External Occulters for the Direct Study of Exoplanets

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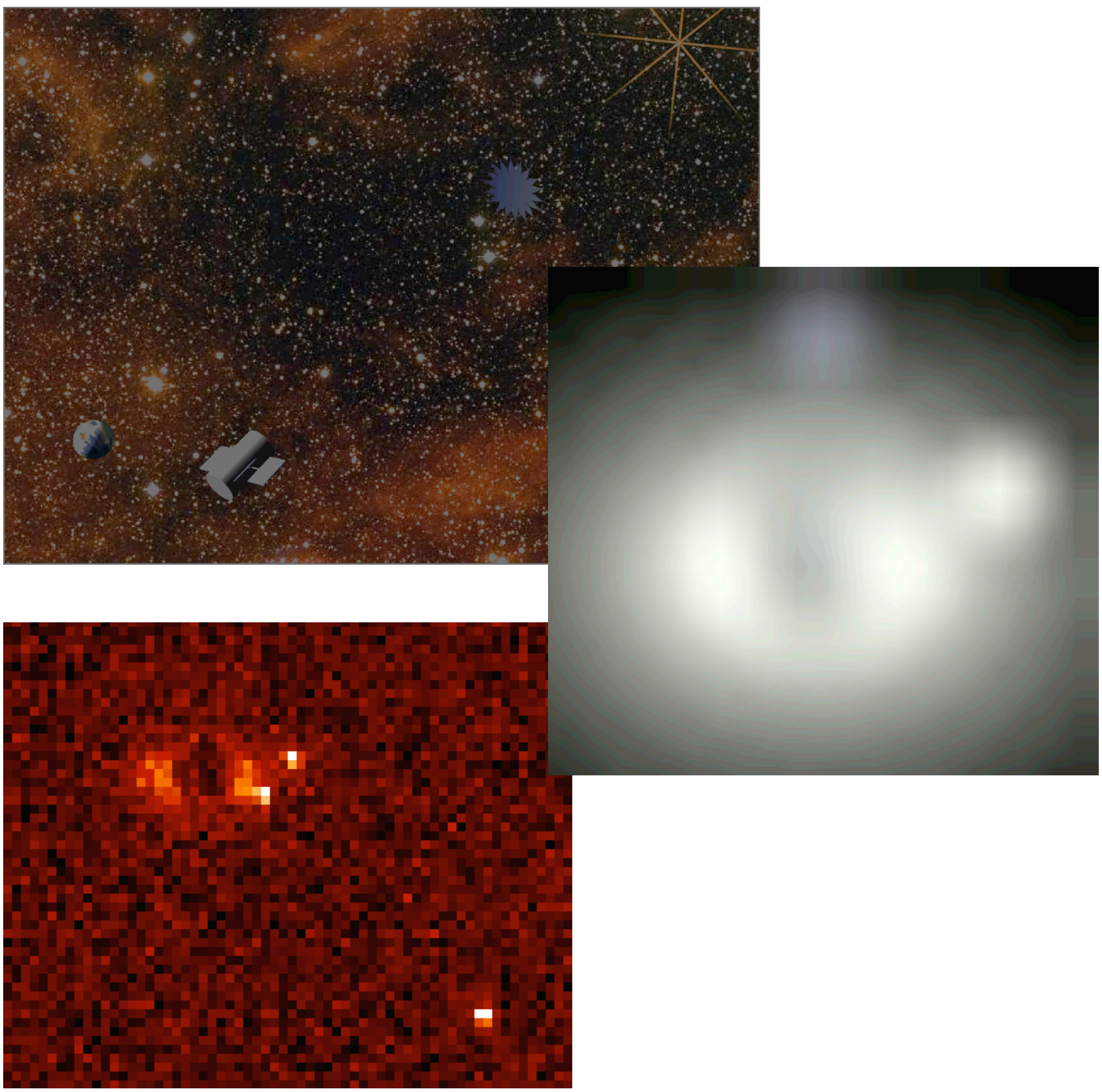
Submitted to the ExoPlanet Roadmap Advisory Committee
in response to the call for white papers
July, 2008



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Abstract

We present the case for using external occulters to suppress starlight in direct observations of planetary systems. These “starshades” are achievable with today’s technology and will allow not only the detection of terrestrial, Earth-sized, planets, but also immediate follow-up spectrometric observations for detailed characterization, with resolution of up to 1000. The high-signal, low noise capability of the approach also enables detailed photometry and polarimetry of exoplanets. Thanks to these unprecedented performances, the search for habitable planets around our neighboring stars and for signs of life outside our solar system can begin in just a few years.

