is narrow despite speckle artifacts.

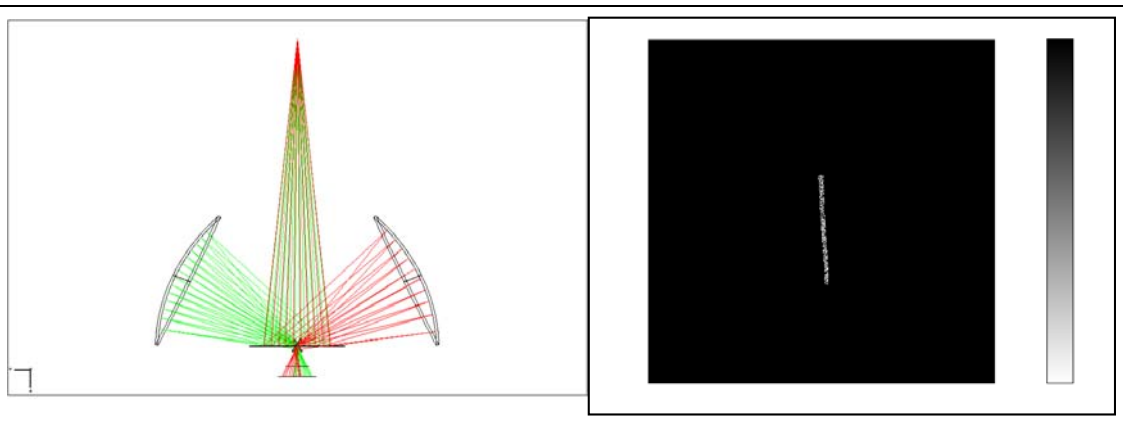


Fig. 13 Dual elliptical reflectors focused to a common point (left) and its resulting interferogram (right). A single region is nulled but speckle precludes clean attenuation.

Competing wavelengths from outside the target exoplanetary system may appear in the fiber feed to this coronagraph, but their wavelengths disperse to the side of the narrow set of wavelengths that are collected at the output. In effect this coronagraph also exhibits a sharp bandpass function. The window bandpass sets the outer working angle just as the interferometer coronagraph sets the inner working angle. Therefore, competing sources from other stars do not appear at the output of the coronagraph and disappear from the signal before the next stage of the optics performs the spectroscopy function.

Along with surface shape needed for the pair of mirrors another question that is not yet answered is the length of the plane grating required. Achieving 0.0001 nm resolving power would nominally require a plane grating of 25 meters. However, what is needed is rejection on the order of 0.001 nm, and that number may be within reach of a shorter plane grating. During initial modeling it was encouraging to see that the change in unit scale from meters to centimeters produced no discernable change in nulling performance as predicted by Zemax, but additional study is required.

f. Spectrograph HOEs

A 25 cm plane grating or even a 2.5 m plane grating can be contemplated as a dispersing element in contemporary optics, but a 50 m HOE is seemingly out of science fiction. Yet, because it is a membrane, fabrication of large HOEs by printing is being pursued.[28] If the disperser is a ribbon shape, a printer can make any length provided that the width in one dimension is narrow enough to fit within the printing train. Whatever the difficulty in the production of its master, replication is a relatively simple process by comparison. UV printing and pressure embossing are routinely used today to make miles of plastic ribbon ultimately seen in consumer product packaging when cut and pasted. Mass replicated gratings taken from meter width rolls sold commercially by Spectratek® were used in experiments with the POG concept illustrated in Figure 9 above.[29]

A single HOE can be made to function as a spectrograph.[30] No curved reflective or refractive power surfaces are required to achieve resolving powers similar to those of plane grating spectrographs that have magnifying optics. Endemic astigmatism can be ameliorated by use of cylindrical lenses of different powers to form the wavefronts creating the HOE.

Given that HOMES presumes a large HOE as its primary objective, we have designed a spectrograph, Figure 14, that would use two more of the same HOE in the secondary. The idea is that if you can realize one impossibly large HOE, you can print as many more as needed to complete the telescope. The concept is consonant with the supposition that to achieve the requisite spectral and angular resolving power to separate the exoplanets, a dispersive surface of a length equal to the primary objective HOE might well be required. Our laboratory bench version of this novel spectrograph is described in the Experimentation Section 4 below and also in a publication.[31]

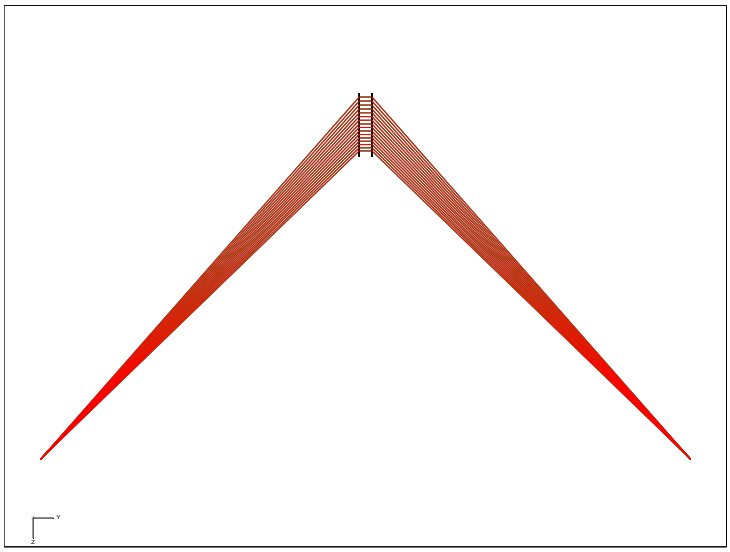


Fig. 14 Spectrograph made from HOEs identical to the primary

g. Sensor

The final elements in HOMES are formation flown sensor arrays. Initial Zemax model rendering appears in Figure 15. We show two points focused on the array over 1.8 cm. The two points can be traced back to a 300 mas angular displacement at the sources of illumination. In order to achieve focus, the array is rotated 77°.

Losses associated with such a steep rotation of the sensor would likely not be acceptable in a practical device. Since refraction reverses the order of spectral dispersion, a glass lens was used in the path to correct astigmatism, but the focal length correction was negligible over the very narrow wavelength differential of 0.001 nm. Instead the refraction only served to increase the spatial separation of the two targets on the sensor. Compensation for the differences in the foci remains to be modeled and may involve another dispersive element. The sharp focus is obviously encouraging, but we have to

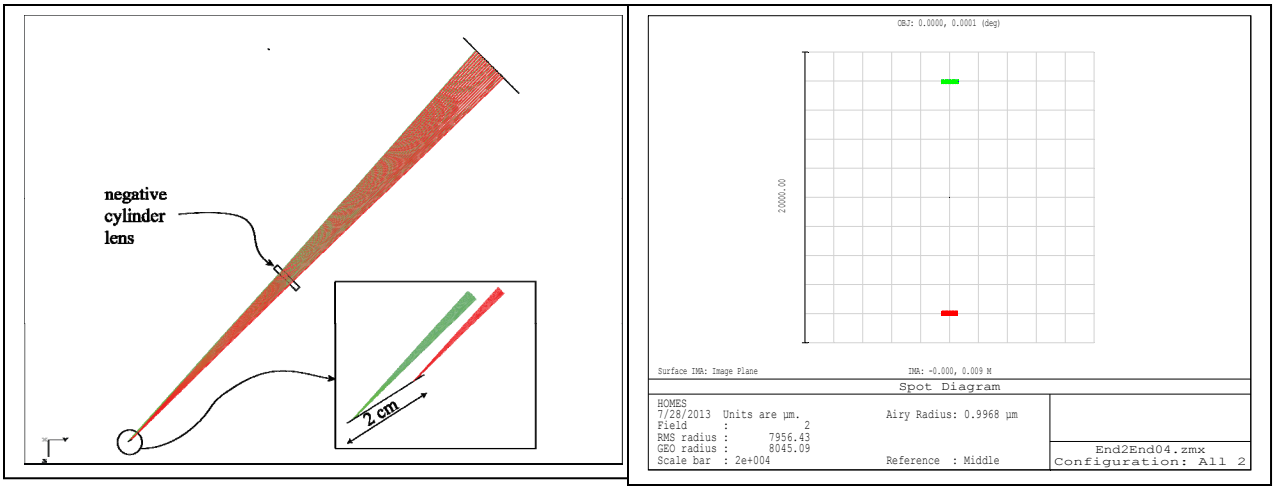


Fig. 15 Distal end of HOMES covering 300 mas of field. Cylinder lens corrects astigmatism.

examine a wide wavelength spread for this exercise to have any meaning. A first attempt to broaden the spectrum beyond the central wavelength was not successful. We did not see other wavelengths as sharply focused as the focal points we studied and are being reported here for the first time.

