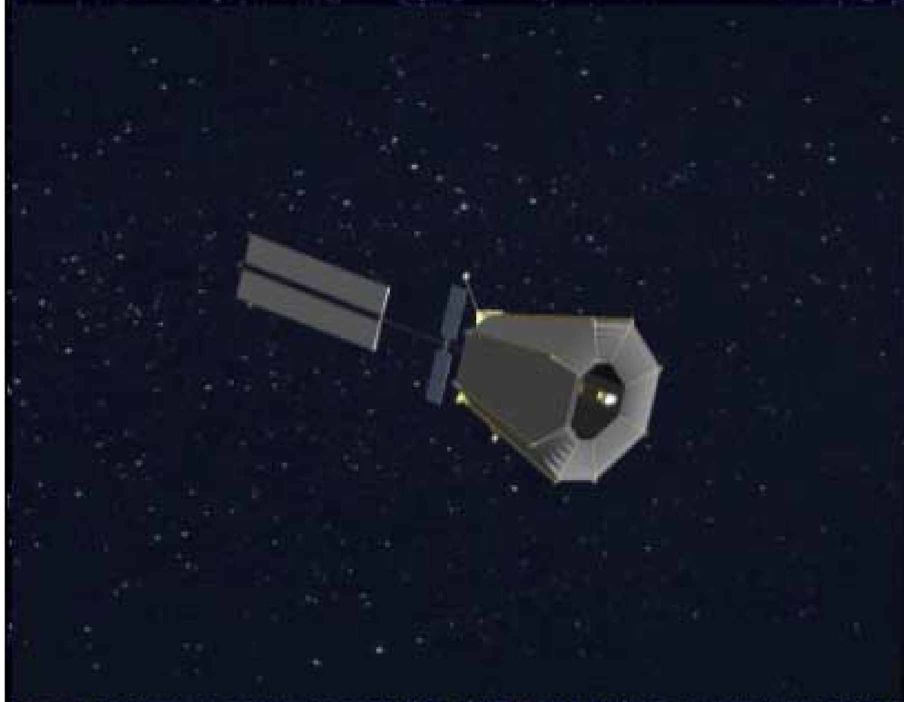
# Are External Occulters Useful for TPF-C?



Are external occulters useful for augmenting TPF-C science and can they be made to work? Simple arguments are presented to outline the science case, and previous analyses are extended to show how occulters could be designed and operated with TPF-C.

# Slide presentation for inclusion with conference proceedings

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Material adapted from and augmenting Poster # 92.

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Artwork on coverpage, page 14,and 16 are courtesy of Ed Rowles (Blue Horizon), Timothy Ho (JPL, couresy of NASA/JPL), and artists for BOSS (CWRU).

# Table of Contents

# 1. Science Utility

Adding the capability for TPF-C to operate with and control an external occulter allows deeper suppression of scattered and diffracted starlight. TPF-C science may then be enhanced in two ways:

- A deeper survey of TPF-C target star systems can be conducted.

- The wavelength range over which TPF-C can characterize exoplanet atmospheres may be extended.

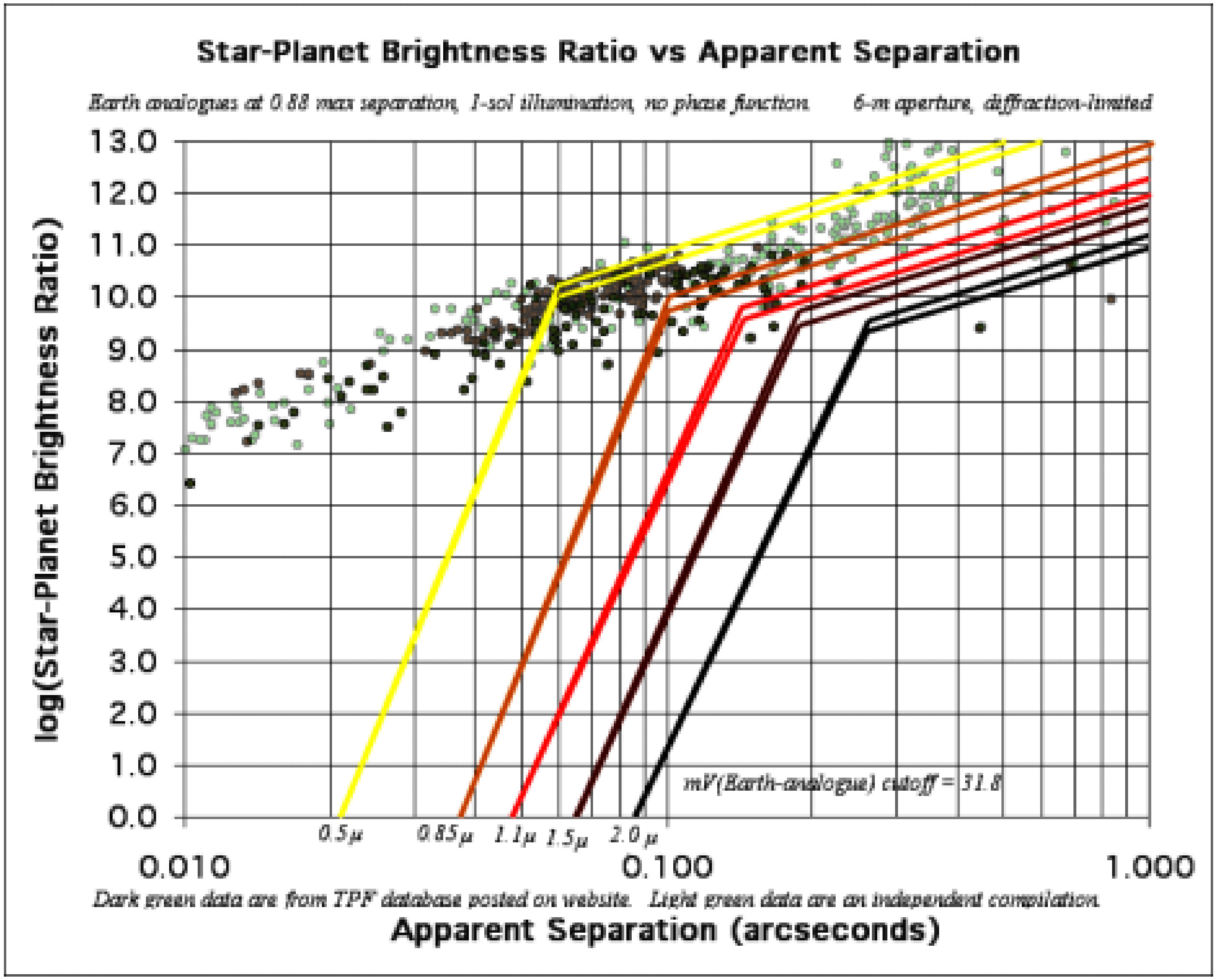
# How does science improve?

