Terrestrial Planet Finder Coronagraph

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ABSTRACT

This paper and oral presentation will describe the technology studies, the testbeds, and the architecture studies that will enhance the understanding and viability of a Terrestrial Planet Finder Coronagraph. Topics to be described fall in two categories: technology development and coronagraph mission design. The focus of the paper will be explanation of the tasks, their organization and current status.

Keywords: coronagraph, telescope, space, terrestrial planet finder

1. INTRODUCTION

1.1 Background

The Terrestrial Planet Finder Mission (TPF) is part of NASA's Origins Program – exploring answers to ancient questions: Where did we come from? Are we alone? Precursors to TPF, Space Infrared Telescope Facility and James Webb Space Telescope will be designed to observe the birth of galaxies and star systems. Using the data from these missions, TPF will peer one-by-one at nearby promising stars to search for planets much like our Earth that could harbor terrestrial-type life.

The survey has both a discovery and characterization component. TPF will image a ring around each star where habitable planets (those with liquid water) might occur. An earth-like planet will appear as a point of light, not resolved into planet geographical features. If a promising point of light is found, further observation will determine if planet-like characteristics such as orbit and mass are present. If a planet is found, it will be observed longer to determine whether it possesses an atmosphere using low-level spectroscopy. The resulting spectrum will be analyzed looking for biomarkers of life. Additional science will be added to the mission as opportunity permits, such as: studying giant planets and planetary atmospheres, and imaging active galactic nuclei and other high contrast celestial objects. International teams of scientists, astronomers, astro-physicists, and biologists have been working to define requirements for the primary mission.

There are two different types of instruments being studied by the terrestrial planet finder program: a coronagraph and an interferometer. Both instruments use the wave nature of light to reject light from the observed star then image on the very faint light from an orbiting planet. The Coronagraph will operate in the visible spectral range where the starlight will need to be suppressed to a level of 10^{-10}. The Interferometer will operate in the infra-red spectral range. TPF Interferometer architecture will be presented in more detail in the paper: System Design and Technology Development for the Terrestrial Planet Finder Infrared Interferometer by G. Blackwood et al and in further papers in this afternoon's session. The mission is extremely challenging – both instruments require development of new and different technology to enable the needed observations. In 2006, these two architectures will be compared and down-selected to carry the most promising technology forward into flight.

1.2 Coronagraph Theory

Coronagraphs were developed to study the corona of the sun on a regular basis. Starting in the mid 1800's, astronomers attempted to create artificial eclipses within telescope systems so that they would be able to study the sun's corona during times when the moon wasn't providing a total eclipse. It wasn't until the 1930s that the French astronomer B. Lyot recognized the causes of previous failures and was able to mitigate them. Lyot recognized that scattered light from the atmosphere and from surfaces within the telescope was preventing imaging of the corona. He started by building good quality optics with smooth, low scattering properties. He located his telescope on the top of a mountain where the atmospheric effects were minimized. He placed an occulting mask at the center of the first focus of the telescope to "eclipse" the sun, then handled the diffracted light scattered from the edges of the mask by collimating the downstream light, effectively performing a Fourier transform of the diffracted light, causing it to be located in a ring at the edge of the field. He blocked the ring of diffracted light with a baffle that both reduced the aperture diameter and absorbed the diffracted light. In the development of the TPF Coronagraph, we are still fighting the same devils – diffracted and scattered light. In order to image a small planet close to a star, we have to reduce light leakage by a factor of 100 billion (10^{10}) times.

2. TPF CORONAGRAPH ORGANIZATION

TPF has three task areas for work on this effort: coronagraph technology research, coronagraph mission design and coronagraph science working subgroup. The technology research area addresses new technology development and supports research, analysis, modeling, and testbed validation. The mission design is occurring through a design team that includes JPL, Industry and GSFC participants. The science working group supports all the efforts with coordination taking place through telecoms, science working group meetings and technical interchange meetings. This paper will address work done in the first two areas. The formal organization chart covering this work is shown in Figure 1.

