Apodized Square Aperture Plus Occulter Concept for TPF

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ABSTRACT

The standard approach to achieving TPF-level starlight suppression has been to couple a few techniques together. Deployment of a low- or medium-performance external occulter as the first stage of starlight suppression reduces manufacturing challenges, mitigates under-performance risks, lowers development costs, and hastens launch date for TPF. This paper describes the important aspects of a conceptual 4-metre apodized square aperture telescope system utilizing a low-performance external occulter. Adding an external occulter to such a standard TPF design provides a benefit that no other technique offers: scattered and diffracted on-axis starlight is suppressed by orders of magnitude before reaching the telescope. This translates directly into relaxed requirements on the remainder of the optical system.

Keywords: TPF Architecture, External Occulter, Apodized Square Aperture, Star Visor

1. INTRODUCTION

The number of different techniques proposed for finding and studying terrestrial planets is almost too numerous to count[1]. Most require off-earth location, although lensing approaches can be used from the ground[2]. All approaches can be classified into multi- or single-aperture techniques. Multiple aperture techniques generally come attendant with the complication of requiring interferometry or some other light-combining scheme. Although single-aperture techniques might seem the simplest, large apertures and exquisite wavefront quality is required for studying terrestrial planets. Given that earth-analogue planets orbiting solar-analogue stars appear ~ 10^10 times fainter than the star in the optical, single-aperture terrestrial planet finding (TPF) designs are faced with the combined challenge of reducing or reshaping the parent star's point spread function (PSF) and controlling scattered light, both on-axis and off.

By employing an on-axis light baffle, at a distance sufficiently far from the aperture to avoid blocking light from the nearby planet, the amount of starlight that diffracts to and scatters across the focal plane can be reduced significantly. This direct gain in contrast ratio occurs before starlight ever enters the telescope aperture, and is a unique feature of external occultation. The factor by which starlight is suppressed translates directly to a reduced stellar PSF and lower on-axis scattered light in the focal plane. An observatory with lower optical performance can be transformed into the planet-finding category with the addition of an external occulter. Adding an external occulter to a planet-finder architecture trades advantages gained against the cost of an additional spacecraft and complexity of requiring formation control to be maintained between the telescope and occulter. However, the cost and complexity are not obviously greater than what is gained by lowering the high optical performance requirements of a system that otherwise does not use an occulter.

In what follows, we will briefly review the diversity of planet-finding external occulter (on-axis light baffle, or star-visor) systems for optical wavelengths, outline a general system and vehicle design for one possible space telescope plus "low performance" occulter system, characterize the optical performance of the occulter system, discuss a possible mission design for a minimal TPF mission, and elucidate the advantages of an occulter for TPF in general. This telescope-plus-occulter system exploits several stages of starlight suppression, lowering the mission risk of underperformance in any of the other stages. Mission risk mitigation in this fashion is an argument in favor of employing an occulter with a single-aperture space telescope for planet finding missions. Ultimately, external occulters can be used to search around stars with luminosity greater than the sun for habitable planets, where the contrast ratio is greater than 10^10.

2. OCCULTER CLASSIFICATION

Although the literature discussing occulters extends back to the early 1960s[3], the diversity of different possible system types employing external occulters has been lost in the numerous publication venues. Consequently the external occulter idea has been re-discovered many times[3, 4, 5, 6]. The parameter space defining their operational utility has only been sparsely sampled given that the literature contains many distinct ways to use them. Large apertures combined with high-performance occulters[5] form a two-stage starlight suppression system, and were considered by TPF architecture review committees[7, 8], but opaque external occulters combined with multiple stages of light suppression were not. Low-performance occulters[9, 10] were not rankable in the TPF architecture reviews because their development was immature and a lack of understanding of their benefits existed.

Classifying occulters by "performance" refers to the amount of light suppression supplied by the occulting screen. The terms "high-suppression", and "high-performance" are used synonymously here, although the more precise description is properly "high-suppression" (q.v., Table 1). Generally speaking, higher-performance systems use techniques such as gradient transmission or complex screen shapes to increase the depth of the starlight null in the telescope aperture plane. A full description of individual occulter types is beyond the scope of this paper and the reader is referred to publications on individual systems for a fuller appreciation of their diversity[3, 10, 4, 11, 5, 6, 7, 9, 12].

Table 1: Simple performance classification of different occulter types. “High”, and “Low” refers to the degree of on-axis starlight suppression achieved in the different systems.