Suppression of starlight before reaching the telescope aperture provides a direct contrast performance gain.

On the next slide is a simplified TPF-C discovery space plot. It contains a set of curves approximating the limits of a 6-metre elliptical TPF-C with a perfect coronagraph and mirror. The different colors represent different observing wavelengths, while the closely spaced pairs of curves show the difference in meeting a $10^{10}$ star-planet brightness ratio performance specification at the red or blue end of the TPF-C benchmark bandwidth.

Earth-analogues around TPF “shortlist” (dark green circles), and other nearby stars (faint green circles) are overplotted at the minimum expected separation for which 95% completeness in 6 visits to each target distributed over 2 years would occur.

# TPF-C Multiwavelength Discovery Space




Over-plotted model curves are for perfect optical performance of a 6-metre mirror. The closely spaced pairs of curves for 5 wavelengths show the $10^{10}$ star-planet brightness ratio goal met at 0.5 μ (lower) and 0.85 μ (upper).

Realistic large angle limits would be much flatter than that shown (Airy-envelope, only) for non-perfect wavefronts. Very flat limit curves result from more advanced theoretical models.

# What occulters do well

Next, consider the benefit offered by an external occulter. From a separate study* of a matched apodized square aperture telescope plus opaque rectangular occulter, it was found that an order of magnitude or more reduction in field brightness in the focal plane was achieved even with lower wave front quality (q.v. graph next page).

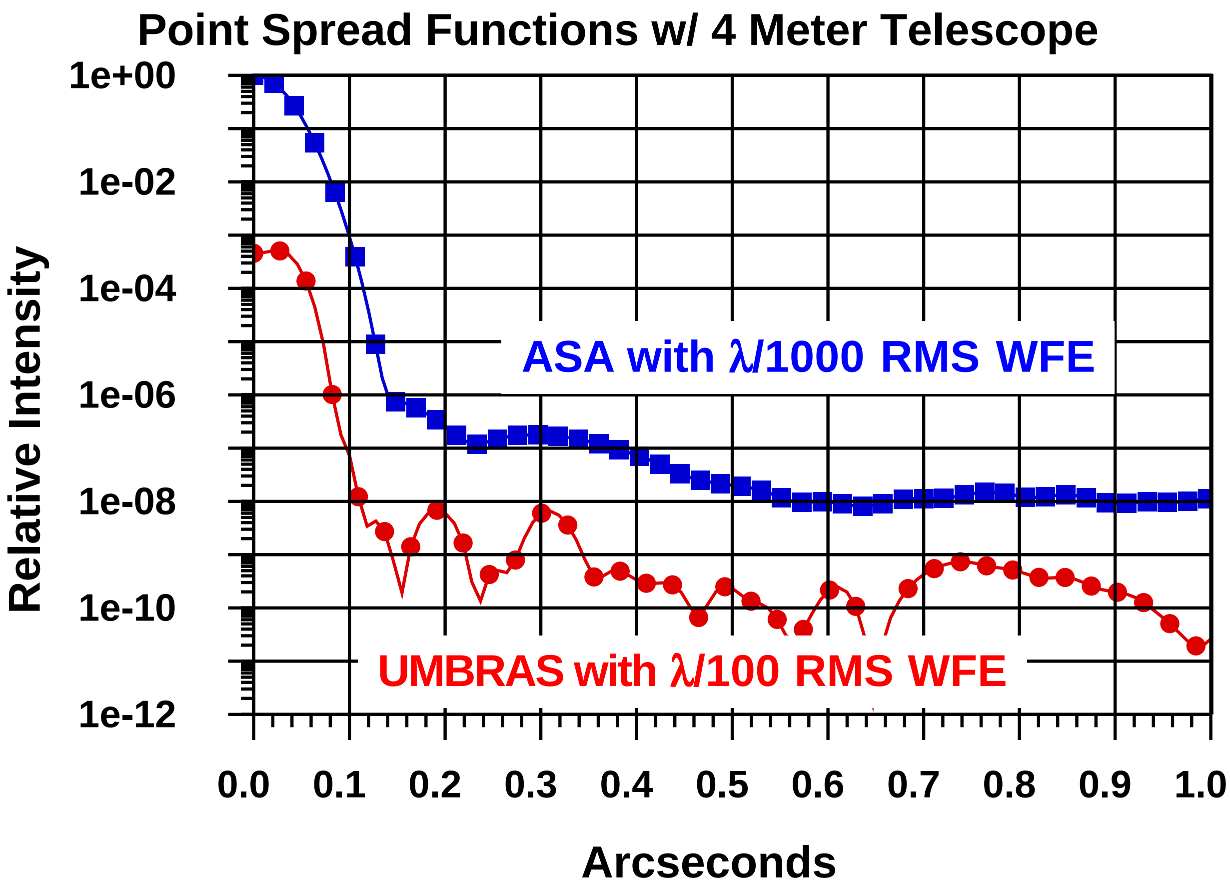
The plot shows cross-sections through two different PSFs. The upper (blue) curve is for a 4-metre Sonine-apodized square aperture (ASA) with RMS wave-front error of ~ $\lambda/1{,}000$. The lower (red) curve is for the same aperture size ASA system having ten-times *worse* ($\lambda/100$) wave-front quality, but *with* a simple opaque external occulting screen 13.3-metres across, 35,000 km away (Fresnel number = 10 at 0.5 $\mu$).

