ADDEDPT - Apparatus for Direct Detection of Exoplanets by Diffractive Pupil Telescopy

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ABSTRACT

Direct observations of habitable zone exoplanets within 10 pc require very high contrast attenuation of the parent star. While "pale blue dot" earth twins have strong signals in the near-UV and blue portion of the spectrum, and a G-class star like our sun has the most energy in the same region, the contrast ratio of star to exoplanet is 10^{10}. However the ratio is 10^{8} when the exoplanet albedo is reflecting an emission band inside of the spectrum of the star's absorption band. These interlaced emission and absorption bands are numerous and sharply defined in the blue region when the system is viewed through circular diffractive pupil optics. We show how to use a circular diffraction grating pupil to create asymmetrical circular diffraction images of exoplanetary systems that can be extracted from the central star's perfectly circular diffraction pattern by a series of iterative data reduction steps. We present a model of the apparatus that forms the diffraction images and a demonstration of the process in a laboratory experiment. The process may prove useful if large circular diffractive optic telescopes are successfully fabricated in on-going projects for earth reconnaissance from GEO where 10 meter diffractive optic telescopes are now contemplated.

Keywords: exoplanet, diffractive pupil, stellar neighborhood, earth twin, earth clone, pale blue dot

1. INTRODUCTION

The NRC Decadal Survey of Astronomy and Astrophysics names exoplanet discovery as a goal but leaves the path to instrumentation unresolved. [1] The Terrestrial Planet Finder missions from the prior decade were all canceled. While Kepler and TESS are specific to exoplanets, their transit photogrammetry method is totally blind to 99% of the exoplanet population. JWST may be repurposed to find exoplanets but will require an external occluding star shade [2] without which JWST cannot directly resolve inner planets in our "neighborhood" of 10 parsecs. None of these missions can take spectra in the blue and near-UV of exoplanets in the habitable zone. While it seems as if everyone wants to know if there are any other "pale blue marbles" like our earth, such high contrast spectral imaging with a 100 milliarcsecond inner working angle has never been achieved before. The problem is to detect and characterize very faint objects very close to the stars that illuminate them.

Just as Kepler was designed to see if exoplanets exist, it is possible to conceive of a type of telescope specified to detect earth twins. Just as Kepler combined the light of parent stars with optical photogrammetry, our ETF (Earth Twin Finder) will combine stellar spectra and spectrographic telescopy into a specialized instrument we call ADDEDPT Apparatus for the Direct Detection of Exoplanets by Diffraction Pupil Telescopy..

1.1 Observational method

A pale blue dot is **blue**. Observation in the near-UV/blue where earth shines brightest is a requisite spectral band for ETF. The earth is strong in this reflectance band due to its characteristic atmospheric Rayleigh scattering and the behavior of the phases of water as they reflect stellar black body radiation.[3] Even as solar black body radiation loses flux over shorter wavelengths, the relative brightness of earth's albedo grows. For all classes of star with irradiance within 300-400 nm, normalized reflectance in near-UV holds a valuable signature for oceans, clouds, snow and ice caps. This was detected by GOMES, a 1990's ESA satellite launched to find ozone but incidentally looking at earth's oceans in the 300 - 400 nm band.[4] See Figure 1.

Exoplanet telescope concepts shy away from blue and favor the infrared. M-class red dwarfs are being studied, [5] notwithstanding that tidal locking in the habitable zone of these systems precludes an earth twin. [6] The infrared is favored, because star to exoplanet contrast is $1:10^{-8}$, whereas relative intensity of parent star to an earth twin is $1:10^{-10}$ in the blue. Infrared telescopes are being readied, particularly from the ground, but they cannot confirm an earth twin in the blue and near-UV bands. All planets exhibit heat signatures, and it is particularly useful that infrared spectrograms may

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contain signatures of biological byproducts such as oxygen and methane. That said, ETF must take spectra in the shorter wavelengths to differentiate exoplanets from each other to say nothing of detecting earth twin candidates.

