Direct Studies of Exo-planets with the New Worlds Observer

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The New World Observer has the potential to discover and study planets around other stars without expensive and risky technical heroics. We describe the starshade, a large, deployable sheet on a separate spacecraft that is flown into position along the line of sight to a nearby star. We show how a starshade can be designed and built in a practical and affordable manner to fully remove starlight and leave only planet light entering a telescope. The simulations demonstrate That NWI can detect planetary system features as faint as comets, perform spectroscopy to look for water and life signs, and perform photometry to search for oceans, continents, clouds and polar caps.

Keywords: Astrobiology, exoplanets, coronography

1. THE SEARCH FOR NEW WORLDS

We live in a time when all the corners of the Earth have been trampled and mapped in complete detail. Few people alive remember first hand the sense of excitement and high adventure that comes from the discovery of new lands. Yet no other endeavor resonates more with the imagination of the young, or carries more promise for the future.

America has led the way in keeping the spirit of discovery alive. NASA probes, rocketed out into our solar system, have revealed alien landscapes and given us new perspective on our own small planet. But extremes of temperature and the absence of breathable atmosphere have, so far, made the expansion of mankind into space a dangerous and economically unrewarding effort.

Since we now know the basic outlines of the Solar System, we naturally desire to extend our knowledge to other planetary systems. Observations will immediately give us fundamental new understanding of the nature of planets and their systems as we break outside of the confines of the single example in which we live.

But, more than anything, we all wish to find that elusive place, the blue, watery planet with a shirt-sleeve environment that might eventually become a comfortable home. Certain knowledge of a habitable destination could drive future generations to innovate and find a way to cross the unimaginable distance to that New Earth.

There is one over-arching problem that has stymied the direct detection of exo-planets. The planets themselves are sufficiently bright to be observed with modest sized modern telescopes. Even a one meter diameter optic can provide enough resolution to separate them. It is the overpowering glare of the parent star that hides the planets. If the solar system were to be viewed from 10pc distance, the Earth would appear 10 billion times fainter than the Sun and only one tenth of an arcsecond (a single Hubble resolution element) away. This problem must be solved before any direct observations can even be contemplated.

1.1. The NASA Program

NASA’s Office of Space Science, recognizing the importance of the search for distant planets, has given a pre-eminent position to exo-planet science. Despite its obvious technical challenge, several approaches are under development. SIM will use astrometry to detect stars swinging about the center of mass with its planets. Kepler is searching for the transits of planets across the disks of stars. But these are indirect observations, equivalent, in some sense, to the Doppler studies from the ground.

To observe planets directly, NASA is designing the Terrestrial Planet Finder (TPF) and ESA is designing Darwin. TPF is receiving a great deal of development money and figures prominently in NASA’s plans. Yet TPF has problems – major problems caused by the contrast ratios between big bright stars and faint, tiny planets a fraction of an arcsecond away. Making a telescope that allows a terrestrial planet to emerge from the glare of its parent star is the challenge of TPF. It in many ways has to be the "perfect telescope".

To remove scatter from the optics, the mirror must be built to incredibly tight tolerances. For example, the surface must be figured to better than λ/5000. The coating must reflect with uniformity better than 99.999%. And it still must deal with diffraction.

The cost of TPF is high, somewhere between $2 Billion and $5 Billion. The risk is high as well, given that the quality must reach levels previously undreamed of, and then be maintained through launch and operation. Clearly, lower cost, lower risk alternatives should be welcome.

1.2. The New Worlds Alternative

We have just completed a six month Phase I study of the New Worlds Observer (NWO) under the auspices of the NASA Institute for Advanced Concepts[1].

NWO separates the planet light from the starlight before it ever enters a telescope, sidestepping the horrific problem of scatter. The concept is based on well established optical and aeronautic practice. A starshade is a large deployable shade that casts controlled shadows on a telescope carried on a separate craft. The starshades enable an extendable architecture. With two craft we have New Worlds Observer, capable of mapping planetary systems and following up with spectroscopy and photometry. With five craft we could create the New World Imager, designed to take high quality pictures (100km resolution) of exo-planets.

2. THE NEW WORLDS OBSERVER – CONCEPT

2.1. Starshades

The idea of a starshade 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.

A telescope, like an eyeball, is in principle capable of separating planet light from star light. But an optic must be virtually perfect to accomplish separation with better than 10 billion to one efficiency at a tenth of an arcsecond. Scatter from imperfections is many orders of magnitude higher and control presents an enormous challenge to TPF. The starshade provides a low risk approach to decreasing the noise from the parent star. We have two approaches to the starshade as shown in Figure 1.

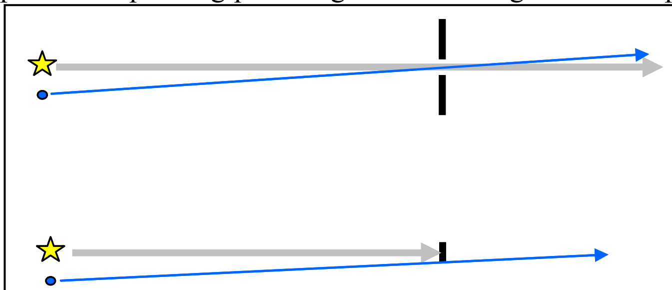

Figure 1: Starshades operate by allowing planet light past, while shadowing the light from the parent star. Above, shown schematically is the pinhole approach. Below is the pinspeck approach.