Overview

This white paper summarizes an affordable, technically-ready observational approach to finding and characterizing exoplanets from the habitable zone to the cold outer edges. Because of a recent breakthrough in the diffraction control of starshades these external occulter missions can reveal planetary systems free from diffracted and scattered light of the parent star. *Spectroscopy, photometry, and polarimetry* can then be performed efficiently with a diffraction-limited space telescope operating primarily in the visible and near-infrared. (Typically 0.4-1.0μ, but with some capability extending from 0.12 to 1.7μ.) With good a good quality spectrum of each discovered exoplanet, we can study the atmosphere, surface, and composition of hundreds of new planets. We will search for signs of life (see Fig. 1).

The exoplanet mission concept we describe in this paper is based on a concept now called the New Worlds Observer. NWO is currently undergoing a detailed study by NASA. Led by Professor Webster Cash of the University of Colorado, the study will provide detailed proof of the readiness and accurate costs for the mission in preparation for the US National Academy of Sciences Decadal Review of Astrophysics in 2009. NWO is a prime contender to be chosen as the highest priority flagship mission for the coming decade, just as the James Webb Space Telescope was in the 2000 review.

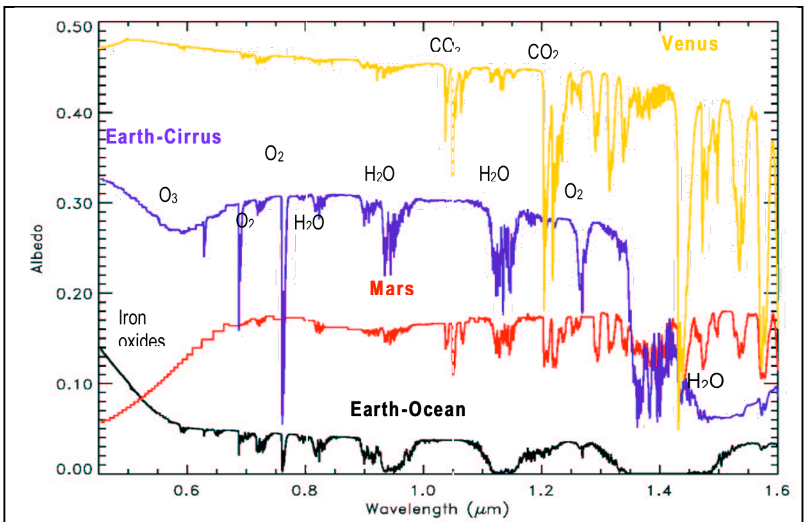

Figure 1. *Albedo simulations in the NWO spectral range of cloudy and cloud-free Earth-like (violet and black), Venus-like (yellow), and Mars-like (Red) planets (Tinetti et al., 2005,2006; Meadows & Crisp, 1996)*.

Technology to build NWO is well in hand. NASA’s Goddard Space Flight Center is managing the study because of its long tradition with leadership in large space telescopes. Northrop Grumman Space Technology Corporation has extensive experience in building and flying large sheet-like deployable systems. Ball Aerospace Corporation is studying the telescope and means for holding the spacecraft in target alignment.

A salient feature of the New Worlds concept is the complete removal of starlight before it ever enters the telescope. This allows the telescope to follow technically in the footsteps of the major telescopes that have gone before, like the Hubble Space Telescope. No additional requirements are placed upon the design of the telescope itself. Thus the telescope can be easily optimized to perform astrophysics outside the relatively narrow field of exoplanets. Furthermore, the starshade spends over half of its time in realignment maneuvers to following systems, during which time the telescope is available for general astrophysical observations from the ultraviolet to the infrared. The telescope would become the true successor to HST and has the potential to be endorsed by a large fraction of the astronomy community.