A darker field in the focal plane is achieved with significantly relaxed optical requirements.

* "Imaging terrestrial planets with a free flying occulter and space telescope: an optical simulation", A. Schultz, SPIE Aug. 2003

# Required wavefront quality relaxed with external occulter

*Blue Plot*: Apodized Square Aperture Telescope with λ/1000 rms WFE (Wavefront Error).
*Red Plot:* External Occulter with λ/100 waves of rms WFE.




Both have wavefront PSD(f) ~ $1/f^3$, D/W = 0.3 and Fresnel number = 10.

External Occulter performs much better with more WFE due to less stellar light actually entering aperture !

R.G. Lyon
05/09/04

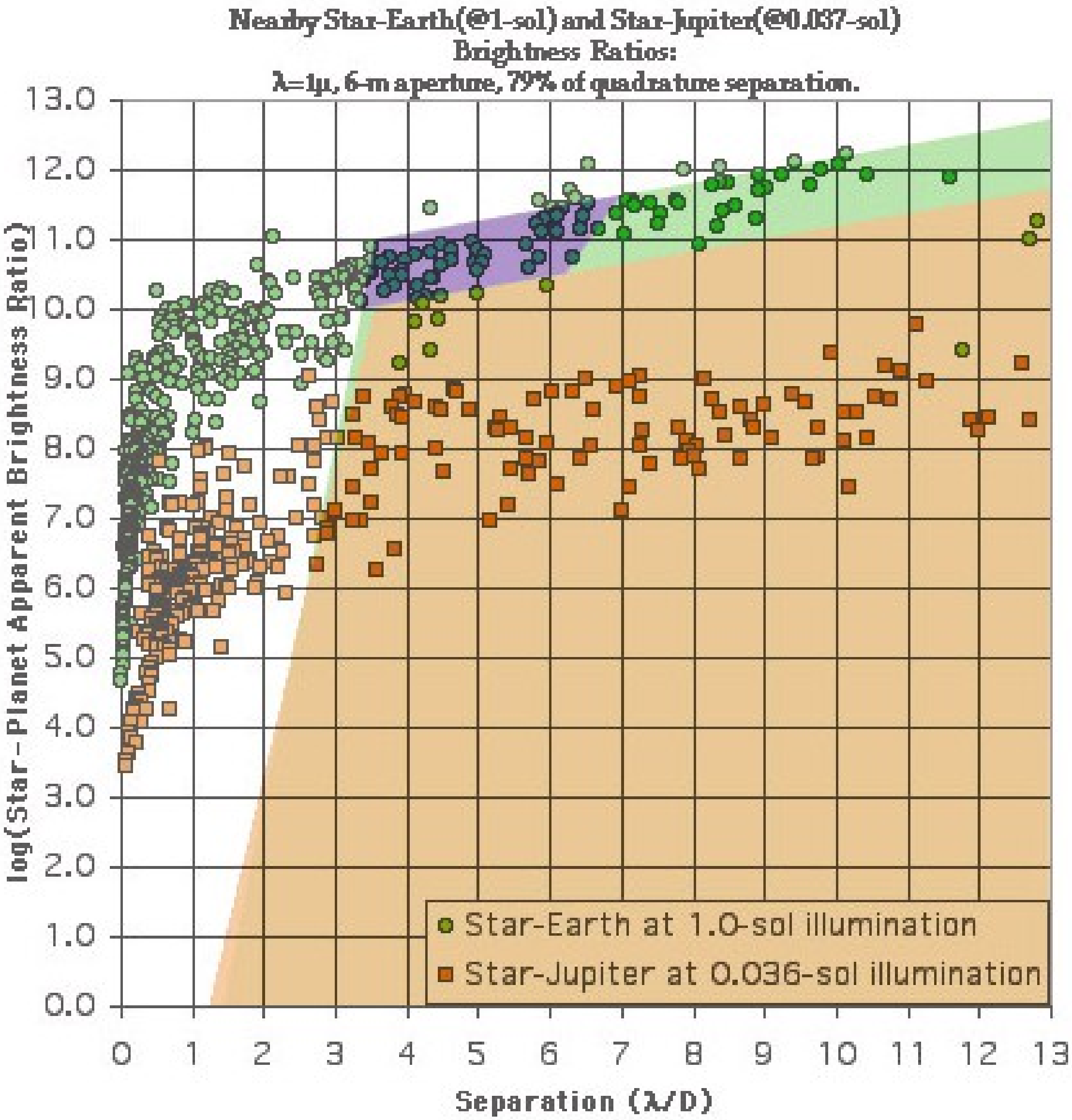
# TPF-C + Occulter Discovery Space?

