Terrestrial Planet Detection Approaches: Externally Occulted Hybrid Coronagraphs

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ABSTRACT

Externally occulted coronagraphs have garnered widespread attention as a potentially viable approach to starlight suppression to enable direct detection and characterization of exo-solar terrestrial planets. Externally occulted coronagraphs consist of a large mask (occulter) in front of the telescope as compared to an internal coronagraph which performs all suppression within the telescope system using combinations of pupil and/or focal plane masks. The advantages of external over internal are that the (i) inner working angle (IWA) is nearly independent of wavelength and (ii) diffracted light is suppressed prior to the telescope; allowing science over a wide spectral band with a conventional telescope with little or no wavefront control. For an internal coronagraph the IWA generally increases with wavelength and scattered/diffracted light levy exquisite tolerances on wavefront, amplitude and polarization errors. An external coronagraph comes with the added complexity and expense of requiring two spacecraft, flying in formation, at separation distances of tens of thousands of kilometers. Re-targeting requires flying one or both spacecraft and aligning them to the target star and hence added fuel and time as well as closed-loop control between them.

One approach may be to construct a smaller occulter possibly at closer distances and use it in series with a simple internal coronagraph, i.e. a hybrid, approach. This may simplify requirements on the external occulter but requires more precise tolerances on the telescope system. The question remains as to whether an acceptable balance between the two approaches exists. Herein we look at one approach to designing a hybrid occulter system.

Keywords: Terrestrial planets, coronagraphy, occulters, starshade, exo-solar, Fourier optics, beam propagation

1. INTRODUCTION

Direct detection and characterization of terrestrial (Earth-like) planets in orbit around nearby stars remains a tantalizing proposition. Planets are expected from a few tens to a few hundred milli-arcseconds in angular separation from nearby stars and of order 10^{-10} times dimmer in visible light, and likely embedded in an unknown amounts of scattered light

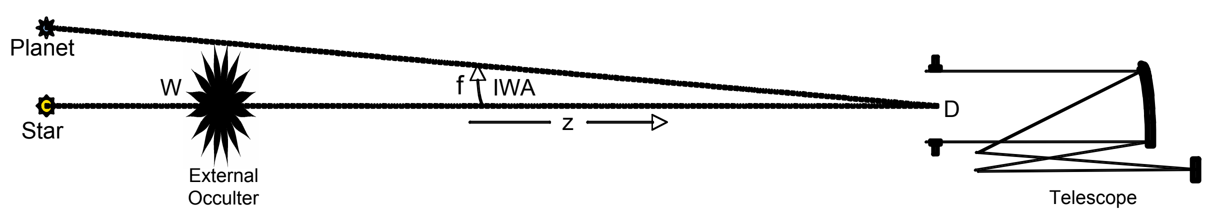

Figure 1 – *Externally Occulted Coronagraph Principle*

from the dust/debris disk surrounding the star and as seen through local dust in our solar system. A multitude of coronagraphic approaches have been studied. These approaches attempt to increase the planets contrast relative to the starlight, allowing for angular separation of the planet light from its parent star and ultimately spectroscopy of the planet, These approaches generally consist of a single telescope with an internal starlight suppression scheme. Various schemes abound and consist of either shaped of apodized pupil masks, and/or focal plane masks, or complex shaped optics, which emulate apodization or an internal nulling interferometer. Each of these internal methods has differing yet stressing requirements on wavefront, amplitude and polarization and generally requires some form of sensing and control. These

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stressing requirements are due to incompletely suppressed diffracted/scattered starlight leaking through to the focal plane subsequently reducing the contrast of the planet with respect to the suppressed starlight.