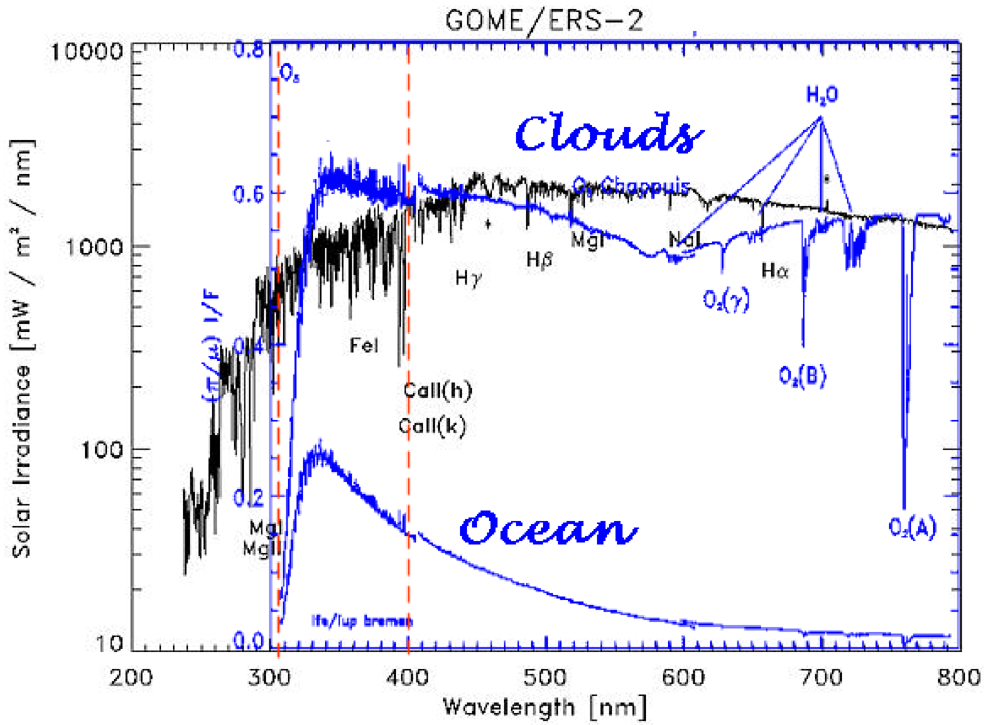


Fig. 1 GOMES solar spectrum (black) super-imposed on earth's water spectra (annotated blue). Band of increasing reflectance of water phases appears in band of decreasing solar irradiance (dashed lines red)

Fortunately, a 1:10^{-8} ratio is available in the near-UV and blue between Fraunhofer lines. In Figure 2 we show Fraunhofer lines for a G-class star, HD 59100, in the near-UV/blue region where earth-like exoplanets exhibit increasing albedo irradiance. The typical peak to valley emission/absorption of the star are in ratios greater than 50:1, peak to trough on some lines ratios of 100:1 can be seen. [7] In a Figure 2 detail we show the high frequency at which these transitions occur in solar irradiance in a deep blue/near UV band. [8]

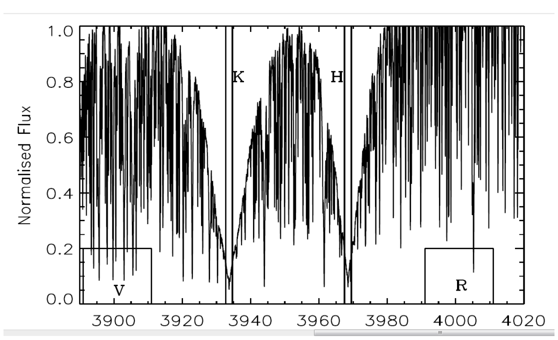
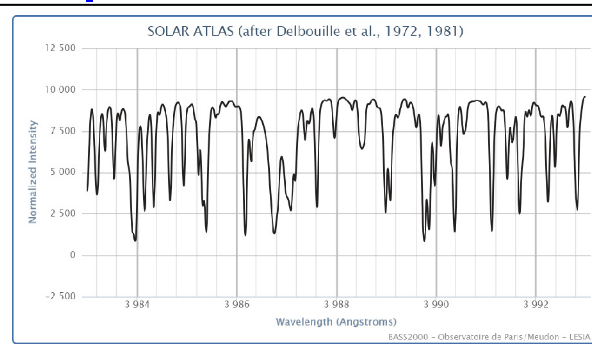


Fig. 2 Near-UV and Blue Fraunhofer lines of G class star



Detail showing wavelengths in near -UV over narrow band

Fraunhofer lines have been closely studied in astronomical measurements related to radial velocity Doppler shift, but direct exoplanet observational techniques do not exploit the phenomenon. Fraunhofer lines exhibit sharp and deep absorption and emission peaks and troughs which are increasingly numerous at shorter wavelengths. The feature can be utilized by an ETF. If each discrete point source in an image has a spectrum around it, the Fraunhofer lines form alternate dark and bright rings. Bright spectral lines from exoplanets then can be extracted from the darker absorption bands of their parent star by using a data reduction image processing technique that we introduce here.

2. DIFFRACTIVE PRIMARY OBJECTIVE TELESCOPE

Diffractive gossamer membrane telescopes overcome problematic diameter limits endemic to mirrors and lenses caused by their dense areal mass, exacting figure tolerances, and inflexible substrates – budget constraints that are inescapable in the design of space telescopes.

2.1 Gossamer membrane architecture

Space telescopes must achieve greater apertures and larger collectors for ETF than other missions, because the images of the exoplanets are faint and must be resolved apart from their parent stars. We have been investigating a new species of telescope with flat membrane primary objective diffraction optics. [9] The concept is also being studied by others. [10] A diffraction telescope is in development at DARPA.[11] A diffractive pupil telescope is on a test bed at Ames.[12]

Diffractive optics are flat. Moreover, we have proven in theory and shown by experiment that low areal mass membrane diffraction gratings and holographic optical elements have highly relaxed figure tolerances. Our assertion has been corroborated by the research that led to the DARPA project. [13] .

