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New Worlds Observer: A Novel Mission Concept for Exoplanetary Studies

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Abstract. This paper describes a novel concept for the direct detection of exoplanets involving two spacecraft. One spacecraft is an occulter, designed to provide adequate starlight suppression within its shadow. The second spacecraft , a conventional telescope of standard quality, is flown into the shadow of the first and used to collect the light from the target planet. The design of the occulter and its expected performance are discussed. It is shown that is possible to simultaneously achieve the necessary contrast ratios and inner working angles necessary to have a scientifically meaningful mission. A brief discussion of the estimated tolerances indicate that such a mission is feasible in the near term.

Keywords. space vehicles, instrumentation: miscellaneous, space vehicles: instruments, telescopes.

1. Introduction

The New Worlds Observer (NWO) mission concept we are presenting is the result of a recently concluded six month Phase I study under the auspices of the NASA Institute for Advanced Concepts (Cash (2005)). NWO separates the planet light from the starlight before it ever enters the telescope, sidestepping the problem of scatter. The concept is based on well established optical and aeronautic practice. The occulter is a large deployable shade that casts controlled shadows on a telescope carried on a separate craft. The telescope on the second craft is required to be of reasonable quality and meter class, but is otherwise unremarkable. The employment of occulters for starlight suppression enable an extendable architecture. With two craft we have New Worlds Observer, capable of mapping planetary systems and following up with spectroscopy and photometry. Additional occulters increases the efficiency of the planet finding mission. Eventually true exoplanet imaging might become possible.

This paper introduces the NWO, a mission designed to detect and characterize exoplanets and exoplanetary systems. The basic operation of the NWO mission is introduced and the viability of the concept shown. We present a design that meets the two main requirements for a successful exoplanetary mission, sufficient contrast ratio to detect terrestrial planets, 10^{-10}, and the ability to have a sufficiently small inner working angle to see in close to the parent star, 40 milliarcseconds (mas). A first look at tolerances for the occulter and station keeping indicates that both are within the state of the art. The paper concludes with remarks about the science that can be expected from NWO.

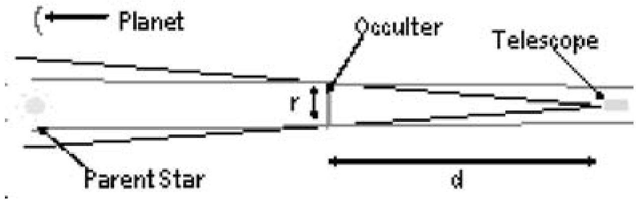

Figure 1. New Worlds Observer Concept.

2. The New Worlds Observer Concept

The New Worlds Observer consists of two spacecraft as shown in Figure 1, the first is an Occulter, and casts a shadow into which the Telescope craft is flown. The idea of an occulter is very simple. When we instinctively raise our hands to blot out the Sun while looking for a fly ball, we are reducing the amount of light that enters our eyes without reducing the signal from the ball. By reducing the amount of light that is potentially scattered, the contrast of the image is greatly enhanced, making it possible to see dim objects, such as planets, near bright ones, the parent stars.

Occulter based systems for the detection of exoplanets have been previously studied (Copi and Starkman (2002)). These previous studies emphasized use of the occulter to improve spatial resolution on various kinds of targets and showed that a simple shape like a circle or a square leads to contrast ratio of about 0.01 diffraction into the dark hole. Other occulter designs that have been studied with Gaussian apodizations result in constrasts of order 10^{-4}. This level of performance is still a full factor of a million short of the requirement. Previous occulter designs achieve their various apodizations by the use of variable transmission. The use of a transmissive element limits the achievable contrast ratio due to wavefront error and scattering.

The breakthrough that makes the NWO a viable mission is a new design that results in acceptable contrast ratios. Furthermore, the NWO occulter design is a pure binary optic, that is the transmission of the occulter is either unity or nil.