High fidelity simulations of TPF-C plus an external occulter have not been done, however, we will make a general argument of how TPF-C science performance improves by employing an external occulter with it.

On the next page, the "yardstick" TPF-C discovery space from slide #6 is re-plotted (log-linear, this time) and shaded tan for a single wavelength (1-μ) with Earth-analogues (green circles) and jovians at 5x the earth-analogue distance (red diamonds). Assuming a simple factor of 10 gain in light suppression, the extended discovery space for TPF-C with an external occulter is shaded (green). The gain in the blue region depends strongly on compatibility of the occulter and coronagraph/DM designs. Deeper nulling with suitably matched occulting screens could extend the discovery space upward even more*.

* "Big Occulting Steerable Satellite", C. Copi, G. Starkman, Ap. J. v.1, 29 Apr 1999.

# Adding a simple occulter




Tan region is the idealized discovery space (perfect optics assumed) for TPF-C.

Green region is the extended discovery space assuming operations with an external occulter providing *only* a factor-of-10 starlight nulling.

Blue region is also potential discovery space, but the extent depends strongly on coronagraph-occulter matchability.

Plotted separation (or greater) is realized ~ 50% of time for randomly oriented circular orbit planes.

# 2. Alignment

Telescope-Occulter-Target alignment may be achieved through a variety of techniques, however the critical science-time alignment may be sensed using equipment onboard TPF-C. Between science exposures, the occulter performs the necessary formation control using alignment feedback information from the telescope.

Drift naturally occurs due to a number of sources, but all are of magnitude small enough that useful starlight nulling can be achieved and controlled*.

* AIAA 2004-6300, “Apodized Square Aperture concept for TPF”, I. Jordan, et.al,

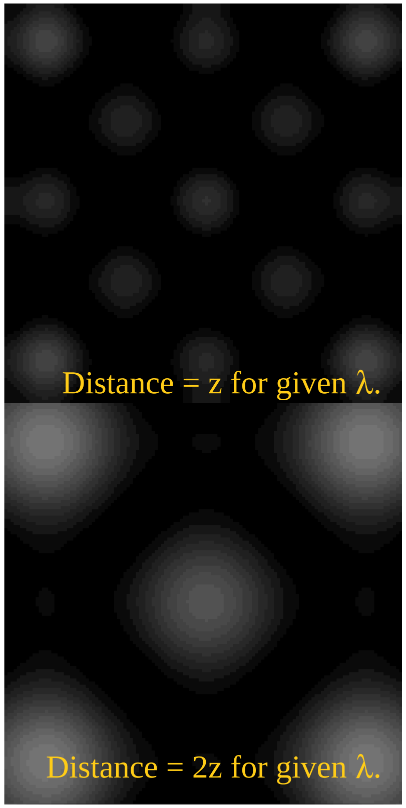
# Alignment Sensing

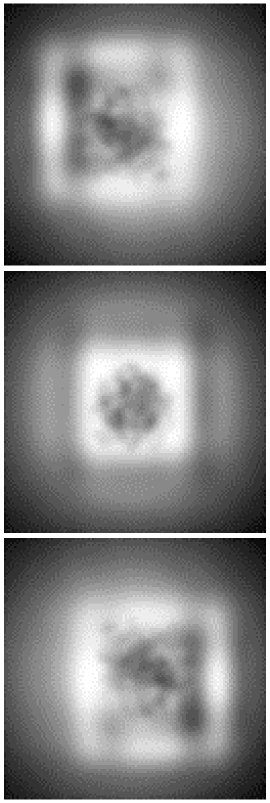
Telescope amplitude senses or images the occulted star.

## Aperture Plane

Starlight amplitude sensing in the aperture plane to localize the null. (e.g., surround pimary aperture with photometric-quality subapertures).

May be best for deep-nulling screens.



## Focal Plane

Conceptually shown at right, the occulted star's appearance changes as the occulter drifts across it. This information can be used to back-compute the alignment.

May be best for moderate-nulling screens.

# Alignment Control

The telescope *points* and the occulter *translates*.

The alignment sensor data is processed to produce a computed "state vector" quantifying misalignment and the desired state vector for the subsequent science exposure(s)*, and then uplinked to the occulter.

The occulter performs the alignment maneuver and informs the telescope to verify alignment and proceed with science activities.