For its primary objective, DARPA/AF's MOIRE [14] uses a variation of the diffractive Fresnel Zone Plate (FZP), a dispersive flat optical element, to directly form images. In some of the associated literature the primary is described as an anti-hole photon sieve. Incident radiation is transmitted through holes that are etched into an opaque surface by means of optical lithography.

An FZP in the form of an anti-hole photon sieve is not efficient, but DARPA's goal is to post an earth surveillance telescope at geostationary to acquire ground images which are much brighter than faint astronomical objects. The critical criterion for the aperture is angular resolution. Diameters greater than 10 m are deemed mandatory to form highly resolved ground images at seeing through the atmosphere, and a diameter is targeted at 20 m for this \$500 M project. Despite government secrecy surrounding the project, enough information has been disclosed (including through this SPIE symposium) to indicate that a Phase II level has been reached in the fabrication of the gossamer membrane diffractive primary. A video simulation of the deployment has also been released. [15] It indicates a folding "flower petal" or "seed pod" concept for the transportation package. The FZP is highly segmented so accommodate the compression of the tight stowage.

ADDEDPT takes MOIRE as its starting point, exchanging its FZP with a Gabor Zone Plate (GZP). We use a published DARPA rendering of MOIRE to show how ADDEDPT might look once deployed, Figure 3. The ADDEDPT GZP annular ring primary is a departure from HOMES and THE MOST, diffractive pupil telescopes with linear ribbon-shaped primaries studied by the author under NIAC Fellowships. [16] The change to an annular ring geometry brings an important benefit. ADDEDPT does not suffer from asymmetrical resolving power resulting from the primary collector's aspect ratio. An entire exoplanetary system is equally resolved over all phases of its exoplanets' orbits.

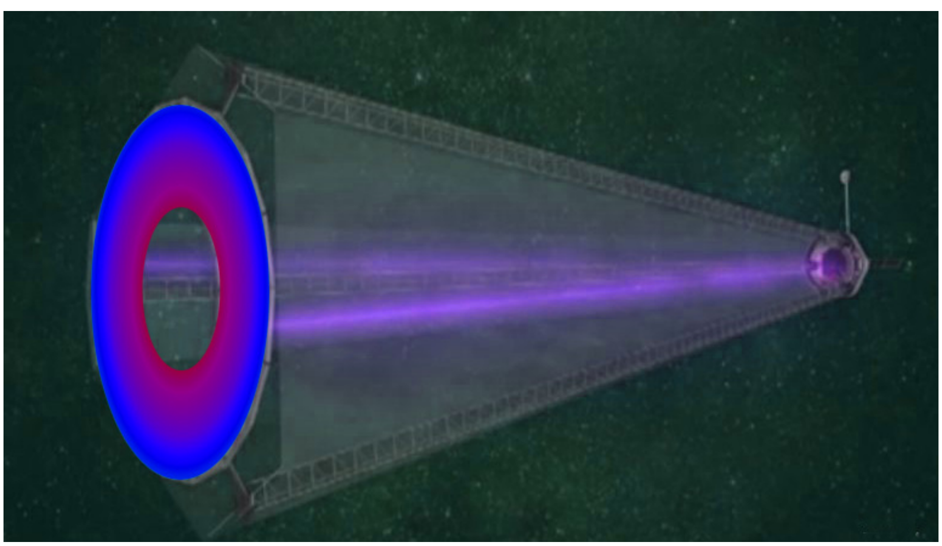


Fig. 3 The MOIRE platform adapted as ADDEDPT. Its Fresnel Zone Plate anti-hole photon sieve is replaced by a Gabor Zone Plate

The areal mass benefit remains. The membrane primary is packaged for transport as a rolled plastic, Figure 4.

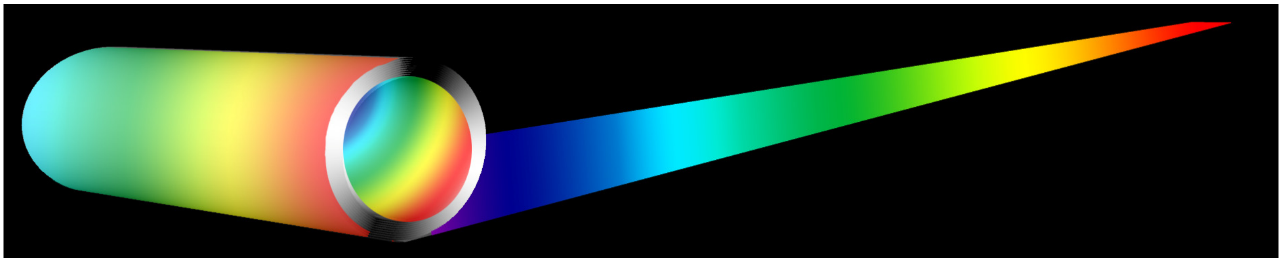


Fig. 4 Gossamer membrane ribbon stowage as a roll plastic can reach L of 1 km on a diameter of less than 1 m mandrel.