The general geometric layout of the occulter is shown in Figure 2. The occulter is central circular obscuration of radius r_1. Around the circumference of the central circle are petals, whose width is an exponential of the form $\exp\left(-\left(\frac{(r-r_1)}{r_2}\right)^n\right)$. The petals cut through the various Fresnel zones, which are indicated by the concentric rings in Figure 2. The effect of the petals is to create a situation where the diffraction from the perimeter is cancelled out, leaving a broad, deep null for on-axis light.

The initial occulter designs were developed via numerical methods. Shortly after the Phase I study was concluded, an analytic result for the contrast ratio, R, was derived (Cash (2006)). The contrast ratio on axis is given by

$$R = \left[n!\left(\frac{d\lambda}{2\pi r_1 r_2}\right)^n\right]^2. \tag{2.1}$$

Many interesting insights can be gleaned about the occulter design and performance from inspection of (2.1). First is that since it we want R to be as small as possible, r_1=r_2 which is the design that also resulted from the numerical optimization. Secondly, that R increases with the occulter-telescope distance d. The increase in R with d is easily interpreted, a decrease in the Fresnel number, $\frac{d\lambda}{r_1 r_2}$,results in fewer zones involved in the cancellation, lessening the depth of the null. As we shall see, this latter trend will be important in the demonstration of the viability of the NWO concept.

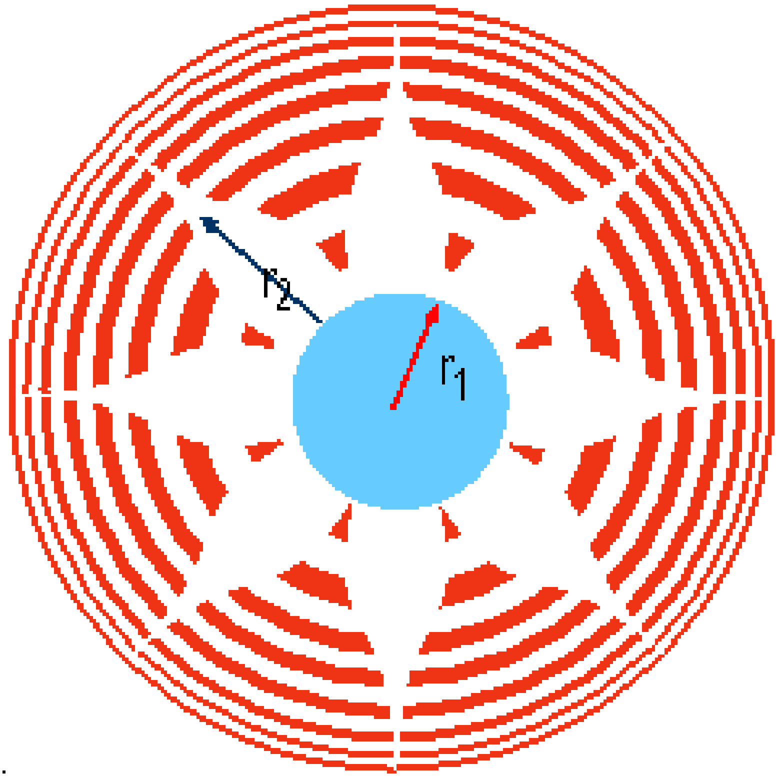

Figure 2. Occulter with Fresnel Zones.

Figure 3 shows numerical results for an occulter operating at $\lambda = 600$ nm with $r_1 = r_2 =$ 12.5 m and at 50,000 km separation. These illustrative results show it is possible to reach $R = 10^{-10}$, and give results orders of magnitude better than previous designs.