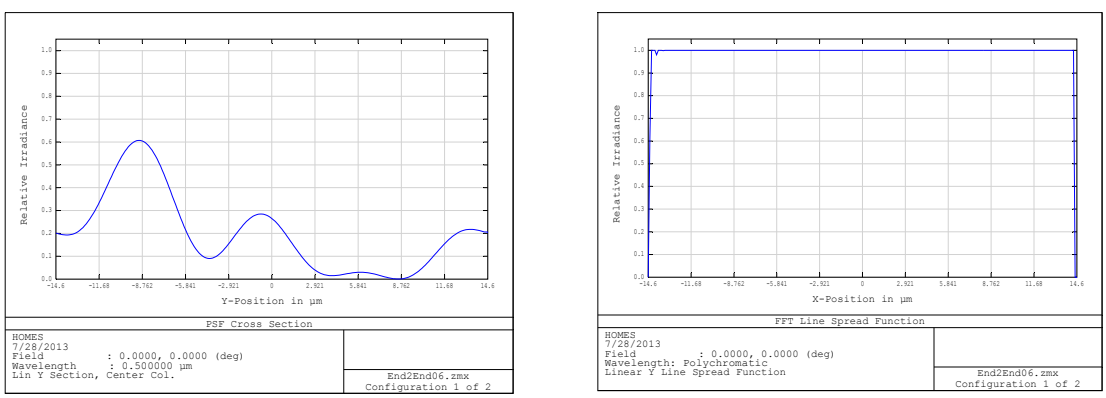


Fig. 16 Point spread functions for orthogonally opposed axes at the image plane

We show point spread functions in Figure 16 calculated by FFT by Zemax but with little confidence we are seeing the true energy distribution. The x,y axes report vastly different phase information, with one dimension being a virtual top hat to the other's multiple phases. The asymmetry is to be expected but how the energy is actually distributed is not likely to conform to these early predictions, especially if and when a flat focus across the sensor array is achieved.

3. Examination

This innovation leads to many choices, but prior art provides quite limited guidance. The concept can be sketched out for the two key venues: ground and space.

a. Ground

The requisite aperture for resolving exoplanets may never permit direct detection on G class stars by terrestrial observatories, not only because apertures cannot be reached due to high penalties in cost, but because the limits on atmospheric seeing require adaptive optics (AO) over these enormous apertures. Is it possible to correct a wide enough column of the atmosphere to 10 mas over broad wavelength bands? Answering this AO issue is beyond the scope of our present investigation, but for the sake of argument, if it is possible to perform AO at scale, it may also be possible to place HOMES on the ground.

In an earlier NIAC study we had proposed a type of ground telescope that can acquire all wavelengths of all stars visible at seeing - one wavelength at a time. [32] In order to achieve a multiple object spectrograph of this type, a POG is oriented in an east/west pose. See the model of The MOST, Figure 9 above. The precession of stars results in a temporal window on each sub-band for each star as it precesses, and a data reduction method is prescribed which acquires all stars inside the field-of-view within one observation cycle, typically one night as the earth rotates. If the telescope is on our moon, the acquisition period is extended in duration to one lunar night, i.e., 14 earth nights. A lunar observatory does not require AO, although issues of lunar dust suspended from the regolith do remain. [33] In either case, we have shown that a static mount does not preclude scanning the sky. A complete disclosure of the concept called The MOST can be found in numerous conference papers.[34]

If the observation is specified as one star at all wavelengths, the platform positioning the diffractive primary objective must be rotated 90° from an east/west orientation to North/South. Figure 17 illustrates The MOST as Grating A and HOMES as Grating B. For each observation, declination is set at a fixed angle. By accounting for sidereal time, a single star can be tracked dynamically over the angle of right ascension by counteracting the rotation of the earth. The mechanics are no different than an equatorial mirror mount. The POG would be an HOE rather than a DOE so that the secondary would acquire the tracked star in all of its available wavelengths all the time as discussed in Section 2 c & d, above.

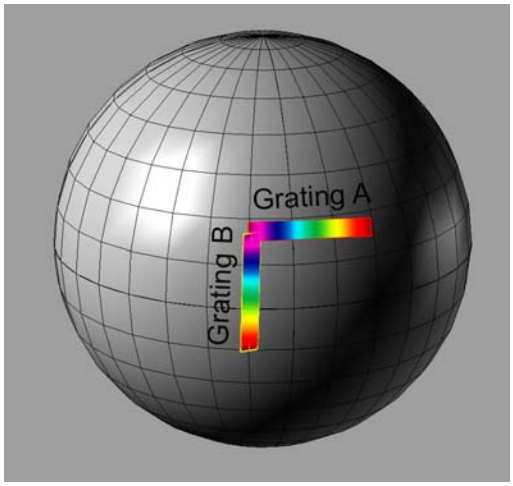


Fig. 17 Grating A for multiple objects Grating B for HOMES (North/South)

The ribbon-like asymmetrical aspect ratio of the HOMES POG simplifies the geometry of the enclosure. This consideration might also apply to mirror primaries if their form factor was of a similar width to length ratio. However, unlike a mirror primary telescope, an HOE can operate in either reflection or transmission. When the HOE is transmissive, the secondary can be below the primary for the transmission case. If secondary optics are buried in the ground, the primary is at ground level. This alters the equation for wind loading – one of the chief obstacles for above-ground mirror telescopes. A further benefit is that diffractive optics are off-axis, so the arrangement of components can be housed at shallow depth relative to the surface. Effective focal lengths that are as long as the HOE can be to the side of the HOE rather than beneath it. This is a critical distinction with on-axis refractive lenses.

A model of HOMES at ground level is shown in Figure 18. Features include pistons that set the declination and a rotation ring on the short axis that adjusts latitude over the integration period. There are wind breaks at the north and south sides of the HOE. In the below-ground chamber is a focal plane that tracks the rotation of the HOE. The fiber bundle is flexible and leads from the moving focal plane to the static elements: coronagraphs, band pass filters, secondary HOE and ultimately the science cameras.

