The Terrestrial Planet Finder Coronagraph: technology and mission design studies

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ABSTRACT

The Terrestrial Planet Finder (TPF) Coronagraph study involves exploring the technologies that enable a coronagraph-style instrument to image and characterize earth-like planets orbiting nearby stars. Test beds have been developed to demonstrate the emerging technologies needed for this effort and an architecture study has resulted in designs of a facility that will provide the environment needed for the technology to function in this role. A broad community of participants is involved in this work through studies, analyses, fabrication of components, and participation in the design effort. The scope of activities – both on the technology side and on the architecture study side - will be presented in this paper. The status and the future plans of the activities will be reviewed.

1. INTRODUCTION

1.1 Background

In 2002, four companies participated in a study of instrument concepts for terrestrial planet finding. As a result of this study, a coronagraph instrument was included in NASA's Origins Program to evaluate possible methods to image and characterize planets orbiting nearby stars. The Origins Program includes precursors to TPF, Space Infrared Telescope Facility and James Webb Space Telescope which will 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.

TPF has a discovery and characterization component. TPF will examine a zone around each star called the habitable zone - where liquid water might occur. If an earth-like planet is found, it will appear as a blurry 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.

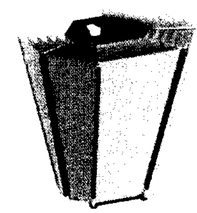


Figure 1. TPF Coronagraph

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 TPF Coronagraph will operate in the visible spectral range from 500 to 800 nanometers with a goal of observing up to 1050 nanometers. In this wavelength range, planets will appear fainter than the star that they orbit by a magnitude of 10^{-10}. The Interferometer will operate in the infra-red spectral range. The mission is extremely challenging – both instruments require development of new and different technology to enable the needed observations. If these technologies are demonstrated, then the TPF Coronagraph will plan for launch in 2014 and the TPF Interferometer will plan to launch around 2016 in concert with the ESA Darwin mission.

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. Lyot placed an occulting mask at the center of the first focus of the telescope to "eclipse" the sun. The downstream light was then collimated, effectively performing a Fourier transform of the light that was diffracted around the occulting mask, 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. The un-diffracted light from objects that are not blocked by the occulting mask pass through the aperture diameter. In the development of the TPF Coronagraph, we are still fighting the same devils – diffracted and scattered light. In addition, in order to image a small planet close to a star, we have to reduce light leakage from the star by a factor of 100 billion (10^{10}) times at angles close to the star. Development of new technologies is required to achieve this level of performance. A schematic of the coronagraph system being tested for TPF is shown in Figure 2.