NWO is designed to map in detail the planetary systems of our nearest cosmic neighbors. In principle, Alpha Centauri could be observed one week, Tau Ceti the next, then Epsilon Eridani, Altair, etc. Each one would be surveyed, with major planets catalogued, mapped, and named. Coarse surface features like continents, oceans, and cloud systems should be evident in time-resolved observations (Ford et al., 2001; Palle et al., 2008; Stam, 2008). Planetary rings, dust and debris disks, comets, and asteroid belts could be detected. Most importantly, exoplanet spectroscopy could be performed, enabling a search for indicators of life. If Earth-like biochemistry is common in the universe, we have an excellent chance of detecting it elsewhere by measuring an exoplanet's unusual atmospheric composition. A few of NWO's science goals are listed in Table 1.

Table 1: Some NWO Science Goals

- How do planetary systems and planets form, evolve, and function?
  - Fit theories of formation to observed distributions of dust and debris and of planetary systems of different ages.
  - Study planets of each known type versus age.
  - Identify new classes of planets that differ from those in our Solar System. Study their environments to find out why.
- Create the field of comparative terrestrial geography and geology
  - With many Earthlike planets to study in different systems we can discover the essential features of habitable planets. What creates oceans? When do we get continents, etc.
- Terrestrial planet atmospheres
  - By gathering equilibrium information on many planets we can increase our understanding of why Earth, Mars, and Venus are so different.
- Biomarkers and Life
  - If some biomarkers are found, we can begin to investigate if this means life for certain, in terms of differences between complex global-scale disequilibrium and life.
  - If an exoplanet appears to have life, we can try to understand the basic chemistry associated with it. Is it necessarily similar to our own?

Configuration

The NWO concept (Fig. 2) features one space telescope at Earth-Sun L2 and one or more starshade spacecraft. The telescope would be a 4 meter aperture, diffraction-limited telescope optimized to work in the visible with somewhat limited extension into the near-ultraviolet and near-infrared.

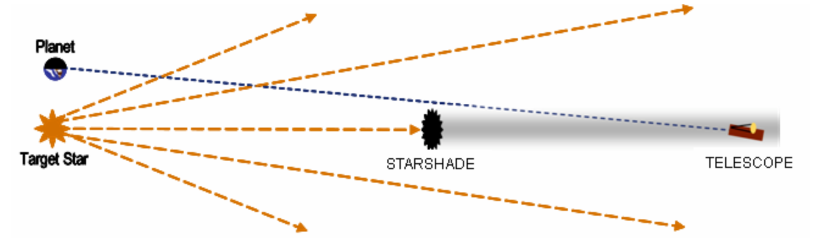

Figure 2. The NWO concept: a starshade throws a deep stellar shadow over the telescope, but allows planet light to pass.

Operating about 80,000 km from the telescope, a starshade would be maneuvered into the telescopes line-of-sight to a nearby star, projecting a very, very deep stellar shadow onto the telescope, while allowing planet light to pass. With this external occulter concept, issues of precision wavefront control in an internal coronagraph design are eliminated, since in exoplanet-observing mode hardly any starlight enters the telescope. Hence, whole planetary systems (except for planets very close to their stars, i.e. closer than 60 mas) will be available for study with a conventional-quality telescope.

The idea of using external occulters is not new. It extends at least back to 1962 when Lyman Spitzer (Spitzer 1962) suggested that such an approach to revealing exoplanets might be one of the most important pieces of science the newly formed NASA could perform. However, he calculated that diffraction around an occulter would be so severe as to hide Earth-like planets, and suggested we would have to settle for exo-Jupiters. Several more optimistic studies based on more capable apodized occulters have since been performed, such as Marchal (1985), UMBRAS and BOSS but failed to define a practical (i.e. buildable) system.

In 2005, Prof. Cash developed a new petal-shaped starshade that suppresses diffraction by many additional orders of magnitude (Cash, 2006), an advance that makes starshades feasible