An alternative approach is to suppress the starlight prior to entering the telescope, thereby mitigating stressing requirements in the telescope system and relaxing it to that of more conventional space telescope technology. This is an old approach dating back to L. Spitzer [1] and can be realized in space by flying two spacecraft: one consisting of the telescope system and the other an external occulter. The external occulter, at distance z in front of the telescope (Fig-1) along the line of sight to the stellar system under study, creates a deep shadow and the telescope resides within it. The starlight is suppressed and the planet light, off-axis relative to the line of sight, passes the edge of the occulter and enters the telescope aperture without reduction in throughput and independent of wavelength. The *geometric* inner working angle (IWA) is the ½ angle subtended by the occulter as seen from the telescope, i.e. $\phi_{IWA} = W/2z$ where W is the diameter of the occulter and z the separation of the occulter-to-telescope, *geometric* since this is only true to the limit of geometric optics, i.e. as the wavelength tends to zero. In practice the *diffractive* IWA, defined herein as that angle at which the contrast of the planet to suppressed starlight exceeds unity, is slightly smaller than the geometric IWA due to diffraction and only a weak function of wavelength over the range of interest. The depth of suppression and focal plane contrast vary with wavelength, occulter width, and separation and telescope aperture diameter.

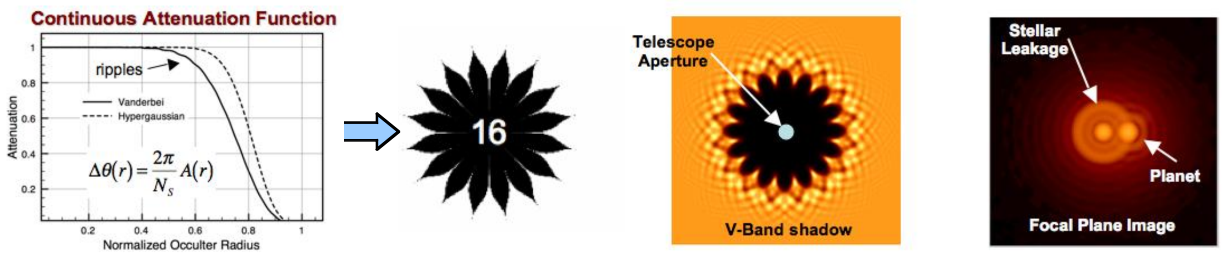

Figure 2 – Left: *Vanderbei and Hypergaussian apodization functions yields a binary 16 petaled mask with approximately the same intensity in the center of the shadow (2nd panel from right).* Right: *Occulted Coronagraph image of a planet and star leakage.*

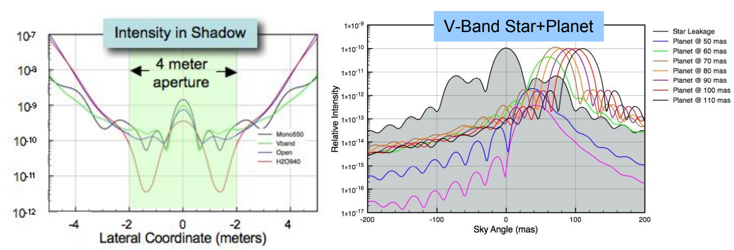

Figure 3 – Left: *Relative intensity in the shadow (at telescope aperture) for monochromatic, V-band, Open (0.4 – 1 um) and a water band.* Right: *Planet crossing the edge of the occulter as shown in the focal plane.*

An external occulter typically contains hard edges, e.g. a circular disk, which causes Fresnel diffraction effects that tend to fill in or brighten the shadow thus leaking starlight through the telescope. Marchal [2] studied the use of large (200-800meter) petaled external occulters placed at separations of 10^5-10^6 km for potential use with the Hubble Space Telescope (HST) for planetary detection but deduced it was infeasible for HST due to its orbital configuration. Copi and Starkman [3] studied more reasonably sized external occulters (~70 m) at separations of 50,000-100,000 km but with apodized transmission, i.e. graded transmission which is blocking in the center and changes continuously to transmitting towards it edge to better mitigate diffraction effects. Shultz et.al [4] studied a hybrid approach consisting of hard-edged (circular and square) occulters but coupled to an internal apodizer to theoretically obtain suppression levels of 10^{10} and Jordan et.al [5] conducted a ground demonstration using a square occulter to suppress Polaris. Cash [6] studied the use of a hyper-Gaussian apodization scheme but realized that a binary petaled occulter would well approximate an apodized occulter and subsequently demonstrated this approach in the lab to ~10^{-7} with broadband light. Vanderbei et.al [7] using constrained linear optimization designed an optimal 1D radial apodization function that suppresses broadband (0.4 – 1.2 microns) while simultaneously maintaining the intensity in the telescope aperture at 10^{-10} and approximated this apodized occulter using a binary petaled occulter. This Vanderbei form for the external occulter is currently the most effective design for an occulter which performs all the suppression external to the telescope, and has the flattest spectral response. This form was studied in detail and reported on in [8,9].