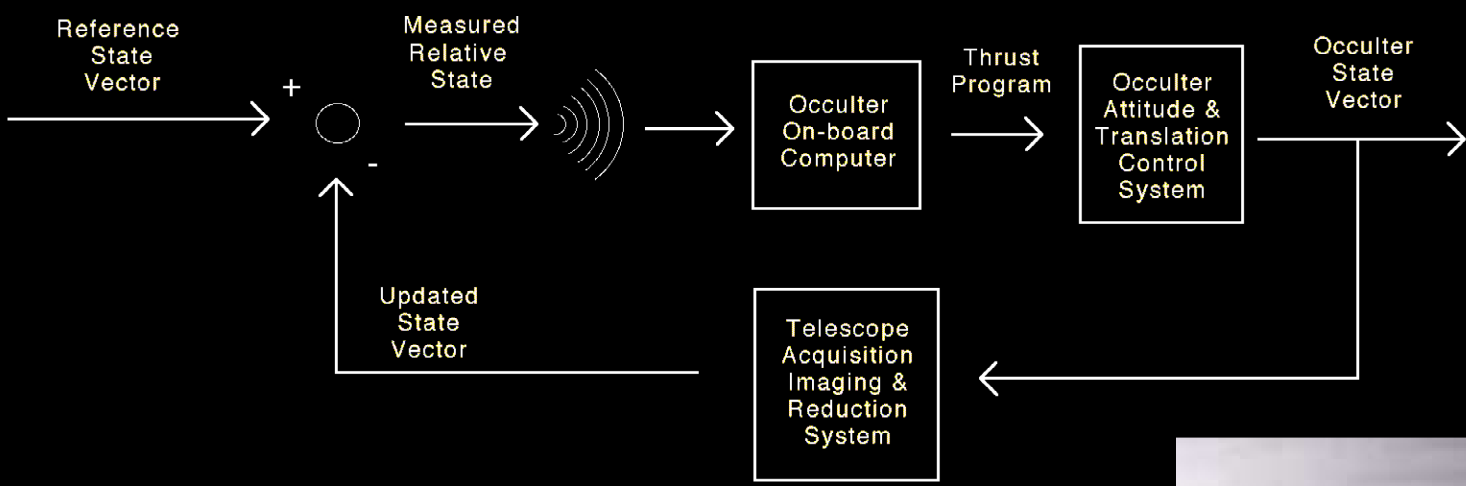
Alignment activities *may* be "hidden" during science readouts, filter changes or other instrument transitions in some cases.

A simplified alignment control block diagram is shown in the next slide.

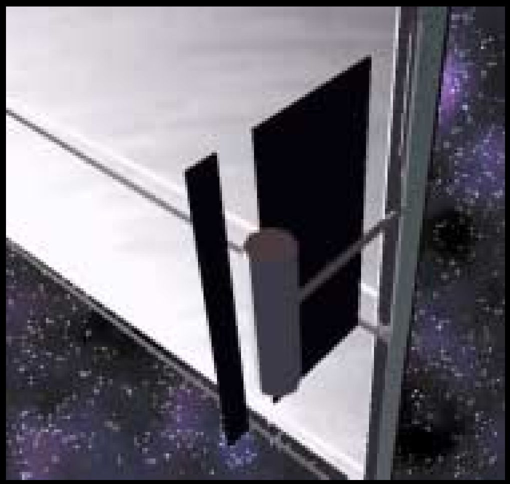
* "Imaging Planets about other stars with UMBRAS:  Target Acquisition and stationkeeping", H. Hart, SPIE 4087, p.993, 2000.

# Telescope-Occulter Control Block Diagram

*Focal plane imaging or aperture-plane null sensing both employ basic PID control system logic.*




- Telescope alignment sensor(s) measure null alignment.
- Null is solved for to determine occulter position.
- Error signal transmitted to occulter.
- Occulter adjusts position & velocity.



# 3. Operations

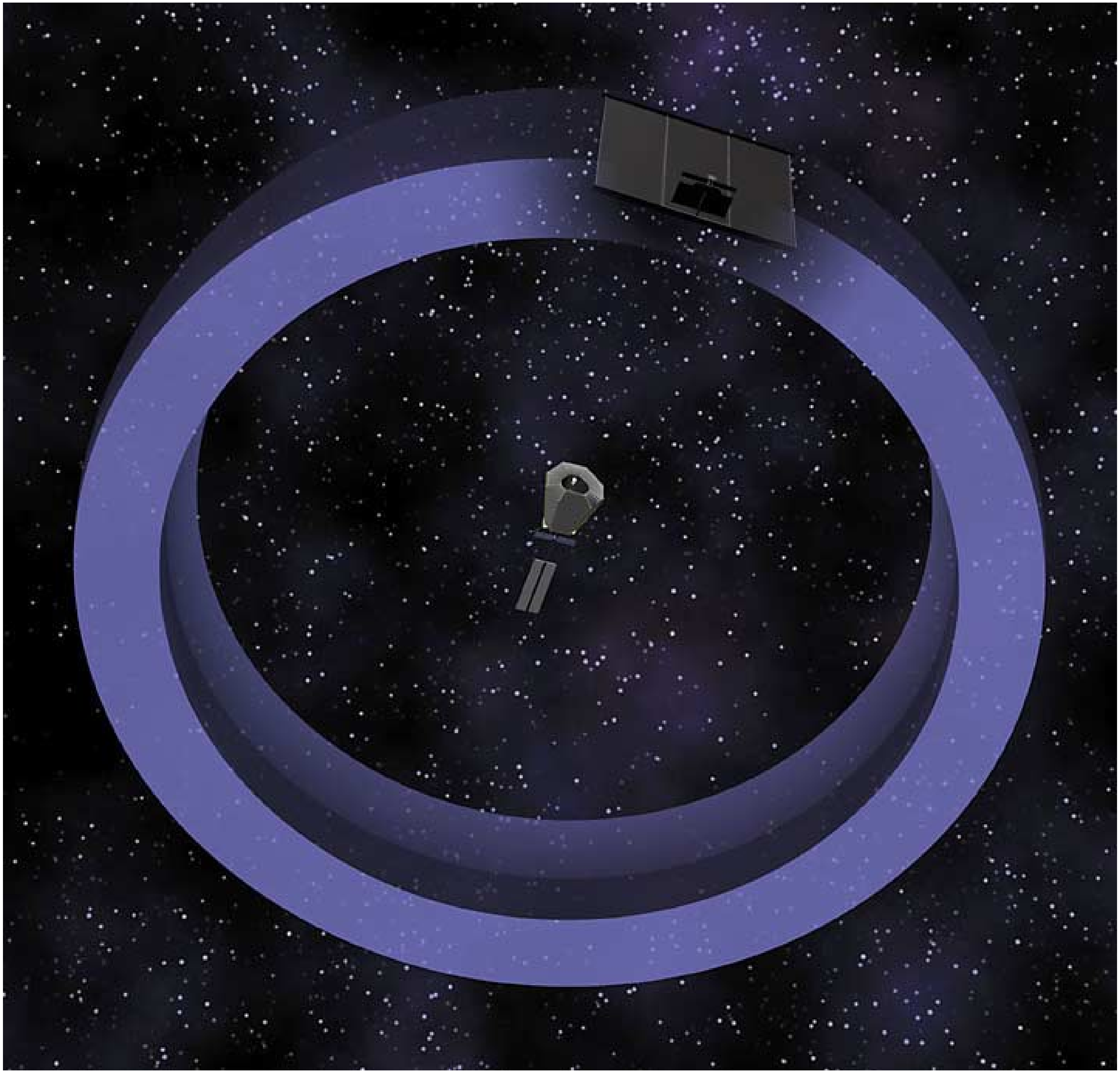
The early-2004 yardstick design for TPF-C has operating characteristics compatible with using an occulter.

