New Worlds Observer: An Occulter Based Concept for Terrestrial Planet Finding

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New Worlds Observer (NWO) is a multi-spacecraft concept that is capable of detecting and characterizing extra-solar planetary systems, as well as obtaining general astrophysics observations. NWO is a rapidly emerging concept only recently introduced into the discussion as a viable concept[1, 2]. This architecture offers an affordable, modest risk option to achieving NASA's long standing goal of identifying and studying Earth-like planets around other stars.

The NWO concept consists of an external occulter and a generic space telescope. The occulter has specific requirements on its shape and size, while the telescope is an ordinary diffraction limited astronomical instrument comparable to the Hubble Space Telescope. This system requires a deep space orbit like that for JWST or Spitzer. The occulter is a specially shaped opaque screen (binary mask) that creates a deep shadow in the target star's light, in which the telescope is flown. This deep shadow created by the occulter is the essential element of the New Worlds concept that enables the detection and characterization of extra-solar planets with an ordinary astronomical telescope.

Mission concepts to detect extra-solar planets using an external occulter have a long history[3,4,5,6,7]. What is novel about New Worlds is the combination of deep, broad band starlight suppression (10^{-10} over an octave or more), a relatively small occulter, and a manufacturable binary-mask implementation[8]. This leap in starlight suppression, discussed below, enables the design of a practicable mission able to detect and characterize extra-solar terrestrial planets.

We briefly review the key factors in the performance of our mission enabling occulter, including our choice of a mask shape, which allows a closed form algebraic analysis[8] and a numerical evaluation of the diffraction problem. Following this overview of the occulter's performance and basic scaling laws, we introduce a concept for a mission design. The conclusion lists the ongoing and planned work on New Worlds.

The New Worlds Observer occulter provides high starlight suppression because its shape manages diffraction very well. It does so by using an edge shape corresponding to a carefully chosen radial profile of attenuation, averaging over azimuth angles at each radius. Our NWO attenuation profile is the offset hypergaussian appodization function, given by

$$\begin{aligned} A(\rho) &= 0 & \rho < a \\ A(\rho) &= 1 - e^{-\left(\frac{\rho - a}{b}\right)^n} & \rho \geq a \end{aligned} \tag{1}$$

where $A(\rho)$ is the appodization (starlight transmission) as a function of radial distance, ρ, from the occulter center; a is the radius of the inner solid disk; b is the 1/e length of the hypergaussian function; and n is the order of the hypergaussian. An example of a NWO occulter is illustrated in Figure 1.

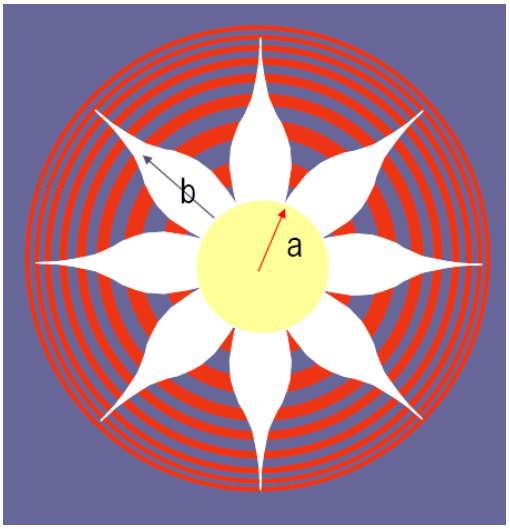

Figure 1: *The NWO Occulter consists of a central solid circle (yellow disk) and (white) petals following a hypergaussian contour. The red rings indicate the Fresnel zones (at which the field contributions in the Fresnel propagation integral reverse sign) due to diffraction of the starlight by the central disk;* a *is the radius of the inner disk; and* b *is the 1/e length of the petals' hyper Gaussian function.*

The occulter operates in the Fresnel optical regime, different from much of the previous works which were been developed for the Fraunhofer regime. The apodization is derived by imposing a complete cancellation of the electric field in the center of the occulter shadow some distance *F* behind the occulter. The binary partition function was also developed in the Fraunhofer regime[8] but was realized later to be also applicable for NWO in the Fresnel regime, given by the following formulae:

$$S = \{\, 0 \le \rho \le a, \theta \in \Theta \}$$
$$\Theta = \bigcup_{q=0}^{P-1} \left[\frac{2\pi q}{P} + \frac{A(\rho)}{2}, \frac{2\pi(q+1)}{P} - \frac{A(\rho)}{2} \right] \qquad (2)$$

where *S* is the parameter set indicating the coordinates where the occulter is opaque (in polar coordinates (ρ, θ); *P* is the number of petals, and *A(ρ)* is the apodization function.