ADDEDPT's ring-shaped membrane can be stowed to kilometer lengths on a conical feeder mandrel. The length *L* of the stored GZP can be known by:

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

where OD is the outside diameter, T is the membrane thickness and N is the number of revolutions in the wrap

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

In another diffraction primary telescope, the NASA Ames diffraction pupil telescope, a coarse dot pattern is placed on a rigid parabolic mirror to induce radial diffraction artifacts that form fiduciary marks around a central star. [17] The considerable length of each diffraction image is measured for precise astrometry. While the AMES method is not a membrane and cannot directly image exoplanets, it does demonstrate how the size of an image is expanded through induced dispersive chromatic aberration. It changes a single pixel into a much larger image that can then be measured more precisely for its position. Taking guidance from this technique, we believe that Fraunhofer lines can be expanded into large concentric circles around exoplanets that are otherwise much smaller on the image plane

While it is gratifying to see primary objective gratings now been adopted by others, our NIAC studies differ significantly from the Ames and DARPA projects with respect to the secondary optics. Spectroscopy appears absent from these diffractive primary telescopes. Their goal is to create photographic imagery. Spectroscopy in the secondary is central to our ETF. Circular spectrograms of the parent star and exoplanets are a means to both characterize exoplanets for water and to geometrically exploit circular Fraunhofer lines.

2.2 Coronagraphy

We propose using Angular Differential Imaging (ADI), used to study exoplanetary systems with the Subaru telescope shown in Figure 5. [18] Spectral Differential Imaging, has also been used to remove speckle. [19] In ADDEDPT, wavelength is important, not only because it can be used to characterize the exoplanets, but also when spectra are subtracted, emission lines overlap with absorption lines. The asymmetry between the position of the parent star with the exoplanets allows the parent to be removed if pointing is held within a few milliarcseconds over each sub-integration period. Such accurate and sustained pointing can be done with reaction wheel stabilization. [20]

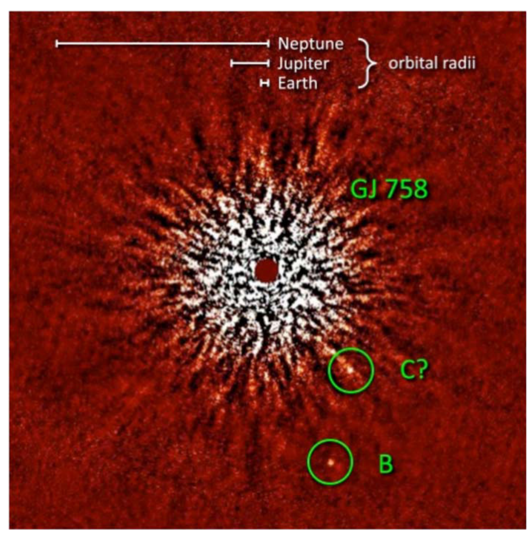


Fig 5 Direct exoplanet detection by ADI from Subaru

A schematic diagram of a single angle for a single Fraunhofer line of a single exoplanet is shown in Figure 6. A simulated spectrogram after processing is shown in Figure 7. After a single iteration of subtraction, exoplanets remain buried in star light 10^8 brighter. After 400 separate exposures and their data reduction on ground computers, the exoplanets should begin to appear above

Poisson noise. After 4000 iterations, S/N > 10. In order to accommodate all exoplanets, the computation is carried out at all angles with each image.

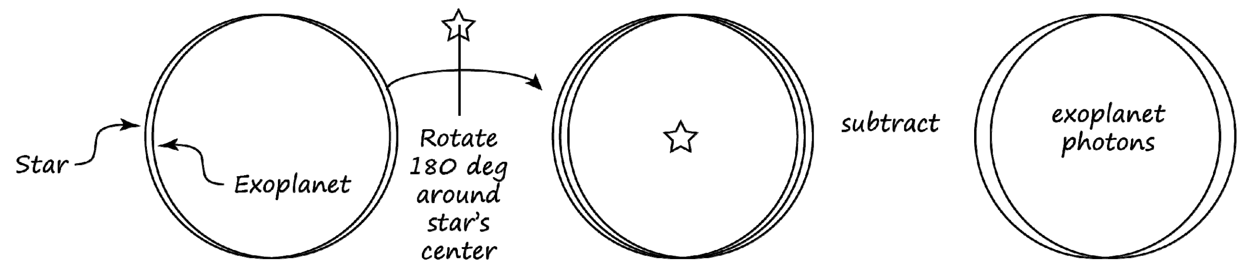


Fig. 6 An ADI iterative data reduction process deletes centric star's Fraunhofer lines leaving eccentric exoplanet spectral lines. This diagram shows a single line at a single angle of rotation for the sake of a simplifying illustration.