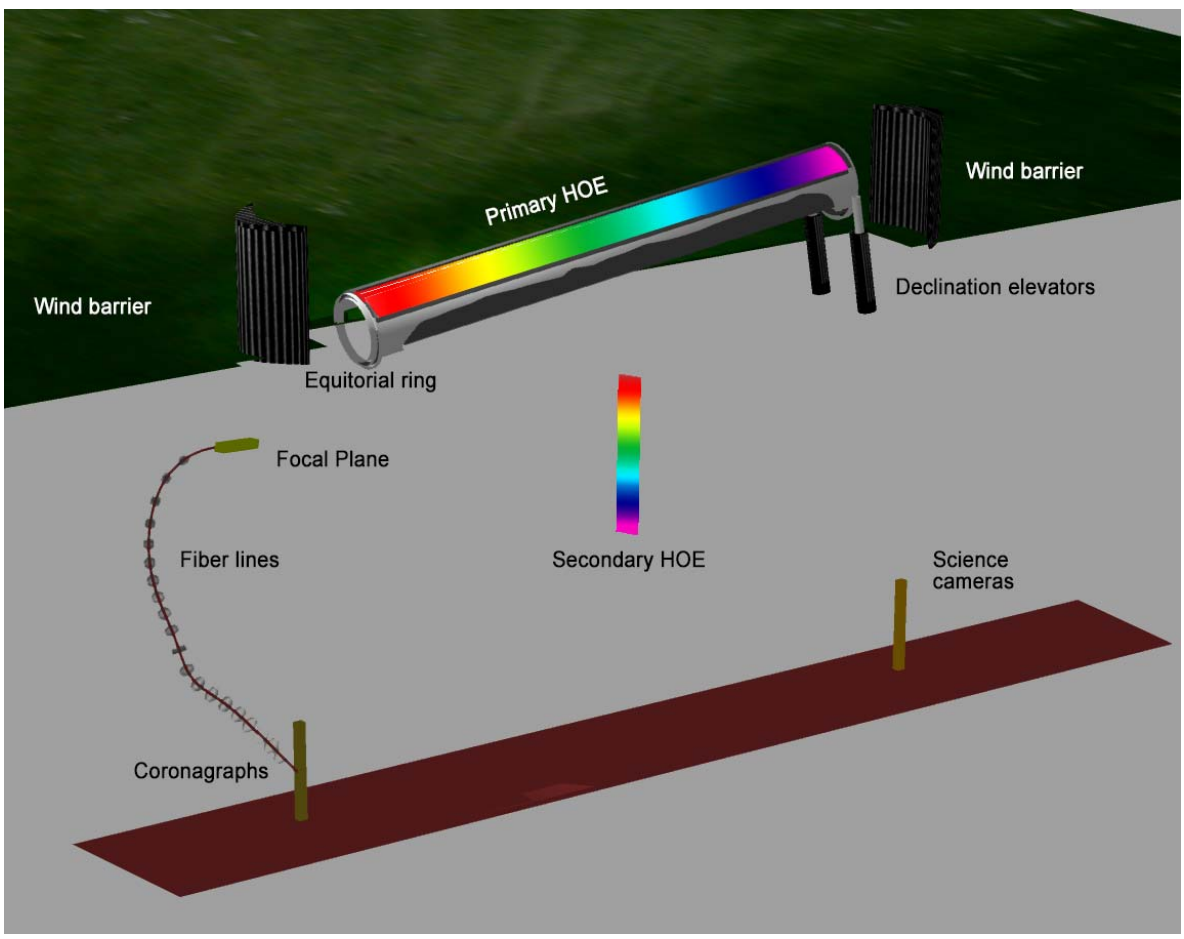


Fig. 18 Facing north to south and with active right ascension on an equatorial mount, the primary is at ground level and remaining optics are buried in a below ground chamber.

b. Space-based

Stationed at the second Lagrange Point or similar orbit, HOMES would have a vacuum environment for seeing, and AO would not be needed. Background sources such as the sun and firmament would be a problem requiring significant attention to shielding. Shielding is not a killer but adds additional formation flown sub-components. The exoplanets themselves are likely to be obscured by zodiacal radiation inside their planetary systems. Zodiacal dust is a general problem for all exoplanet telescopy. The long aperture and spectrographic selection of HOMES would facilitate sight through dust.

The HOMES concept does distinguish itself from all prior spaces telescopes by its use of flat gossamer membrane optics. These can be transported on cylinder drums that conform to payload bay geometry under rocket farings. The wrap required to transport length *L* can be calculated by the approximation of

(1) $$L = \sum_{n=0}^{N} \pi(OD - nT)$$

(2) $$N = \frac{OD - ID}{T}$$

OD is the outside diameter
ID is the inside diameter
T is membrane thickness
N is the number of wraps

Drum lengths carrying up to 1 km compatible with stowage are graphed in Figure 19. The areal mass for membrane plastic is much less than 1 kg/m^2. A film polyimide such as CP 2, 52 μm thick, has a mass of 0.08kg/m^2. [35]

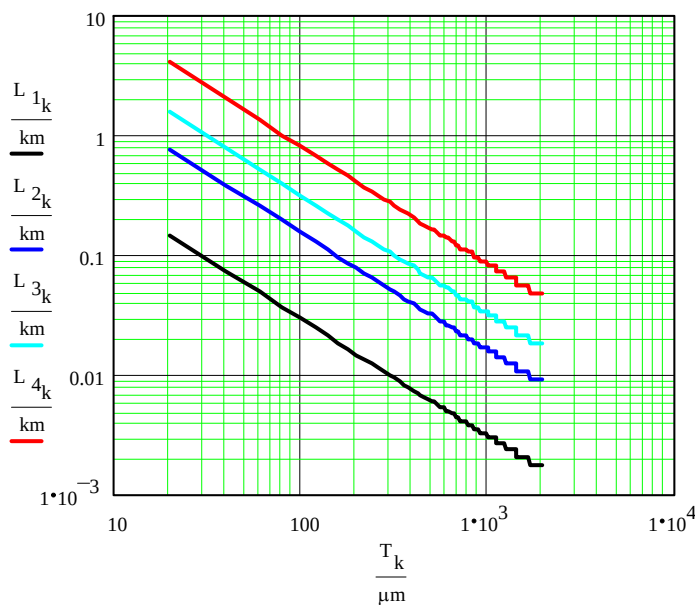


Fig. 19 Stowable lengths of membrane on rolls with OD = 0.5, 1, 2 and 4 m (L_1 to L_4)

For a ribbon HOE, drum stowage during transport could offer optical surface protection without significant mechanical or weight overhead. The tensioning frame could present a mechanical and launch weight problem. Study is needed. We presented a paper at the AIAA in 2007 seeking collaborators.[36] Recently, we have initiated discussions with Tethers Unlimited. Their research under NIAC and DARPA programs contemplates a truss building tender that accompanies large scale space structures such as solar arrays. When coupled with the HOMES architecture, the loads for delivery are within feasibility for today's lifters. Their team rendered a concept image for robotic construction of the trusswork used in The MOST, Figure 20. [37] HOMES would use a similar structure. Combining a robotic construction concept with the use of gossamer membrane flat ribbon optics opens up the possibility of 100 m or even kilometer scale space telescopes. A rendering of the components delivered into orbit is shown in Figure 21.

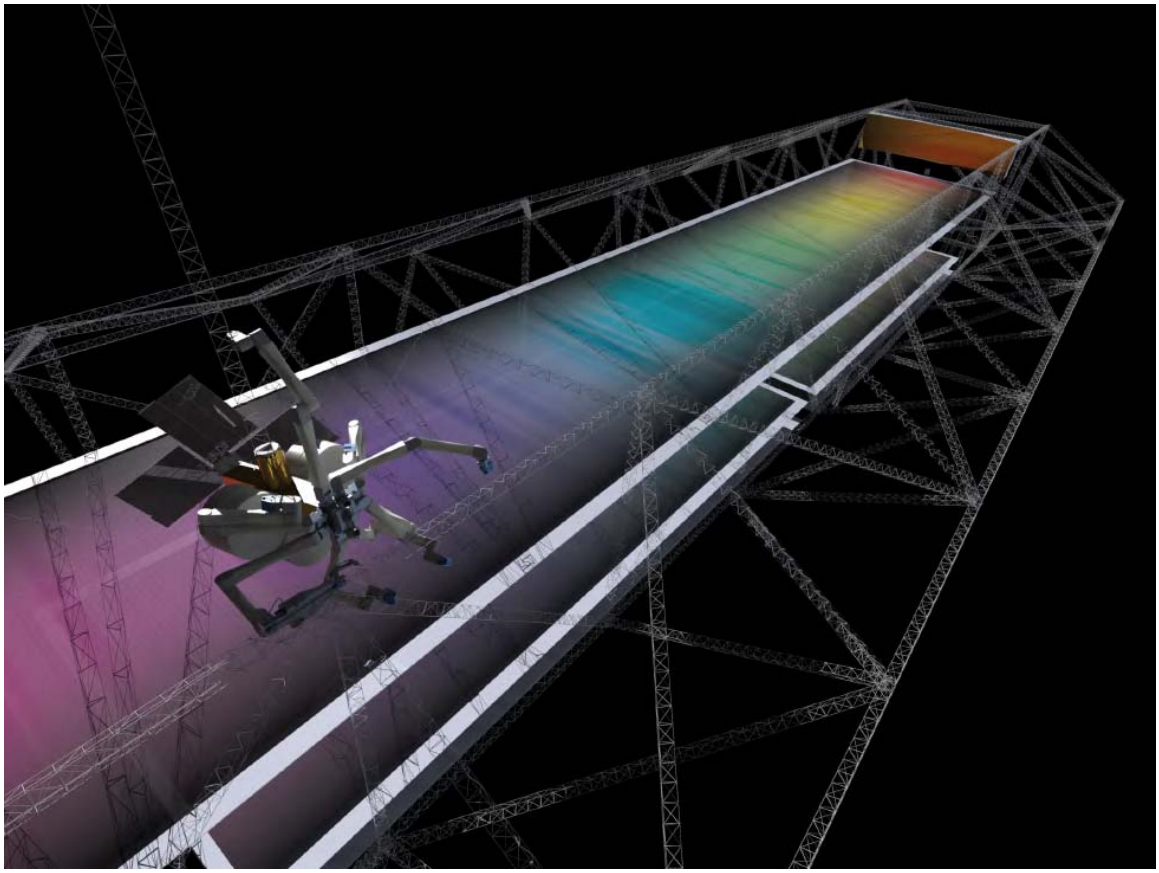


Fig. 20 Concept of SpiderFab® Construction of a membrane spectrographic telescope