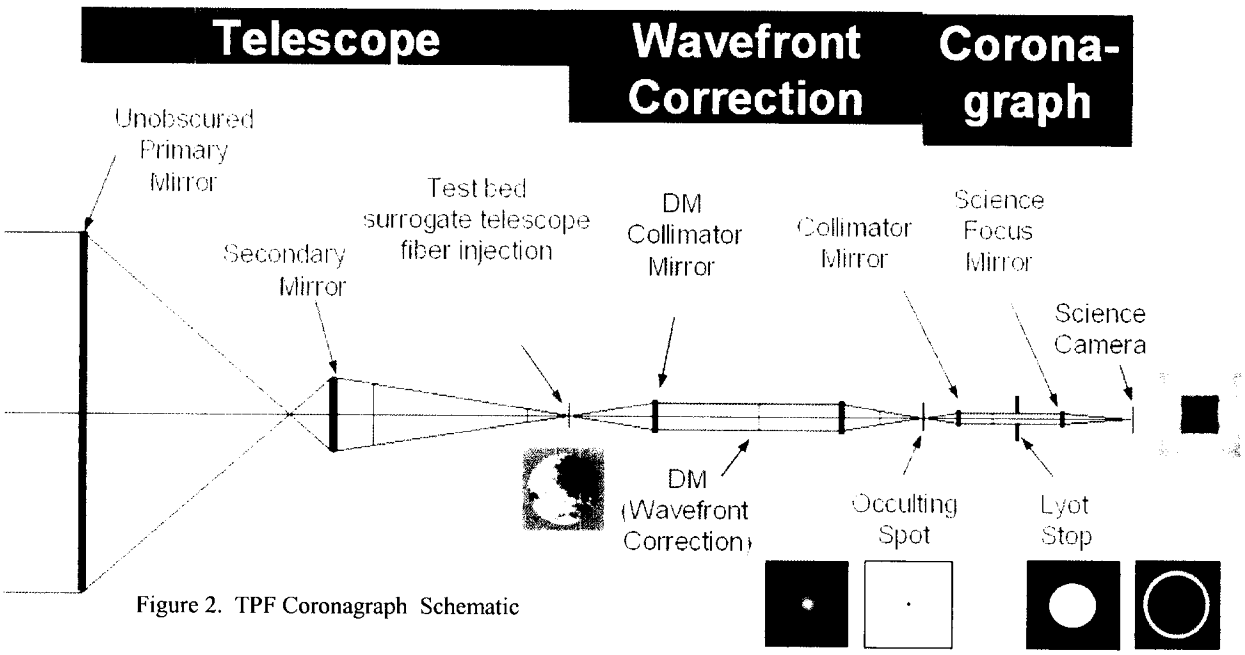


Figure 2. TPF Coronagraph Schematic

2. NEW TECHNOLOGY DEVELOPMENT

A suite of new technologies are needed to enable the TPF Coronagraph to extinguish the light from a star to levels required to detect terrestrial-type planets orbiting that star in its habitable zone.

2.1 Scattered Light Management

Several efforts are underway to understand, model, analyze, and fabricate devices that enable us to control diffraction, polarization and other sources of scattered light so that we will succeed in rejecting the light from the central star adequately. These efforts are taking place at locations all over the United States in a coordinated effort.

2.1.1 Masks and Stops

A variety of styles and applications of masks and stops is being studied. The electro-magnetic effect on wavefront of different mask forms and materials is being analyzed to understand what will perform best in a coronagraph telescope that is as ambitious as TPF. Performance parameters that are being analyzed for each mask type are: pattern of diffractive light scattering, light transmission throughput, polarization effects and effect on telescope system tolerances. UC Berkeley, Ball Aerospace Corporation and Princeton University are involved in analysis of mask performance parameters. The performance results help guide requirements for design and fabrication of new styles of masks for testing. HEBS glass masks have been successfully fabricated, measured, and tested. Figure 3 shows a mask design and analysis that is used to guide the selection of mask fabrication choices. New fabrication techniques for pupil plane and binary focal plane masks are being developed. Princeton University is leading an effort to fabricate and test pupil plane masks. A metrology test set is being developed to measure geometric characteristics of fabricated masks as well as the phase and amplitude affect the devices produce on a passing wavefront.

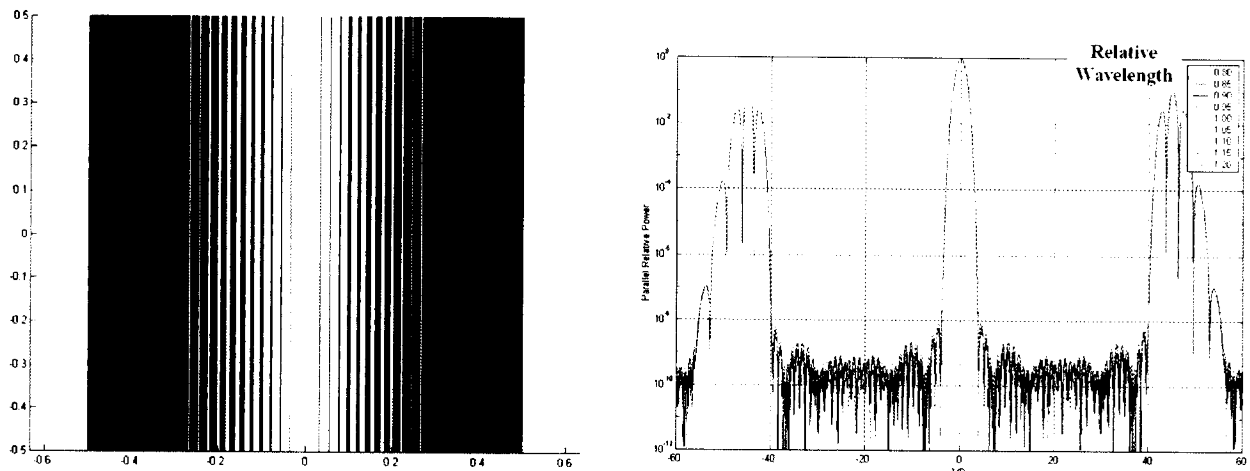
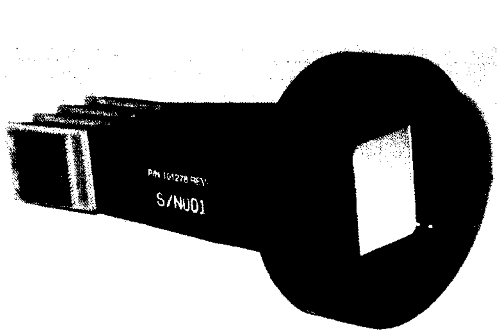