External occulters require two spacecraft [10] each with a spacecraft bus [11], attitude control, fuel and communications, and when acquiring a new target the telescope just re-points but the occulter must "fly" to the new line of sight to the target star, or alternatively both the telescope and occulter must reposition themselves. This levies additional requirements on the system and reduces the science duty cycle – however it may be the only viable approach with existing technology for direct planetary detection. This approach contains large design margins since suppression of starlight to 10^{-10} at the telescope aperture yields a focal plane contrast significantly higher at the IWA.

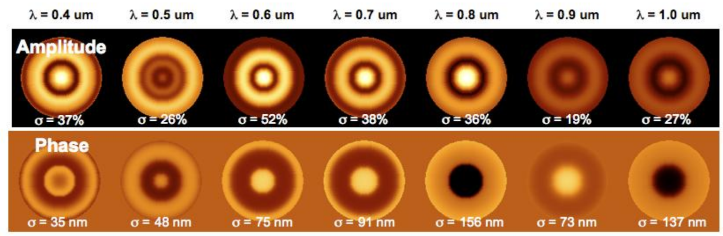

Figure 4 – *Amplitude & Wavefront Error of Leakage Field within Telescope Aperture*

Hybrid approaches are also possible whereby an external occulter performs partial suppression but is subsequently cascaded with an internal coronagraph within the telescope. This approach would require more stringent telescope tolerances - increasing the telescope's cost, but may allow a smaller closer in occulter with relaxed tolerances and lower fuel mass, while increasing the science time since less time is required to "fly" to the next target star. Thus a complex trade space exists between science, technical feasibility and cost. Studies of this complex trade space are actively being pursued. Herein is developed an approach for designing an external occulter to function as a hybrid coronagraph.

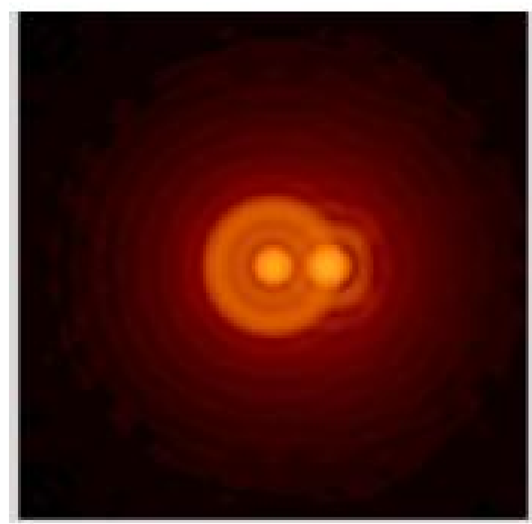

Figure 5 – *Star leakage and Planet at the IWA. Star leakage appears like spherically aberrated halo due to ripples within the aperture.*

2.0 Hybrid Coronagraph

In [8] it was shown that one of the effects which preclude simply cascading an external coronagraph with an arbitrary internal coronagraph is that a series of ripples in both amplitude and phase are resident across the diameter of the telescope aperture. These ripples vary dramatically with wavelength and of approximately 3 – 5 cycles per aperture. These ripples are shown in figure 4. A numerical propagation of both the star and planet light from the occulter to the telescope aperture was performed and the amplitude and phase of the field only over the region of the telescope's aperture was extracted and shown in Figure-4. The top row of Fig-4 shows the amplitude of the electric field with increasing wavelength from left to right and the bottom row shows the phase over the aperture for each of the same wavelengths. The structure of the both the amplitude and phase looks like a combination of focus and spherical aberration and has rotational symmetry. The effect of this residual structure in the focal plane is shown in Figure 5 which shows a V-band image of a planet, at the IWA, and the residual (leaked) starlight. The residual starlight has a halo which looks likes a spherically aberrated point spread function. It is this halo which corrupts conventional internal coronagraphs. Most internal coronagraphs require both very flat amplitude and phase across the aperture. The amplitude and phase could be corrected using active optics with wavefront control; however, since the ripples vary dramatically with wavelength such a system would require many narrowband channels.

