External Occulters for the Direct Study of Exoplanets

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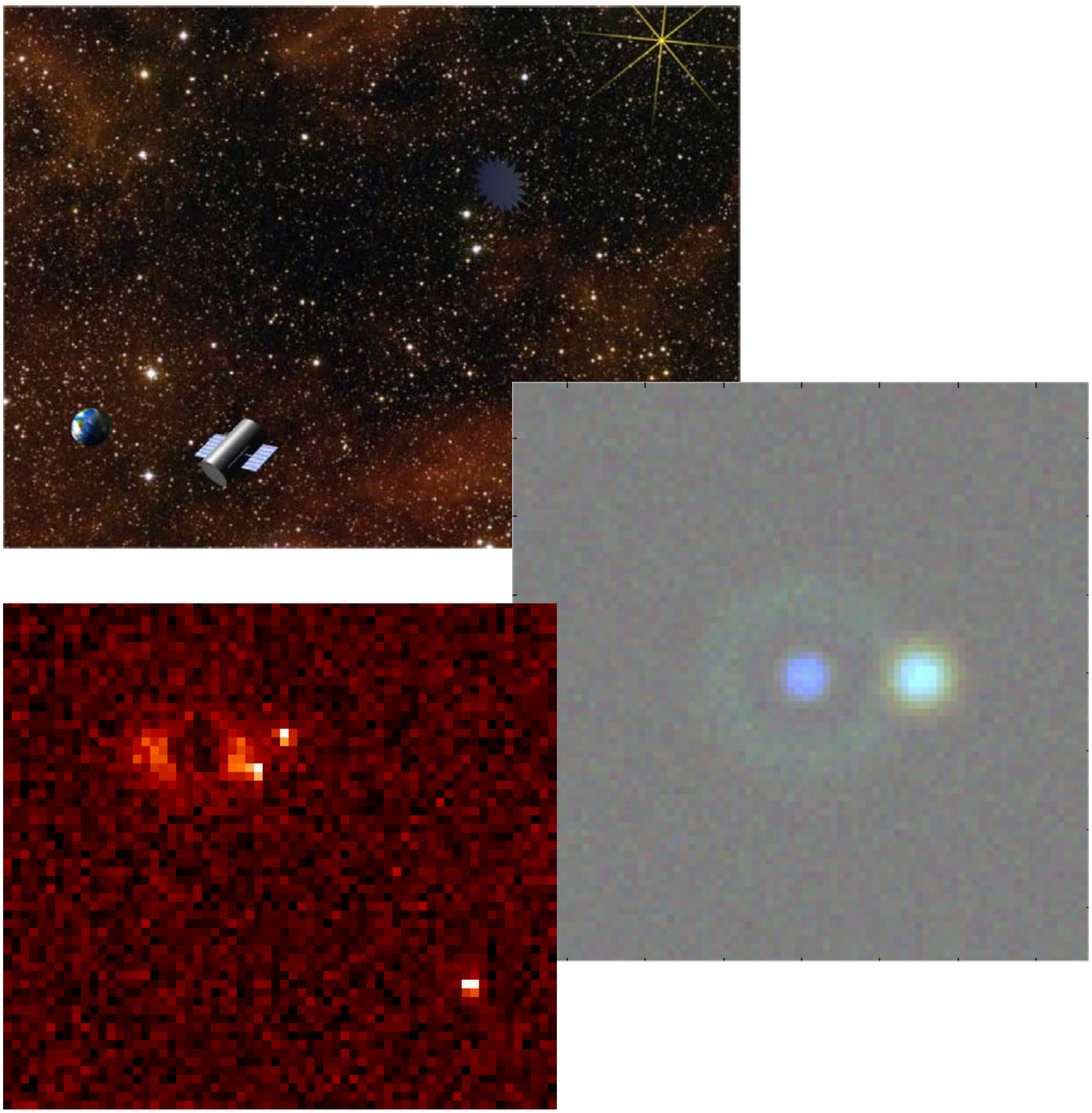

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Abstract: We present a case for the use of external occulters to suppress starlight in direct observation of planetary systems. Such a system is achievable with today's technology and will allow not only the detection of Earthlike planets, but follow-up spectroscopic observations to characterize them. A search for habitable planets around our neighboring stars and for signs of simple 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 extrasolar habitable terrestrial planets based on a recent breakthrough in the diffraction control of starshades – external occulters that can reveal planetary systems nearly free from light scattered by the parent star. Spectroscopy, photometry, and polarimetry can then be done efficiently with a diffraction-limited space telescope operating primarily in the visible. With a single spectrum we can identify and classify a planet, learn about its atmosphere and surface, and look for signs of life. (See Figure 1. Turnbull 2006; Kaltenegger 2007.)