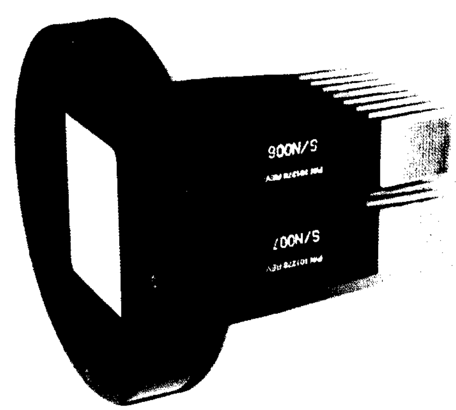
Figure 3. Two-dimensional binary mask design and analysis of contrast showing wavelength effect

2.1.2 Wavefront Control

Imperfections, strains and thermal gradients on telescope mirror surfaces will scatter light into the terrestrial-planet regions near the stars. By introducing a deformable mirror at a pupil plane before the occulting spot, the imperfections can be cancelled by introducing counter-deformations on the surface of the deformable mirror. Specialized deformable mirrors are being developed for this application – with low power dissipation, high density actuators, and fairly slow response time. Figure 4 shows two generations of deformable mirrors that are currently being used in testing. An effort is underway to develop fabrication processes that result in robust reliable devices that can be qualified for space flight. In addition, drive electronics has been developed and continuously improved. A surface gage testbed residing in a vacuum chamber in a dynamically isolated environment has been assembled to test and calibrate deformable mirrors as they are delivered from the vendor and before they are tested in a coronagraph setting.

Figure 4. 32x32 and 64x64 Deformable Mirrors





2.1.3 Wavefront sensing and algorithm development for wavefront control

Several locations for sampling the wavefront for closed loop control of the deformable mirror have been tried. What is currently in use is the camera located at the science focal plane at the final position at the end of the optical train. Algorithms have been developed to evaluate residual speckle patterns at the science focal plane, calculate deformable mirror perturbations, and eliminate speckles that fall within the zone of the focal plane that represents the habitable zone of the star. New algorithms are being tested and developed to improve the process – both by increasing the depth of the contrast that is achieved within the controlled area and by improving the speed of the speckle rejection. Ultimately, success will also depend on modeling ability to capture effects of the optical system and predict accurately what the resulting contrast will be. Modeling efforts are proceeding at JPL, Goddard, and Ball Aerospace to provide predictive models of testbed systems. In this way, the analytical results can be validated using testbed results.

2.1.4 High Contrast Imaging Testbed (HCIT)

The HCIT shown in Figure 5 provides a dynamically isolated, thermally controlled vacuum environment for coronagraph system and component testing. Using a fiber-optic and pinhole supplied source to represent a star, HEBS glass occulting masks, hard-edged Lyot stops, a state-of-the art Xinetics deformable mirror, a 16 bit MUX and algorithms developed through the collaboration of Chris Burrows, John Trauger and Dwight Moody, a contrast has been reached of $2x10^{-9}$ using laser light at 785 nanometers. The HCIT is set up to be run semi-remotely with guest scientist participation in algorithm development. Focal plane images can be sent via secure internet websites to remotely located scientists. Algorithm solutions for deformable mirror changes can be returned to the HCIT team via internet websites for implementation. Already at this time, scientist and post doctorate, Chris Burrows and Pascal Borde, have exercised the HCIT remotely using their own algorithms. The HCIT has been set up for a guest testing scenario and is intended to be available for remote operations on a priority basis. It is also intended that the HCIT will pause testing for a few months during spring and summer of 2004 to fully characterize and instrument the optics and the environment so that coronagraph modeling verification can be done using the HCIT conditions and performance. Figure 6 shows results from recent testing in the HCIT demonstrating the high contrast achieved. The square-shaped dark hole reflects the shape of the deformable mirrors. The linear stripe in the center reflects the shape of the occulting mask used for this experiment.