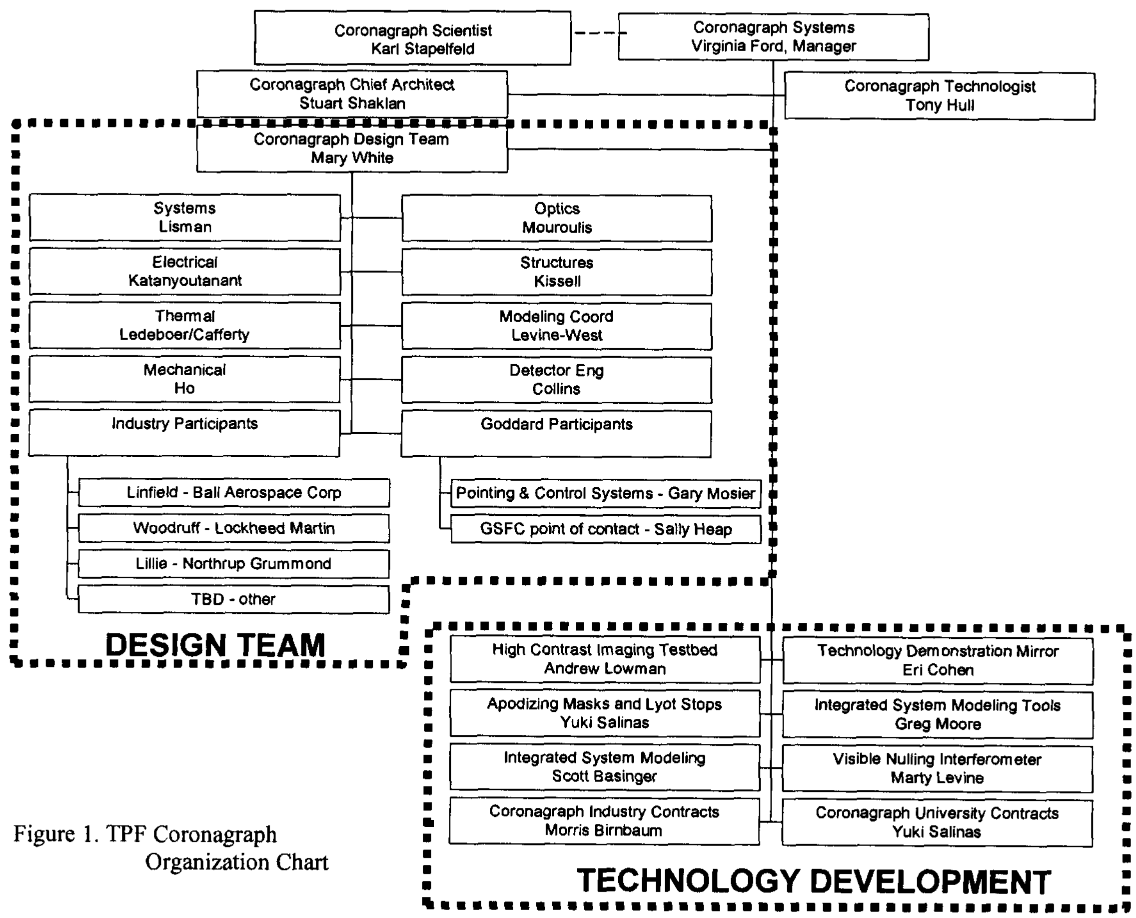


Figure 1. TPF Coronagraph Organization Chart

2.1 Technology Research and Development

Our challenge is to eliminate(a) stray light caused by system phase and amplitude errors, and external light sources; (b) diffracted light; and (c) leakage caused by the breadth of the wavelength range and resulting polarization and phase changes within the system. Technology development is organized into six areas –

each area addresses aspects of the challenge. They are: 1) fabrication of a demonstration mirror that provides pathfinding to light-weight mirror fabrication techniques and coatings, and establishes the state-of-the-art in fabrication of large, off-axis, low-scatter mirrors; 2) development of a testbed for testing contrast and wavefront sensing and control including algorithm development and development of a deformable mirror that will correct errors in wavefront thoughout the system; 3) analysis and fabrication of masks and stops; 4) system modeling to correlate testbed performance, predicted performance, and integrate the system effects if on orbit and development of an integrated modeling tool that will provide the precision needed as well and the end-to-end system performance; 5) development of a visible nulling testbed to develop an alternative architecture to masks and stops; 6) contracts for hardware, theory, and analysis from industry and universities.

2.1.1 Technology Demonstration Mirror (TDM)

The primary mirror will be an elliptically shaped off-axis parabola ranging from 6 to 10 meters major axis by 3.5 to 4.5 meters minor axis. The requirements for the TPF coronagraph primary mirror are unusual in that surface quality is specified in terms of error values specific to relevant spatial frequencies. When the spatial frequency of surface figure deviations is one-to-two cycles per aperture, stray starlight from the deviations will fall within the Airy disk of the star. As the spatial frequency decreases, the stray starlight will fall within the zone where terrestrial planets are expected. In this range, the allowed errors must be tightly controlled. The Technology Demonstration Mirror (TDM) has a diameter, 1.8 meters, selected to represent the lowest spatial frequency of interest. Fabrication of the TDM will demonstrate whether state-of-the-art technology can meet these requirements. Within the defined spatial frequency range, the surface error must be very low – between 1 and 5 nm RMS. This tight requirement has resulted in the selection of ULE as the substrate material.

It is important that this mirror be monolithic. Since edges cause diffraction, the scattered light from a segmented mirror would overwhelm a planet, or complicate the mask design with accompanying loss of light. Edge blocking structures would create their own diffraction scatter and simply complicate the problem. The monolithic mirror size fitting within a launch vehicle shroud is currently one of the limits for sizing the coronagraph telescope.

Kodak has just received the contract to fabricate this mirror. The contract includes formation of the mirror blank, grinding, polishing, testing, coating and supporting the mirror. Kodak will be performing coating tests to help characterize polarization, phase and wavelength relationships as well as coating uniformity in preparation for the final coating design and application. Figure 2 shows the mirror concept with the front face sheet removed. The delivery of the mirror is planned for in 2006.

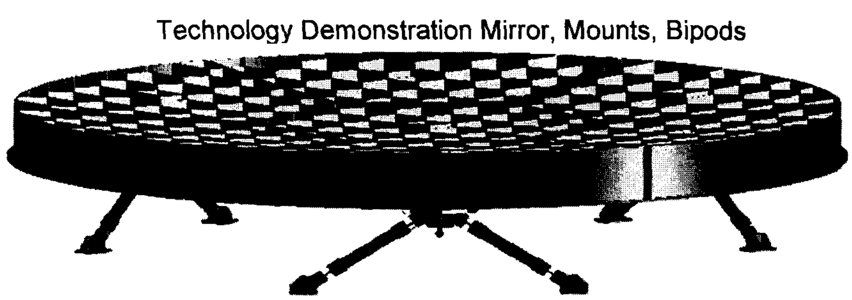


Figure 2. Technology Demonstration Mirror (front facesheet removed)

2.1.2 High Contrast Imaging Testbed (HCIT)

The heart of the coronagraph system is the coronagraph sensor assembly where the starlight is suppressed, the wavefront is sensed and controlled, and the focal plane is imaged and detected. The High Contrast Imaging Testbed is a real-environment exploration of the methods and hardware that will perform these functions. Masks and stops designs, optical designs, and wavefront sensing concepts are all included in a variety of theories on what will work best. The HCIT provides a facility to put concept to test. The current configuration is shown in Figure 3. The testbed layout is flexible so that alternate concepts can be tried - guest testing will be available. The testbed is installed in a vacuum chamber and has been measured to have milli-kelvin thermal stability and wavefront stability to within Angstroms. A new deformable mirror with 1024 actuators is scheduled to be installed this month. With a flat mirror in the place of the deformable mirror and a Lyot mask and stop installed, a contrast of $2*10^{-6}$ has been reached. This contrast involves no wavefront sensing and control, so significant improvement is expected when the new deformable mirror is installed.