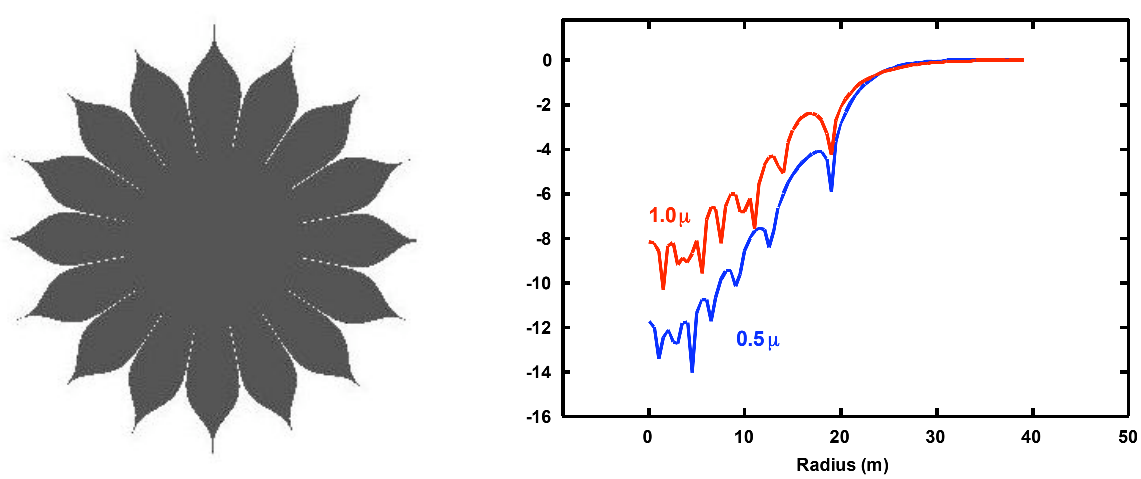

Figure 3: Shape of starshade and the profile of the stellar suppression in the shadow.

with today's technology. Such a flower-like starshade is shown in Fig. 3. The center of its shadow, extremely dark over the entire spectral band from 0.4 to 1.1 μm, accommodates the space telescope with margin for alignment control. For NWO, starshades will need to be about 50 meters in diameter and may be made of any dark, opaque, deployable material.

Because of the large distance (about 80.000 km) between the telescope and starshade, slewing between stellar targets is a challenge for this mission. An occulter must physically move thousands of kilometers to occupy its next line-of-sight. Moving slowly to conserve fuel, this can take up to two weeks, depending on the location of the next target. Obviously, while the NWO concept requires only one starshade, its overall efficiency is greatly enhanced by a second shade that can travel while the other is in use. Because the occulters are low in cost compared to the telescope, this is a highly cost-effective upgrade.

The NWO team estimates that the exoplanet observing efficiency can be near 50%. Thus there will be large amounts of time available for general astrophysics (like dark-energy studies) using a space telescope with capabilities exceeding HST's. In addition, the long-exposure observations of planets and the wide field-of-view surrounding them will yield deep-field images that are highly useful for, e.g., cosmology. These capabilities should allow a merger of interests across several disciplines.

Operations Concept

NWO is designed for a detailed study of individual exoplanets and planetary systems, but given the limited knowledge we have of these systems, we envision explorations as follows.

Approximately once every ten days a starshade reaches its alignment position. Light from the central star is blocked out, and the planetary system emerges from the glare. Imaging observations begin, with the very center of the system obscured within an Inner Working Angle (IWA) as small as 60 milliarcseconds in radius. The residual starlight provides an astrometric reference to the star while not interfering with the system image.

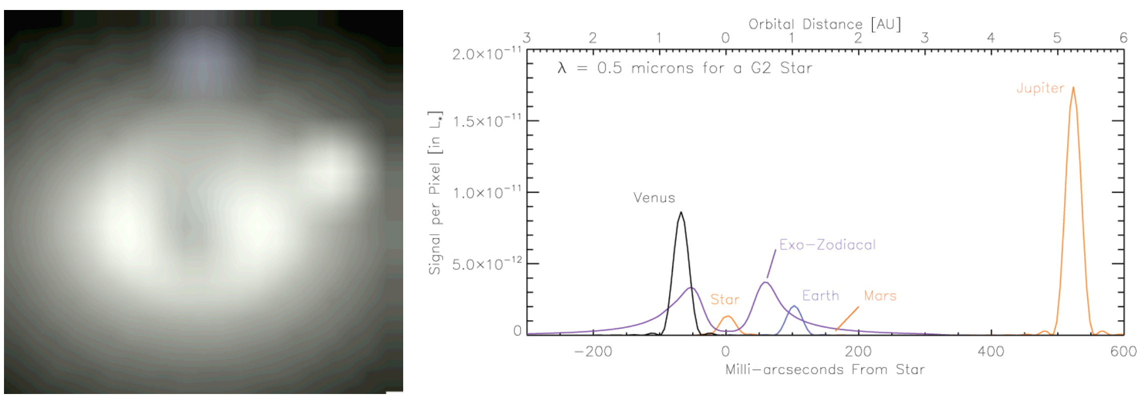

Figure 4: Simulated NWO image of an occulted star with two planets. To the right is the cross-section brightness profile.