The on-axis cancellation achieved by the occulter, seen in Figure 1 and described by equation (2), is enabled by the sign reversals illustrated by the red Fresnel zones in Figure 1. In fact, the on-axis attenuation is lost in the Fraunhofer limit (infinite distance). Using the Fresnel integral to propagate the mask function of Equation (2) forward by a distance *F* to the telescope, Cash has shown[8] that the fraction of on axis starlight that is found behind a New Worlds occulter is:

$$R = \left[n! \left(\frac{\lambda F}{ab} \right)^n \right]^2 \qquad (3)$$

where F is the occulter to telescope separation. This simple and elegant result captures the basic performance and scaling of the occulter. If the occulter is designed for a given wavelength, it works better (with more suppression, *R*) at all shorter wavelengths. Equation (3) also shows that for a given sum of *a*+*b*, the best performance (smallest *R*) is obtained when *a* and *b* are equal. The hypergaussian index *n* plays a more subtle role, linking suppression performance above and below the design wavelength with the on-axis extinction of star light.

Finally, Equation (3) can be seen as relating the occulter Fresnel number (given by $(a+b)^2 / \lambda F$) to the extinction of starlight, and leads trivially to the understanding that the occulter operates in the optical near field, namely in the Fresnel regime.

If, for simplicity, we assume a particular occulter with designated *n*, *λ*, *a*, *b* and *F,* the scale of the tolerances can be derived from a perturbation analysis[8]. Table 1 summarizes the tolerances of the occulter. Specific values for the occulter tolerances will be the result of a rigorous derivation including all sources of performance degradation[9].

An external occulter designed to find terrestrial planets must:

- achieve starlight suppression adequate to control statistical and systematic noise in the planet pixel
- create a shadow of high suppression that is large enough to cover the telescope
- subtend a small enough angle to see close (< 100 mas) to the parent star
- meet these requirements over a wide optical bandwidth.

Table 1: *Tolerances for the NWO occulter.*

Tolerance	Category	Value
Position	Lateral	Several Meters
	Axial	100's Km
Angle	Rotation	Any rotation
	Pitch/Yaw	Many Degrees
Shape	Truncation	1 mm
	Scale	10%
	Blob	3 cm^2
Hole	Single Hole	3 cm^2
	Pinholes	total area < 3 cm^2

In addition, the occulter must be practical to manufacture:

- the occulter should be binary for ease of manufacturing; graded transmission is difficult to achieve.
- the occulter must be small enough to be deployed by existing technology
- the occulter must be insensitive to microscopic errors to allow manufacturing of a large optical element.

The architecture of NWO is illustrated in Figure 2. A four-meter class telescope located on a separate spacecraft is positioned 10,000 to 100,000 km away from at least one occulter spacecraft carrying a starshade that is tens of meters in diameter.

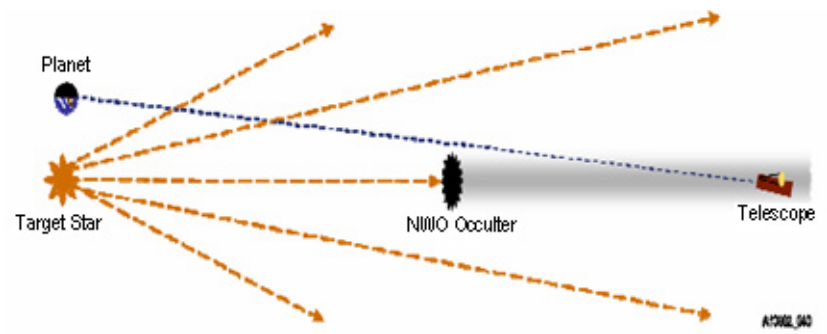

Figure 2: *New Worlds Observer Architecture*

The occulter's function is to create a shadow into which the telescope is flown, The petals of the occulter are designed to suppress the Spot of Arago (on-axis bright spot) that would occur if the occulter was a simple disk. These petals diffract light so that there is destructive interference for on an on-axis source and no effect for off-axis light.