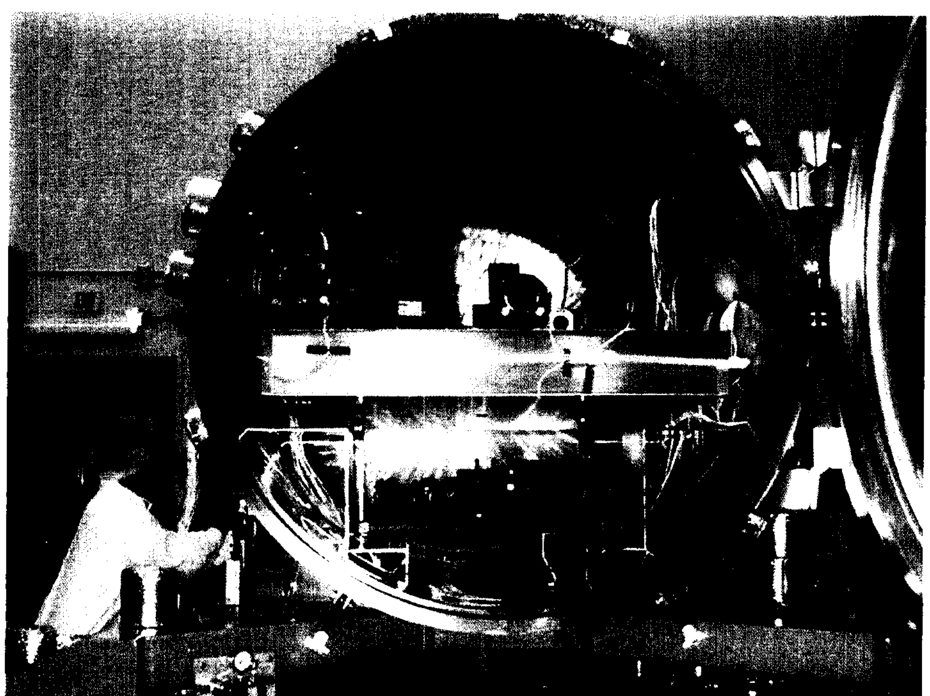
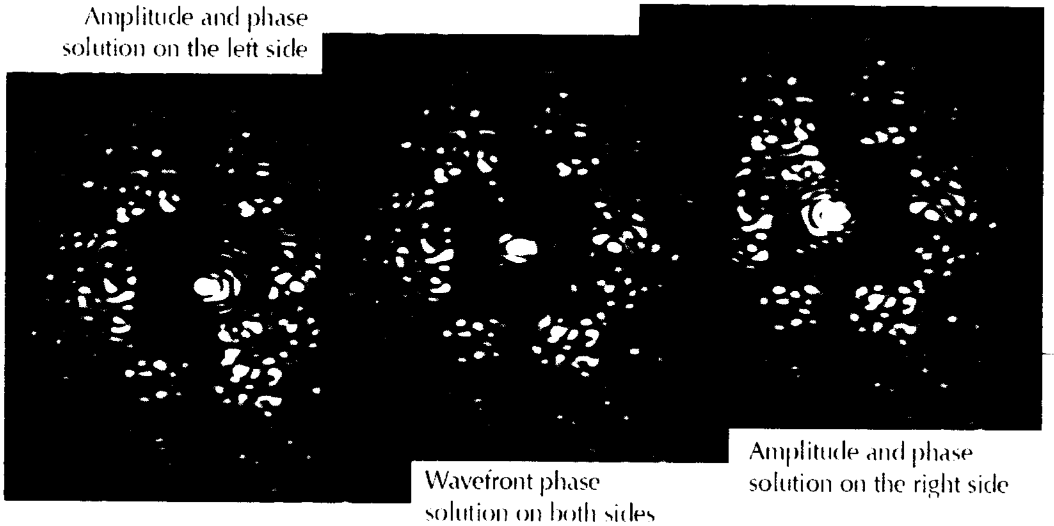


Figure 5. High Contrast Imaging Testbed

Figure 6. Dark hole (contrast) development in the HCIT



2.1.5 Separate Control of Phase and Amplitude

Currently in the HCIT, one deformable mirror is being used to correct the wavefront errors, but eventually, two mirrors will be needed so that both phase and amplitude can be controlled independently. Mirror imperfections (both in surface figure and in coating uniformity) can cause independent error in phase and amplitude. This can be handled by using only one deformable mirror and half of the field of view where the distinction of the phase and amplitude errors can be ignored through comparison of one side to the other, and rejection of speckles from one side into the other. It is desired to use the full field of view for observing for planets, so a system needs to be developed and tested for controlling phase and amplitude independently. This is being studied and developed by Chuck Bowers at Goddard Space Flight Center and by Jeremy Kasdin's group at Princeton University. It is intended to transfer the Goddard Space Flight Center device into the HCIT sometime next year to be available for full coronagraph testing algorithms development.