High Performance Occulters	Low Performance Occulters
BOSS (apodizing) Marchal-type (petals) Spergel-type (petal)	UMBRAS (opaque screen) NOME (opaque segmented screen) IRIS (opaque screen) Woodcock-type (disk/umbrella)

At first consideration, high-performance occulters might seem to be the preferred technique, however these systems have greater manufacturing and operating challenges than low-performance occulters. The technological readiness levels (TRLs) of most low-performance occulter subsystems are closer to flight than for high-performance occulters. Many individual factors can favor lower-performance occulters over their higher-performance cousins. The degree to which each factor favors low-performance occulters is not discussed, but varies depending upon the factor, the particular architecture, and the mission goals. Compared to high-performance occulters, low-performance occulters have:

- Smaller telescope-occulter separations,
- Higher target observation rates,
- A broader target field of regard,
- More easily manufactured screens,
- Easier ability to package the screen for launch,
- Greater robustness of screen design against damage,
- Easier and less critical scattered ambient and sunlight control,
- Easier formation alignment control scheme,
- Looser alignment tolerances

The relaxed requirements translate into advantages for low-performance occulters when the remaining required light-suppression is distributed among other stages in the telescope design[13] (e.g., shaped apertures, pupil apodization, internal coronagraphs, deformable mirrors). Employing multiple stages of starlight suppression is important for the simple reason that the greater the number of stages in a system, the lower the required performance on each individual stage.

3. GENERAL SYSTEM AND VEHICLE DESIGN

Following the manner in which the distribution of the duties of light-suppression between stages were discussed in the previous section, the apodized square aperture[14] plus occulter (ASA+O) planet-finder system[15] discussed here employs 4 stages:

- Occulter
- Square Aperture
- Off-axis, unobstructed mirror
- Pupil Apodization

The mirror size itself is classifiable as a suppression stage because larger aperture sizes have narrower PSFs, and therefore better light suppression at a given angular separation from a star. The square aperture affords steeper PSF roll off between the diffraction spikes than circular apertures (~ r^4 as opposed to r^3), while pupil apodization attenuates diffraction features even further. The off-axis design helps control the diffraction features, as well. For an example minimal terrestrial planet-finder ASA+O, the required wavefront quality is ~ $\lambda/300$ for a 4-metre diagonal aperture (ASA4+O). If the occulter were not a part of the system, then wavefront quality would need to be at least an order of magnitude better to achieve the same performance. One can imagine a TPF system where more stages downstream of the pupil apodization (such as a coronagraph or deformable mirror) are employed. The 4-m diagonal system is classifiable as marginal in its TPF capacity at $\lambda/300$ wavefront quality, however larger apertures and architectures with better wavefront control could be expected to perform correspondingly better.

Occulter

The occulter consists of a solar-powered spacecraft designed to fly in formation on the line-of-sight to an astronomical target thousands to tens of thousands of kilometres distant from the space telescope. Between observations, the occulter spacecraft accelerates and decelerates while moving to the line of sight to the next target. The occulter is classifiable as a low-performance one (q.v., Section 2: self-shaded, opaque, multi-layer, rectangular screen) employed in controlled occultations.

In the ASA4+O system, at least one screen architecture has been identified which is robust and simple (Figure 1). The occulting screen could unfurl after launch by unrolling like a Venetian blind from a cassette as a single segment, triple-layer, opaque, rectangular structure approximately 12-metres wide and 24-metres in length. The screen and support structure itself may weigh as little as 25 kilograms. The screen sheets would be composed of commercial-grade, aluminum-coated 2.5-micron Mylar with protective coatings[12]. The three layers provide redundancy against damage. Astromast or uncoilable polysulphone S-glass composite rods provide rigidity to the rectangular structure while two fine-filament meshes strung between the supports prevent loads from being transferred to the screen itself. Each of the three sunward (during observations) edges is rimmed with a high radius-of-curvature blade to minimize scattered and reflected sunlight toward the telescope.