An alternative approach is to attempt to design an external occulter which gives the flattest amplitude and wavefront across the telescope aperture and herein we report on our ongoing approach to performing this. Beam propagation is accomplished via using scalar diffraction theory via the Fresnel approximation implemented by a Bessel function form of the Fresnel transform. This transformation of the field is unitary since we have that:

$$\begin{cases} E_T(x',y') = \dfrac{-i}{\lambda z}\displaystyle\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_0(x,y)\, e^{i\frac{\pi}{\lambda z}\left[(x-x')^2+(y-y')^2\right]}dxdy \\ E_0(x,y) = \dfrac{i}{\lambda z}\displaystyle\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} E_T(x',y')\, e^{-i\frac{\pi}{\lambda z}\left[(x-x')^2+(y-y')^2\right]}dx'dy' \end{cases} \tag{1}$$

where $E_0(x,y)$ represents the scalar electric field at the plane of the occulter and $E_T(x',y')$ is the scalar electric field at the plane of the telescope's aperture. The top equation in (1) is the Fresnel transform of the occulter field and results in the field at the plane of the telescope aperture and is the forward propagator. The 2nd equation in (1) is the inverse Fresnel transform ($z \to -z$) and takes as input the field at the telescope and back propagates it back to the occulter and hence is the back propagator. These two equations form a unitary pair. If these two equations are iteratively cycled as in a similar manner to phase retrieval [12,13] but such that constraints are employed in both the occulter and the telescope domain then an occulter function can be designed. Such an algorithm is shown schematically in Figure-6.

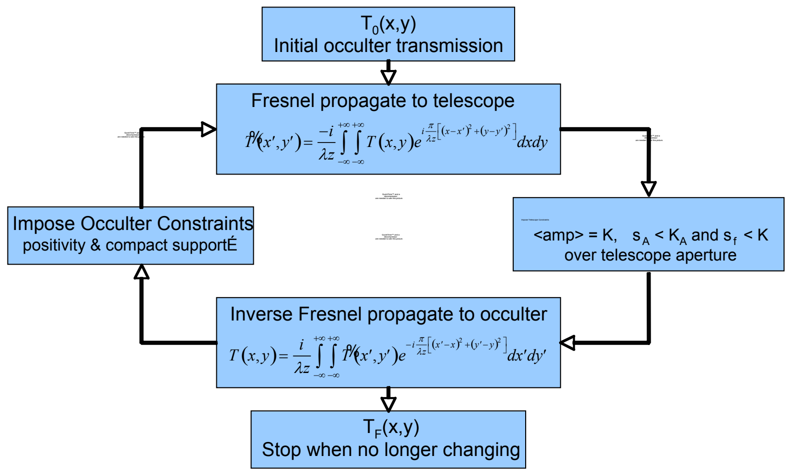

Figure 6 – *Iterative Fresnel propagation Algorithm*

In practice the algorithm is implemented using a summation over weighted Bessel functions instead actually evaluating the Fresnel integrals that are shown in Figure-6. The algorithm proceeds as follows: an initial occulter shape is assumed and propagated to the telescope aperture plane and the field at this plane is retained. Over the region of the aperture the mean amplitude and the mean phase is calculated and the standard deviation of amplitude and phase is calculated. Both the amplitude and phase standard deviations are reduced by removing the mean and multiplying the amplitude and phase over the aperture by an annealing factor, e.g. 0.9, but leaving the field outside the aperture the same. The mean amplitude and the mean phase is added back and the entire field constructed but modified only over the region of the aperture. This field is inverse propagated back to the occulter plane. The field at the occulter must have flat phase and this is equivalent to setting the imaginary part of the field at the occulter to zero. Then this entire loop is iteratively cycled until neither fields are changing and a stable solution is found. Note that this approach does not guarantee that a solution exists.