When focused by the telescope, the residual starlight appears on-axis as an extended image whose size is on the order of the IWA convolved with the telescope PSF. This defocusing of on axis light produces an extra factor in suppressing the light from the star. Thus, it is more proper to discuss the suppression of starlight in the telescope's image plane, rather than at its entrance aperture. For telescopes and occulters sized for a TPF class mission, this additional factor is 10 to 100.

The effect of this angularly dependent focus is depicted in the rightmost image of Figure 3, where we show three simulated focal plane images of an Exo-planet detected with an NWO occulter + telescope system. The faint dot pattern may be thought of as the occulter + telescope system's "point spread function" for the central star. Incomplete destructive interference produces gradual roll off of the intensity of the PSF, and is the chief source of the "background" signal outside of the IWA. The off-axis planet light competes with this background signal, but because the residual starlight is spread out over many pixels, the intrinsic on-axis contrast ratio only needs to be at the 10^{-8} level.

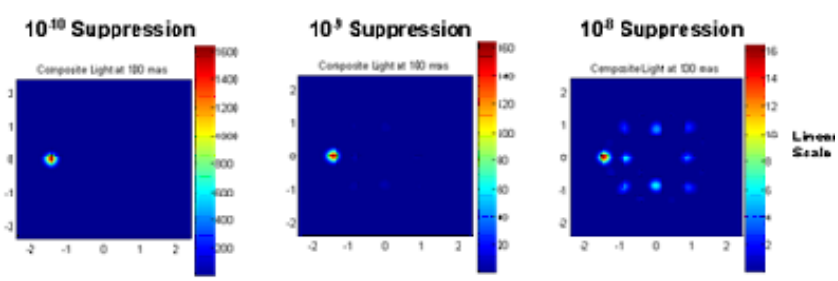

Figure 3: *An external occulter needs a smaller contrast ratio than an internal occulter because it spreads the star's residual light over many pixels. The leftmost image shows the planet signal with a 10^{-10} contrast ratio. The right-most figure shows the same scene with a 10^{-8} contrast ratio. The "PSF" of the central star is visible in the rightmost image. Even with only a 10^{-8} contrast ratio, NWO can obtain a clear detection of the extra-solar planet.*

The occulter's diameter and its separation from the telescope, *F*, must be chosen such that the IWA is sufficiently small to meet the science requirements. This same occulter must also be large enough to provide sufficient starlight suppression. These conditions can generally be met, but such a solution implies a minimum occulter size[10].

During manufacture, deployment, and operation, the occulter is subject to various perturbations that cause it to lose some performance capabilities, whether in IWA or suppression. For example, manufacturing errors may cause imperfect interference and reduce the suppression ratio. We can recover these capabilities by building larger occulters. Figure 4 illustrates the minimum occulter size needed to achieve the indicated IWA and suppression ratios for an ideal or perfect occulter. The phase space of manufacturable occulters is continuous, such that a larger occulter situated farther away can always improve the performance in both IWA and suppression by the desired amount. This phase space is constrained first by manufacturability, where the size of occulter is limited by current deployment capabilities to around 60 m. It is also constrained by the occulter's propulsion system capability, where the total distance traveled by the occulter is limited by its fuel capacity, which restricts the maximum mass of the occulter and separation between the occulter and the telescope.

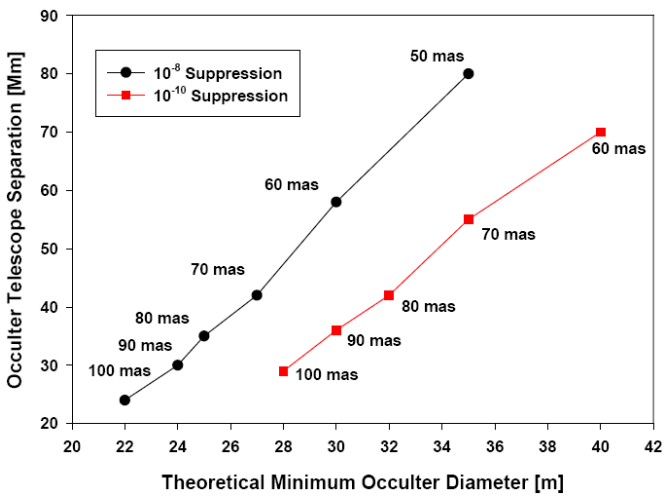

Figure 4: *The NWO design is flexible; there are many occulter sizes that can meet the science requirements. By making larger occulters, we can compensate for other performance degrading error sources.*

Multiple occulters increase the mission coverage and functionality. One of the main drawbacks of the NWO concept is the somewhat limited number of pointings due to the need to move the occulter over large distances. If, instead of one, there are two or more occulters, the observing efficiency and operational capability are greatly increased. We envision a two occulter NWO concept that is capable of detecting and characterizing terrestrial planets in the solar neighborhood. Figure 5 illustrates this dual occulter concept.