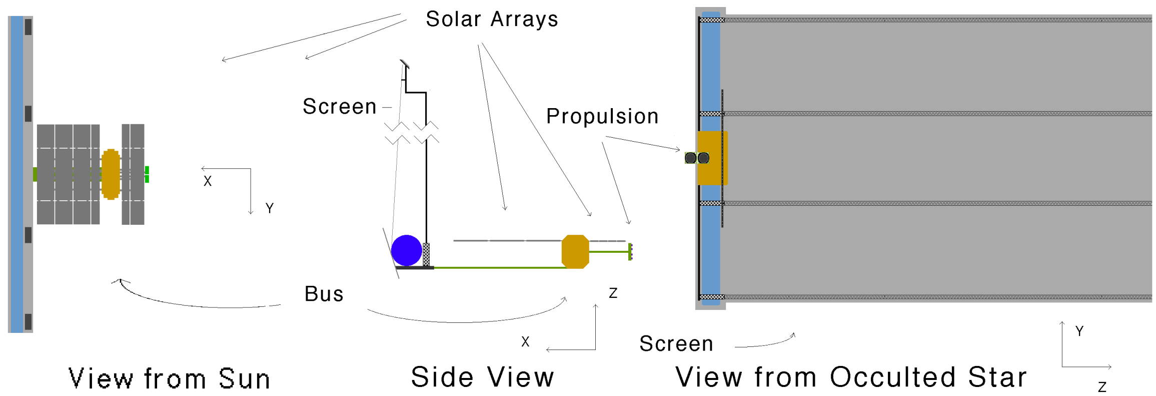


Figure 1: Three orthogonal views of the occulter in its observing configuration. In transit configuration, the screen rotates 90-degrees around the y-axis to present a near-symmetric structure that can easily be controlled as it moves to the next target.

The spacecraft carrying the occulting screen has many conventional features of other spacecraft. However, its unique performance requirements mandate optimizing a number of subsystems for the occulter mission. A single 90-mN solar electric propulsion unit using xenon expelled at 3000 seconds specific impulse, plus a backup unit[16] move the occulter from target to target. Approximately 10-15 square metres of high-efficiency solar cells are needed to provide adequate power during transit and formation keeping activities.

Table 2: Maximum differential drift rates produced by various environmental factors for a 20,000 km telescope-occulter separation at Earth-Sun L2. Earth tides can be reduced below that of solar tides with Halo or Lissajous orbits. Propellant leakage must be below the stated limit, otherwise mission duration would be shortened. Solar wind and radiation pressures are functions of telescope and occulter configuration. The differential accelerations are computed for the local stellar-inertial reference frame in which observations occur.

Factor Producing Differential Telescope-Occulter Drift	Differential Acceleration
Earth Tides	<3.6 x 10^-06 m/s^2
Solar Tides	<1.3 x 10^-06 m/s^2
Lunar Tides	<1.2 x 10^-07 m/s^2
Solar Radiation Pressure	<1.0 x 10^-07 m/s^2
Propellant Leaks	<3.0 x 10^-08 m/s^2
Solar Wind Pressure	~3.5 x 10^-11 m/s^2

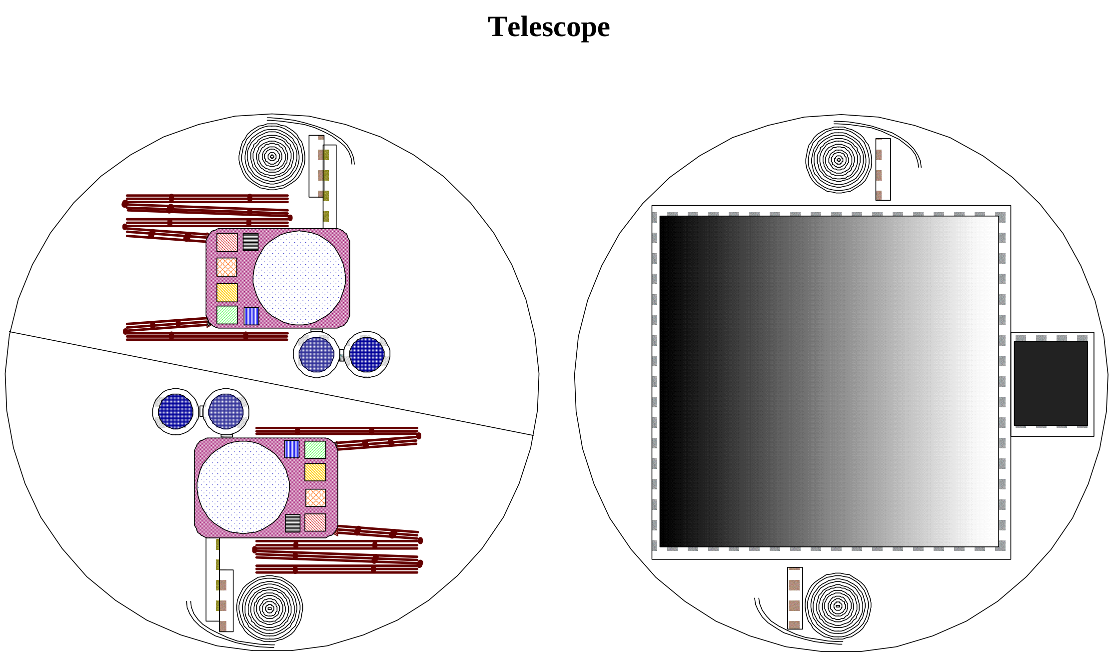
Formation keeping would employ an attitude and alignment control system with ~20 mN thrust level between science exposures yielding over 50% of alignment time performing science (q.v. Table 2) when taken with typical occulter masses. The alignment control system could share the same propellant feed system, as does the primary propulsion. On-target alignment control techniques present no obvious feasibility objections[17, 9, 12]. For this low-performance occulter the light diffracting around the screen to the telescope aperture can be used for guiding during the alignment control phase.