2.2 Large Mirror Fabrication

In addition to technology challenges related to the physics of controlling the scattering of light, it also will be necessary to build a large primary mirror that meets unprecedented requirements tailored to coronagraph needs. An unusual requirement for power spectral density (PSD) related to spacial frequency of errors on the mirror surface defines the specifications for a mirror that will scatter light into zones that are either controllable by the deformable mirror or out of the zone where terrestrial planets are expected to orbit. The mirror also must have extremely controlled uniformity of coefficient of thermal expansion and all other mechanical properties. The mirror will be an elongated, off-axis parabola with size falling between 6m x 3.5m and 8m x 3.5m. In preparation for understanding the difficulties of this fabrication, a technology demonstration mirror is being fabricated at Kodak Eastman using Corning ULE glass. This demonstration mirror is 1.8 meters circular, will be made of ULE with carefully measured and selected properties, has similar light weight construction processes to what will be needed for the TPF primary mirror, and will require similar metrology. The ULE properties will be measured and characterized with unprecedented accuracy to allow selection of complementary properties in boules to be used for this mirror. In addition, the coating of the technology demonstration mirror will follow the same process as the TPF primary mirror will require and will allow evaluation of induced coating stresses on the mirror as well as final performance measurements of the coating uniformity.

2.3 Integrated Modeling Tool Development

A modeling tool called Integrated Modeling of Optical Systems (IMOS) is being developed that will eventually be used for the TPF Coronagraph design, modeling and analysis. The goal of this effort is to develop an integrated modeling approach so that one tool will permit structural, thermal and optical analysis. This will enable the modeling to eliminate errors often caused by translation between tools. The tool is focusing on including the features that will be required for a TPF Coronagraph design. The tool elements are being verified by comparing performance of a modeled text book case to the closed solution result. Eventually, models of testbeds will be made using this tool so that verification can be done through comparison with measured data.

2.4 Alternative Architectures

Two additional efforts are supported to evaluate alternative architectures for the TPF Coronagraph relating to the methods used for scattered light control. These are instrument studies involving testbeds that have potential to meet the TPF Coronagraph star-light extinction requirements. One method is through a shearing, nulling interferometer concept developed by Mike Shao and Marty Levine. The other method is using a pupil remapping concept developed by Steve Ridgeway and Olivier Guyon. An analytical study is also taking place through a contract with Princeton and SAO to study and variation of the pupil mapping approach. Both these methods could possibly provide star-light extinction for TPF Coronagraph if the coronagraph techniques that are the prime approach end up being unable to attain the required performance.

3. SYSTEM STUDIES

3.1 Architecture

The architectural configuration of the TPF Coronagraph mission is driven by analysis of alternative system performances related to science requirements.

3.1.1 Assumptions

Conservative system assumptions were made in order to develop a generic system model for evaluation. The assumptions were that the DM is set & forget so that a static wave front budget is required during a star observation. Modeled dynamic and thermal wave front changes have not yet been validated against measured data. During the stare mode, no dither, no roll, and no background subtraction takes place. It is also assumed that speckles look like planets and that no chromatic smearing will be detectable to differentiate speckles from planets. Optics were divided into 5 classes: primary, secondary, DM, small flat, small power with each class having assumed properties. The properties were used for beam-walk and aberration calculations. Two final assumptions were that near field diffraction effects were ignored and that all errors are uncorrelated therefore the related contrast adds linearly.

3.1.2 Alternative architectures

A spread sheet analysis approach was adopted based on the assumptions listed above. Variable parameters in the spread sheet were defined to allow evaluation of alternative system architectures. The parameters that were varied are: primary to secondary distance (f number), aperture size, Airy ring which forms the inner working angle of the instrument, and the types of masks used for coronagraphy.

	D1 (m)	D2 (m)	n	# Rolls	Segments	Deff / D1	Coron. Throughput	Planet Detec-tions	# Stars w/ Composite 90% Completeness	NOTES
10x10	10	10	5	1	7 - 9	0.5[1]	0.1	11	85	pupil plane mask e.g. crossed 1-D linear (Vanderbei, 2004)
8x7	8	7	4	1	2	0.8[2]	0.26[3]	12	66	image plane mask, Lyot plane w/cutouts for edges and 2ndary
6x6	6	6	4	1	2	0.8	0.26[3]	8	39	image plane mask, Lyot plane w/cutouts for edges and 2ndary
8x3.5	8	3.5	4	2	1	0.8	0.51[4]	7	38	elliptical 1-sinc^2 mask, throughput = 0.8*0.8^2
6x3.5	6	3.5	4	2	1	0.8	0.51	5	20	elliptical 1-sinc^2 mask, throughput = 0.8*0.7^2
6x3.5	6	3.5	3	2	1	0.7	0.39	5	48	elliptical 1-sinc^2 mask, throughput = 0.8*0.7^2