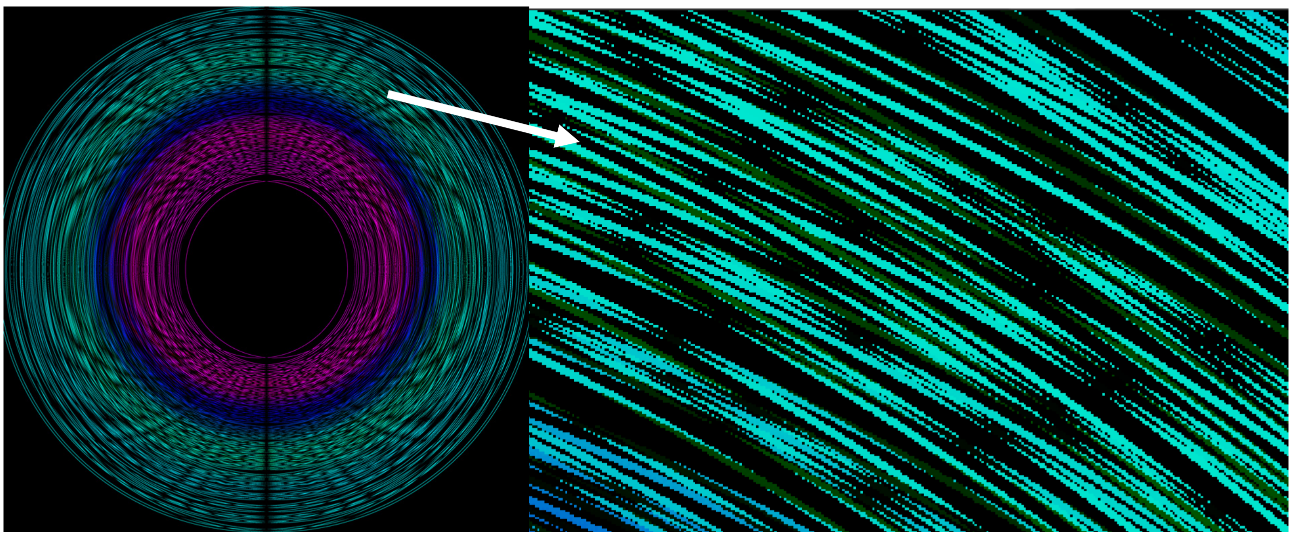


Fig 7 A simulated ADI extraction of earth-like exoplanet spectrum in the near-UV. The image on left shows all the spectral lines. In detail to right, subtracted lines are black.

ETF must see at least to the 30th magnitude. ADDEDPT can enjoy a primary collector on the order of 2000 m^2. It could be made from a volume phase transmission hologram shown to be 90% efficient within a 50 nm working range.[21] The Hubble Extreme Deep Field recorded galaxies of 30th magnitude to S/N ≈ 8 in 9 bands over a total of 23 days with a "bucket" of 4.2 square meters [22] (1/250th the scale of ADDEPDT). If an exoplanet is 30th magnitude and the bandwidth is 50 nm, a "back of the envelope" estimate would be that observation periods of ADDEDPT might average 10 days per star composed of sub-integration periods on an average of three minutes. In three years 100 "neighborhood" stars (10 pc) could be mapped to a S/N ≈ 10. Admittedly, this is a “back of the envelope” estimate. More study is needed.

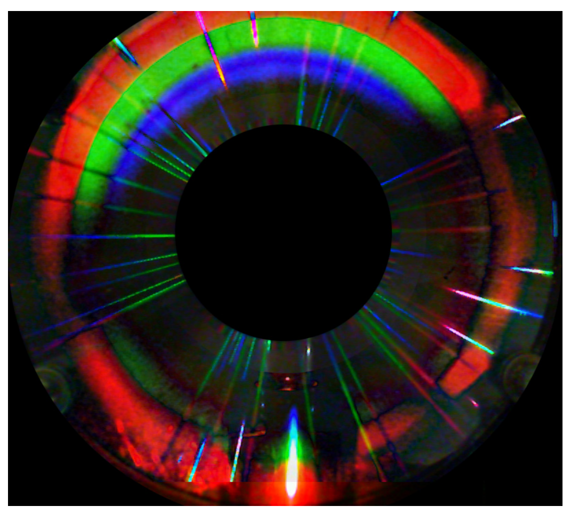


Fig. 8 A circular grating on an optical bench diffracting an artificial star and many artificial off-axis proximate stars.