The design balances low spacecraft mass with a reasonably large number of target observations. Design drivers are screen size, deployment robustness, packagability on a single launcher with a telescope, propellant mass, and propellant tank thermal control. A representative mass statement for an ASA4+O occulter is provided in Table 3. The design is conservative in that two titanium tanks each storing 125 kg of xenon at up to 200C (little or no implied thermal control) were assumed.

Propellant quantity is sized for a 4-year mission with approximately 2/3rds of the time spent transiting between targets for a single occulter. Figure 2 shows packaging of two such occulters in a 5-metre fairing, therefore packaging one occulter in the fairing constraints should not pose a problem. Flying additional occulters yield gains in target observation rates and total targets, as well as propellant and individual occulter mass savings[18].

Table 3: Mass statement for a single occulter spacecraft.

Component	**UMBRAS '04 13L90m20K design**	**Mass (kg)**
Screen	13mx25m + cassette + masts + deploy drives	60
Propulsion	1 NSTAR + backup + PCC + Xe tank & feed	190
Propellant	4 yr mission, inc. formation keeping	250
Power	4 kW arrays + battery + PCU	350
Attitude/Translation	SESK 50% redundant ATCS system	180
Navigation, Guidance	RSUs + RWs + FHSTs + SunSens + NavCam	50
Communications	S-band omni + high-gain + backup	50
Commanding	S/C computer + backup	30
Bus Structure		100
Thermal Control		20
Subtotal		*1280*
Margin (20%)		256
Grand Total		1536



Figures 2: On the left is a cross-section through the upper part of a 5-metre (4.6-m envelope shown) fairing containing two folded occulter spacecraft. Shown are the bus, folded solar arrays, primary and spare folded 30-cm ion engines, internal subsystems packages, 1 of two propellant tanks, extension boom, screen pedestal, rolled screen, and pedestal light shield. On the right is a cross section through the same fairing several metres below passing through the 4-m diagonal square aperture, off axis telescope. The rectangular secondary optical path enclosure is visible on the extreme right. At top and bottom are the rolled screens of the two occulters which project down the sides of the telescope. The two occulter spacecraft ride atop an adapter extending above where the telescope rides in the fairing. Approximately 9-metres of height in the 12-metre Delta IV fairing is available for the telescope in addition to its launch adapter.

The reference observatory employs a square entrance aperture[14] with a primary mirror composed of a single off-axis element so that diffraction from neither the monolithic primary nor from secondary mirror or support structures degrades the system's optical quality. A comparable mass statement for the observatory is not provided, however we note that if a Delta IV were used as the single launch vehicle to launch both telescope and occulter(s), then the 9-tonne earth-ejection capability would allow up to about 6.5-tonnes for the square aperture, 4-metre diagonal telescope (assuming ~ 0.5 tonnes for each launch adapter) with a single occulter, and 4.5 tonnes for the observatory with two occulters riding in the top of the shroud.

Packaging requirements to fit the telescope within the 5-metre fairing allow the occulter(s) to ride in the top of the shroud with the screen(s) projecting down along the outside of the telescope (Figure 2). The corresponding sizes mandate that the primary be very fast (f/2), with the secondary optimized for other mission requirements. The primary mirror is 4-metres clear-aperture diagonal, however only about 2.8 metres along each edge. The instrument housings may be placed in one of several locations—behind the primary, or directly in-line with the secondary beam path.