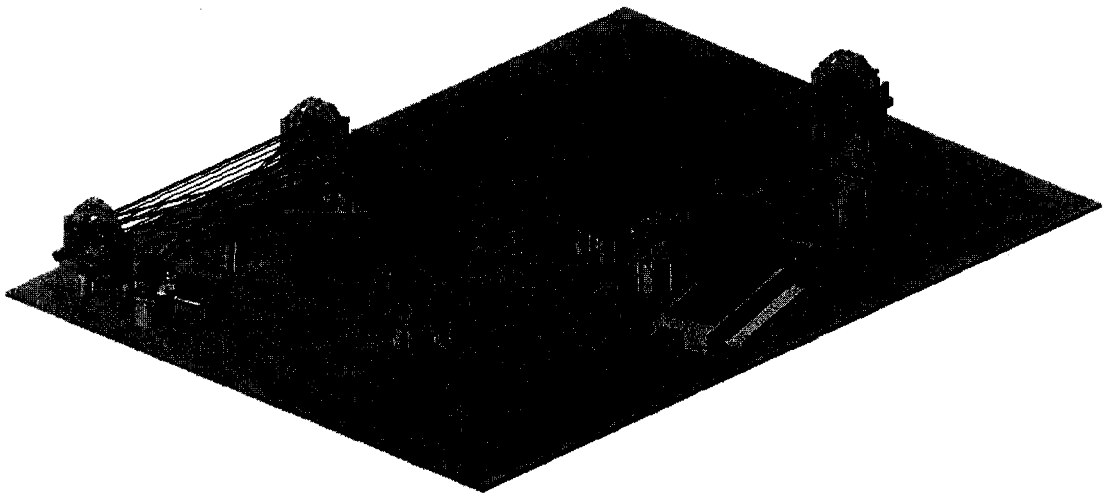
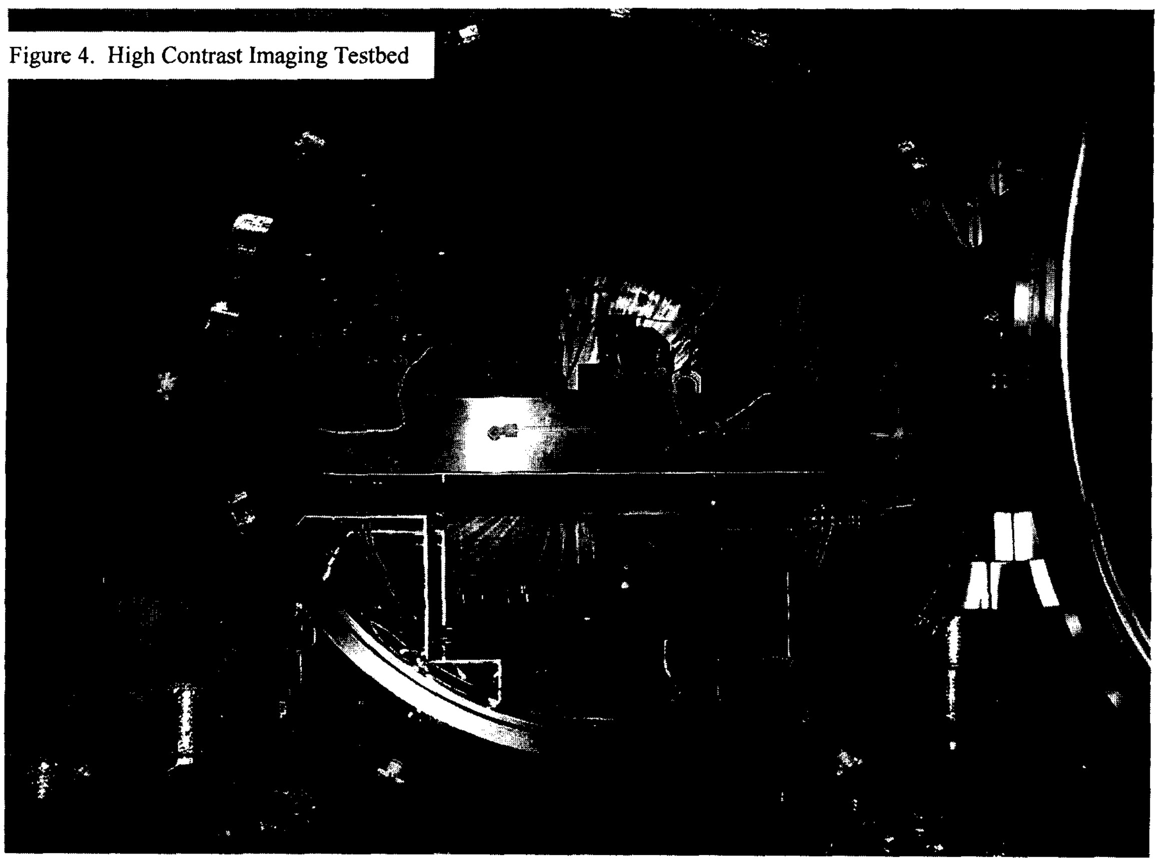


Figure 3. The High Contrast Imaging Testbed optical design

In September, a larger deformable mirror with 4096 actuators will be delivered by Xinetics. This should bring the testbed performance closer to the goal of 10^{-10} contrast. Further improvements in wavefront sensing and control methods and algorithms as well as further testing of alternate masks and stops are expected to bring the test bed to its performance goal.