2.2. The Pinhole Camera

The first is the pinhole camera. This takes a large shade, hundreds of meters across, to blot out not only the central star but the planetary system as well. The lens of the pinhole camera is a carefully shaped hole in the middle. The telescope can only see one planet at a time. Two spacecraft are launched together into a high, stable orbit where they are deployed. The first spacecraft unfurls as a large umbrella of thin, opaque, dark material hundreds of meters across. At its center is an open aperture, carefully designed to suppress diffraction. The starshade thus functions as a large pinhole camera which creates a high quality image of the planetary system many kilometers away and a hundred meters across. The second craft carries the detector and must align with the target star at the specified distance. To acquire a planet it literally flies around the planetary system.

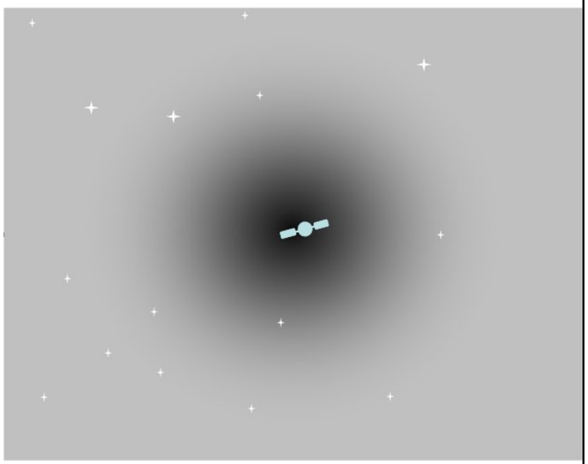

Figure 2: The pinspeck starshade projects a dark hole many meters across wherein light from the parent star is highly suppressed. The spacecraft must be flown into that hole and held there during the observation.

The use of a pinhole camera forces the detector to fly a large distance from the starshade, but the pinhole is crucial. A pinhole lens creates zero distortion to the wavefront, creates perfect uniformity of transmission and has no dust or cleanliness issues. It may be shaped to suppress diffraction of the central aperture. It is the perfect lens, limited only by the quality of its edges. The Earth at 10pc is 0.1" from the parent star, so if Earth is to be 10 diffraction widths from the star and well outside diffraction, the resolution of the pinhole must be .01". This implies that the pinhole must be $2x10^7\lambda$ across, or 10 meters in the case of yellow light. Then, to create geometric separation at the diffraction limit, the focal plane must be $2x10^7$ apertures away, or about 200,000km. The two craft must then hold this formation to better than a meter of tolerance relative to the line of sight. The detector craft carries a Cassegrain telescope that focuses all of the light from the planet onto a detector or spectrograph slit.

2.3. The Pinspeck Camera

The pinspeck is an occulter. An opaque shape is moved between the telescope and the target. If properly sized and positioned, it will cover the line of sight to the star but not to the planets. The difficulty has been the diffraction of starlight around the edges of the pinspeck.

At the start of the study, we assumed that the starshade would be a pinhole, because, not only was the pinhole lens perfect, the Princeton group had shown that shaping the aperture would lead to excellent suppression of diffracted light[2]. But the smaller size of the pinspeck allows a much lighter, less expensive approach. Also, the pinspeck has much higher sensitivity for planet detection. Since the entire planetary system could be viewed at once, the telescope could be much smaller. A disadvantage was that the telescope had to have somewhat higher resolving power.

Occulters have been studied before. The pinspeck concept that emerged from our study resembles the Big Occulting Steerable Satellite[3]. They emphasized use of the occulter to improve spatial resolution on various kinds of targets. But they also discussed using it to blot out a star and reveal planets. They showed that a simple shape like a circle or a square would lead to 1% diffraction into the dark hole. Gaussion apodization