The square aperture telescope complements the rectangular occulting screen. Both produce diffraction features radiating at 90-degree directions. When the rectangular occulting screen is tilted with respect to the telescope to present a square profile and is aligned properly with the square aperture, it matches the shape and orientation of the aperture. The roll of the telescope and occulting screen can be adjusted to direct diffraction spikes along common directions, minimizing the pollution of the focal plane with diffracted light. Over the course of observing a particular target, the roll can be adjusted to sweep the diffraction spikes and null regions around the star, allowing a full mapping during a single target visit.

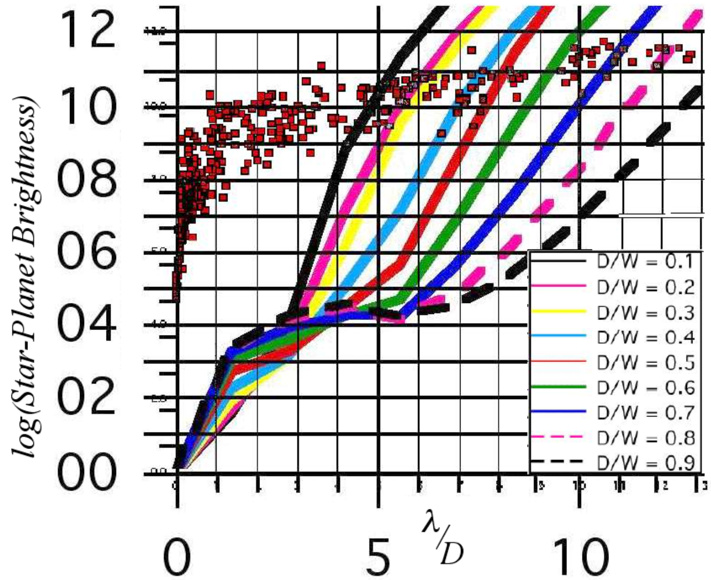
6. OPTICAL PERFORMANCE

Any optical design has theoretical limits for faint source detection at given separations from bright stellar point sources. Figure 3 shows parameterized star-to-planet brightness limits and inner-working radii for an idealized (i.e. no wavefront error or scattered light) ASA+O system with various ratios of aperture diameter to opaque screen size for a given fixed Fresnel number (F_N=10). F_N=10 may not be optimal, however it is chosen to represent the mission concept described here. The ASA4+O system with a 13-m wide screen ideally performs along the yellow line (suppression levels noted in Table 4). Non-ideal wavefront quality and scattered light will degrade these limits.

Table 4: Ideal starlight suppression levels of the ASA4+O system for given separations.

Brightness Ratio Performance	**λ/D**	**Separation at 0.5µ**	**Separation at 1.0 µ**
10^10	6	0.16"	0.32"
10^11	6.75	0.18"	0.36"
10^12	7.5	0.20"	0.40"

In order to perform a survey that allows atmospheric characterization, looking for the "water hole" at 0.95 microns, a mission with a wavelength range out to 1.0 microns at spectral resolution $\lambda/\Delta\lambda$ = R = 10-20 is assumed as a minimal requirement. At F_N=10, the occulter would be 15,000 km away for 1.0 µ observations. The equivalent F_N for 0.5 microns and the same distance would be F_N=20. At higher Fresnel numbers, a system suppresses starlight better; therefore the contrast level specified for shorter wavelengths (Table 4) is met by using the long-wavelength as a limiting requirement. Higher fidelity modeling with λ/300 wavefront error indicates that the ASA4+O system has the capacity to image objects 10^10 fainter than the star at separations closer than 0.15 arcseconds.



Figures 3: Parameterized ASA+O System Performance. The colored curves show the ideal (no wavefront error) ASA+O system performance (ratio of star central intensity to PSF) in the focal plane along a 45-degree diagonal to the diffraction spikes for a perfectly aligned ASA+O system at Fresnel number F_N=10 (=W^2/λz, where W is screen width, λ is observing wavelength, and z is telescope-occulter separation). Ideal ASA+O performance was simulated for various aperture-to-screen-width ratios (D/W) in GSFC's Optical Systems Characterization and Analysis Research (OSCAR) package on the Beowolf HIVE cluster[13]. The overplotted data points show earth-analogues at quadrature in the habitable zone around several hundred nearby stars scaled to the 4-metre diagonal aperture observing at 0.5-microns wavelength.

Importantly, in Table 5, note that scattered sunlight from the edge of an occulter is quoted for a diffusely scattering, micro-bead edge (albedo = 1.0). If a perfectly specular cylindrical edge (0.1 mm radius of curvature (ROC) were precisely aligned with the telescope, it could appear as bright as 4th stellar magnitude. However, by tilting the occulter by less than half a degree, the apparent brightness would be diminished to less than the diffuse component.