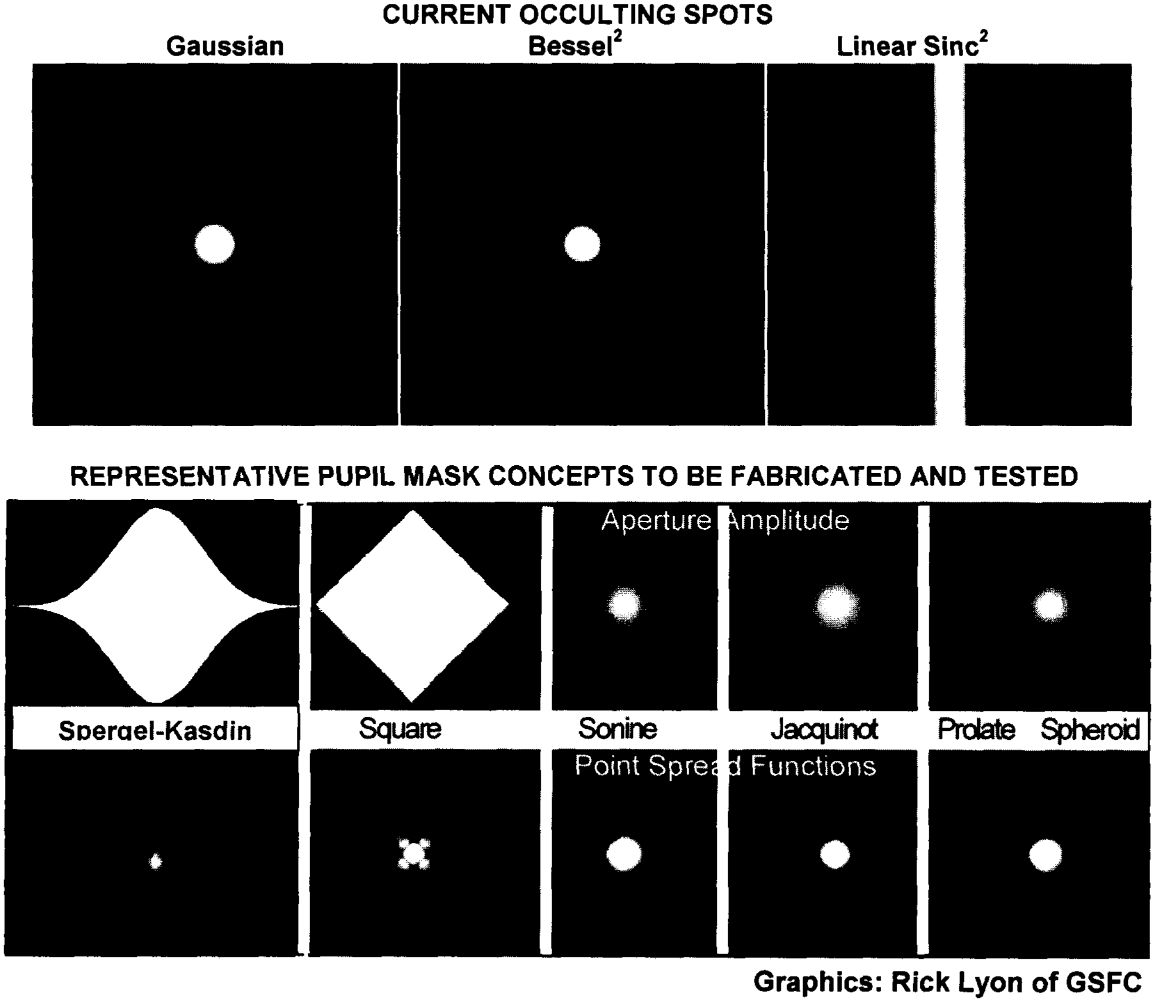
Figure 4. High Contrast Imaging Testbed



2.1.3 Research in Masks and Stops

We are concerned with three areas of masks and stops development: theory, analysis, and fabrication. Development of theories of mask and stop forms, locations and combinations that improve scattered light control and enhance coronagraph system performance is essential to achieving the final contrast goal of 10^{-10}. The range of apodizing masks shown below in Figure 4 have been evaluated theoretically with resulting predictions comparing their performance. Additional theories have been proposed that have yet to be evaluated. TPF continues to fund studies – primarily in the university arena, but also in industry and JPL/NASA – to evaluate and compare mask types as well as to fabricate and test. Several papers in this SPIE Proceedings will address Masks and Stops

Figure 4. Some Forms of Masks



In addition to performance analysis, analysis and understanding of material-related effects, diffraction effects, and substrate interaction with the passing wave front have also been pursued and will continue to be funded. Dan Hoppe and Tom Cwik have been modeling electro-magnetic wave propagation through binary masks. Though the models aren't complete, they have been predicting important performance related to material interactions and tolerances.

Fabrication of devices is the final challenge. Throughout the past year, high quality devices have been fabricated using electron beam and HEBS glass. Sputtering and deposition techniques have been tried with no success so far, though efforts are continuing. Measurement of devices that have been built has begun. A mask metrology testbed being developed will measure optical density and wave front phase and amplitude effects in the x-y plane. A future challenge to mask designers will be to optimize mask efficiency in the context of realistic manufacturing errors and electromagnetic effects.

2.1.4 Modeling Efforts

The TPF Coronagraph will rely heavily on modeling and analyses throughout its mission lifecycle, and as such the methods by which models are developed, validated, and implemented are a key task for the project. Current modeling activities can be separated into 3 broad areas: predictions of on-orbit performance, analytical tool development in support of specific Coronagraph needs, and verification and validation of the analyses.

The first task includes system modeling activities such as: a) the development of performance models that flow down requirements from the science to sub-system levels; b) the mechanical CAD models that ensure the overall design is compatible with launch and flight configurations; c) the thermo-mechanical-control-optical integrated models which use detailed engineering models to simulate the end-to-end contrast performance of the instrument from thermal/jitter environmental disturbances and which verify the requirements defined by the performance models; d) the science models which propagate the wave-front error through the optical system and controlled deformable mirror to predict contrast and ultimately science capability; e) straylight models; and f) launch and orbit trade models.