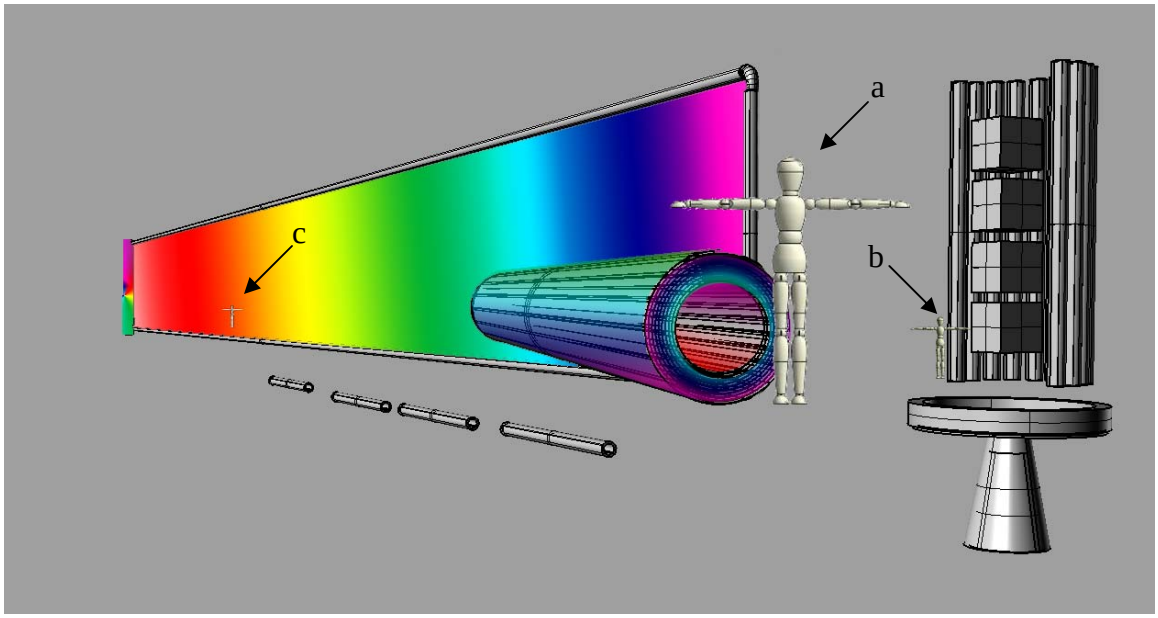


Fig. 21 Deliverables: Roll HOE and instrument packages. Dimensions are compared with a human figure, **a**,**b** & **c**. The stretched 50 x 10 meter membrane HOEs are bussed on 1 m diameter drums and unrolled into service across trusswork frames.

4. Experimentation

a. HOE fabrication and bench mount

i. Zemax model

We began our study by modeling an HOE that when combined with an identical HOE primary objective would resolve wavelengths at 0.0001 nm.[38] A Zemax model of the HOE is shown in Figure 14 above. The 300 μm fiber tip projects a very narrow spectrum that in the operation of the exoplanet finder combines the images of all exoplanets within one exosolar system at unique and distinct wavelengths proportional to their angular separation from themselves and their parent star. Their spectrum is fed to the spectrograph HOEs. In the Zemax model, distance from a fiber tip to the first HOE is 700 meters. This is a very large device designed to ultimately form an image on a focal plane that is merely 2 cm wide. It is shown in this full scale model that the HOEs are resolving 0.0001 nm over 1.8 cm. This translates to 300 mas total separation, the presumed region of habitable planets on G class stars within 10 pc, a performance goal for the telescope. The angular resolving power of the telescope with a 50 m primary is better than 10 mas.

An HOE based on the Zemax model in Figure 22 was physically made on a holographic bench to test the concept. The HOE was scaled to a focal length of 500 mm, and the Zemax computer model of the physical HOE is shown in Figure 2. The laser selected was the HeNe line of 632.8 nm. In the Zemax model all spatial filters are ideal point sources and do not have pinhole diameters. The reference beam is a plane wave at 0° (directly above the plate) and the object beam is set at 45° relative to the plane of the plate by placing the object as a point source at 353.553 mm on the construction y and z axes. When played back near to the recording wavelength, the predicted performance over a 2 nm spectrum is shown in Figure 22. The focal plane is slanted as with the telescope model of Figure 15. Zemax predicts a 7 mm separation on the focal plane between the two playback wavelengths.

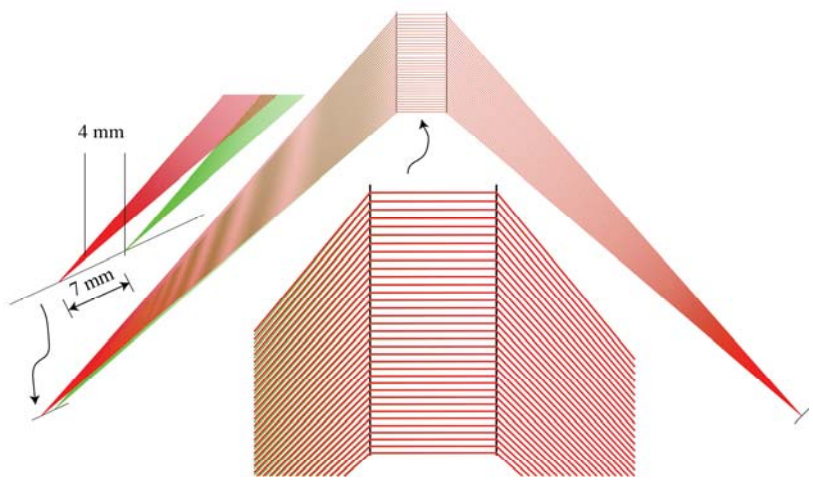
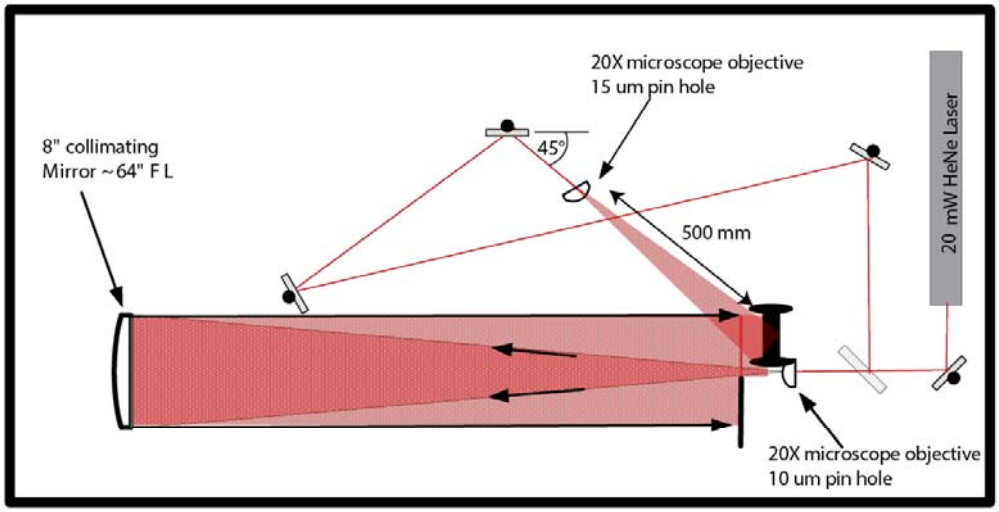


Fig. 22 Zemax model of physical HOE. Inserts show focal plane for 2 nm separation between spectral lines and the divergence of the two wavelengths.

ii. Holographic recording



Notes: INTEGRAF silver halide 4 x 5" plates
Beam Ratio: Reference to Object 2:1
System settling 10' Exposure 30"
Development 30" Bleach 45"

Legend

Light block Beam:	2x2" Mirror:	Spatial Filter: Microscope objective & Pin hole	Beam Splitter:
Expanded Beam:	Film Plate Holder:	Collimating Optic	Path Lengths = Reference 133" Object (collimated beam) 133" 45° Reference Angle

Fig. 23 HOE recording bench setup from above with component legend.