Table 5: Brightness limits of sources of light reflecting from the opaque occulter and their magnitude. Unwanted stray light from sources other than the star are significantly below the suppressed target starlight.

Source	Equivalent Stellar Brightness limit
Scattered sunlight from edges	~ 14th magnitude diffuse beads (1-mm ROC).
Scattered earth/moon-shine from screen	~ 19th magnitude.
Doubly scattered sunlight telescope-->occulter	~ 33rd magnitude.

7. OPERATIONS

The basic operations cycle is described in detail elsewhere[19, 9]. Fundamentally, however, there is a cycling between observations and inter-target transits. Inter-target transit times can range up to 2 weeks for this configuration, during which time observations on other non-occulter targets may be performed (Figure 4).

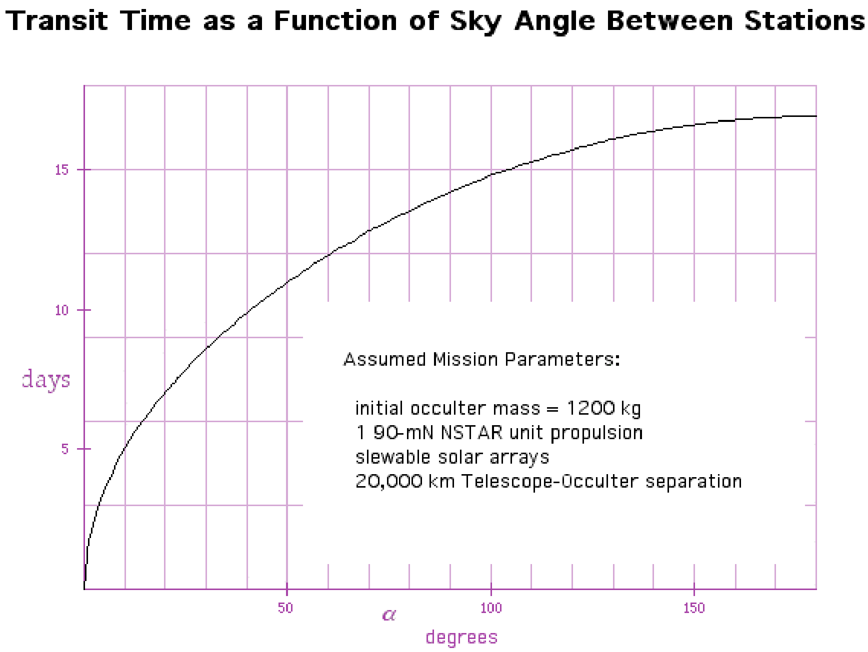


Figure 4: Typical times required for moving the occulter from one target to another.

During inter-target transits, half the time is spent accelerating toward the next target, and half decelerating. Figure 5 schematically shows this and other inter-target transit phases for the occulter. Navigating from one target to another and converging on the subsequent TTLOS is a multi-step process.

One promising scheme employs a passive phased-array microwave detector onboard one of the two spacecraft which receives periodic pings from the second craft, allowing degree-level navigation information to be acquired in conjunction with spacecraft attitude sensing. When within a few degrees of the next target station, an optical navigation camera aboard the occulter images the field where the telescope is, determining the vector between the telescope and occulter to within arcseconds, facilitating guidance much closer to the TTLOS. When within arcseconds of the TTLOS, a camera in the primary focal plane of the telescope images the target field to further guide the occulter into TTLOS alignment. Re-alignment activities occur between science exposures with the aid of alignment sensing from the telescope's alignment imaging system. In Halo orbits around Earth-Sun L2, differential drift can remain tolerable over science exposure times (~ 10 cm).

Once the occulter arrives on target location and achieves alignment, the initial science observations could include a set of unfiltered imaging sweeps around the star with different rolls of the telescope and occulter to spot the location of faint point sources. With the ASA+O system, the roll of the telescope and the occulter would likely match in order to keep the direction of the diffraction spikes aligned and maximize the depth of the focal plane null. The size and extent of the null region depends upon the system design specifics, but ranges between about 15 and 40 degrees in each quadrant around the star. Broadband photometry and spectroscopy of these sources would follow, with roll optimized for observing particular faint sources.