Figure 7. Simplified evaluation of alternative architecture performance

3.1.3 Model Features

The performance calculated by the model is expressed as contrast between an input source (like a star) and the amount of light from that source left in the science focal plane at the inner working angle after the coronagraph elements are applied. RMS wave front error was not used as a criteria. Power Spectral Density and beam walk were used to calculate scattered energy versus field angle where energy was compared to spatial frequency for a given beam walk and power spectral density. Low-order wave front errors were modeled as scattered energy versus field angle. The wave front errors were expressed as coefficient values of the first 16 Zernike modes. It was also assumed that all movement degrees of freedom of all optical elements are uncorrelated. The model depends on a sensitivity matrix developed using MACOS software that determines contrast sensitivity to beam walk and Zernike amplitudes of the wavefront along the optical path.

3.1.3 Sensitivity and Error contributors

Optical element errors that were considered were: static errors (assumed to be caused during assembly and fabrication); motion and mirror deformation leading to wavefront aberration; thermal and dynamic effects, micrometeorite impact damage and particle contamination, leakage caused by pointing error and mask fabrication error, beam walk contributions, polarization effects, and the diffraction caused by different architectures. The impact of the errors was derived using sensitivity matrix calculations where each error in each degree of freedom is perturbed until the resulting contrast reduction is unacceptable. In particular, for each coronagraph architecture, the sensitivities studied included: occulting spot effect on the desired inner working angle of the system; optics aberration and displacement; beam walk; integration time with respect to signal to noise ratio; and pointing error and mask leakage.

3.1.4 Error Budget process

The full process used to develop the error budget includes calculation of wavefront deformation in terms of Zernike coefficients (Å); using wavefront errors, calculate contrast at various points in the image plane; use the same matrices with varied parameters to compare the error budgets for different coronagraph systems; and finally, allocate the error budget for each term in the total error allowed.