It may be insufficient to do the subtraction on the star without first having a coronagraph stage. This value of coronagraphy is appreciated, and a coronagraph can be included. We have shown elsewhere that a "divide and conquer" approach to nulling interferometry produces a single central null with deep extinction per selected wavelength..[23]

A bench test was performed to validate this concept, Figure 8. We used a circular plane grating and simulated the parent star and many proximate stars. The diffraction first-order central ring and first-order streaks from the proximate stars appear as expected. Most streaks fall out-of-band and would never enter the ADDEDPT secondary. Streaks that do penetrate are predictable from star maps and can be deleted in data reduction.

2.3 S/N and resolution

Zero-order flux suppression is also a factor to be considered. For example, if the annular GZP is 1000 m^2 and the secondary has an aperture of 100 cm^2, then background contamination from zero-order flux to first-order is at the ratio of 10^{-5} to 1 above Poisson noise.

In an annular diffraction primary, the distinction must be made between resolving power and angular resolution. The former is determined by the number of GZP fringes, while the latter is determined by considerable diameter of the entire GZP where $R = D/ \lambda$. Hence for a 60 m diameter telescope operating around 400 nm, $R = 1.5 \times 10^8$, resolving about 10 mas. However, any resolved point will have a FHWM > 30 mas, a value that will not change significantly even if the diameter is grown. These numbers are near to performance specifications needed for ETF telescopes, since the habitable zone inner working angle is likely > 30 mas. However, these numbers must be scrutinized with a Zemax model.

A GZP suffers from wavelength-dependent focus. We have published a theoretical study on correction using high index refraction in secondary optics.[24]. Refractive disperses in the reverse order of wavelengths compared to dispersion by diffraction. Our Zemax model, Figure 9, is built around a holographic optical element (HOE) primary objective and shows how a plastic lens corrects for chromatic aberration over wavelengths spanning 400, 550 and 700 nm, which is a far greater bandwidth than would be required for ADDEDPT.

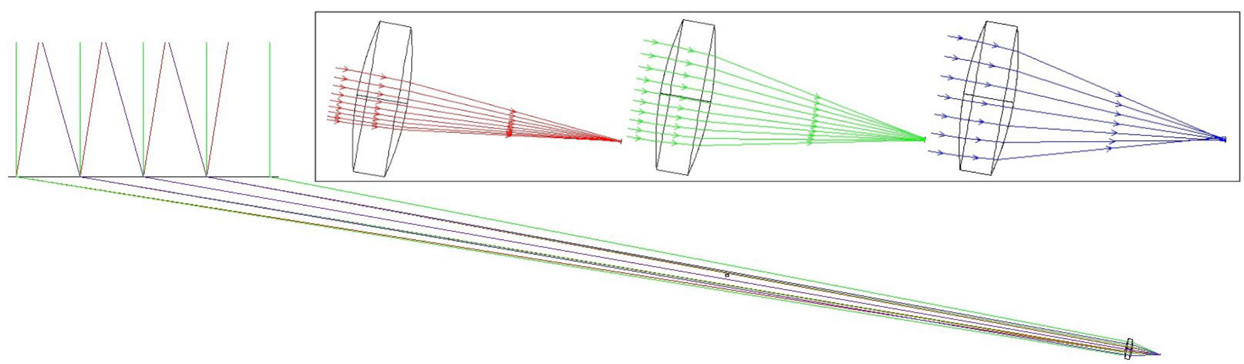


Fig. 9 Dispersion by diffraction from a HOE is corrected by refraction from a lens.

Figure 9 also serves to illustrate how this architecture results in an unobstructed wavefront. Spiders are not needed, leaving fewer diffraction artifacts. If a coronagraph must be installed to suppress flux from the parent star, an unobstructed pathway to the coronagraph is valued.

The secondary spectrometer must be able to resolve Fraunhoffer lines, hardly unprecedented in telescopes. However, the strategy is to produce circular diffraction lines as per Figures 6 to 8, and this is unique. Another GZP can be used. A Zemax model is shown in Figure 10. The model presumes a ring with inner diameter of 560 mm and an outer diameter of 700 mm. The active HOE surface is 140 mm. Rather than correct the focusing errors, the image plane is formed on a conical substrate. This wrap around image plane is notional, but it geometrically solves the chromatic focusing problem. The PSF at the image plane for the central wavelengths are shown in Figure 11. An orthogonal cross-sectional sketch of ADDEDPT is shown in Figure 12. Secondary optics resolve Fraunhofer lines and could also be realized with a relatively compact instrument, such as a toroidal hologram, [25] [26] a self-focusing disperser which operates in reflection for deep UV but for ADDEDPT should work in transmission over blue and near-UV.