Both observe or operate in the "quadrature ring" (a subset of the TPF-C field of regard, shown in the next slide). An occulter has natural solar- and anti-solar avoidance zones.

"Long" occulters may be tilted with respect to the line-of-sight to maintain appropriate shadowing and apparent screen size.

The TPF-C telescope autonomously controls occulter operations*.

* "External Occulter Operations Requirements", M. Kochte, et.al., Space Operations Conference, Montreal, May 2004



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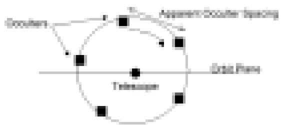
Occulters
Apparent Occulter Spacing
Orbit Plane
Telescope

# 4. Target Rates

A simple model of occulter operations jointly bounds an operations and design parameter trade space:

| | |
|---|---|
| $M_{init}$ | = initial mass of the occulter (kg). |
| $M_{final}$ | = mass of the occulter at given propellant depletion level (kg). |
| $I_{sp}$ | = propellant/propulsion specific impulse (seconds). |
| $F_{max}$ | = thrust level of main propulsion. |
| n | = number of target stars. |
| v | = number of visits per target star. |
| $T_s$ | = science time per target, per visit. |
| $T_{mission}$ | = duration over which targets and visits are observed. |
| z | = telescope-occulter separation. |
| ρ | = statistical model parameter to adjust for required target sky density (~1). |
| q | = statistical model parameter to adjust for preferred directions of occulter travel between targets (~ 0.3-0.5 for TPF-C). |

# How to meet TPF-C Minimum Goals

## 2 Years, 95% completeness, > 35 targets.

With 4 occulters, each vehicle can visit 9 targets, 6 times, in 2 years, and fuel to spare for an extended mission.

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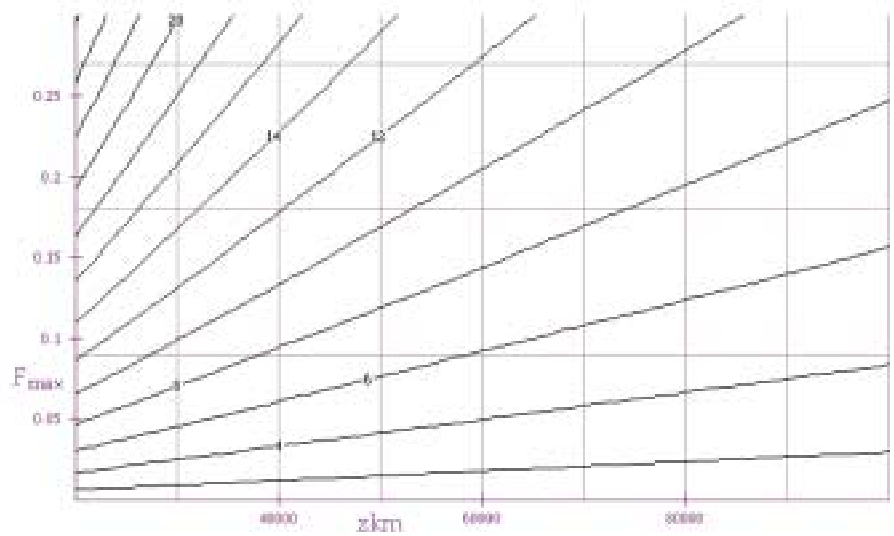
$$64\rho n^3 z^2 v^4 F_{\max}^2 = q \cdot M_{init}^2 \left[ \left( g \cdot I_{sp} \right) \cdot \ln\left( \frac{M_{init}}{M_{final}} \right) \right]^4$$

$$T_{\text{mission}} = n \cdot v \cdot \left( T_s + \sqrt{\frac{z \cdot M_{init}}{F_{\max}}} \sqrt{\frac{64\rho}{n \cdot q}} \right)$$

An operations model shows the trade between telescope-occulter mission characteristics.

