Terrestrial Planet Finder Coronagraph 2005: Overview of Technology Development and System Design Studies

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ABSTRACT

Technology research, design trades, and modeling and analysis guide the definition of a Terrestrial Planet Finder Coronagraph Mission that will search for and characterize earth-like planets around near-by stars. Operating in visible wavebands, this mission will use coronagraphy techniques to suppress starlight to enable capturing and imaging the reflected light from a planet orbiting in the habitable zone of its parent star. The light will be spectrally characterized to determine the presence of life-indicating chemistry in the planet atmosphere.

This summary of the developmental studies leading to definition of this mission represents the work of research and design teams at Jet Propulsion Laboratory, Goddard Space Flight Center, Ball Aerospace & Technologies Company, Lockheed Martin Space Systems Company, Northrup Grumman Space Systems, ITT Industries, Xinetics, Inc., University of Hawaii, National Optical Astronomy Observatory, Princeton University, University of California Berkeley, Colorado University, University of Florida, Boston University, Night Sky Systems, TC Technology, and Astro Aerospace.

Keywords: coronagraph, telescope, space, terrestrial planet finder, deployable structures, optical

1. INTRODUCTION

1.1 Background

Exciting things are occurring in astrophysics. Since the mid 1980s dust disks around distant stars have been observed to have swirls, lumps and clear feature s which are believed to indicate the presence of planets. During the past 4 years, Astronomers using ground-based telescopes have been detecting planets orbiting around nearby stars – the count is now above 150 detected planets external to our solar system.

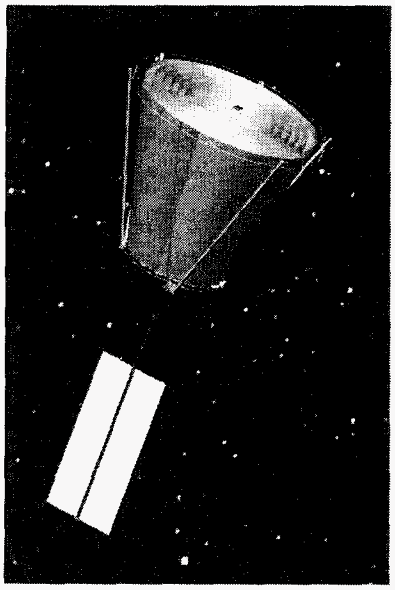

Figure 1. Terrestrial Planet Finder Coronagraph - Flight Baseline 1 Configuration (Ho)

The primary method used for this detection, called radial velocity detection, is to sense the Doppler-effect color shifting caused by the star wobble as the planet pulls on the star it orbits. Using this method, the planet's orbital radius and period and the planet's mass can be derived. This technique is optimized for sensing fast moving, heavy planets such as gas giants with very short orbital periods because the fast moving, heavy planets displace the star more quickly with larger amplitude. Both effects increase the Doppler shift of star light making detection easier. In addition, slow-orbiting planets take a long time to perturb their sun's position, so take longer observing time to discover. Even with these limitations, within the past few years, gas giant planets have been observed with orbital radii similar to Jupiter and a few small planets (~6 Earth size) have been found that are likely to be large rocky planets. They are in small rapid orbits close to their stars, so must be extremely hot, but they continue the expansion of our knowledge about what might be out there. All these exciting discoveries lead to the conclusion that planets are likely to be orbiting other stars that could carry life as we know it on Earth.

With this in mind, NASA is funding a mission called Terrestrial Planet Finder (TPF) that intends to find and characterize terrestrial (or rocky) planets that might harbor life. The ability to harbor life is defined as having liquid water present on the planet surface. In order to meet this criterion, the planets must be orbiting in the habitable zone or the spherical region around a star where water will be liquid. This is based on the temperature on the surface of the planet and is related to the brightness of each star and the orbital radius range for each particular star where a planet would have the correct thermal characteristics.

When a planet is found, by studying the light from that planet, the presence of life can be detected from the spectrum of gases that are present in its atmosphere. The presence of life-indicating gases such as water, oxygen, ozone, carbon dioxide, chlorophyll, and methane can be detected in the spectrum of light reflecting off of a planet's atmosphere.

In order to perform this mission, two instruments are being proposed: a visible coronagraph and an infrared interferometer. The coronagraph, called Terrestrial Planet Finder Coronagraph (TPF-C), shown in Figure 1, is currently scheduled for launch in 2016 and will be the focus of this talk. The interferometer is currently scheduled to launch in the 2020 timeframe. Both instruments provide complementary data to establish the presence of life on any planets that may be found and studied.

1.2 Coronagraph Theory

Prior to the invention of coronagraphs, astronomers interested in studying the corona of the sun had to travel around the world chasing eclipses. Coronagraphs were developed to study the corona of the sun on a convenient, 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 at the times and in the conditions that they chose. 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's breakthrough was to recognized that diffracted light from telescope and masks structures could be mitigated using a technique suggested by Fourier Transform mathematical representation of light propagation. 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. The transform mathematically predicted that the diffracted light would be sent to a ring at the edge of the field. Lyot provided a baffle to absorb the ring of diffracted light called a Lyot stop. This stop both reduced the aperture diameter and absorbed the diffracted light. In addition, Lyot recognized that scattered light from the atmosphere and surfaces within the telescope was overwhelming the image of the corona. To overcome this, he built optics with extremely smooth surfaces and low scattering properties and located his telescope on the top of a mountain where the atmospheric effects were minimized. His theories were proven correct and the first coronagraph was created. 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 by a factor of 100 billion (10^{10}) times. At this required level of starlight suppression, polarization, amplitude and wavelength dependent effects, and basic materials properties also have to be considered.