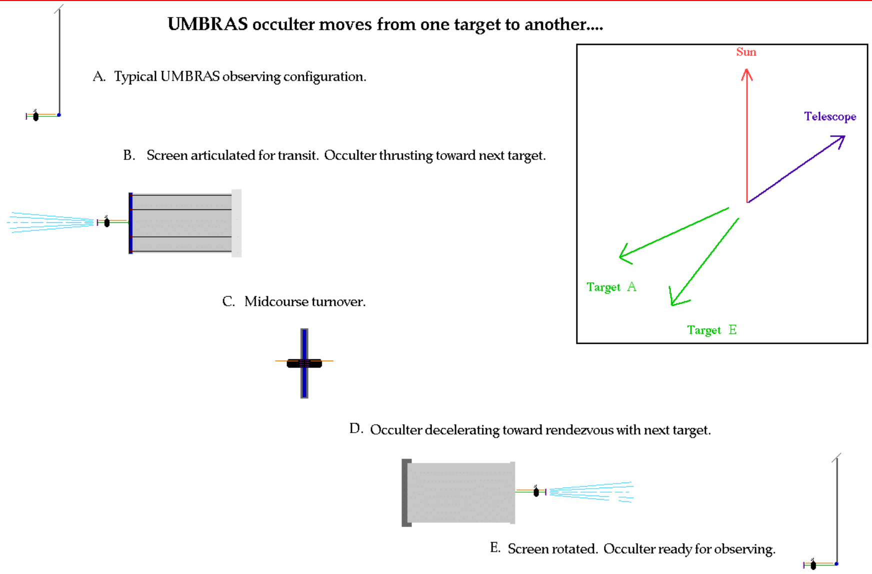


Figure 5: Inter-target transit by the occulter spacecraft. The beginning and end orientations show the occulter in the observing configuration relative to the telescope. In between the occulter accelerates continuously halfway to the next target, and the turns around to decelerate the remaining distance.

8. POSSIBLE MISSION SCOPE

A mission with TPF must specify the targets for which it can survey and detect earth-like planets. For our purposes here, we define "earth-like" to be earth-analogues orbiting at a distance from the parent star where it receives roughly 1356 W/m^2 stellar radiation. Using such a criteria, stars with the greatest apparent brightness will have this 'habitable zone' at the greatest apparent separation from the star. However, stars that are intrinsically brighter (greater absolute luminosity) will have a greater brightness ratio of star-to-planet. If 10^10 star-to-planet brightness ratio is used as a benchmark, then the λ/300 wavefront error, 4-metre diagonal system performs only a marginal TPF mission. However, if a higher quality wavefront is achievable, such as that required for standard TPF coronagraphic missions, then the possibility of observing earth-analogues around stars brighter than our sun becomes possible if stray light is comparably controlled. The ability to detect earth-analogues at star-to-planet brightness ratios of 10^11 or even 10^12 then becomes a possibility. Note that Figure 3 implies that the ability to observe targets with star-to-planet brightness ratios of 10^11 or greater can open the discovery potential for an entirely new class of potentially habitable planets around higher luminosity stars, as well as smaller planets and fainter planets, than the standard "10^10" TPF goal affords.

One oft-cited "drawback" of the occulter architecture can actually be viewed as an advantage. Since the occulter spends time transiting between targets, observations of other astrophysical phenomenon, besides extrasolar planet studies, may be conducted with the remaining time. Given a single occulter, the entire mission then may be more appropriately classified as a joint TPF-Astrophysics endeavour.

9. FUNDAMENTAL ADVANTAGES: RISK, MARGIN, TIME, AND MONEY

Construction of a TPF coronagraphic flight system based on one of the standard architectures cannot achieve the required system performance level without risk, extended construction time, narrow performance margins, and great cost. The advantages of developing the external occulter approach can be succinctly expressed in terms of those four related factors.

- *Risk*: High risk of underperformance in any stage of starlight suppression jeopardizes mission success and schedule. An external occulter can reduce requirements on the at-risk stage, lowering overall risk to the mission.
- *Time*: If an occulter-less system cannot be launched until the TRL for a given stage of starlight suppression reaches a certain performance level, then the relevant stage's performance requirements can be relaxed by use of an occulter in the system. Reducing stage requirements brings launch date earlier.
- *Margin*: Integrating a low-performance occulter into operations with the telescope allows factors of 20-50 margin to be gained in the remainder of the system. This margin can be distributed appropriately among the individual stages inside the telescope, reducing the performance requirements in each stage without reducing the performance of the mission.
- *Money*: If high development costs would be required for bringing a starlight suppression stage to a given performance level without using an occulter, then employing an occulter in the system and lowering the stage's requirements can lower the cost.