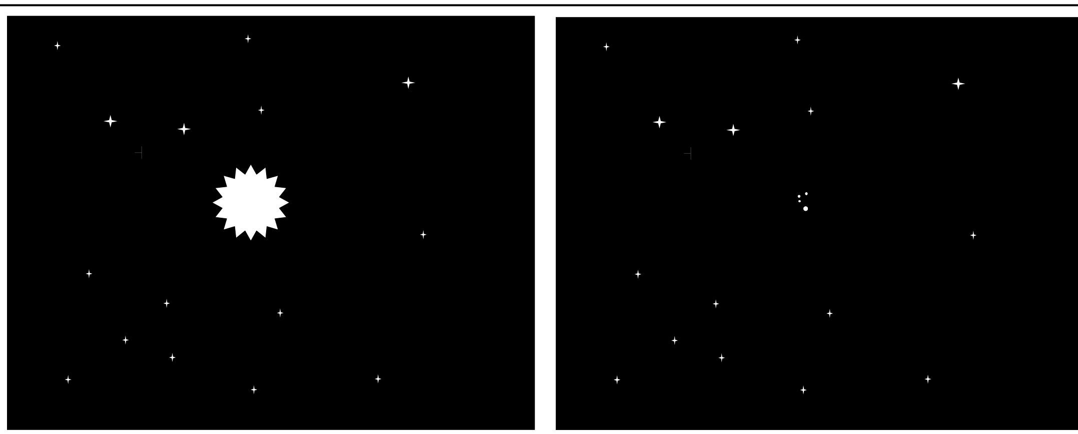

Figure 3: Schematic representation of the scene viewed by the telescope. To the left we see the star, swamping planets with its intense light. To the right, after the starshade is in place, the star is nulled away, but the planetary system remains visible.

supports 10^{-4}, but this is still a full factor of a million short of the requirement.

The Pinspeck Camera operates in an analogous way. The occulter is 20 to 150m in diameter and flies in formation 20,000 to 200,000km from the telescope. On the focal plane, where the telescope sits, there is a dark hole cast by the pinspeck as shown schematically in Figure 2. The telescope must be maneuvered into that hole and remain there for the duration of the observation. As it moves from outside the hole into the center of the hole, the view of the planetary system changes dramatically. Figure 3 illustrates this effect. Before the pinspeck 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 only the planets.

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.

2.4. Diffraction Control

The control of diffraction for exo-planet applications started with apertures in the focal planes of telescopes. Spergel[4] was the first to realize that shaped pupils could be used to achieve nulls of essentially any depth close (but not arbitrarily so) to the central star, and that such an idea could be useful for planet finding. His first suggestion was to use a Gaussian-shaped mask. Shortly thereafter, J. Kasdin discovered

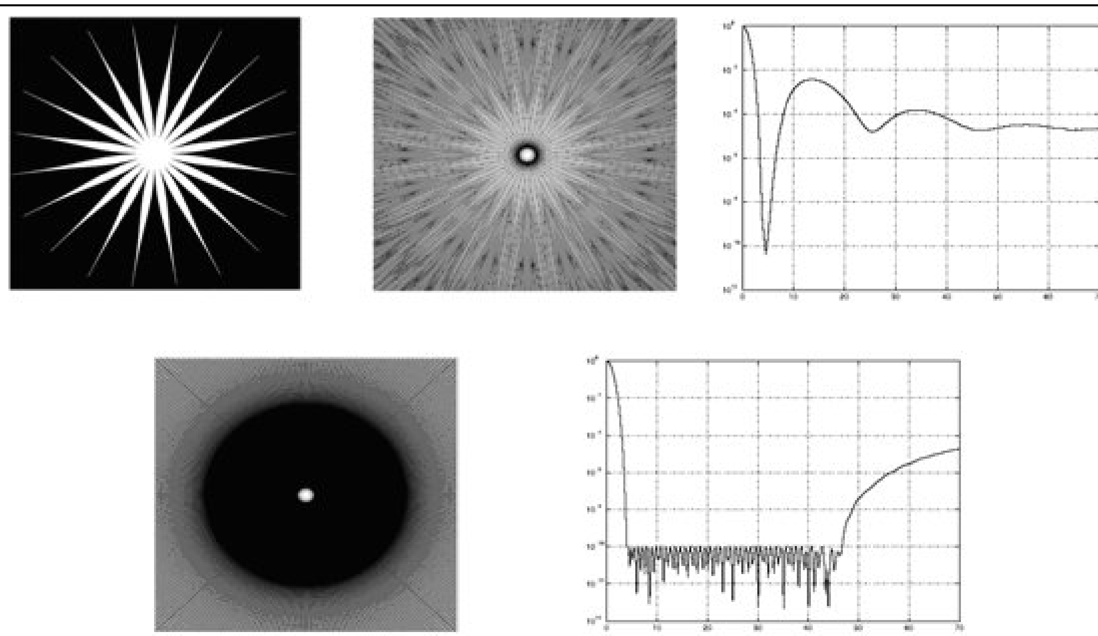

Figure 4: PSF and profile for 20 point starshape mask (top row) and 150 point mask (bottom row)

that Slepian's prolate-spheroidal wavefunction is the optimal shape for achieving high-contrast along one axis of the image plane[2]. It achieves a contrast of 10^{-10} everywhere along the x-axis except within $4\lambda/D$ of the center of the Airy disk.

Of course, the apodizations derived above assume that the opaque part of the mask extends to infinity. In reality, the mask will be a large, but finite, umbrella. The starlight will diffract around the outer edges of this umbrella. This effect must be taken into account. If one considers just a hard outer edge, then the diffraction will behave like a conventional pupil. In order to ensure high contrast at the planet location it will be necessary to make the umbrella about 100 times larger than the pupil at its center. But, if the edge is apodized (or, in the 2-D case, shaped), then one can expect to be able to use a much smaller mask - probably in the 5 to 10x range. 2-D umbrellas may be designed to simultaneously control the diffraction through the pupil and around the outer edges and ensure high contrast where the planet image is expected.