Analytical tool developments include: a) diffraction modeling capabilities that can accurately predict contrast to orders of -10 or better using the JPL tools MACOS [Ref. 1] and SPICA [Ref. 2]; b) optical error modeling tools and processes that establish sensitivities between optical perturbations and contrast; and c) fully integrated modeling tools which can simulate under a single computational code the thermal, mechanical, control and optical performance of the flight system. This last task includes a completely upgraded IMOS [Ref. 3] with embedded thermal radiation and conduction capabilities, a NASTRAN native input format for the model description, scalability to very large problems with very efficient numerics, seamless interface to optical analysis codes, and eventually full end-to-end sensitivity and optimization capabilities.

In terms of verification and validation activities, the modeling process and approach for integrated analysis and optical error modeling are being validated on a representative test case basis. Accuracy of the analytical diffraction predictions is verified through a variety of ways. First through verification of 1-D propagation problems for which there are derivable solutions. Then through comparison of results from a baseline problem generated using several codes, including SPICA and MACOS, and possibly a commercial diffraction code. Finally the HCIT will be modeled and analytical contrast predictions will be compared to the actual testbed measurements. In parallel, a performance model is being developed for the HCIT in a manner identical to the Coronagraph flight performance model, and verification of the HCIT performance prediction will then serve as a validation of the performance modeling capability for the flight system.

2.1.5 The Visible Nulling Testbed

An additional method of starlight suppression is being studied. A test bed has been developed using visible light and interferometric techniques to create a null over a star enabling imaging of orbiting planets. The testbed has been creating nulls in air using closed-loop control. It is being moved into a vacuum chamber. Later in this SPIE Proceedings, the paper Planet detection in visible light with a single-aperture telescope and nulling coronagraph, M. Shao et al will describe this device more thoroughly.

2.1.6 Industry and University Contracts

TPF has recently announced the proposals selected for funding that responded to a solicitation primarily to educational organizations related to all the six technology topics listed above. An RFP for studies leading to fabrication and delivery of a telescope front end attachment to the High Contrast Imaging Testbed will soon be released. This hardware will simulate the TPF Coronagraph telescope, thus completing the suite of experiment capabilities that will allow full coronagraphic on orbit performance evaluation. Shortly following this, an RFP will be released to solicit proposals for industry studies primarily in the areas of mask and stop research and wave front sensing and control. These contracts, along with the TDM contract and deformable mirror contract, allow the community to be involved and contribute to solutions for the technical challenges facing the TPF Coronagraph system. Additional solicitations will be initiated as the project progresses.

3. TPF CORONAGRAPH DESIGN TEAM

The design team is responsible to create a configuration of the TPF coronagraph mission, to analyse it, and to make systems trades and eventually estimate the mission cost. The connection between the technology area and the design team is a performance model developed by the architecture team led. As of now, the coronagraph sensor assembly is still undefined: final technology choices are yet to be evaluated. The technology efforts will be clarifying this hardware as experiments continue. The coronagraph sensor assembly, or the optical path aft of the telescope, can be considered to be simulated by the current configuration of the HCIT – which has a flexible configuration to test many theoretical approaches. The design team treats this as a black box, but the architecture group is using the HCIT as a strawman. The model is flexible and compares performance of different architectures. The comparisons drive design team choices, but primarily in the areas outside of the coronagraph sensor assembly.

3.1 Coronagraph Performance Model

The TPF telescope and coronagraph system are required to work at unprecedented levels of image quality and stability. Virtually every aspect of the design pushes the state-of-the-art, including the ability to model the system and predict its performance. We are in the process of developing a performance model that will allow prediction of scattered light levels at any point in the field for a variety of coronagraph and telescope designs.

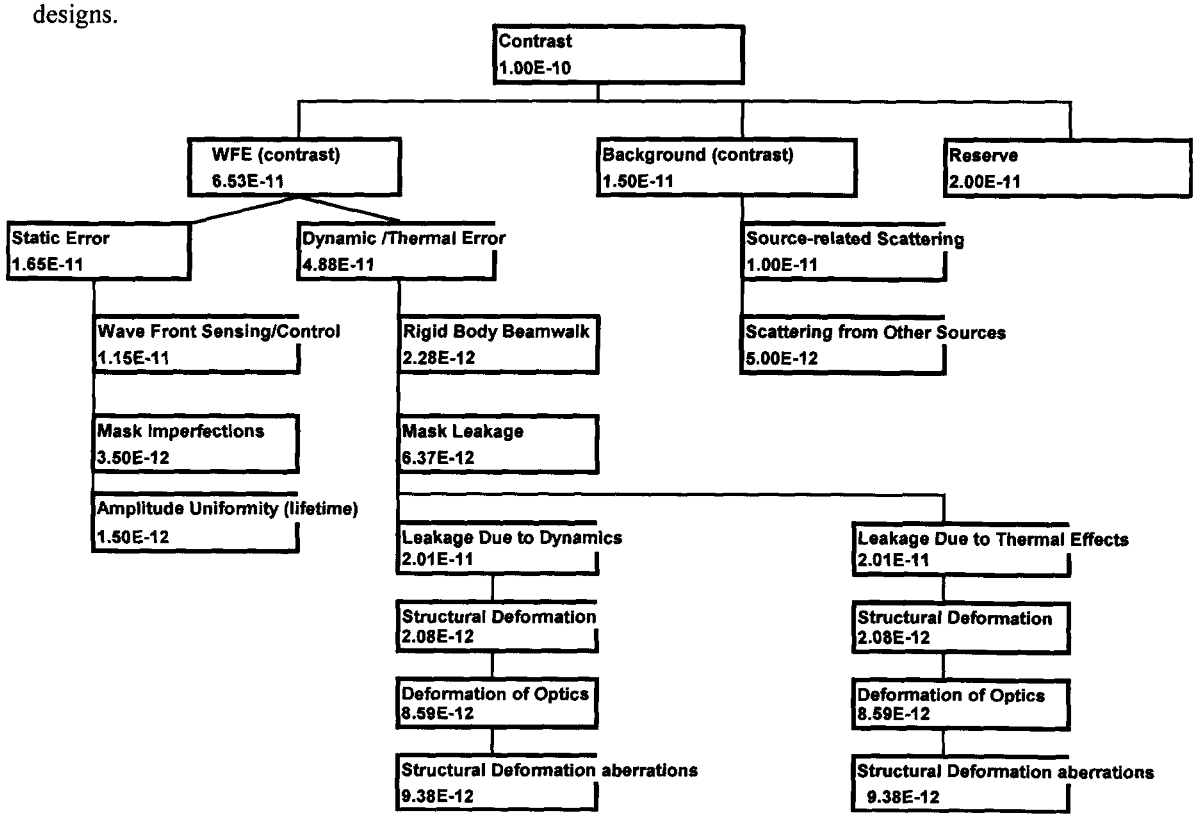


Figure 5. TPF error tree for 3lambda/D. Boxes are described in the accompanying text.