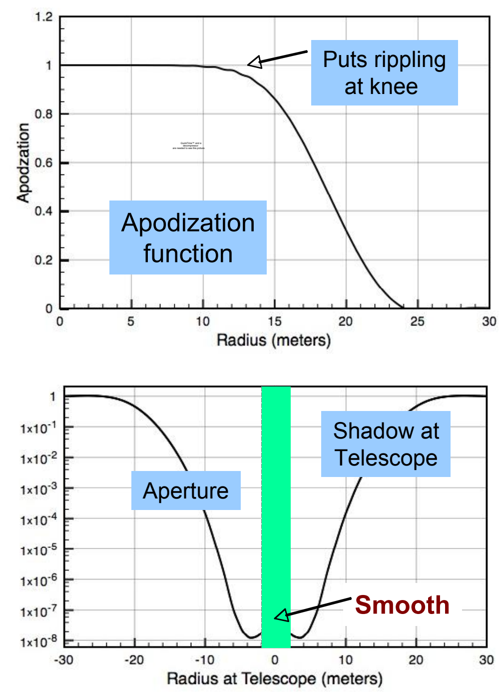

Figure 7 – *First Results with Algorithm*

Figure 7 shows some first results with this approach. The top shows a design occulter apodization function. The design approach puts in rippling at the top near the knee of the curve but suppressions some of the ripples within the aperture (bottom of Figure 7). Over the region of the aperture (shown in green) the rippling is gone but a bump (Poisson spot) is still evident. It may be possible to also suppress this spot as part of this ongoing investigation. The occulter apodization function can be used to generate the occulter mask shape which approximates it (Figure 8).

This algorithm can also be developed to work broadband by correctly applying the constraints in both the telescope and the occulter domains. Additionally the propagation from the occulter to telescope can be continued by applying the aperture function and propagating through to the focal plane and applying further constraints in the focal plane and subsequently inverse propagating from the focal plane back to the aperture. In this expanded approach the propagators are no longer unitary as the field is truncated by the aperture, however the field from the previous steps forward propagation outside the aperture can be stitched in. This will result in a step at the aperture edge that will be propagated back to the occulter as rippling but can be suppressed in that domain and after a few iterations may stabilize. This is an approach which is in development.

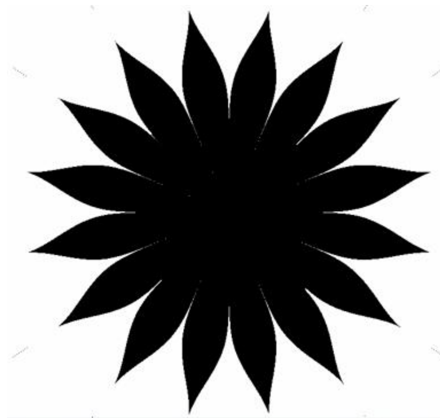

Figure 8 – *Occulting mask designed from Iterative Fresnel Algorithm. There are small ripples along the inner edge of the occulter near the central blocking region.*

3. SUMMARY AND CONCLUSIONS

An external occulter coronagraph has the advantage that the starlight is suppressed before entering the telescope thereby levying no stringent optical requirements on the telescope. It has no outer working angle that usually arises from a deformable mirror which corrects speckle out to specific outer working angle on the sky. The inner working angle is only a weak function of wavelength over the optimized spectral band. The primary drawback is that the occulter must fly at some 10,000's of kilometers in front of the telescope necessitating formation flying. One approach that we are exploring is to attempt to design smaller closer in occulter that suppress less, but then combine it with a simple internal coronagraph. During the design process it was noted that while this is a good idea it is really driven by how flat the amplitude and phase ripples are across the telescope aperture. Thus we have developed and briefly reported on a new algorithmic approach to attempt an occulter design which flattens the ripples thus allowing the starlight suppression function to factor between the occulter and the internal coronagraph, i.e. without any ripples the starlight suppression factors.

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