We have studied the formalism developed at Princeton and have found it can be applied to occulting screens as well. For an occulter the constraints are different. The aperture functions in the Fraunhoffer regime, but an occulter is a fundamentally Fresnel geometry. A null at the center of the system in Fraunhofer configurations cannot be achieved as the occulter does not cover more than one zone. Furthermore, the bright spot at the center in the Fraunhofer regime cannot be shrunk to more than a few λ/D. As demonstrated in the pinhole studies, the telescope must move to 4λ/D just to allow nulling to occur in the high contrast region. Fresnel conditions imply that occulters obscure many zones allowing for broad regions of stable high contrast both off axis and across wavelengths. The shape of the occulter is carefully chosen to include the same number of zones at the leading edge as are revealed by the trailing edge moving off the Fresnel pattern in an off-axis shift. Similarly, a change in wavelength simply scales the widths of the Fresnel zones. The shaped masks should be able to account for the change by compensating for zone loss with wavelength change.

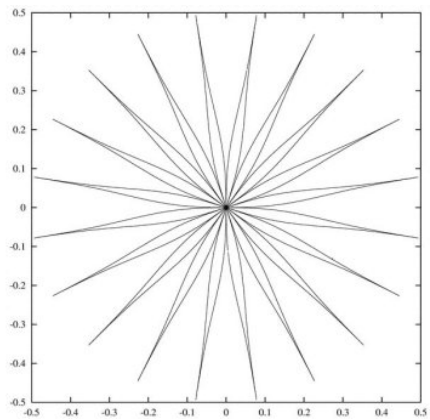

Figure 5: The "Vanderbei Flower" as developed for an open aperture pupil.

The analysis used to determine optimal apodizations for the Fraunhofer regimes can be adapted to Fresnel. Because the approximation that F >> D can no longer be made, the electric field integral acquires an extra exponential factor solely dependant on r, the radius on the aperture plane.

$$E(\rho,\phi) = \int_0^\infty J_0(kr\rho/F)\, e^{-\frac{ikr^2}{2F}} A(r) r dr$$

where A(r) is the apodization function, F is the distance to the telescope, k is 2π/λ, and ρ is the distance off axis in the telescope plane.

To make the electric field integral tractable, the complementary behavior of apertures may be exploited. Babinet's principle states that optical disturbance from two complementary apertures add to the unobstructed electric field as the limits of integration of the open area go to infinity (E1 + E2 = E0). Thus to determine the optical disturbance from the occulter, the solution for the aperture can be subtracted from the undisturbed electric field. The solution then becomes

$$E_{occulter} = E_0 - \int_0^\infty J_0(kr\rho/F)\, e^{-\frac{ikr^2}{2F}} A(r) r dr$$

The integral part of the above solution can be written as a complex number with C signifying the constant derived from the cosine integral and S the constant from the sine integral. All graphs of interest require 10^{-10} contrast in irradiance which is simply the optical disturbance squared. So that the quantity

$$I = \left(1 - \sqrt{C^2 + S^2}\right)^2$$

must be less that 10^{-10} in the region of interest.

At the end of the NIAC study we found a pinspeck design that both meets the contrast requirements and is small enough to launch. The design is based on the work of Vanderbei, Spergel and Kasdin[5]. They showed a flower-like shape (see Figure 5) could be used as an aperture to create a pupil that allows high transmission in the center and a fast falloff to high contrast in all directions around the central spot. This shape is a prime candidate for use in a pinhole camera.

It occurred to us that such a shape might work well as an occulter if it were made sufficiently large to cover the central (Fraunhofer) zone. After some searching we found just such a solution. Shown schematically in Figure 6, it consists of a dark central zone, with spines (or petals) that taper outward. The number of petals shown is 96, but optimization of the design may reduce the required number.

Numerical evaluation of a somewhat larger example is presented in Figure 7. In this case our central obscuration is 100m diameter, with the petals falling to half width at 140m diameter. The thin (low mass) ends of the petals taper out past 300m diameter. The occulter is 200,000km from the telescope. So, this is a large occulter, but it is sufficiently small to be launched by a single rocket and deployed at L2.

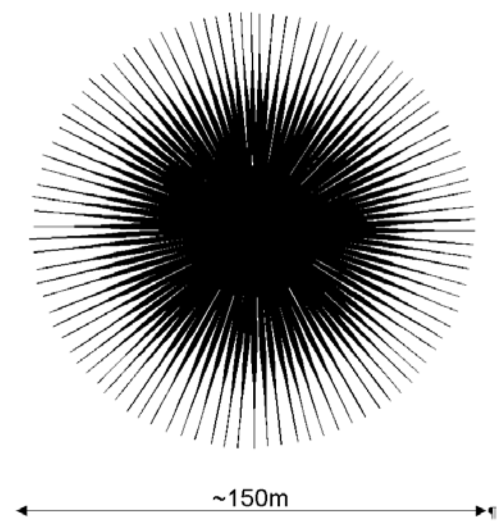

Figure 6: The "Vanderbei Flower" as it might appear for the New Worlds Observer. It resembles a sea urchin more than a flower.