The performance model is a spreadsheet that ties together the analytical and computational physics models, laboratory-results, and dynamics models. A general overview of these models is given in Section 2.1.4. The contrast requirement is 10^{-10} over the spatially-controlled region of the image plane (roughly 100 Airy rings wide). The contrast is the sum of scatter from the controlled portion of the complex wave front, stray light, and a reserve term. Note that because contrast refers to the intensity of the stray light, contrast terms add linearly rather than as a root-sum-square behavior associated with uncorrelated effects. Because the contrast adds linearly, the budget for the various contrast contributors, even at the high level shown here, is typically below 10^{-11}.

The controlled portion of the system is divided into two parts, static and dynamic. At the present time, static terms are assumed to have a white power spectrum over the controllable spatial bandpass. For wave front sensing and control, this is supported by laboratory repeatability results for up to 15 cycles/aperture (ref: Green). Contrast loss due to mask shape imperfections and amplitude non-uniformities is also assumed to be white because we presently have no good models for these terms. The levels allocated are equivalent to the scatter from a white 0.2 Angstrom wave front (for λ=700 nm) over the spatial bandpass. The stray light background is also white, in this case because the scattering effects are mainly due to single scatter events from particles with diameters << the diameter of the optical beam. The stray light level is consistent with the primary and secondary mirrors having BRDF = 10 at zero scatter angle, and the small downstream optics having BRDF = 0.2 for zero angle. This is conservative estimate in that it assumes all the scattered light is incoherent. In fact, most of the single-scatter light will be forward-scattered light that will be indistinguishable from the nominal wave front. Therefore we expect to relax the BRDF requirements once we have studied the wave front control aspect in more detail.

The dynamic terms represent the leakage that occurs when the system is perturbed from its nominal state with controlled wave front. Figure 5 shows that dynamic terms are expressed as either beam-walk or Zernike polynomials. The beam walk terms represent the leakage that occurs when thermal and mechanical perturbations cause the optical beam to walk across imperfectly-manufactured optics. The optics are assumed to have spatial power spectra that are flat at low frequencies and follow an f^{-3} law at higher frequencies. Beam walk equations (Noecker) essentially filter the power spectra by the motions derived from the integrated structural/thermal/optical model (ref: IMOS) and are evaluated at spatial frequencies corresponding to a given position in the image plane.

Zernike polynomials are used to represent the change in the wave front that occurs with both rigid body motions of the individual elements as well as deformations of the elements, e.g. bending of the primary mirror. In a separate paper at this Conference, Green and Shaklan describe the Fourier plane model that is used to compute the leakage of low-order Zernike terms through various coronagraph designs. This model forms the 'Diffraction aberration sensitivity' model in Figure 5.

The beam-walk and wave front sensitivity models allow us to derive requirements on the position and shape stability of the elements in the system. The integrated models are used to convert these to perturbation requirements and to identify those parts of the coronagraph that are most troublesome.
It is worth noting that our performance model does not rely on a near-field diffraction model. Near-field diffraction results in both phase and amplitude ringing across the optics. These are treated as static terms that are corrected by the wave front control system.

3.2 Design Team Results

The goal of the design team has been to understand the mission requirements and to select a configuration that would enable meeting those requirements. New technologies either developed or being developed by other projects are being used, such as: the deployable sun shade concept adopted by James Webb Space Telescope; the metrology devices developed by Space Interferometer Mission; and some of the spacecraft isolation schemes developed by industry for James Webb Space Telescope.

The design team is chartered to develop designs for a Minimum TPF mission and a Full TPF mission, with the difference primarily being the number of stars that can be searched and the spectral range for characterization detected planets. The most important requirements are stated in Table 1.

Key Parameter	Full TPF	Minimum TPF
Number of Stars Visited	150	30
Spectral Range	0.3 to 1.1 μm	0.5 – 1.0 μm
Angular Resolution at $\lambda = 0.5$ μm	10 mas	30 mas
Inner Working Distance	30 mas	63 mas
Outer Working Distance	2000 mas	1000 mas
Contrast	10^{-10}	10^{-10}
Stability timescale	4 sec	10 sec

Table 1: Science requirement flow down to TPF design teams (mas = mille arcsec)

Currently the design team has selected one strawman design for development. Alternative designs will follow. The requirements that are used to drive the design will be reviewed by the TPF Science Working Subgroup for the Coronagraph on August 12 – 13, 2003.