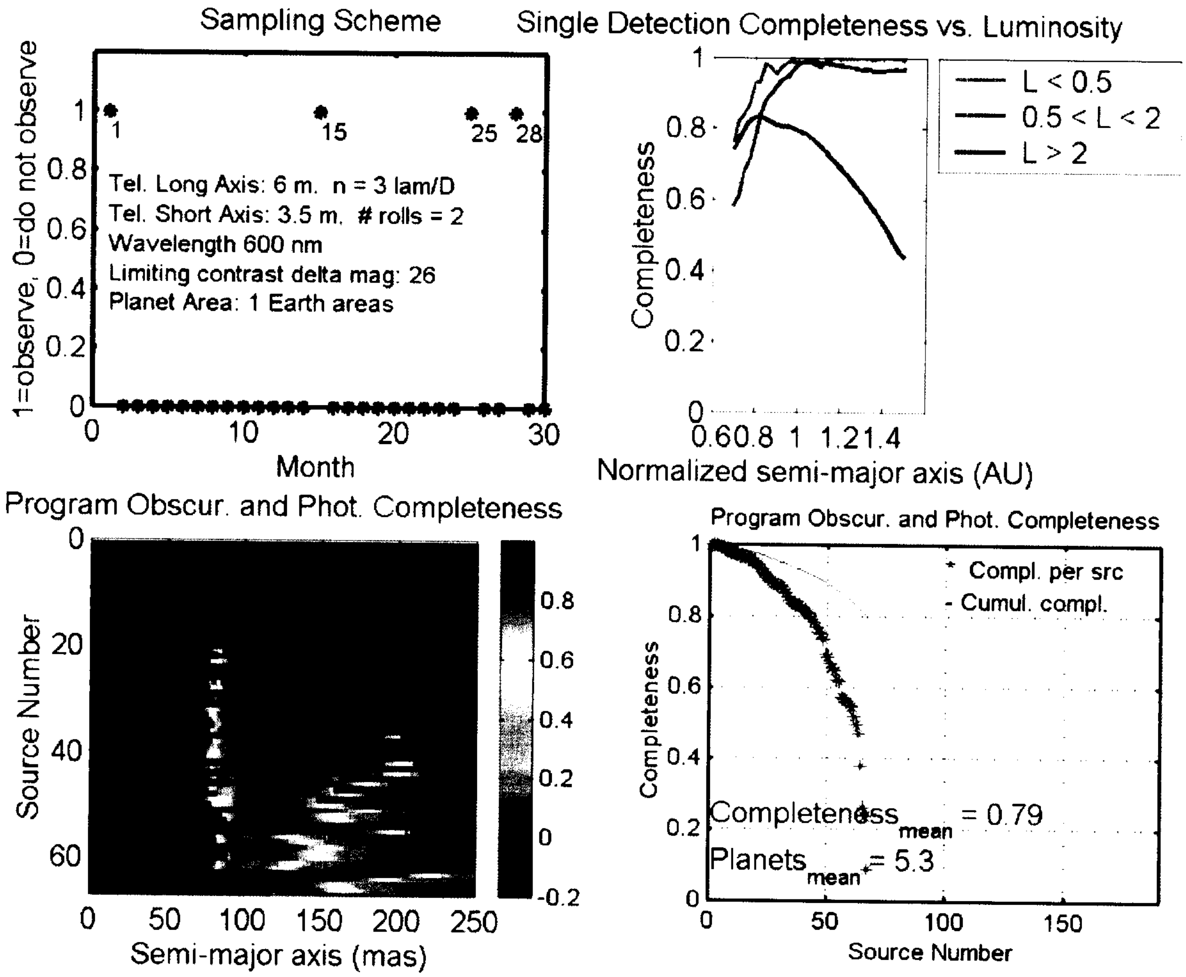
3.2 Design Reference Mission

Jet Propulsion Laboratory and Goddard Space Flight Center, working independently and comparing results to ensure validity, have developed models to calculate and compare science performance of different coronagraph systems. In particular, the goal of these models is to understand the architectural impact on ability to detect planets when completeness, mission operations and integration time are considered.

Based on the work of Bob Brown[b], completeness must consider two effects. Obscurational completeness refers to the visibility of a planet in the coronagraph dark hole: is the star-planet separation > Inner Working Angle (IWA) of the coronagraph system. This includes the effect of the planet orbiting around its star and disappearing in front of and behind the star during its orbit. Photometric completeness refers to the difference in planet-star intensity. This includes the effect of the illumination of the planet being in phases that affect its brightness as observed from the coronagraph instrument. Code was developed to simulate an assumed circular orbit, uniform distribution of orbits between 0.7 –1.5 AU, random orbit orientation, and random planet orbital phase. The results were compared to Bob Brown's figures 1 and 2 with matching results for identical cases. The code considers telescope parameters, wavelength, inner working angle, temporal sampling, star to planet magnitude ratio, planet area and statistically calculates cumulative fraction of possible planets found on two or more observing visits. Planets are assumed to be Lambertian spheres with earth-like albedo. Area, magnitude ratio, orbit orientation and inclination, and star characteristics are varied to capture a statistical sample of planet types.

In addition, integration time for each planet magnitude was factored in the calculations to determine planet detection efficiency on a source-by-source basis. Based on this calculation, the star list for TPF coronagraph has been sorted from most to least efficient. The cumulative integration time was calculated and all star sources that fit within an allotted time (assumed to be 1 year) were considered to be successfully observed. Results of evaluation of one architecture are shown in Figure 8.

Figure 8. Completeness plots for a 6 x 3.5 meter aperture, 2 roll system looking for a planet of 1 earth area



Current results indicate that there is trade space between the predicted number of planets that can be detected and the completeness that each star is observed. By visiting each star 4 times during the mission, then completeness is optimized. For elliptical apertures, 2 rotations about the line-of-sight is better than more to enable highest resolution detection based on time constraints. If integration time is set for planets that are sized the same as earth, then a significant fraction of planets of ½ earth area will be detected. Finally, the integration times vary based on exo-zodi values and are fairly independent of architecture selection.