When the Fresnel integrals are evaluated across this shape with an apodization function as shown in Figure 7(a), the diffracted light follows the profile shown in Figure 7(b). The contrast is below 10^{-10} across a large (nearly 100m) diameter. The diameter is so large that any planned telescope can be easily fit within. Equally important, the contrast rises to above 10^{-1} at the position of the Earth, so the planets are not simultaneously occulted. This behavior persists across a wide band of the spectrum. It works even better in the ultraviolet as short as Lyman α (1216Å). As the wavelength moves longward of a couple microns the contrast starts to drop as the longer wavelengths no longer interfere against each other completely.

This particular design is simply an example that proves the pinspeck cameras will work and are practical. We expect that optimization will allow us to shrink them substantially. That work is ongoing.

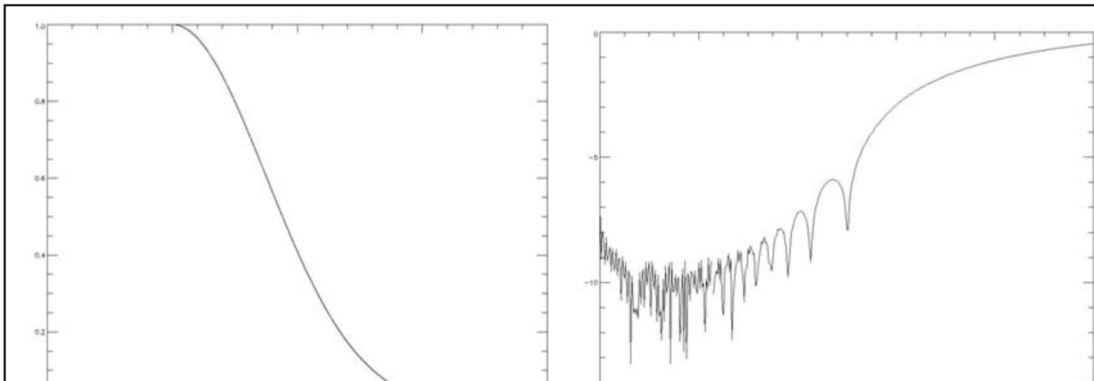

Figure 7: A sample configuration for the apodization of a pinspeck. To the left is a plot of the apodization function in the limit of many petals. To the right is the expected response which shows a broad region of suppression to below 10^{-10} followed by a fast rise to the region where the planets are found.

2.5. Starshade Deployment

An occulter has two major characteristics – a circular exterior and multiple radial members. Deployment of such a device consistent with packaging in a small fairing could be performed in at least two ways with direct heritage to proven deployable designs. The two methods are:

1. The petals of the flower can be pulled outwards and tensioned by creating a circular structure around the outside of the occulter,
2. The flower petals can be pushed out by an array of telescoping linear actuators

Both of these approaches can be accomplished using proven hardware.

A circular structure can be developed from the flight-proven Astromesh perimeter truss reflector. These types of structures have been flown successfully on four major commercial missions to date.

2.6. Formation Flying

The crucial break with tradition that enables the New Worlds Observer is the use of formation flying spacecraft at large separations. No analog of this concept is possible from ground-based or single spacecraft observatories. Precise formation knowledge and control is needed to reach the high angular resolution for direct exo-planet sensing. It appears that the requirements for generating the knowledge of the line of sight and then holding the craft in their respective positions can be handled with techniques combining high precision celestial and inertial sensing and stabilization. The tradeoffs and optimization of the formation flying approach are being performed starting from an allocation of allowed errors amongst the key observatory subsystems. An example of the allocation and trade study process is given by consideration of the effect of solar wind pressure on the large, light structure of the starshade. The added image degradation due to increased motion of a larger starshade will be compared to the increased diffraction scatter from a smaller starshade to find the best shade size to use for the mission.

NWO's mission requires absolute and relative position knowledge for both the detector and occulter, coupled with a robust metrology system to quantify and qualify the state of each component to aid in image reconstruction. To achieve these requirements, the system must operate in a quiescent environment where the effects of various perturbative forces can be detected, predicted and ultimately mitigated by the flight control system.

By operating at one of the Earth-Sun libration points, NWO can leverage the point's region of quasi-stability to simplify the dynamics of the system and allow for active control of each component to within 10 cm in real time across a 20,000 km focal length. From operational experience and analysis, the benefits and costs associated with maintaining a mission about each of the Lagrange points is well understood. Of the five Lagrange points, only three are viable candidates for the proposed mission. L3 is within the photosphere of the Sun, and L1, while lying between the Earth and the Sun, presents an unnecessary constraint on the visibility of the effective system by precluding targets located both sunward and towards the Earth. At L2, L4 and L5, the dominant force acting on the system is solar radiation pressure, with secondary perturbative effects due to the Earth and Moon. Of these three potential points, L4 and L5 are less attractive candidates since the influence of solar radiation pressure is greatest at these two points and when combined with the asymmetric torque induced by the gravitational attraction of the Earth and Moon, requires increased stationkeeping cycles and budgets for the objective mission life.