Assuming 1350 kg occulters, numbers of distinct target stars each occulter can visit are plotted as a function of transit thrust (NSTAR 90mN) and telescope-occulter separation.

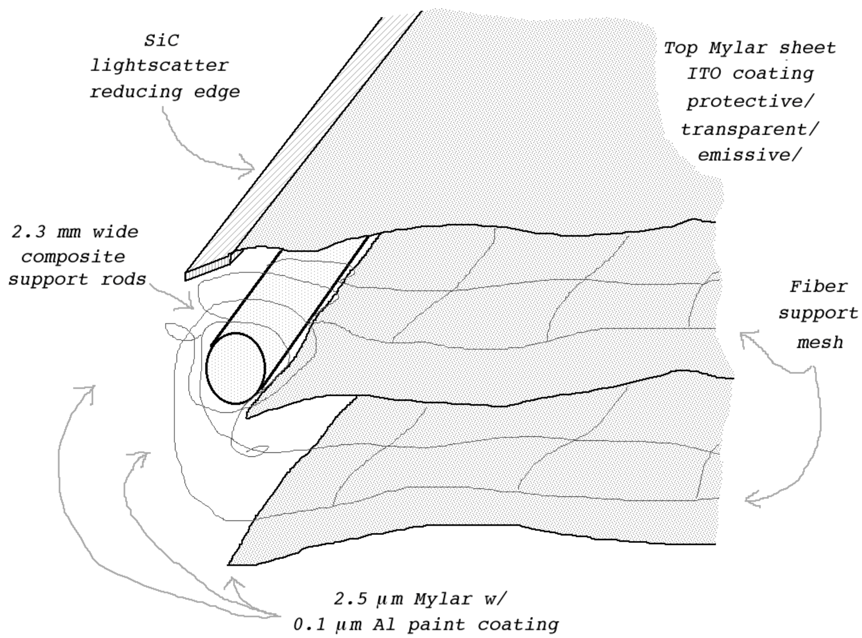


# 5. Occulter Design

Spacecraft designs integrated in with the occulting screen or discrete from it may be adapted for occulters operating with TPF-C. Their important characteristics are noted below.

- Multilayer thin-film screens
- Lightweight deployment structures
- Rolled or folding screens
- Sharp edge, sunlight-scatter abatement

# Simple Screen Multi-layer Design: Redundant & Robust




A screen design and its support structure using commercially available parts masses under a few tens of kilograms.

Fully opaque or apodized.

Roller-blind packaging for narrowest screens

Options to obtain the benefits of gradient transmission apodization appear viable.

# Matching a “Simple” Occulter with TPF-C

## Simple occulter: opaque, rectangular, “roller-blind”.

- Long axis of the TPF-C mirror “matches” the roller-blind’s greatest length. Occulter width (short axis) is sized adequate for fairing packaging.
- Screen permanently unwinds lengthwise to yield adequate field suppression in the “working direction” of TPF-C’s mirror.
- The occulting screen physically rolls about the line-of-sight to match TPF-C mirror orientation on a target star (roll matching).
- Apparent rectangular occulter shape: parallelogram (tilt to maintain sun shadow) allows use in significant fraction of the TPF-C field of regard--i.e., the quadrature ring.
- TPF-C aperture may be ringed with occulted starlight amplitude sensors (small photometers), or use an oversampled focal-plane imager.

# 6. Launchability

The strawman TPF-C fairing appears quite crowded and will become more so as TPF-C design progresses. Packaging occulters in that fairing is therefore not advised unless occupying a tiny fraction of the fairing.

Occulter designs with minimum deployment complexity are quite long. Since at least several occulters are required to meet TPF-C target observation rates, packaging designs which allow all to be placed in a single launch vehicle are desirable and not unrealistic.