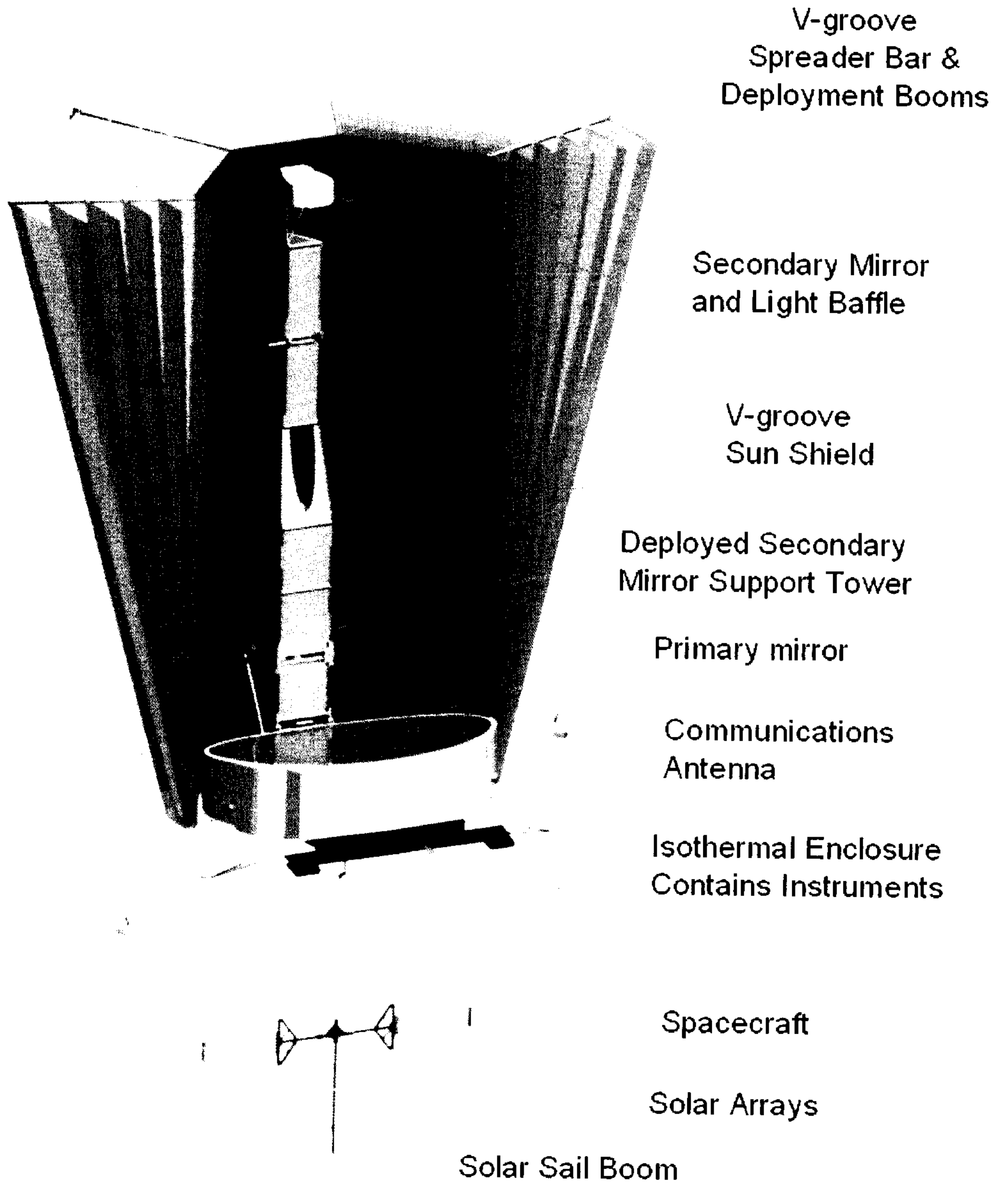
Architecture calculations will improve as more analysis is completed to predict performance parameters of different mask and stop architectures. As this work is finalized, the baseline design for a flight TPF coronagraph will be selected.

3.2 Design Development

The TPF Coronagraph design team set out first to design a system that would meet minimum science requirements and used the telescope style selected by Ball Aerospace Corporation during the 2002 architecture evaluation study. The objective of the design team was to use this starting point as a model to evaluate if an environment can be created that could feasibly provide the environmental stability needed for coronagraph performance to the planet-detection levels.

To this end, experience-based choices were made for the facility configuration. The trades that were made are detailed in the presented paper: 5487-59 Design and performance of the Terrestrial Planet Finder coronagraph by Mary White et al. Figure 9 shows some features of the concept.

Figure 9. TPF Coronagraph Minimum Mission Design



This concept has been frozen and structurally, thermally, dynamically and optically modeled with analysis completed. This design has been reviewed by a panel of experts from outside of the TPF project. The comments of the review board, the analysis results, and the final architecture calculations, will guide changes to the concept to form the baseline flight design.

4. PROJECT STATUS

Current program direction for the TPF Coronagraph mission is to prepare for flight in 2014. This will involve acceleration of both technical and systems efforts so that a reasonable plan for success can be followed.

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