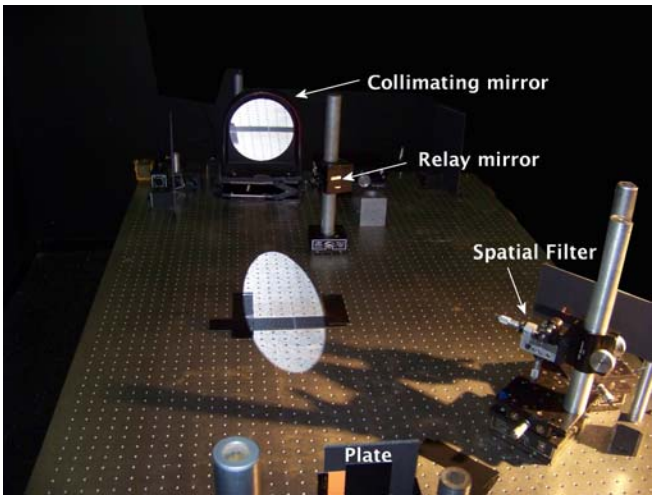


Fig. 24 The optical table. The plate is shown from backside. The oval is a reflection of the camera

HOEs were created on 4 x 5 in. silver halide glass plates. [39] Figure 23 shows a schematic of the setup. Figure 24 is a photograph of this bench. The transmission HOE was mastered in quadruplicate that yielded a pair of plates for each of two participating laboratories. They were tasked with corroborating test results. While plates differ in efficiency based on variations in development chemistry and timing, geometries were invariant.

The fabrication of the HOEs was undertaken as co-funded NIAC and NSF project to fulfill an NSF SBIR Phase II-A program for technology training at minority universities.[40] The bench, all optics, mounts and laser were left by 3DeWitt at the University of Puerto Rico.

ii Spectrograph test benches

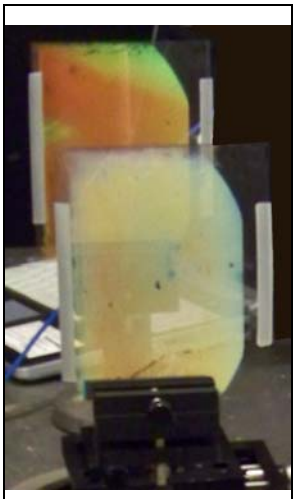


Fig.25 Dual HOE optics on bench at 3DeWitt laboratory.

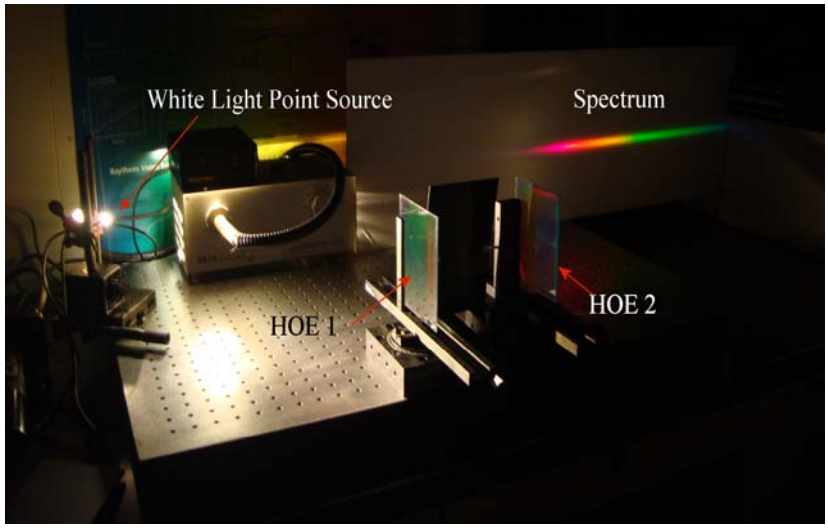


Fig. 26 University of Puerto Rico (UPR) dual HOE breadboard

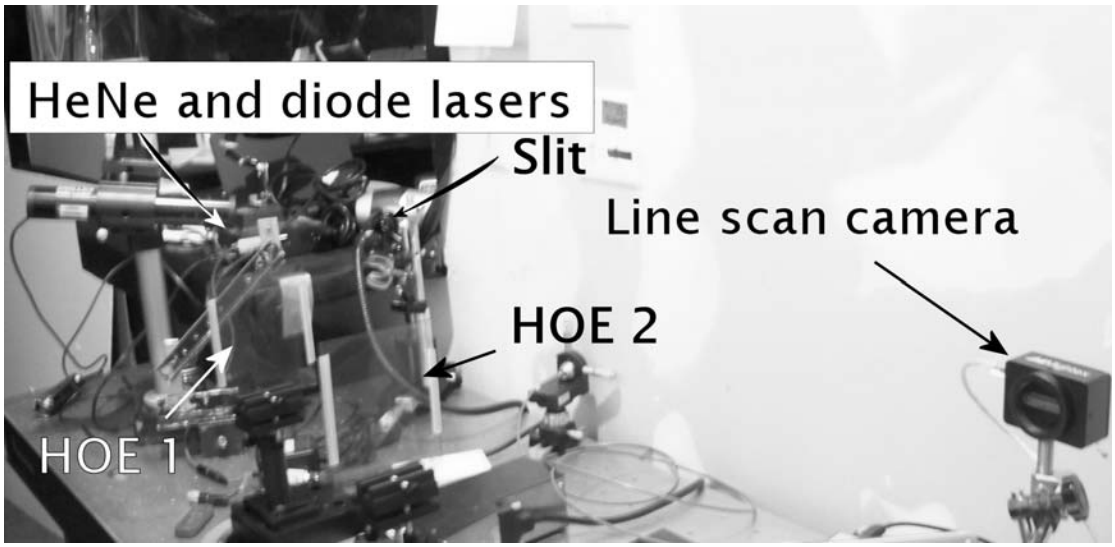


Fig 27 Dual HOE spectrograph with laser sources at 3DeWitt lab, Cairo, NY

Figure 25 shows an HOE pair in service on a spectrograph bench. The 8 inch collimating mirror that projected a plane wave reference beam during exposure did not completely fill the plate leaving two corner areas unexposed. Blemishes are visible on the plates but did not noticeably affect geometric performance. Figure 26 shows the spectrograph in the Physics Department at the University of Puerto Rico (UPR). Playback from a white light point source was made at the same angle and distance as the spatial filter that was the object beam of the hologram. The spectrum from the second HOE projected onto a diffusing screen and spanned to nearly a meter. A bench with equivalent HOE optics was set up at the 3DeWitt laboratory in New York to corroborate results, Figures 25 and 27.

b. Performance

i. Dual HOE Spectrograph

In the UPR experiment conducted independently by Dr. Sergiy Lysenko, a diode-pumped solid state (DPSS) laser was used which generated two narrowly spaced laser lines (two laser modes) of similar intensity near to 656.7 nm. Spectral separation between these laser modes was measured by calibrated Triax 320 Horiba Spectrometer. This is a scientific-grade single grating spectrometer with a plane diffraction grating of 1200 lines/mm. It proved extremely challenging to separate laser modes with this spectrometer when set up at the limit of its resolution using a 10 µm slit width. The acquired spectrum of the DPSS laser is shown in Figure 28. The two laser lines are spectrally separated by 1.2 Å. The same two laser modes were imaged through the dual HOE spectrograph and recorded by a CCD camera. The resulting image is shown in Figure 29. The scale bar is 1 mm. Separation between laser lines in Figure 29 is 0.43 mm. The lines are clearly resolved and their intensity maxima fit within a single-pixel line of the image. Therefore in this particular case, the resolution is limited by resolution of CCD matrix. Resolution of the holographic spectrometer in present geometry is estimated to be higher than 0.004 nm. Coma appears between the lines tapering off to one side This was ignored to make the resolution calculation.