Figure 4 shows a simultaneous plot of the inner working angle and contrast ratio as a function of the distance between the occulter and telescope. For the purposes of discussion, this occulter is intended to operate at 1 μm wavelength, and is 40 m in radius, so $r_1 = r_2 = 20$ m. The curve with symbols and growing with d is R. If a requirement of $R < 10^{-10}$ is enforced then d can be no greater than 250,000 km, which is indicated by the solid arrow labeled "contrast". The curve decreasing to the right is the inner working angle, $(r_1 + r_2)/d$, which decreases with increasing d. Taking a typical inner working angle requirement of 40 milliarcesconds, then d must be at least 200,000 km as indicated by the rightward point bold arrow with the label "IWA". As can be seen from Figure 4, that there is a zone, namely between 200,000 and 250,000 km where both contrast and inner working angle requirements are met. This region of viability shows that there is a region in design space where

the seminal requirements can be met, indicating that NWO can see some of the most interesting science targets.

Initial studies of the accuracy of the shape required to achieve the contrast ratio values shown above, imply that the tolerance is of order of the square root of the area (Cash (2006)). Namely, for the occulter discussed above, the areal tolerance is of order 250 cm^2. It is expected that this result will be confirmed on the basis of further (planned) analysis, so that the contour tolerances will be shown to be well within the state of the art.

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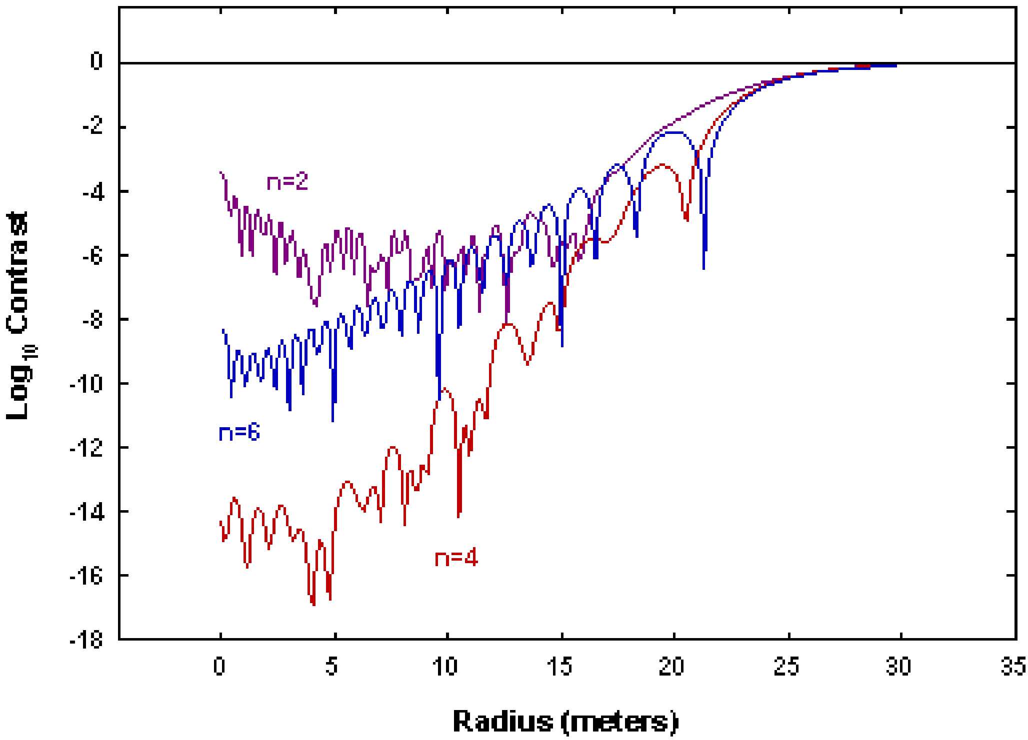

Figure 3. Contrast Ratio.

3. Science Performance

As the telescope moves from outside the hole into the center of the shadow, the view of the planetary system changes dramatically. Before the system is aligned (i.e. before the telescope is fully in the shadow) the view is of an overpoweringly bright star with scattered light all over the field of view. Once inside the hole the star disappears completely, leaving the light from off axis sources, i.e. the planets, visible.