This is in stark contrast with the beneficial alignment between the Sun, Earth-Moon and the spacecraft at L2. This linear arrangement affords NWO with an improved visibility of target stars, along with aligning the resultant forces due to solar radiation pressure and n-body gravity. Therefore, a halo orbit about L2 provides NWO with the most benign environment to support operations both actively and passively. At L2, a preliminary analysis estimates that the ΔV required to support imaging operations is approximately half that at L4 and L5. This reduction in required stationkeeping benefits the system as a whole. With fewer thruster firings, the fuel mass required for NWO is reduced, which directly translates to mass and cost savings at launch. Additionally, with smaller and more infrequent maneuvers, the control system becomes less complicated which in turn increases the system's reliability.

Injection into and operation at L2 has been successfully demonstrated by other missions, highlighting that the necessary infrastructure and knowledge base exists to support NWO. These benefits combine together directly to effectively lower the risk of NWO, while improving the operational duty cycle of the overall imaging mission. The requirements for the propulsion system can be met by either pulsed plasma thrusters or field emission electric propulsion technologies.

2.7. Telescope & Spectrograph

The role of the telescope is to collect the light from the target and feed the light into a photometer, spectrograph or relay optic, so the telescope need only image a very small field of view and can operate on-axis. This allows the use of simple two-element telescopes, e.g. a Cassegrain.

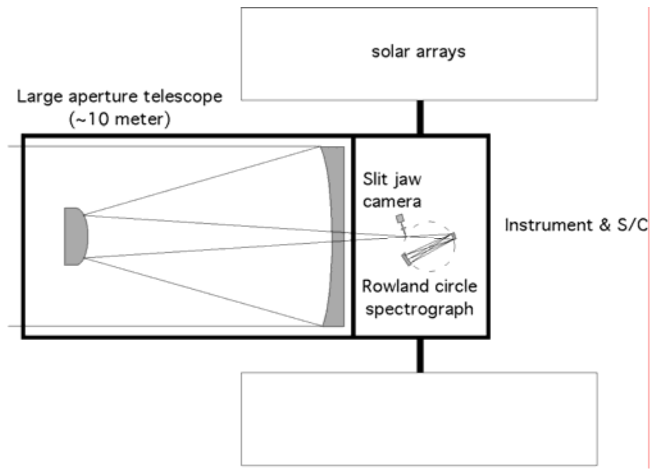

Figure 8: Simple schematic of the planet sensor craft. It is a conventional telescope and Rowland circle spectrograph combination.

The resolution of the telescope is set by the size of the starshade in the pinhole case, and can be as poor as 1 arcsecond, but the increased background from scatter off the starshade recommends resolutions closer to 0.1".

In the case of the pinspeck camera, the telescope should be no poorer than 0.3" because it would be unable to separate planets from each other in the inner planetary system as viewed from 10pc. A tenth of an arcsecond is approximately the diffraction limit of a one meter telescope which, coincidentally, is the minimum size needed to collect the signal. So we have chosen 0.1" as the quality needed.

The detector used in the spectrograph must have an extremely low intrinsic background to minimize the noise in the spectrum, as the fluxes from the planet will be low. The number of detected counts can be computed versus telescope collecting area along with intrinsic noise from the detector. Assuming the Earth's flux distribution, and a spectral resolution element .03 mm x 1 mm we calculate the telescope diameters and count rates (see Table 1).

Detector technology will play a crucial role in the instrument; intrinsic detector background can overwhelm the weak signals and force unacceptably long integration times (see Table 1). However, in the UV, silicon MCPs are proving to be far superior to glass MCP detectors in their intrinsic background, due to the lack of radioisotope contamination in the silicon. Current silicon MCPs are demonstrating background rates of 0.02 counts/sec/cm^2 compared to 0.5 counts/sec/cm^2 for glass MCPs. CCD detectors are unlikely to be suitable, but CMOS detector technology is advancing rapidly and remains very promising. In any event, we will thoroughly parameterize the required detector performance characteristics and evaluate current detector technology for suitability.

Table 1

		Detector Noise (counts)		
Diameter (m)	Required integration time (days) to get 100,000 counts	MCP_{glass}	MCP_{Si}	CCD
1	28	363	15	604800
5	1.1	15	0.6	24192
10	.3	4	0.1	6070
15	.1	2	0.06	2700
20	.07	1	0.04	1512

Assumptions: F_λ~3e-9 photons/cm^2/sec/Å for Earth at 10pc, system efficiency ~0.35, λ=5000Å. Background calculations done using MCP_{glass}=0.5 counts/cm^2/sec, $MCP_{silicon}$=0.02 counts/cm^2/sec, CCD=1e- read noise and readout every 20 minutes, and a 0.03x1 mm resolution element with 0.010 mm pixels.