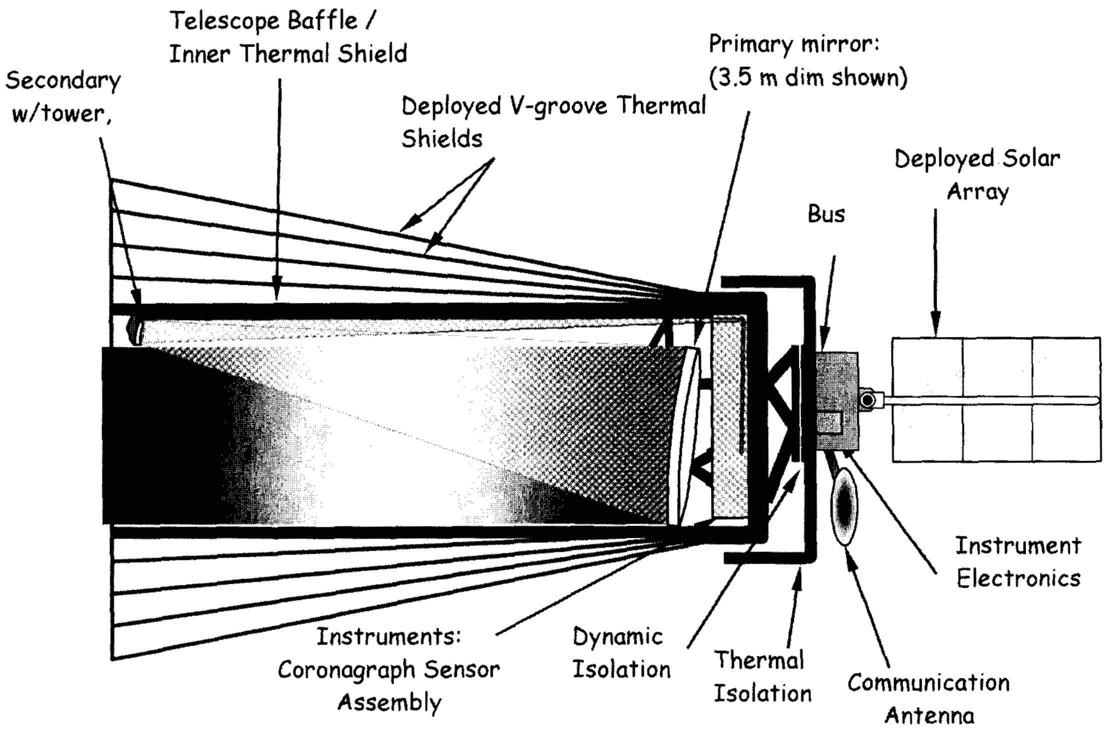
3.2.1 Strawman Observatory Description

Figure 6 shows a schematic of the design concept. The coronagraph observatory will view stars in the hemisphere away from our sun, with frequent revisits to attempt to find a planet that may have been poorly placed in orbital phase. While the observatory is viewing a star, it will roll incrementally around its viewing axis to position the long axis of the primary mirror at a series of orientations to the star. The long axis has higher resolution, thus will detect a planet aligned to this axis most easily. The roll may also be used for mapping and removing residual speckles of diffracted light in the image plane. Due to these maneuvers, the telescope must be protected from thermal transients caused by the changing sunlight view factors. Two types of sunshade configurations were considered: a flat shade configuration; and a conic shade configuration that would cocoon the telescope. The cocoon-type shade was selected because it did not require a gimballing system to move the observatory relative to the stationary sun shade. Instead, the shade will move along with the observatory, with the reaction wheels on the spacecraft controlling the motion. The flat sunshade option will be revisited if necessary. Both shades use a v-groove configuration to minimize heat from the sunlight. The v-groove layers are specular and work on the principle that infrared radiation from heating will reflect out of the radiator because the groove geometry forces only outward reflections. This system will maintain the inner layers at a steady, cool temperature, no matter what the orientation with respect to the sun.

The optical path enters the telescope baffle and reflects off the 6m x 3.5m off-axis parabolic primary mirror. The light is imaged before it reaches the secondary mirror, then reflects off the secondary towards a fold mirror that directs the beam into the coronagraph sensor assembly.

The primary mirror is mounted kinematically with a hexapod to an aft metering structure (AMS). The secondary mirror is mounted on a 10 meter long boom that also mounts to the aft metering structure. The secondary mirror mount will be a hexapod system with actuators on each strut for six degrees of freedom solid body adjustment. The coronagraph sensor assembly also will mount kinematically to the aft metering structure.

Figure 6. TPF Coronagraph observatory schematic



The aft metering structure and the sensor assembly will be wrapped in thermal blanketing to shield it from the spacecraft components. It will mount to the spacecraft though a kinematic hexapod. Thermal isolation will be incorporated in the design of the hexapod, as well as dynamic isolation to prevent propagation of vibrations from the spacecraft to the observatory. An additional layer of thermal shielding will be provided on the spacecraft side of the hexapod to protect it from thermal perturbations.

Stray light suppression will be necessary to meet the requirements for planet detection. For now, it is assumed by that light from the Sun, earth and moon cannot be allowed to enter the opening of the telescope. The current baseline orbit is at L2. In order to eliminate the Sun, the greatest possible sky coverage at any time is 2π steradians. For the elimination of the earth and moon light, there will also be a further reduction in the instantaneous sky coverage to about $1.5\ \pi$ steradians.

The spacecraft will contain its own housekeeping electronics as well as all the instrument electronics. It will also provide a mounting platform for the communications antenna and the solar array.

Figures 7, 8, and 9 show the current solid model configuration of the observatory deployed with v-groove radiator assembly.

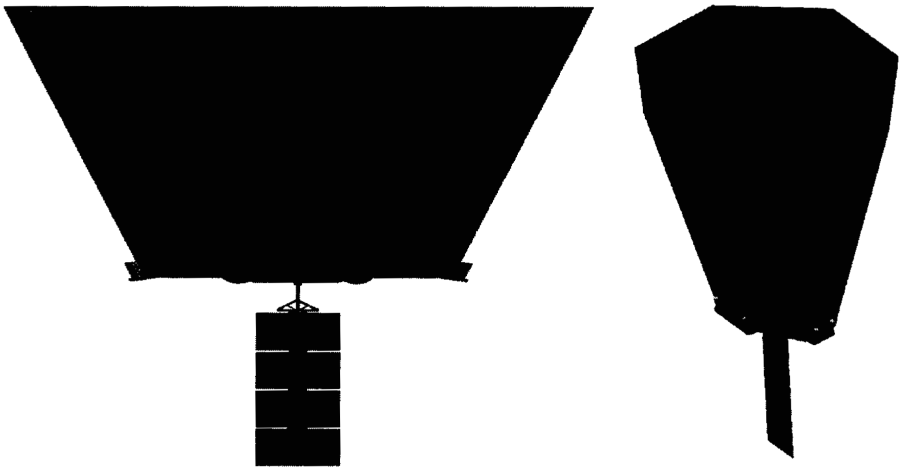


Figure 8. The partially deployed observatory – v-groove radiator removed, radiator support structures and secondary mirror tower are deployed.