The lateral positioning tolerance for the telescope to the occulter is approximately the radius of the shadow minus the radius of the telescope and is of order meters. Such an alignment is not beyond the current state of the art, and therefore not an extreme challenge or risk to the realization of NWO as a viable mission. As for axial tolerancing, Figure 4, shows that the R changes about a factor of 10 in 50,000 km, so maintaining the occulter telescope distance need only be done to kilometers and is argued to be easy to accomplish.

When the NWO is aligned, the planets can now be studied by the conventional techniques developed by astronomers for the study of faint stars. Long term imaging of the system will show changes in brightness of all the planets simultaneously as their features rotate in and out of our sight. Spectroscopy can be performed on planets by placing a spectrograph slit at the correct position.

The feasibility of the New Worlds missions is entirely dependant on the telescope's ability to achieve sufficient signal to noise from an exoplanet in a short amount of time. Larger telescopes allow for higher photon counting rates, while at the same time increasing resolution. Still, increasing apertures can drive up costs significantly, so we have studied the tradeoffs between the different proposed designs.

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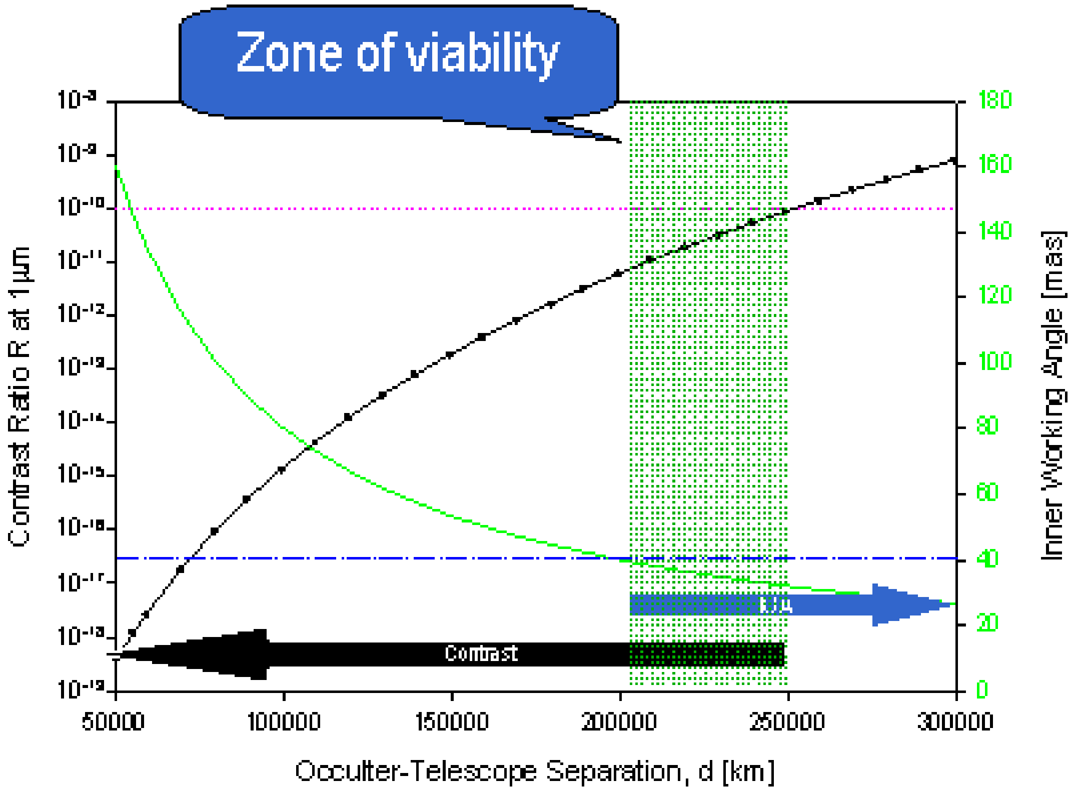

Figure 4. Contrast Ratio and Inner Working Angle versus Occulter to Telescope Separation.