Although an occulter necessitates a second spacecraft, the risks, costs, and development times for it are not obviously higher than for a single-aperture TPF architecture that does not contain an occulter. An occulter-less architecture places higher performance requirements on the stages internal to the telescope. If it becomes necessary to fly an external occulter with a single-aperture TPF system in order to prevent excessive launch schedule slippage, then by carrying the development cost and effort now, time is saved and risk is reduced compared with incurring them at some later time.

10. SUMMARY

Employing an occulter with a single aperture telescope such as an apodized square aperture telescope, allows the use of smaller, lower-quality optics to achieve the same contrast capability for extrasolar planet studies. Use of a low-performance occulter avoids many of the risks and challenges that were posed for higher-performance occulters. Reasonable designs for such a system allow a TPF system to share time with other astrophysical observations on the same observatory.

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REFERENCES

1. NASA JPL Terrestrial Planet Finder Mission Architecture Study Reports, JPL Publication 02-017 08/09, Electronic Publishing Services.

2. B. S. Gaudi, "Microlensing Searches for Extrasolar Planets", *Scientific Frontiers in Research on Extrasolar Planets*, ed. D. Deming, S. Seager, ASP Conf. Series v. 294, p.79, 2003.

3. L. Spitzer, "The Beginnings and Future of Space Astronomy", American Scientist, v.50, no. 3, p.473, October 1962.

4. C. Marchal, "Concept of a space telescope able to see the planets and even the satellites around the nearest stars", *Acta Astronautica*, v. 12, no. 3., pp.195-201, Pergamon Press, 1985.

5. C. Copi, G. Starkman, "The Big Occulting Steerable Satellite", Astrophysical Journal, v. 532, p. 581, 2000.

6. A. Schultz, D. Schroeder, et.al., "Imaging planets about other stars with UMBRAS", in *Infrared Spaceborne Sensing VII*, M. Strojnik, B. Andresen, v.3759, no. 49, 1999.

7. Ball TPF Preliminary TPF Architecture Review, op. cit. NASA JPL Terrestrial Planet Finder Mission Architecture Study Reports.

8. TRW TPF Preliminary TPF Architecture Review, op. cit. NASA JPL Terrestrial Planet Finder Mission Architecture Study Reports.

9. I. J. E. Jordan, A. Schultz, et.al., "UMBRAS: Design of a free-flying occulter for space telescopes", AIAA 2000-5230, Space 2000 Conference proc. Sept. 2000, ISBN#1-56347-461-1.

10. G. R. Woodcock, "Future Space Transportation Systems Analysis, Appendix to NAS9-14323, December 11, 1974.

11. G. D. Starkman, C. J. Copi, "The Improved Resolution and Image Separation (IRIS) Satellite: Astronomical Observations with a large occulting satellite", SPIE Proc. v.3356, pp.608-621, 1998.

12. I. J. E. Jordan, C.-C. Wu, et.al., "NOME: Modifying Nexus into an occulter for use with NGST", *Journal of the British Interplanetary Society*, v. 56, no. 7/8, 2003.

13. R. G. Lyon, J. M. Hollis, J. E. Dorband, "Comparative Optical Analysis of Extra-Solar Planetary Imaging Techniques", SPIE v. 4860, p.251-265, 2002.

14. P. Nisenson, C. Papaliolios, "Detection of Earth-like Planets using Apodized Telescopes", Astrophysical Journal. 548, L201, 2001.

15. A. B. Schultz, R. G. Lyon, et.al., "Imaging terrestrial planets with a free flying occulter and space telescope: an optical simulation", Proc. SPIE Vol. 5170, 262-271.

16. J. R. Brophy, J. Sovey, T. Bond, etc., "Ion Propulsion System (NSTAR) DS1 Technology Validation Report", NASA Center for AeroSpace Information (CASI), Deep Space 1 Technology Validation Reports, Oct. 2000, http://nmp-techval-reports.jpl.nasa.gov/ .

17. H. M. Hart, I. Jordan, "Imaging planets about other stars with UMBRAS: target acquisition and station keeping", SPIE v. 4087, pp.993-1003, 2000.

18. I. J. E. Jordan, H. M. Hart, et.al., "The advantages of multiple coronagraphic vehicles in occulter missions", AIAA 2003-6300, Space 2003 Conference proc. Sept. 2003, ISBN#1-56347-647-9.

19. M. Kochte, A. B. Schultz, et.al., "External Occulter Operations Requirements", Eighth International Conference on Space Operations, May 17-21, 2004 Montreal, Canada, AIAA pending.