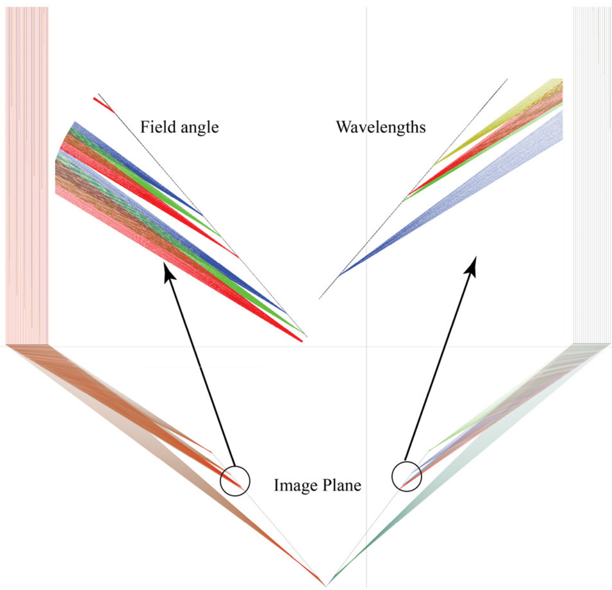


Fig. 10 Notional spectrograph with GZP focused onto a conical image plane. Spatial separation of exoplanets from parent star is indicated by field angle (insert left) Fraunhofer lines are shown resolved by wavelengths. (insert right)

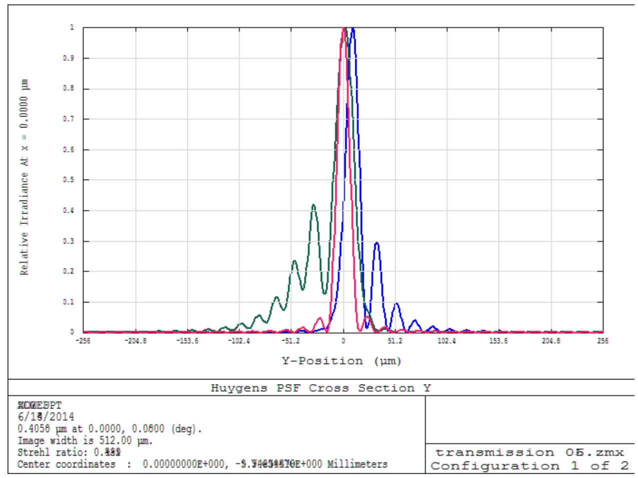


Fig. 11 Three superimposed cross sectional PSF's for conical image plane from center and from opposite sides

3. CONCLUSION

We know there are exoplanets, The question invariably is asked if any of them are earth twins. Direct detection methods are needed to answer this common question. Thermonuclear reactions in stars produce emission and absorption Fraunhofer lines that are deep and frequent at near-UV and blue wavelengths that also happen to be associated with earth's albedo where water can be detected in its liquid and solid phases. This can be exploited in an ETF telescope by ADI. We propose a secondary spectrograph that images Fraunhofer lines as overlapping circles. If the primary objective has a wide aperture for high resolving power, the spectrographic image of the star can be subtracted from the offset exoplanet albedo lines, leaving trace images of photons that are a signature for an earth twin. We are also exploring a new type of space telescope with a gossamer membrane primary objective GZP that would enjoy adequate aperture and area to resolve exoplanets and collect their scarce photons sufficiently well to make the determination that an earth twin candidate has been directly detected.

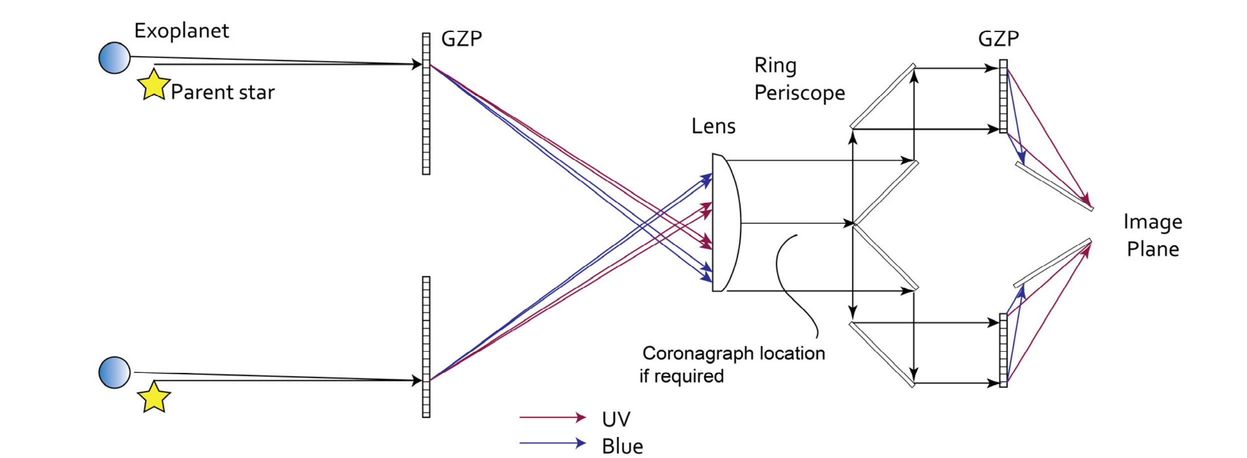


Fig. 12 Schematic of ADDEDPT optics in cross section. [Not to scale]