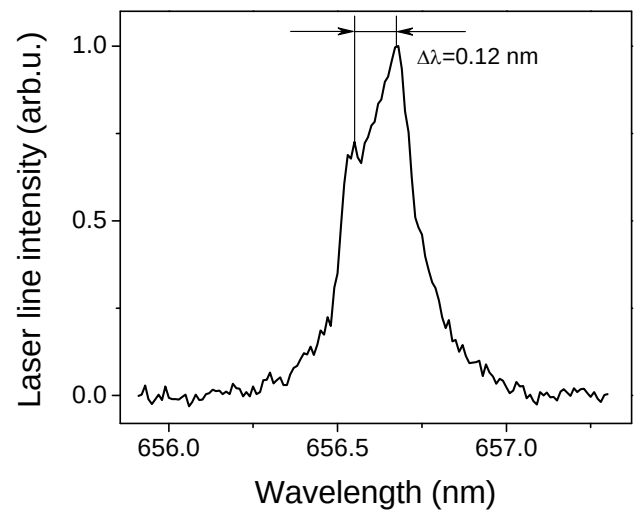


Fig. 28 DPSS mode lines as recorded on a laboratory grade Triax 320 Horiba Spectrometer

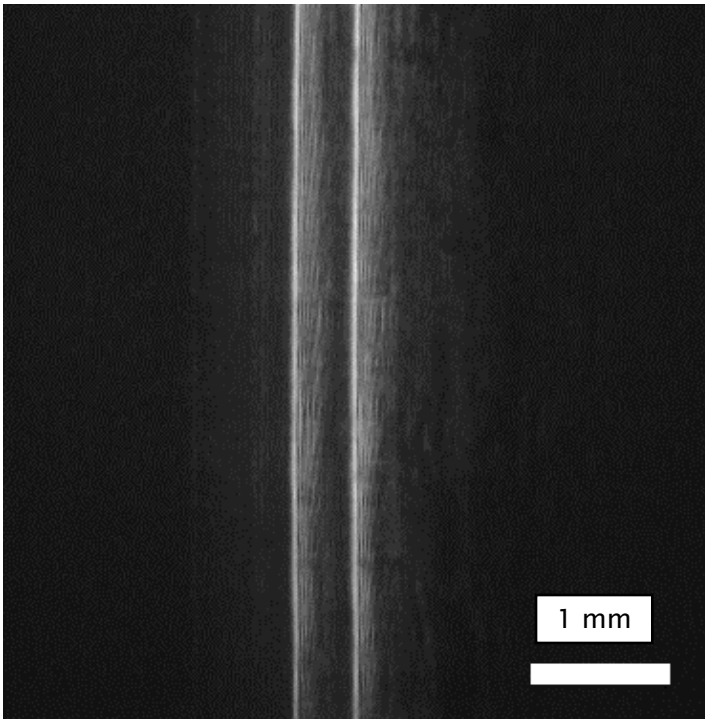


Fig. 29 Two DPSS modes resolved through the Dual HOE as recorded by a CCD camera

In the experiment run at the 3DeWitt laboratory using the bench of Figure 27 there were two lasers. The experimental result is shown in Figure 30. A laser diode exhibiting 2 modes was measured at a center frequency between modes of 631 nm. The diode is referenced to a HeNe laser with a known emission of 632.8 nm. The displacements were imaged through the dual HOE using a Mightex SSE-1304-UWE line scanner which is without a glass cover and intended for uses that image coherent radiation. Speckle artifacts are evident from the sources' diffusing surface (paper). For comparison we used an Ocean Optics USB-4000 spectrometer, Figure 31. The USB-4000 could not resolve the two modes or speckle. The output of the USB 4000 in is shown with pixel and wavelengths in the abscissa. The dual HOE spectrograph scan covers 600 pixels on center while the USB-4000 spans 35 pixels. Pixel width is 8 μm for the line sensors in both spectrometers. The resolution of the dual HOE spectrograph is approximately 0.003 nm, closely matching the result of the corroborating independent UPR experiment.

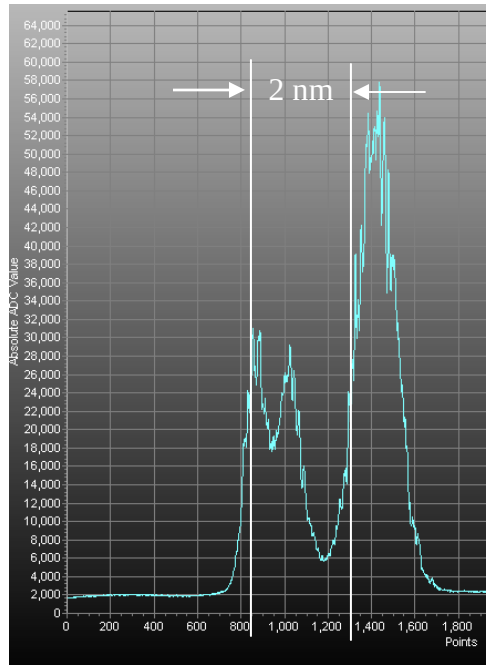


Fig. 30 Comparison of diode exhibiting two modes (left) and HeNe laser (right) using dual HOE and line scan sensor. Arrows show 2nm separation over 600 pixels

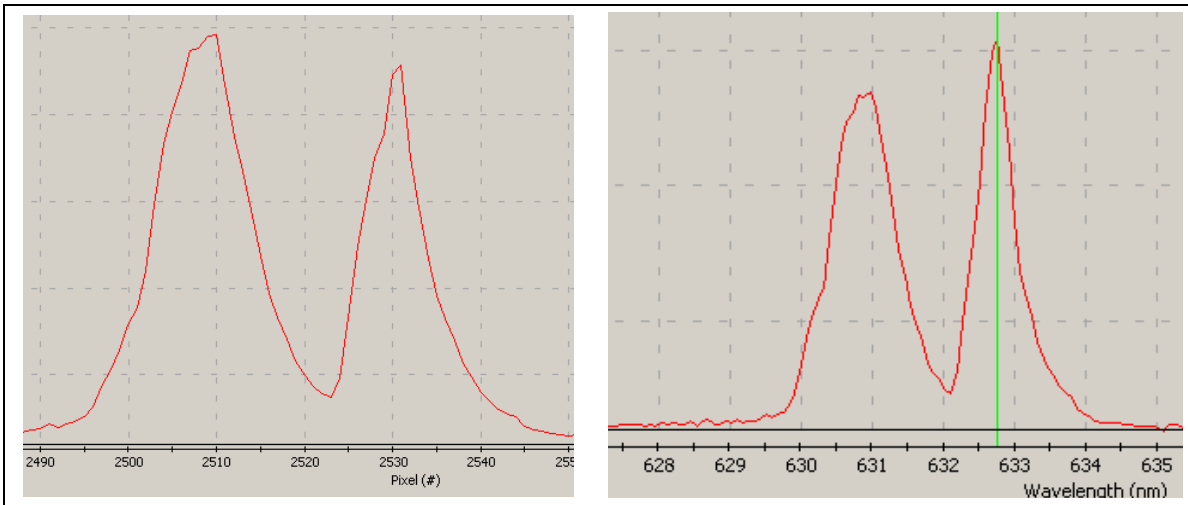


Fig. 31 Ocean Optics USB-4000 spectrometer in pixels (left) and wavelength (right)

The dispersion D_ℓ can be known by

$$D_\ell = \frac{d\lambda}{d\ell} = \left(\frac{\text{Å}}{\text{mm}}\right) \tag{3}$$

So for the spectrometer of the experiment of Figure 29

(4) $$D_\ell = \frac{d\lambda}{d\ell} = \frac{1.2}{0.43} = 2.79 \quad \left(\frac{\text{Å}}{\text{mm}}\right)$$

To estimate throughput, a Newport 1830 picowatt optical power meter took readings of HeNe laser flux emitted after the slit and as received at the line sensor. A measured flux of 3.66 nW was emitted out of the slit, and the focused energy near the image plane after the second HOE was measured at 0.9 nW. Therefore, throughput efficiency was 25%.

ii Comparison with Zemax models

The displacement of lines in the experiment of Figures 30 and 31 was 2.2 mm which is less than the Zemax prediction owing perhaps to the angle of incidence on the line sensor. It was not rotated from the grating plane normal. This may also explain why the two diode modes are not completely separated at the image plane. The linear sensor was tracked in a line parallel to the normal of the grating plane and not at the slanted focal plane calculated by Zemax as shown in detail in Figure 32 . There is coma on one side of Figure 29 which is predicted by its Zemax model, shown in the breakout box, Figure 32, which shows the anticipated foci.