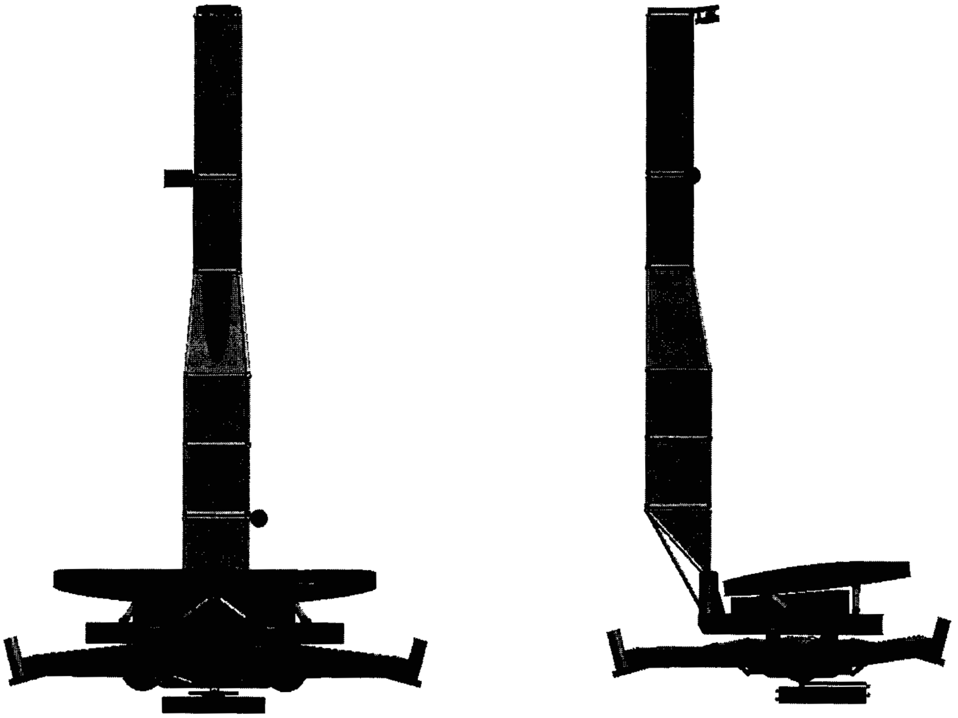


Figure 9. Sequence of stowage in launch vehicles – DeltaIV Heavy

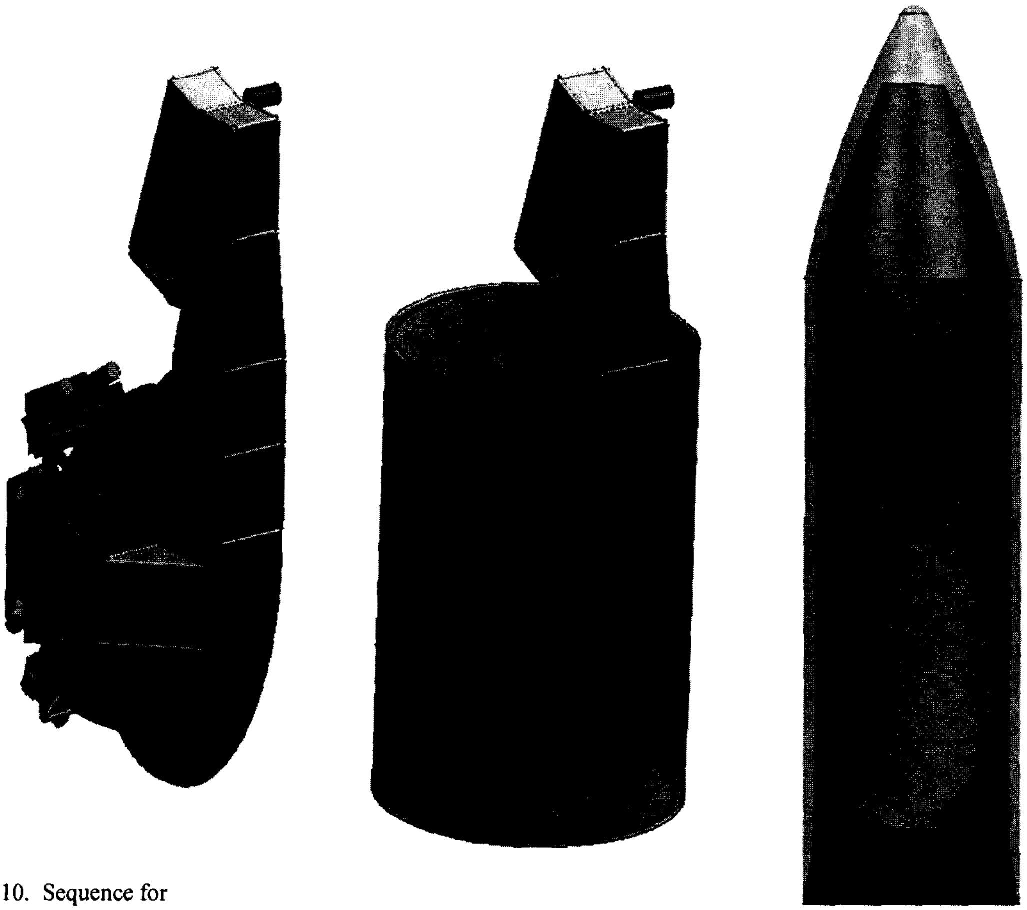


Figure 10. Sequence for stowing in launch shroud

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