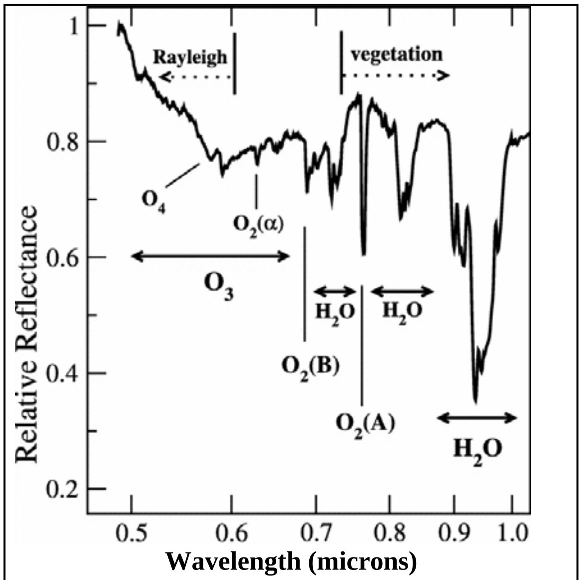

Figure 1. Visible spectrum of Earth at spectral resolution of 300 (Turnbull et al 2006)

In this white paper we summarize an exoplanet mission concept that, for purposes of abbreviation and harmony with NASA history, we'll refer to as TPF-O (the Terrestrial Planet Finder occulter option). Using results of studies and proposals called New Worlds Observer and New Worlds Discoverer (W. Cash, PI), we show how a TPF-O can search for nearby terrestrial planets and look for signs of life on such planets.

In less than a week TPF-O's imaging telescope system could obtain spectra of an exoplanetary system. Alpha Centauri one week, Tau Ceti the next, then Epsilon Eridani, Altair, etc. Each one would be surveyed, with major planets catalogued, mapped, and named. Water planets might be found, with coarse surface features like continents, oceans, and cloud banks possibly evident in photometric data. Dust and debris disks, comets, and asteroid belts could be detected. A few of the potential science goals are listed in Table 1.

Most importantly, exoplanet spectroscopy could be performed, enabling a search for indicators of life. If Earthlike biochemistry is common in the Universe, we have an excellent chance of detecting it elsewhere by measuring an exoplanet's unusual atmospheric composition.

Technology to build a TPF-O is well in hand. With funding from the NASA Institute for Advanced Concepts and contributed expertise from Northrop Grumman Space Technology, Ball Aerospace, Princeton University, NASA's Goddard Space Flight Center, and Jet Propulsion Laboratory we have performed studies pointing toward solutions to the main mission challenges.

We suggest that NASA consider implementing this program soon. The exoplanet science and the other capabilities of a telescope of this class should satisfy many needs of large parts of the astronomy community, giving it a wide base of community support.

Table 1: Some TPF-O 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 planet 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 possible life, we can try to understand the basic chemistry associated with it. Is it necessarily similar to our own?

Configuration: The TPF-O concept (Figure 2) features two or (more efficiently) three spacecraft flying at Earth-Sun L2 or in a drift-away solar orbit (orbit options are under study). One craft carries a 4 meter aperture-diameter diffraction-limited telescope optimized to work in the visible band (extension into the near-ultraviolet and near-infrared is likely). The other "occulter" craft would each carry a starshade. Operating 70,000 km from the telescope, one starshade would be maneuvered into the telescope's line-of-sight to a nearby star, blocking starlight while passing planet light. Each starshade can project a very deep starlight shadow wherein the telescope operates. 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) will be available for study with a conventional-quality telescope.

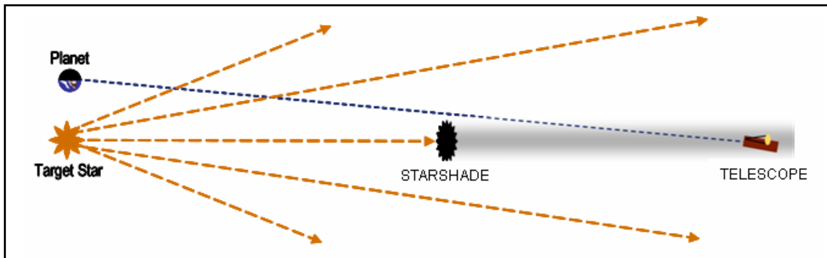

Figure 2. TPF-O throws a deep stellar shadow over the telescope, but allows planet light to pass by the starshade

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 then that diffraction around the 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 UMBRAS and BOSS. With our recent investigation of petal-shaped occulters, work that first began with Marchal (1985), starshade requirements now appear achievable with existing technology.