The first occulter is a small occulter, with an effective diameter of 25 m. This occulter is separated by ~30,000 km from the telescope, and is the survey occulter, capable of looking at one star every 6–7 days. This occulter obtains the first extra-solar system detections, and over the course of a 5 year mission, occults at least 130 stars two times, for ~300 pointings.

The second occulter is a large occulter, with an effective diameter of 50 m. This occulter observes a system once every 17 days and is capable of remaining aligned with the telescope and the star for more than 100 hours. This allows spectroscopy of Exo-planets to be performed for the detection of absorption or emission features of interest. In 100 hours, we estimate the occulter and telescope will be able to observe the molecular oxygen line with a signal to noise ratio of well over 10. This larger occulter would enable longer integrations, and let us see in closer to the star, due to its smaller IWA. The longer integration time also allows us to more effectively remove exo-zodi contributions. The velocity change (ΔV) requirements (which determine fuel requirements) of the two occulters are given in Table 1. Due to the large ΔV requirements, a solar electric propulsion system could be an expedient method to enable the necessary number of pointings.

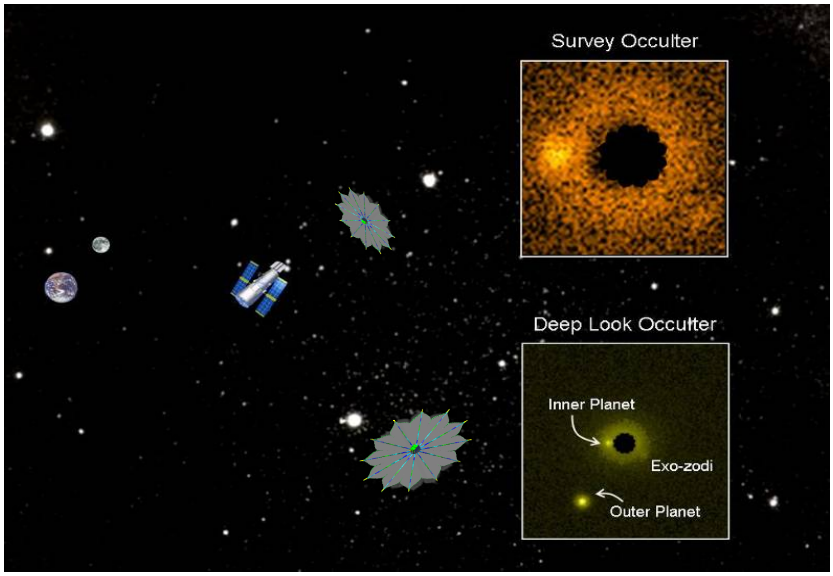

Figure 5: *In the full NWO terrestrial planet finding mission concept, two occulters work in tandem to survey nearby stars and detect and characterize Exo-solar planets.*

We have introduced the New Worlds Observer concept. The key enabling technology, the occulter with its hypergaussian shaped petals, has been shown to be capable of reaching the IWAs and broad band starlight suppression levels that are required for a mission to find extra-solar terrestrial planets. Such an occulter can be built and can be aligned, maintained and moved to another target with current technologies. A mission using an external occulter requires only an ordinary, modest-sized (diameter 3–4 m) telescope to detect and characterize extra-solar terrestrial planets. As currently envisioned, NWO will spend half of its time in the search for Exo-Earths and the other half devoted to general astrophysical observations. The fact that the NWO telescope is a generic astronomical instrument will make it easier to find partners for a highly capable dual-purpose mission.

Table 2: *ΔV Requirements for the Dual Occulter NWO Concept*

	Small Occulter	**Big Occulter**
Per Pointing ΔV	41 m/s	77 m/s
Total Pointings (1 yr)	61	21
Total Pointings (5 yr)	304	107
Total Required ΔV	12.4 km/s	8.2 km/s

The New Worlds concept is developing rapidly and much effort and time is being spent to advance the concept. Among the current and future steps planned are additional laboratory measurements with higher fidelity occulters, continued study of the orbital dynamics of the mission concept, building a subscale occulter model and continued study and simulation of the optical properties of the occulter.

The New Worlds team looks forward to sharing its progress.

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