The image of the planetary system stretches outward from the IWA, limited only by the size of the detector and the telescope resolution – a starshade has no intrinsic Outer Working Angle. The first images (flux and polarization) will probably be taken broadband in the blue, where the telescope gives the best spatial detail (see the simulation in Fig. 4). Outer planets will be visible (depending on their brightness) against the background of faint stars and spatially extended galaxies. Along most lines-of-sight, exoplanet identification will be swift, as very few stars will have comparable brightness and color. In addition, stars and galaxies will be unpolarized, while the planets can be expected to have degrees of polarization of several tens of percents (see Fig. 5), especially in the blue where most of the light is Rayleigh scattered (see Stam et al., 2004). Deeper inside the planetary system, concentrated in the habitable zone, we expect to see exozodiacal light (exozodi). The exozodi elongation indicates the inclination of the system's ecliptic to our line of sight. The shapes, swirls, and sizes of dust and debris features will reveal detailed dynamics of the planetary system and perhaps some of its history. The degree and direction of (linear) polarization of the light yields information about the dust particle sizes and optical thicknesses (see e.g. Graham et al., 2007).

Planets inside the habitable zone are, of course, of special interest. Their signals will be revealed by modeling and subtracting the residual starlight and exozodi, and polarimetry can be used to identify them as planets. A series of (flux and polarization) images through strategically chosen filters can help to determine the nature of each planet.

Time-resolved imaging photometry and polarimetry may be used to detect planet surface features and rotation. Ford et al. (2001) and Palle et al. (2008) show that the continents and oceans on a true Earth analog could be inferred from photometry (see Stam, 2008, for polarimetric examples). With NWO's relatively short exposure times the rotation periods of fast rotators (like Earth) can be measured for multiple planets in the system simultaneously. We may be able to coarsely map the geography of many new planets!

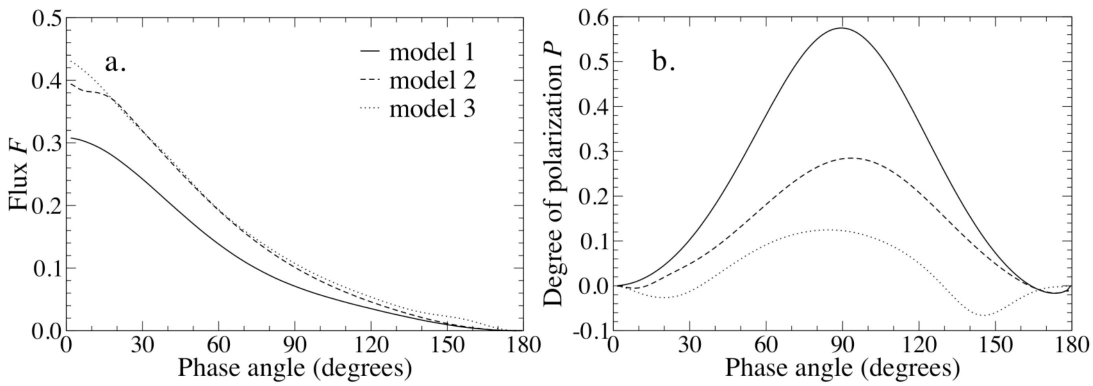

Figure 5: Simulated flux (a) and degree of polarization (b) of starlight that is reflected by 3 model gas giants (model 1: only gas, model 2: gas + low cloud, model 3: gas + low cloud + high haze) as functions of the planetary phase angle, averaged over the wavelength region between 0.65 and 0.95 microns (Stam et al., 2004).

NWO will carry an integral-field spectrometer to provide high-quality spectra across the entire habitable zone and outside it. Several planets can be studied simultaneously. Gas giants will be immediately evident, and chemical signatures of the atmospheres may yield new understanding of atmospheric physics. Planets like Mars or Venus will show distinctly different spectra (Fig.1) and can be rapidly classified. Major molecular species will be detected and compositions estimated.