In 2005, we built on earlier shaped-pupil designs (Vanderbei et al., 2003) to develop a new petal-shaped starshade that suppresses diffraction by many orders of magnitude (Cash, 2006), and allows systems feasible with today's technology. Such a flower-like starshade is shown in Figure 3. The center of its shadow, extremely dark over the entire spectral band from 0.4 to 1.1 μm, accommodates the telescope with margin for alignment control. For TPF-O, starshades will

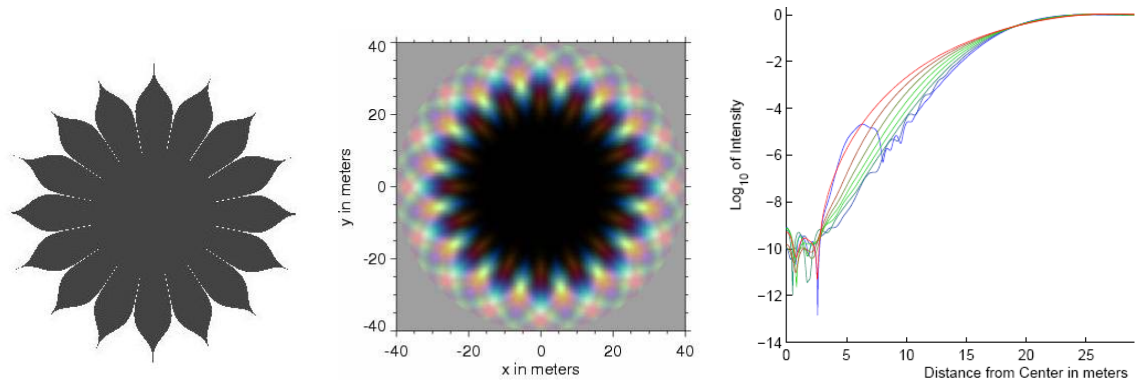

Figure 3: Shape of starshade, shape of starshade shadow, and profile of the stellar suppression Vanderbei et al, 2007.

need to be about 50 meters tip-to-tip and may be made of any dark, opaque, deployable material.

Because of the large distance between the telescope and the occulter, slewing between stellar targets presents a challenge for this mission. The 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. While TPF-O requires only one occulter to function, its overall efficiency is greatly enhanced by a second occulter that can travel while the other is in use. As the occulters are low in cost compared to the telescope, this is a highly cost-effective upgrade.

We estimate that with two starshades 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, simultaneous long-exposure observations of planets and of the wide field-of-view surrounding their position will generate many deep-field images highly useful for cosmology. These capabilities should allow a merger of interests across several disciplines.

Operations Concept: TPF-O is designed for 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 to two weeks 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.

The image of the planetary system stretches outward from the IWA, limited only by the size of the detector and the telescope resolution – an occulter has no intrinsic Outer Working Angle.

The first image taken should probably be broadband in the blue, where the telescope gives the best spatial detail. (See the simulation in Figure 4.) We should see exozodiacal light (exozodi) deep inside the system, concentrated in the habitable zone. 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. (See ExoPTF white paper by Kuchner et al.)

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 the habitable zone the residual starlight and exozodi will be modeled and subtracted to reveal more planets. Planets inside the habitable zone are, of course, of special interest. Some may be identified immediately as giants if they are quite bright. The fainter ones deserve further study. A series of images through strategically chosen filters can help identify the nature of each planet.

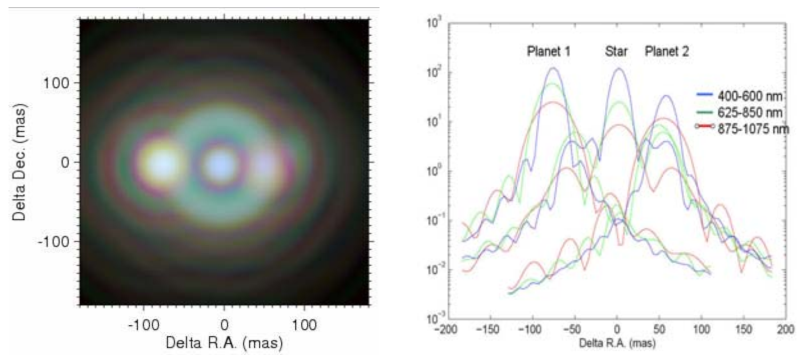

Figure 4: Simulated TPF-O image of an occulted star with two planets. To the right is the cross-section brightness profile.

Extended imaging photometry and polarimetry may detect planet surface features and rotation. Ford et al. (2001) showed that the continents and oceans on a true Earth analog could be inferred. With TPF-O'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 partially map the coarse geography of many new planets!

TPF-O 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 (Meadows 2006) 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 (Figure 1). The basic atmospheric components will be detected and their abundance measured. Geology of continents could be studied through absorption features of surface materials.

A major spectral signature of Earth is the molecular oxygen absorption feature at 760 nm. On our planet this feature is due solely to the existence of life, specifically plant life. At the moment we know of no abiotic mechanism to produce oxygen in planets in the habitable zone (Kasting 2006), so any exoplanet exhibiting abundant O_2 must immediately be considered a candidate for harboring life. More detailed spectra are then called for, and we would maintain our gaze on the system to glean every possible clue.