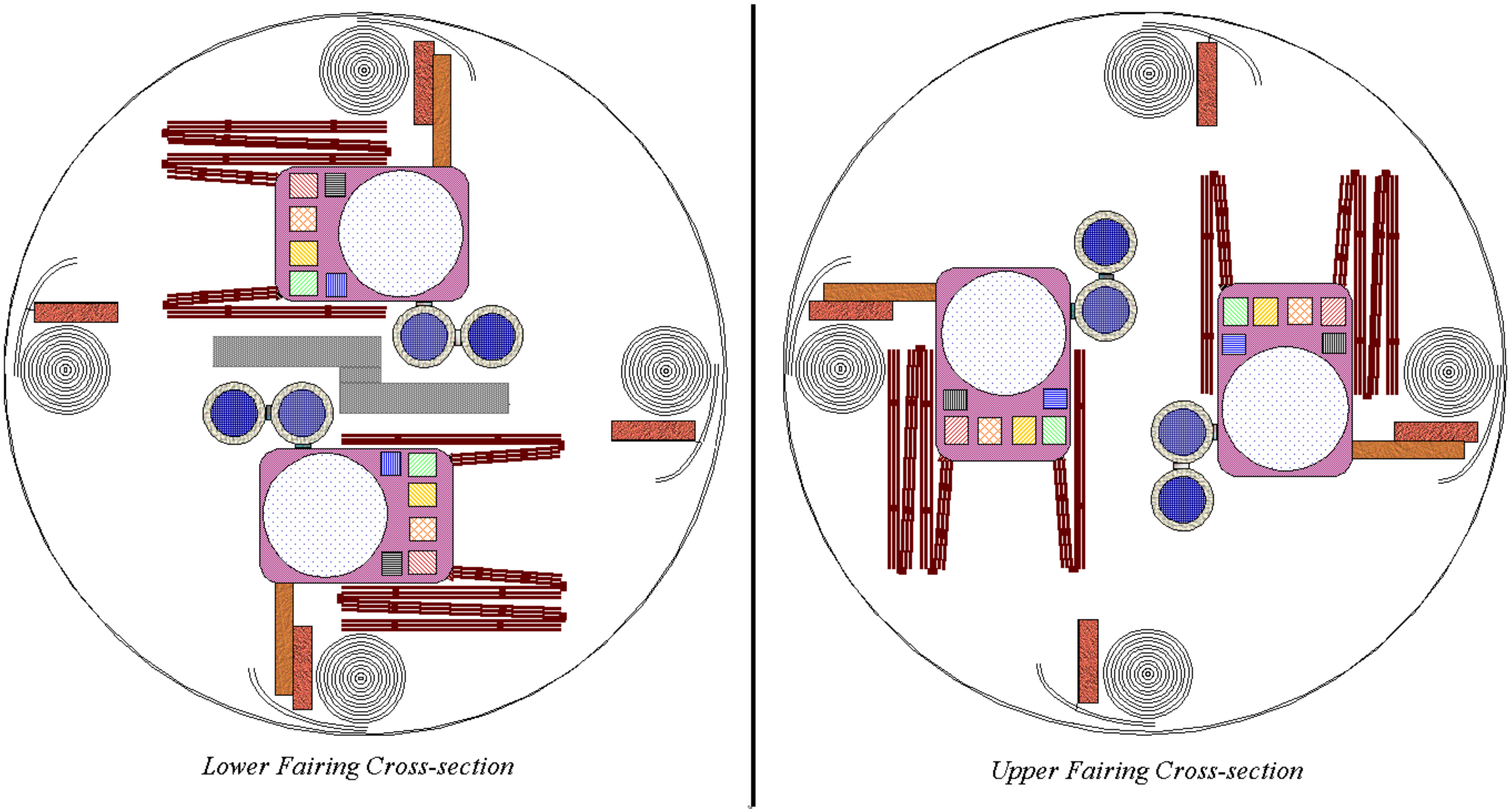
Four to six simple occulters can likely be put inside one launch vehicle. An example of a folding design follows.

These occulters are scaled and modified versions from a previous study*, however other designs are possible.

* Ref: AIAA-2000-5230 "Design of a Free Flying Occulter for Space Telescopes", Jordan, I., et.al.

# Four Occulters in a Fairing

*How to package 4 folded occulter spacecraft into 1 launch fairing*



*Lower Fairing Cross-section* *Upper Fairing Cross-section*

Delta IV H fairing. Six of these simple occulters can fit by altering SEP engine mounting and solar array hinging. Options for further shrinkage are possible.

# 7. Requirements on TPF-C

Need to ensure that requirements do not break *Beichman's Commandments*, if possible. Alternately, if they must be bent, the manner in which they do must be clear and well understood.

Biggest impacts on TPF-C observatory design:

- Alignment sensing system (numerous ~ 8" light buckets, or additional high-resolution camera/mode).
- Alignment data processing (enhanced memory & onboard image processing).
- Inter-spacecraft communications (low-gain is adequate).
- Software development allowing PID control of, and communications with, the occulter spacecraft.

## Critical Path Development Elements

Operating an occulter with TPF-C requires that specific studies be performed and technology adapted.

- Alignment sensing and control technique validation.
- Sensitivity studies of matched occulter-coronagraph/mask optical and science performance.
- Control software definition and development (real-time, automated feedback control, process alignment sensor data, attitude and translation control hardware).

# 8. Programmatic Considerations

Maturing the technologies for flying occulters with TPF-C is prudent from two standpoints:

- ***Underperformance Insurance***: If TPF-C's DM/coronagraph underperforms, the occulters may "buy back" lost performance and maintain the ability of the system to meet TPF-C's goals.

- ***Launch Date Insurance***: If the DM/Coronagraph nulling performance cannot converge on the TPF-C goals, launch will slip. Having occulters as an option may then boost TPF-C performance, restoring launch schedules.

# Presentation Summary

| *Section* | *Aspect* | *Resolution* |
|---|---|---|
| 1 | Science Utility: | Improves PSF and scattered light suppression; Extends λ-range and planet faintness detection limit. Insurance (under-performance recovery) |
| 2 | Alignment: | Telescope-Occulter only. Oversampled focal plane imaging or photometric aperture plane null sensing for at least simplest occulter. |
| 3 | Operations | Semi-autonomous occulter. Extension of normal TPF-C science operations. |
| 4 | Target Rates: | 4-6 SEP occulters match TPF-C goals. Simplest occulter design requires one additional launch to TPF-C's Delta IV H. |
| 5 | Occulter Design: | Range of architectures. Higher-lower complexity options, both make TPF-C better. Compatible with at least some coronagraph/mask designs. |
| 6 | Launchability: | 4+ simple occulters practical, although there are cleverer designs. At least simplest occulters appear feasible. |
| 7 | Requirements on TPF-C | Alignment sensing system; Low-band inter-s/c comm;. Must be able to participate in occulter alignment control. Autonomous alignment control software; several alignment sensor options. |
| 8 | Programmatic | Insurance (mission risk mitigation). Science formation flying testbed. |