Of course, we seek the precious water planets. Water vapor absorption from the atmosphere can be identified unambiguously in the reflection spectrum (Fig.1). The basic atmospheric components will be detected and their abundance measured.

The greatest surprise in the composition of the planets in our solar system is the large amount of molecular oxygen (O_2) in the terrestrial atmosphere. This molecule is so reactive chemically that it must be continuously produced at enormous rates to persist. Thus the Earth's atmosphere can only be understood as a large input from the biosphere (Lovelock, 1979). The challenge of remotely detecting life on a planet that has not developed a biogenic source of oxygen is fraught with unknowns. O_2 shows clear, albeit narrow, spectral signatures only in the VIS-NIR wavelength range (Fig. 1). Ozone, a by-product of O_2, has a strong absorption band in the UV (the so-called Huggins band), and a broad, shallow band in the visible (the Chappuis band) (see Fig.1).

Requirements and Capabilities

Table 2 presents some typical design parameters for the New Worlds Observer.

The sensitivity to terrestrial planets rises very quickly with aperture because higher resolution leads to greater suppression of the exozodi beneath the planet signal. The telescope must be diffraction-limited at 0.5 μm, with angular resolution < 0.03". This resolution is achieved by a 3.5-m (or larger) aperture. However, near 4-m aperture there is a rapid increase in telescope price due to launch constraints and required ground development facilities.

Table 2: Typical NWO Parameters

Telescope diameter	4m
Angular resolution	0.026"
Spectral resolution	300-1000
Starshade separation	80,000 km
Outer diameter	50 m
Number of petals	16
Inner Working Angle	0.058"

We have calculated the exposure times needed to make a 5σ detection of an Earth-like planet orbiting a Sun-like star 10 pc away as seen at quadrature (i.e. contrast~1.5×10^{-10} for an albedo=0.26). We assumed that the dust density in the exozodiacal cloud is 1.5 times that of the zodi, i.e. the total (zodi + exozodi) is 4 times brighter than the zodi. We also assumed a 4-m telescope having a high optical throughput=0.8, an IFU spectrograph throughput=0.8, and CCD detector having a DQE=0.8, read noise=0, and dark count plus spurious charge rate=0.001 counts/s/pixel. The Earth at 10pc will generate about 1c/s, while the exozodiacal light will create about 100c/s. Since the exozodi is spread across about 100 resolution elements, we expect images of Earth-like planets to stand out strongly. We estimate an exposure time for a 5σ detection of well under one hour for NWO. We have also calculated the exposure times needed to detect the prime spectral features for the same Earth-like planet. For example, we estimate that NWO would take only a few hours to make a 5σ detection of the O_2 λ=0.76 μm absorption band (the so-called O_2 A-absorption band). The relatively short exposure time for NWO spectroscopy brings the added benefit of spectrally confirming and characterizing a planet *in the same visit* as its discovery, thereby avoiding the difficulties involved in astrometric confirmation and identification via later observations looking for common proper motion (Brown, 2006).

Because NWO suppresses total starlight into the telescope and has no outer working angle, it will be highly sensitive to distributed light from dust and debris in exoplanetary systems. This is likely to be limited by the local zodiacal light level, so emissions at or below our own can be studied.

In order to survey enough stars, the system IWA should be <0.06". The IWA at any given level of suppression is a function of starshade separation and size. Adequately suppressing the starlight for planet detection demands an occulter shadow large enough, say 6m, to cover the telescope aperture with positioning margin. The shadow must be adequately dark over wavelengths from 0.4 to 1.1 microns. Because of diffraction effects, these constraints imply an optimal separation of about 80,000 km and occulter diameter of 50 m.

At large separations of the starshade from the telescope, starshade size and mass increase, as does starshade travel time between targets. Distances as large as 100,000 km and IWA's as low as 40 milliarcseconds have been considered and found viable. In many ways NWO is simply propellant- and mission-lifetime-limited. It conserves propellant by moving slowly between targets. About 10 times as much propellant is expended per second during transit between targets as is spent holding alignment during observation.

Considerable time has been spent investigating the "Traveling Salesman Problem" that emerges when one tries to choose a sequence of observations and starshade maneuvers across the course of a year. In all such studies the conclusion is that on the order of hundreds of lines-of-sight may be studied in the course of a five-year mission. Each of those lines has the potential to reveal a complex and intriguing new planetary system.