A TPF-O launched within a decade from now could find out if life is common in the universe!

Table 2: Typical TPF-O Parameters

Telescope diameter	4m
Angular resolution	0.026”
Spectral resolution	100
Starshade separation	72,000 km
Outer diameter	50 m
Number of petals	16
Inner Working Angle	0.058”

Requirements and Capabilities: Further study is needed before we know the optimal mix of parameters for TPF-O. Table 2 presents some typical numbers.

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.

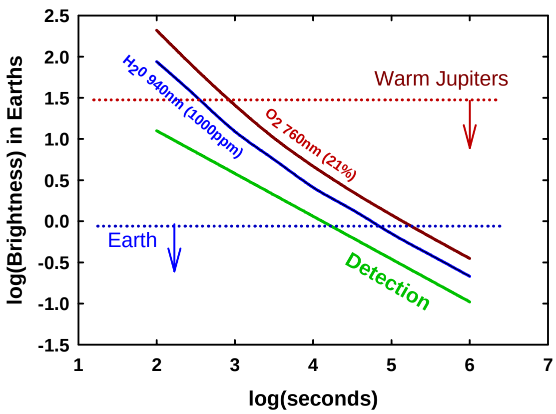

Figure 5: For a planetary system at 10pc, we show the sensitivity limit of TPF-O in fractions of an Earth brightness. Simple detection requires a few hours. The time required to detect the terrestrial water (λ940nm) and oxygen (λ760nm) lines is also shown. The level of sensitivity required to study the Earth and Jupiters (at 1AU) is shown to aid the eye.

We have calculated the exposure times needed to make a 10σ 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) as shown in Figure 5. 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 10σ detection of 3.2 hours for TPF-O. 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 TPF-O would take only 1.6 days to make 5σ detection of the O_2 λ0.76 μm absorption band. The relatively short exposure time for TPF-O 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 TPF-O 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 a minimum separation of about 70,000 km and a tip-to-tip occulter diameter of about 50 m. One JPL estimate states that with optimal revisits and eta_earth assumed equal to 1, and 5σ detection required, we would catalog 28 terrestrial-planets with 64 stars searched.

At large separations of the starshade from the telescope, occulter size and mass increase, as does travel time between targets. Distances as high as 100,000 km and IWA’s as low as 50 milliarcseconds have been considered and found viable. In many ways we are simply propellant- and mission-lifetime-limited. We conserve 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.

We have spent considerable time 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 several-year mission. Each of those lines has the potential to reveal a complex and intriguing new planetary system.

We are still evaluating optimum orbit choice and propellant requirements. Preliminary studies have showed that a baseline heliocentric orbit requires considerably less propellant mass but longer re-targeting travel times than a baseline L2 orbit. Analysis of a 50,000 km occulter separation distance in an Earth-trailing or Earth-leading orbit found station-keeping requirements to be ~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. While the Δv requirements will approximately double, 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. Further studies are required to apply this approach to transfers between defined candidate stars and for the larger occulter separations needed to provide adequately small IWA, and to compare the performance of optimized trajectories in both heliocentric and L2 orbits.

NASA has invested heavily in theoretical and analytical work on precision formation flying and control, but has not yet followed up with actual missions. TPF-O 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. We will also need 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, and our analysis based on current technology has led to our estimate of a 2 m margin in the shadow diameter. While more modeling, analysis, and hardware demonstration is needed, past work by us and others, 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 TPF-O. Yet, since this is a new type of mission, inevitably there are technical concerns. Some of these are listed in Table 3.

Laboratory demonstration of a scale-model starshade was performed at the University of Colorado in 2006, achieving 10^{-7} 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^{-9}. 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 CU and NGST.

Table 3: Technical Tall Poles

Concern	Design Solution Options	Technology Sources
Deployment of large starshades	Booms, inflatable, strain	SRTM, military
Controlling starshade 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

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 Cost: TPF-O meets the exoplanet science goals in NASA's strategic plan. It is where we want to be scientifically ten years from now.

Because no new technology areas are involved, the mission can be pursued on a fast track. Following Phase A and B mission definition studies, launch might occur in as little as five years given optimal funding. The pacing items are expected to be the telescope primary mirror system and the high-precision starshade deployment.

Cost figures in a white paper of this nature must be considered only speculative. Partly because of different possible approaches to acceptable mission reliability and risk, no detailed estimate has yet been attempted. Some members of our group reached consensus on a guess at 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 4m telescope immediately puts the cost above $2Billion. A generic number of $3 (+/-1) Billion covers the range of likely mission scenarios. This puts TPF-O in a cost range similar to other flagship missions under consideration.

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