Simulations were run to test NWO's ability to detect extrasolar planets assuming a configuration capable of 10^{10} contrast (Schindhelm *et al.* (2005)). Integration times were studied from 50 kiloseconds (ks) to 400 ks in increments of 50 ks to see signal to noise improvement and which planets are detectable. The occulter based architecture of NWO gives a large advantage in the study of exoplanets, namely the entire planetary system simultaneously since there is no outer working angle limitation.

The simulations include the expected level of detector noise, but some sources of background come from space. A major concern for TPF, operating deep in the IR, is Zodiacal Light. Dust in the planetary system scatters starlight and creates a diffuse glow detectable in the inner planetary system (Hahn *et al.* (2002)). But, in the visible, this is a lesser problem. Our first simulation with zodiacal light added looked no different. With a deep exposure and a ten times increase in zodiacal scattering made the effect visible, but it still did not interfere with the planet studies as shown in Figure 5.

It is also a concern that in many directions there will be background objects such as the deep field galaxies shown so spectacularly by HST (Williams *et al.* (1996)). We simulated frequency and brightness of these faint galaxies and discovered that they will be a nuisance. Figure 5 shows a simulated observation with a typical deep field galaxy included. Over 90% of the time we will not find one inside the habitable zone. During the 10% frequency of unlucky observations, it should usually be apparent by the shape and color that the object is a field galaxy. If the galaxy interferes with our image, then we will have to return in a few months when proper motion of the nearby system has carried it out of the critical line of sight. It should be noted, that the problems of zodiacal,

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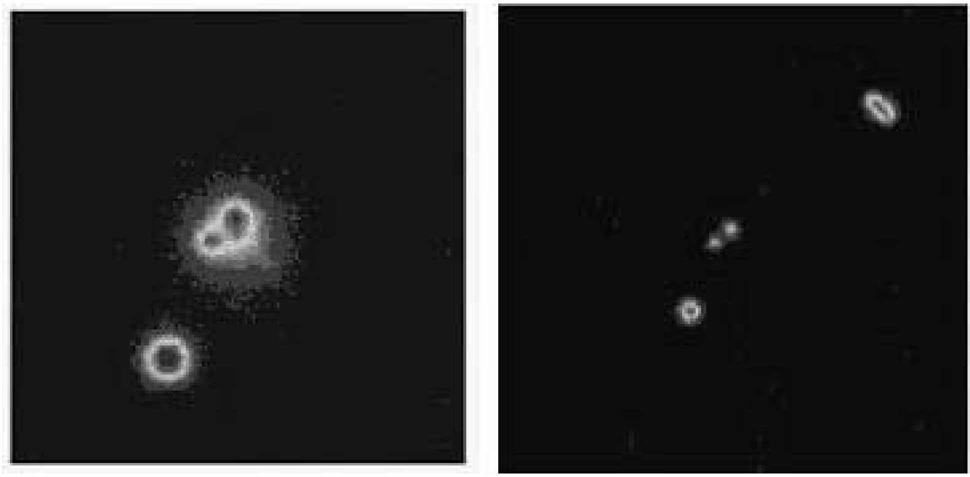

Figure 5. Simulated Imagery from New Worlds Observer. Right panel shows background galaxy.

exo-zodiacal light and background galaxies are common to all direct expolanetary detection methods.

This quick analysis has shown that a telescope of a couple meters in diameter, operating in concert with a high performance New Worlds design occulter, can produce scientifically relevant observations in reasonable amounts of time.

4. Conclusions

The concept for the New Worlds Observer has been introduced as consisting of an occulter and telescope flying in formation. NWO has been shown to be able to achieve sufficient contrast ratios with a binary optic. Also, it was shown that the occulter based system can result in small enough inner working angles for meaningful science. Neither the occulter or the telescope are beyond the start of the art and while requiring some development are relatively low risk technologies

The nature of the NWO also gives some science advantage, since entire systems can be viewed at once, it is expected that observations will give us a profound insight into the nature of our solar system and its place in the galaxy.

New Worlds Observer has been selected for funding as a Phase II NIAC study, which will be concluded in 2007.

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