The NWO team has investigated optimum orbit choice and propellant requirements. The studies have showed that a halo L2 orbit is the most attractive. Analysis found that station-keeping requirements are about 0.2 m/s/day, with accelerations sufficiently low that low-thrust propulsion, such as solar electric propulsion, is applicable and strongly recommended as a better alternative to chemical propulsion methods. The low-thrust engines are about 10 times more efficient, yielding a significant net mass benefit. For representative 10-20 day transfers of 15-degree angles (based on a 4500 kg spacecraft, 3000 s I_{sp} thrusters, and 10 kW of power), a low-thrust system requires approximately 1 kg propellant/day for the duration of the transfer which conservatively translates into 1000 kg of propellant (plus low-thrust system overhead) to visit 100 stars in 1000 days.

NASA has invested heavily in theoretical and analytical work on precision formation flying and control, but has not yet followed up with actual missions. NWO would make a good first mission because it needs only meter-class precision formation. Its success will mainly be driven by the availability and quality of the sensors and actuators. Needed is a low-noise, high-bandwidth, very accurate measurement scheme, which can be based on optical data from the telescope. Also needed are low-noise, preferably continuous, thrusters with very small minimum bit levels. The minimum thrust level drives the requirements on measurement accuracy and the excess of shadow size over telescope aperture. While more modeling, analysis, and hardware demonstration is needed, past work, including studies for the MAXIM pathfinder mission, indicate that the level of precision control we require should be achievable.

Technical Readiness

Studies by our team and others have now established that NASA and the US aerospace industry already possess the basic technology needed to build NWO. Yet, since this is a new type of mission, inevitably there are technical concerns. Some of these are listed in Table 3.

Table 3: Technical Tall Poles

Concern	Design Solution Options	Technology Sources
Deployment of large starshades	Booms, inflatable, strain	SRTM, military
Controlling star-shade shape to ~mm	Deployed, inflatables, truss	Military missions
Controlling sunlight (edge) scatter	Knife edge, ultra-black paint	Lab demos
Alignment sensing to ~ 30 cm	Telescope, occulter camera	Deep Impact, HST FGS
Retargeting capacity (Δv)	Solar-electric, slower slews	DS-1, Deep Impact
Large telescope (up to 4 m)	Meniscus, segmented	JWST, Kepler, HST
Fitting in launcher and mass limits	Membranes, lightweighting	JWST

A laboratory demonstration of a scale-model starshade was performed at the University of Colorado in 2006, achieving 10^{-8} shadow depth using broadband solar light in air. With an expected additional two orders of magnitude star suppression from the imaging of the telescope this indicates a demonstrated contrast level of 10^{-10}. Because we would like somewhat improved contrast performance, and experience with the realities of using optics at such high contrast levels, further studies in vacuum chambers are ongoing at the University of Colorado and at Northrop-Grumman.

A full-scale starshade is under continuing study at NGST. The baseline starshade material is the JWST heritage Kapton E membrane. Three layers of Kapton E provide protection from light leaks due to micrometeorites and offer complete opacity in all relevant spectral bands. The three layers are separated by gaps, so that starlight would be trapped and not reach the telescope; even in the highly unlikely event of micrometeorite penetration along the optic axis a slight tilt of the starshade will effectively obscure the holes. Based on our experience with classified missions and JWST, the affordability of this mission element seems a good prospect.

Programmatics and Costs

NWO meets the exoplanet science goals in NASA's strategic plan: it takes us where we want to be scientifically ten years from now. Because no new technology areas are involved, a mission like NWO can be pursued on a fast track. The pacing items are expected to be the telescope primary mirror system and the high-precision starshade deployment. Following Phase A and B mission definition studies, and given optimal funding, launch could take place in as little as five years.

Partly because of different possible approaches to acceptable mission reliability and risk, no detailed estimates of the costs of a mission like this have yet been made. A very rough total mission cost based on considering all main categories bottoms-up, with the major single element being the 4-m class telescope. Building two spacecraft, one with a 4-m telescope immediately puts the cost above $2 Billion. A generic number of $3 (+/-1) Billion covers the range of likely mission scenarios. This puts NWO in a cost range similar to that of other Flagship missions under consideration.

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