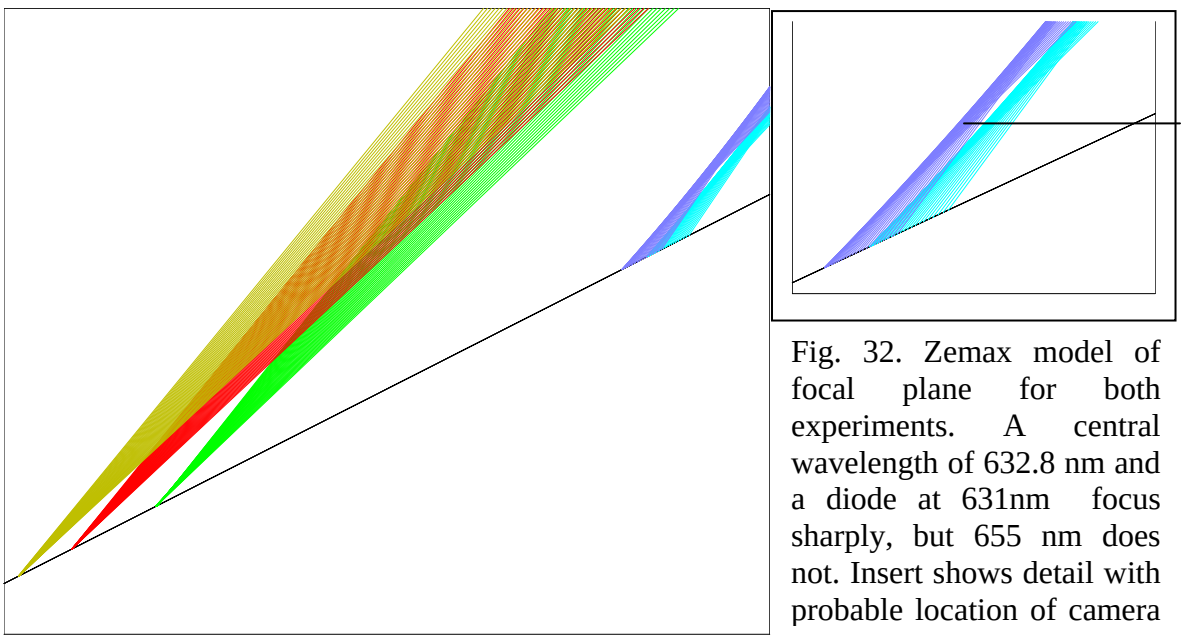


Fig. 32. Zemax model of focal plane for both experiments. A central wavelength of 632.8 nm and a diode at 631nm focus sharply, but 655 nm does not. Insert shows detail with probable location of camera

Similarly at shorter wavelengths, focus is not maintained. The Hg lines at 579.066 and 576.960 were modeled in Zemax and are shown in Figure 33. An image taken with a line scan is also shown in Figure 33. A weak source contributed to the poor resolution, but the intrinsic soft focus does not recommend the spectrograph over a useful bandwidth.

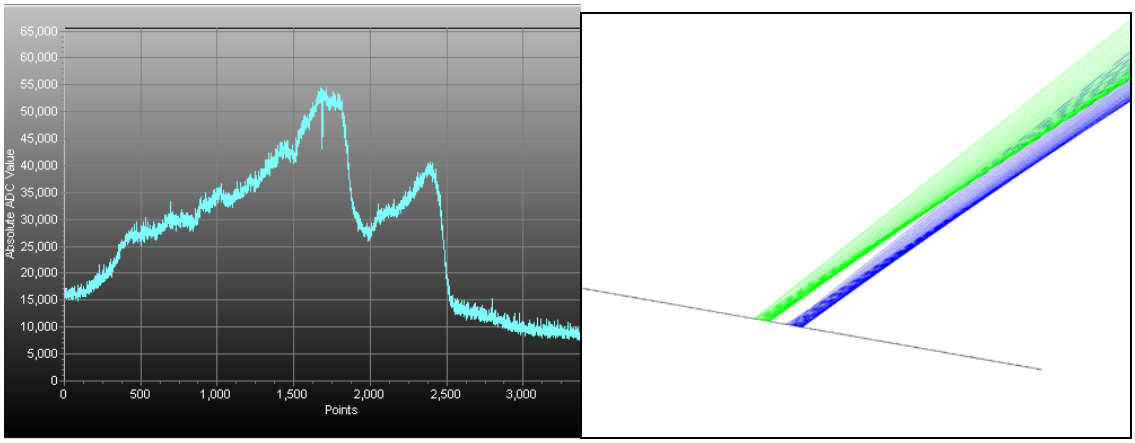


Fig. 33 Bench recording of Hg lines 2nm apart (left) and a Zemax model at image plane (right) predicting the soft focus.

iii Single HOE Spectrograph

Although it was observed during the experiment of Figure 33 that the Hg lines did not focus well after the second HOE. the lines were quite clear to the eye from the first HOE. The image was recorded with a color CMOS camera, Kodak Z812 IS, and is shown in Figure 34 with the derived intensity curve across several of the resolved lines.

Fig. 34 Hg lines of 579.066, 576.960 and 546.074 nm as seen through HOE 1 and recorded with a CMOS camera, Kodak Z812 IS.

The performance of the single HOE spectrograph can be compared with the Ocean Optics USB-4000 in Figure 35.

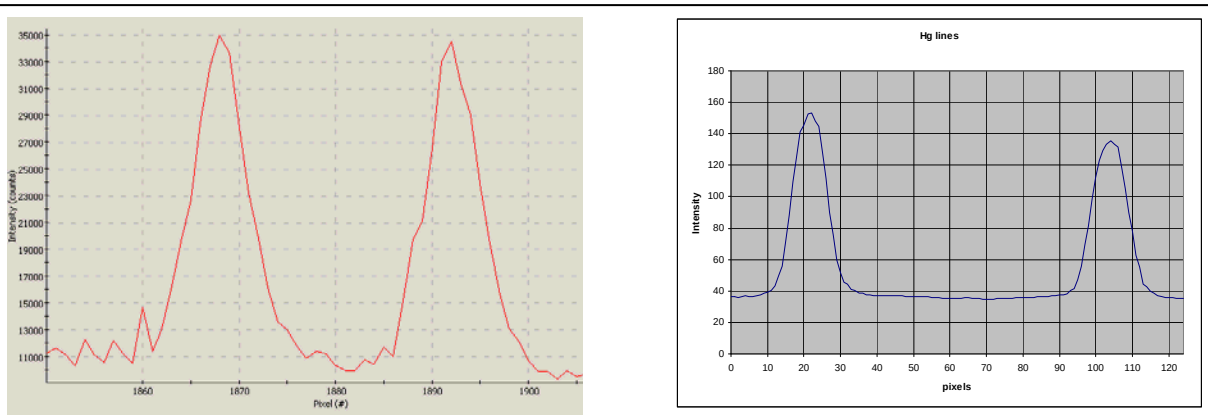


Fig. 35 The USB-4000 miniature spectrometer scan of Figure 33 over lines 579.066 and 576.960 nm (left). The same lines dispersed from a single HOE are graphed (right)

Using NIH ImageJ software to analyze the Hg lines of 579.066 and 576.960 nm, the intensity curve of Figure 35 was derived from a table. Camera pixels are 1.56 μm wide and the two wavelengths span 82 pixels over a band of 2.1 nm. The HOE is resolving approximately 0.026 nm, roughly an order of magnitude less than the double HOE but without its loss of focus over the same Hg lines as show in Figure 33. Absent the second HOE, the empirically measured efficiency was not surprisingly twice the double HOE or 50%. This single HOE spectrograph could be realized with a larger HOE. If the HOE was 30 inches wide instead of 4 inches, the resolving power would be 0.004 nm and possibly extensible for the intended use as the secondary HOMES.