REFERENCES

[1] Committee for a Decadal Survey of Astronomy and Astrophysics; National Research Council, *New Worlds, New Horizons in Astronomy and Astrophysics* (2010), http://www.nap.edu/catalog/12951.html

[2] http://newworlds.colorado.edu/documents/ASMCS_Report/nwo_E_starshade.pdf

[3] Marina von Steinkirch, "... Earthshine," http://astro.sunysb.edu/steinkirch/talks/poster_poster.pdf

[4] http://www.iup.uni-bremen.de/gome/gomeinst.html

[5] Paul Gilster, "ESO: Habitable Red Dwarf Planets Abundant," http://www.centauri-dreams.org/?p=22313

[6] "Tidal Lock...", http://physics.stackexchange.com/questions/12541/tidal-lock-radius-in-habitable-zones

[7] J. S. Jenkins *et al*, "Metallicities and activities of southern stars," A&A 485, 571–584 (2008), http://dx.doi.org/10.1051/0004-6361:20078611

[8] http://bass2000.obspm.fr/solar_spect.php?WL=3983&DW=10&sel_resol=0.01&Find.x=6&Find.y=5

[9] Thomas D. Ditto, http://www.nasa.gov/directorates/spacetech/niac/2012_phase_I_fellows_ditto.html

[10] Howard A. MacEwen and James B. Breckinridge, " Large diffractive/refractive apertures for space and airborne telescopes ", *Sensors and Systems for Space Applications VI*, Proc. SPIE 8739 (May 21, 2013); http://dx.doi.org/10.1117/12.2015457

[11] http://www.darpa.mil/NewsEvents/Releases/2013/12/05.aspx

[12] http://www.science.gov/topicpages/d/diffractive+pupil+telescope.html

[13] G. Andersen, "Membrane Photon Sieve Telescopes," Space Telescopes and Instrumentation 2010: Optical, Infrared, and Millimeter Wave, Proc SPIE 7731 (2010), http://dx.doi.org/10.1117/12.855675

[14] http://www.darpa.mil/Our_Work/TTO/Programs/Membrane_Optic_Imager_Real-Time_Exploitation_%28MOIRE%29.aspx

[15] MOIRE deployment video, http://www.youtube.com/watch?v=q5oqle9Ct4Q

[16] http://www.nasa.gov/directorates/spacetech/niac/2012_phase_I_fellows_ditto.html#.U5s0a7FOu1o

[17] Olivier Guyon *et al*, "High-precision astrometry with a diffractive pupil telescope," *Astrophysical Journal*, Vol. 200, No. 2, (June 2012), http://dx.doi.org/10.1088/0067-0049/200/2/11

[18] Christian Thalman, "A short introduction to Angular Differential Imaging," http://www.mpia.de/homes/thalmann/adi.htm

[19] Marois, Don Phillion & Macintosha, "Exoplanet detection with simultaneous spectral differential imaging: effects of out-of-pupil-plane optical aberrations," arXiv:astro-ph/0607002v2, (30 Jun 2006)

[20] Kendrick, Stober & Gravseth " Pointing and Image Stability for Spaceborne Sensors - from comet impactors to observations of extrasolar planets." *Space Telescopes and Instrumentation I: Optical, Infrared, and Millimeter*, Proc. SPIE Vol 6265 (15 Jun 2006) http://dx.doi.org/10.1117/12.669068

[21] SALT HRS Throughput Modeling, http://elite.cfai.dur.ac.uk/salt/HRS/throughput/Site%203/Data.html, Fig. 4

[22] G. D. Illingworth et al, The HST Extreme Deep Field XDF...," arXiv:1305.1931v2 [astro-ph.CO] (11 Sep 2013)

[23] Thomas D. Ditto, "Self-nulling spectrograph for star glare rejection," *Optical and Infrared Interferometry III*, Proc. SPIE Vol. 8445-80 (2012)

[24] Thomas D. Ditto, Jeffrey F. Friedman & David A. Content, "Astronomical telescope with holographic primary objective," *UV/Optical/IR Space Telescopes and Instruments: Innovative Technologies and Concepts V*, Proc. SPIE Vol 8146 (2011)

[25] Roger J. Thomas, " Toroidal varied-line space (TVLS) gratings*," Innovative Telescopes and Instrumentation for Solar Astrophysics*, Porc. SPIE 4853 (1 Feb 2003), doi:10.1117/12.460375

[26] West et al, " Toroidal variable-line-space gratings: the good, the bad, and the ugly," *Optical System Alignment, Tolerancing, and Verification III*, Proc SPIE 7433 (20 Aug 2009) doi: 10.1117/12.825709