3. SIMULATIONS

3.1. Planet Finding

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.

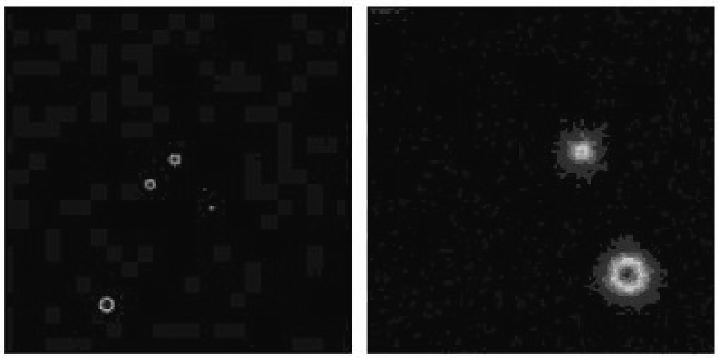

Figure 9: Pinspeck simulations for an 8 meter telescope integrating for a half day (left). To the right is a zoom in on the region close to Mars, where a comet is detected.

Simulations were run to test NWO's ability to detect extrasolar planets assuming a configuration capable of 10^{10} contrast. A more detailed report of the simulations is given elsewhere in this meeting[6]. These simulations were done for both the pinhole and pinspeck configuration observing our solar system at 10 parsecs. 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. In the search for planets, the pinspeck is always greatly superior to the pinhole because the telescope images the entire planetary system simultaneously. For planet photometry the pinspeck has the advantage of studying all the planets simultaneously. For planet spectroscopy and planet imaging, the performance is similar.

In Figure 9 we show a full simulation of a 50,000 second observation of our solar system viewed pole-on. To left we see that Jupiter, Venus and Earth are easily detected. Mars is a little fainter, but we show a detail in the right panel that shows Mars was easily detected (it's just fainter than the others) and there is another, smaller feature yet, which simulates Halley's comet. It is a remarkable thought: we now know how to build a telescope that can detect comets in other planetary systems!

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[7]. But, in the visible, this is not a 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 10a. In short, because we operate in the visible band, zodiacal light is not expected to be a problem.

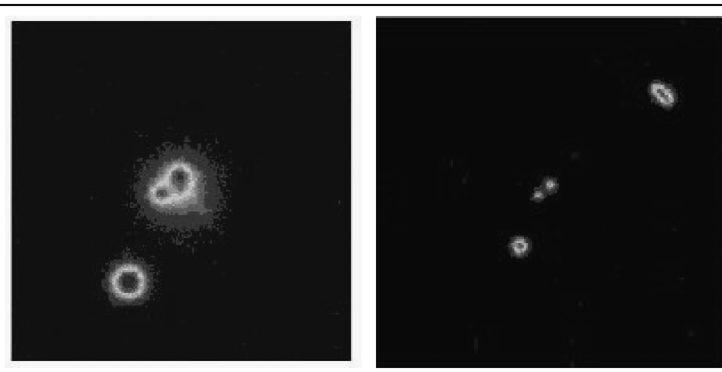

Figure 10: (Left) A 100,000 second observation with a one meter telescope and ten times the zodiacal scattering we experience in our system, shows the dust is detectable but does not interfere with planet studies. (Right) A simulation showing the same planetary system, but with a typical deep field galaxy included. Statistics show that 90% of the time background galaxies will not intrude on the habitable zone of a target.

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[8]. We simulated frequency and brightness of these faint galaxies and discovered that they will be a nuisance. Figure 10(b) 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% 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.

3.2. Planet Spectroscopy

In Figure 11 we show a simulated spectrum of the Earth as viewed from 10pc by the New Worlds Observer. The New Worlds Imager can provide high resolution spectroscopy from the far UV to the near IR with excellent sensitivity. New Worlds will be able to detect methane, water, oxygen, ozone, and other gases at Earth's current and past levels of concentration. NWO will have high enough sensitivity and spectral resolution to detect important atmospheric signatures and chlorophyll-type absorption edges. By operating at visible wavelengths (which penetrate to the ground) NWO will be able to determine the planet's rotation rate, presence of weather, and even the existence of liquid oceans. Combined with atmospheric diagnostics, this information will extend the reach of biologists, geophysicists, and atmospheric chemists to worlds and ecosystems far beyond Earth.

Table 2: Spectroscopic Biomarkers

Water	Necessary for habitability
Oxygen	Free oxygen results only from active plant life
Ozone	Results from free oxygen
Nitrous Oxide	Another gas produced by living organisms
Methane	Life indicator if oxygen also present
Vegetation	Red edge of vegetation at 750nm

Most studies of Earth-like planet biosignatures to date have focused on present-day Earth or small variations of it[9,10]. But experience in planetary exploration and exo-planet detection amply shows we should not be held hostage to our only example of planetary life. Indeed Earth has, in the past, exhibited different atmospheric signatures due to extreme climatic states such as glaciation, the rise of photosynthetic organisms, and methane bursts. Moreover, just as each of our rocky planets differs greatly from each other, there is no reason to expect extrasolar terrestrial planets to be similar to Earth. If a planetary atmosphere is determined to have a severe departure from chemical and thermodynamic equilibrium would we be able to identify the disequilibrium features with biological modification of atmospheric composition? Or will there always be an ambiguity with geological processes? Will we be able to unambiguously identify a spectral signature not consistent with any known atomic, molecular, or mineral signature in the solar system and Universe (such as Earth's vegetation red edge)?