5. Evaluation

a. Tradespace

We have modeled an HOE and played it back at the wavelength of its construction where it performs optimally. Other wavelengths do not focus nearly as well. An example is shown in Figure 36 which shows a wavelength spread of 20 nm. The broader range of focus appears in a column that is normal to the HOE surface. The example insert shows a 5 cm column inside of which sharp focus is seen over a 20 nm spectral range. More work remains to optimize the bandwidth over which the HOE will focus.

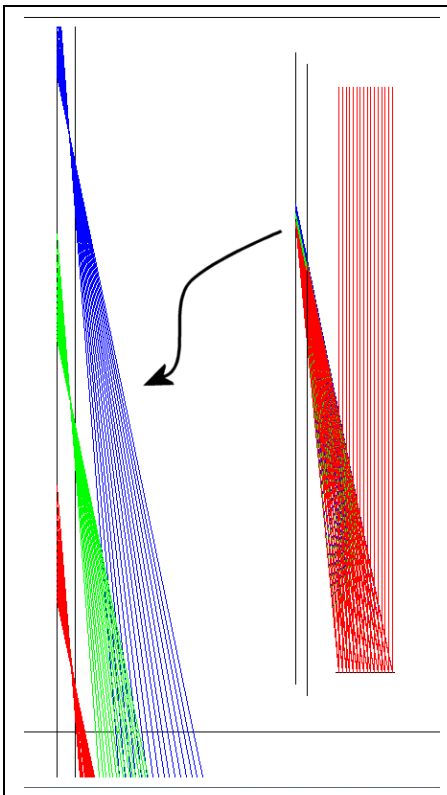


Fig. 36 Sharp focus over 20 nm

A distinction between a parabolic mirror and a plane grating is that the mirror is a three dimensional optic whereas grating grooves can reside on a flat substrate. Errors in groove blaze do carry a penalty in throughput efficiency but not in spectral or angular resolution. However, if there are any variations in the groove spacing from end to end, the resolving power of the grating is degraded. Grooves must be printed at a precise submicron spacing over many meters. The substrate must remain uniform through temperature gradients, as well. This is an engineering problem.

A theoretical problem, on the other hand, is throughput. Compared with mirrors, gratings are inefficient. An antihole photon sieve was reported to achieve an efficiency of 0.2%. [41] A transmission grating in silver halide made with the geometry of the HOE primary was measured at 50% efficiency. Our expectation is that size may be a saving grace for architectures using holographic primaries. That said, it is possible to set a narrow waveband-specific HOE such as a phase volume hologram to better levels of efficiency. If a particular spectral signature is sought, the system throughput could be improved by customizing the holograms for a narrow band.

Large collectors bring implementation problems associated with maintenance. The presence of particulate matter on a large optical surface can become part of the signal, and with extremely faint objects like exoplanets, solar glints from particles of dust on the collector can overwhelm the exoplanet's signal.[42] The glint problem is compounded by formation flying where multiple sun shields are necessary. Smaller co-axial primaries are easier to shield. It is not known if POG architecture is robust under particulate glint when compared reflective surfaces, but it can be said that the optical principles involved are not identical. We have shown a surprising immunity to ambient light in a small model of the POG telescope which is unaffected by room illumination 100 times greater than the source under study.[43] The immunity may be related to some unexamined consequences of using wavelengths as measures of angular position, since in the near-field a solar glint has a completely different chromatic spread than a far-field object. In any event, if this is a show stopper, the proof will have to be made rigorously if the problem does not present itself in the laboratory first.

Another trade is that resolving power is asymmetrical. The POG promises unprecedented apertures that accommodate the inner working angles required to see close to the parent star, but there is a second dimension to the problem that is compromised by a ribbon-shaped collector. Observations that work well in one dimension are marginal if not inadequate in the other. A flare from leakage around the nulling spectral interferometer can be anticipated so that only the side lobes will be effective. The consequence may be that only half years are available for observation. That said, a ribbon of 10 x 50 meters would have adequate lateral resolution to acquire many exoplanets in the Goldilocks zone within 10 pc.

b. Recommendations

Revolutionary technologies introduce unfamiliar parameters that trade their undeniable advantages for undesirable limitations. The difficulties associated with characterizing exoplanets using established technologies invites study of unexplored alternatives, but it also is prudent not to entertain methods that violate first principles. The next steps going forward should test the new concepts in HOMES to determine the extent of their limits.

The acuity of focus of an HOE over a meaningful spectral range has been a limitation that appeared as our computer models were being rendered off the central wavelength used in their construction. The single HOE spectrograph of Figure 34 & 35 gives us empirical evidence that across spectral bands of 100 nm resolving powers are within specifications for the secondary spectrograph, but the primary must do much better than that if the proposed coronagraph is going to work as imagined. We have been advised that "conformal" or concave gratings with curved surfaces can improve focus.[44] It may be that geometry holds the answer, but a curved HOE would vitiate the benefit of a flat surface that makes our membrane concept so attractive. We recommend looking at corrections to the HOE geometry which incorporate the behavior of a conformal grating into a flat surface. This would entail corrective optics in the object spherical wave and the reference plane wave used to record the HOE.

The coronagraph concept we introduce here has no known prior art. It was gratifying to see the initial predictions, but they were predicated on mixing plane waves. In the near-field an elliptical surface provides the requisite dual foci, but it turns out not to work as well as we had hoped. This may be a killer. An inquiry into the dual foci curved reflective surface intermediated by a plane grating needs to be pursued. It may not exist. It does not appear to be a classical conical section.

Failing to achieve a nulling coronagraph using our novel design, there are alternatives that can be investigated. We note that optical fiber communications have interferometers built into the fibers themselves. Typically these take the form of Mach-Zehnder types where the phase delay is controllable electronically. We have not found extinction ratios of 10^{10} being reported in the literature, but theory does not preclude such performance. It is more problematic that in-fiber interferometers of this type have the same fringe artifacts that limit nulling interferometers in other coronagraphs.

While our approach is geared toward collection surfaces of unprecedented area, photon collection is so sparse that efficiency is a critical parameter. Surface relief holography of the type we have assumed may achieve 80% throughput for one of two polarities, but overall efficiency is unlikely to be greater than 50%. It would be informative to study all alternatives including but not limited to highly efficient volume types. Even though these are "thick" materials, we are talking about tenth millimeter cross sections, preserving the gossamer membrane areal mass that makes this approach attractive for space deployment.

The image plane on our initial model is rotated 77° from the co-axial ray of the lens before it. The angle is not conducive to efficient photon collection. Additional optics are needed to alter the ray path so that the image is focused on the normal to paraxial rays, as is the universal practice in cameras. We have studied the Schiempflug condition in a prior publication [45] where a similar focus correction was employed for diffraction range finders, and it is not surprising to see off-axis image planes recur in a diffractive optic telescope. Nonetheless the off-axis image plane causes losses whenever it crops up. While not a killer, it is an undeniable problem we will address going forward.

Also at the image plane our Zemax model is producing perplexing intensity maps. While one axis has a cross section that varies, the other is perfectly flat. In all likelihood, neither representation is correct. There is work to be done in refining the Zemax model so it can make predictions that are reliable, perhaps by restructuring the model. The model certainly can be refined with regard to the HOE itself by using the special optical holography feature rather than the idealized hologram construction of this preliminary study.

Our NIAC Phase I study is a beginning. It is not conclusive. We expect to submit a Phase II proposal in the next cycle that will follow up on these recommendations in pursuit of advancing this concept to a higher technology readiness level.

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