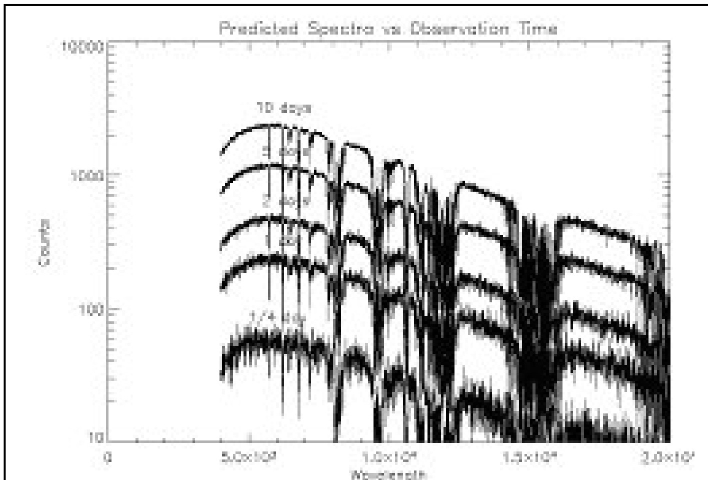

Figure 11: Spectrum of an Earth-like planet.

3.3. Photometry

For a suitably bright planet, a time series of sufficiently high quality spectro-photometric data could reveal a wealth of physical characteristics at wavelengths that penetrate to the planetary surface. Visible wavelengths are more suited for these measurements than mid-IR wavelengths because the albedo contrast of surface components is much greater than the temperature variation across the planet's surface. Moreover, the narrow transparent spectral window at 8-12 microns will close for planets warmer than Earth and for planets with more water vapor than Earth.

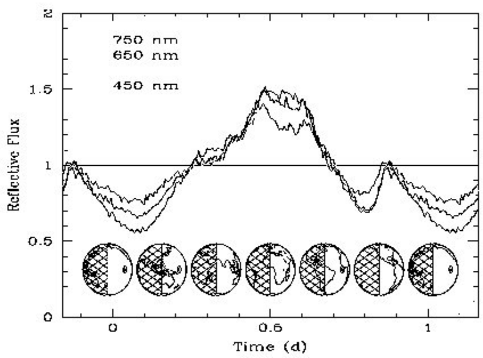

Figure 12—A light curve for a cloud-free Earth model for one rotation. The x-axis is time and the y-axis is the reflectivity normalized to a Lambert disk at a phase angle of 0°. The viewing geometry is shown by the Earth symbols, and a phase angle of 90° is used. Note that a different phase angle will affect the reflectivity due to a larger or smaller fraction of the disk being illuminated; because of the normalization the total reflectivity is << 1 in this case of phase angle of 90°. From top to bottom the curves correspond to wavelengths of 750, 650, 550, and 450 nm, and their differences reflect the wavelength-dependent albedo of different surface components. The noise in the light curve is due to Monte Carlo statistics in our calculations. The images below the light curve show the viewing geometry (cross-hatched region is not illuminated) and relative contributions from different parts of the disk (shading ranges from < 3% to > 40%, from white to black) superimposed on a map of the Earth. At t = 0.5 day, the Sahara desert is in view and causes a large peak in the light curve due to the reflectivity of sand which is especially high in the near-IR (top curve). From Ford, Seager & Turner[11].

Earth is the most variable planet in our solar system, photometrically speaking. This variability is due primarily to weather: cloud formation, motion, and dissipation. The variability at visible wavelengths is approximately 10 to 20% and is caused by the contrast in albedo between the reflective clouds and the underlying, darker land or ocean[11]. Evidence of variable water clouds combined with water vapor in the atmosphere is indicative of large bodies of liquid water. A variable planet would definitely warrant further study—compare the variable Earth to the constant, 100% cloud-covered Venus which shows relatively little change.

The rotation rate of a planet is an important physical characteristic because it is a fundamental driver of atmospheric circulation patterns and weather and it is a record of the planet's formation history. The rotation rate can be determined at visible wavelengths on a relatively cloud-free Earth-like planet if the planet has different surface components. The light scattered by such a planet will vary in intensity as the planet rotates, with a repetitive pattern. For example, Earth's major surface components (land, ocean, and ice) have very different albedos (< 10% for ocean, > 30-40% for land, > 60% for snow and some types of ice), and in the case of a cloud-free Earth viewed at the equator the rotational surface variation can be up to 200% (Figure 12). Even considering the Earth with its cloud patterns, the rotational period is still determinable because large-scale cloud formations persist coherently in some regions for several days.

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