2. TECHNOLOGY RESEARCH AND DEVELOPMENT

Our challenge is to eliminate stray light caused by system phase and amplitude errors and external light sources; to control diffracted light; and to understand and control light 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 that address aspects of this challenge. They are: 1) fabrication of a demonstration mirror that provides path-finding to materials, light-weight mirror fabrication techniques, spatial frequency requirements 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 types of masks, wavefront sensing and control, algorithm development and development of a deformable mirror that will correct errors in wavefront though out the system; 3) investigation, analysis and fabrication of more advanced masks and stops; 4) development of modeling tools that will represent the extreme precision needed to model the test beds and the flight system so that feasibility for the mission can be understood; 5) development of testbeds to develop alternative architectures for starlight suppression; 6) precision materials properties measurements.

2.1.1 Technology Demonstration Mirror (TDM)

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 and not influence planet finding. As the spatial frequency decreases, the resulting stray starlight falls within the zone where terrestrial planets are expected so errors in this range 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 the special frequency requirements. Understanding how to measure the mirror and interpret the measured data to ensure compliance with the requirements also will be learned.

Trade studies have resulted in the selection of light-weighted, fuse-bonded ULE as the substrate material. The ULE boules being used have tight requirements on coefficient of thermal expansion (CTE) and have been selected to meet them. Calibration standards to measure the CTE of the selected boules were re-measured to verify calibration and that the CTE requirements were met. Boules to be used for core pieces have looser CTE requirements than boules for the facesheets.

In addition, coating the mirror will be a challenge because coating uniformity requirements are tight. Non-uniform coatings will cause amplitude errors that will interfere with the starlight suppression requirement. In addition, polarization effects of the candidate coatings are being studies to understand the polarization effect on starlight suppression, as well as to develop concepts for mitigation of the induced polarization of the light.

ITT and Corning are fabricating this mirror. Figures 2 shows the mirror concept with the front face sheet removed. Figure 3 shows some core segments being fabricated.

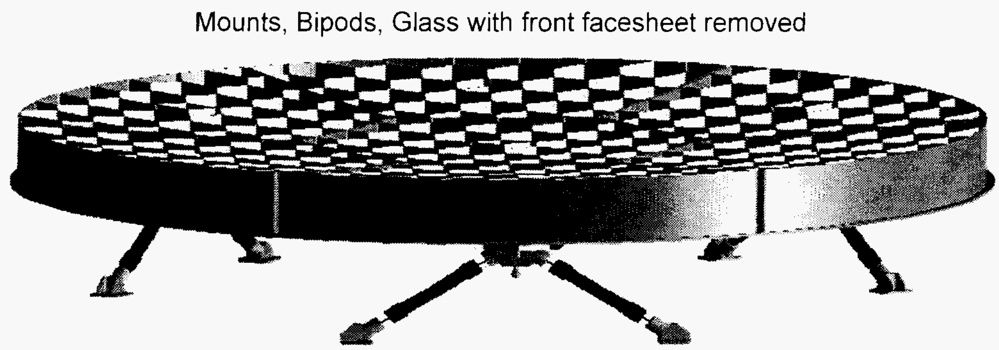

Figure 2. Technology Demonstration Mirror Design Concept (ITT)

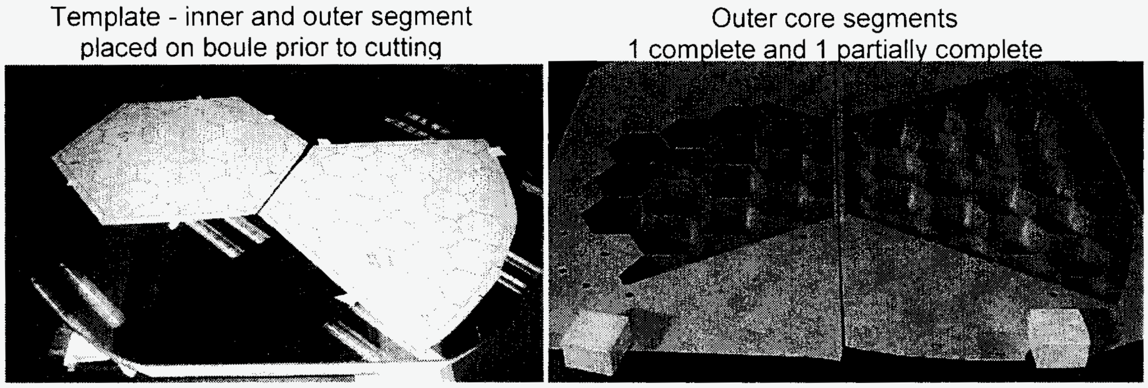

Figure 3. Technology Demonstration Mirror core is made from 6 outer and one inner segment (Cohen, ITT)

2.1.2 High Contrast Imaging Testbed (HCIT)

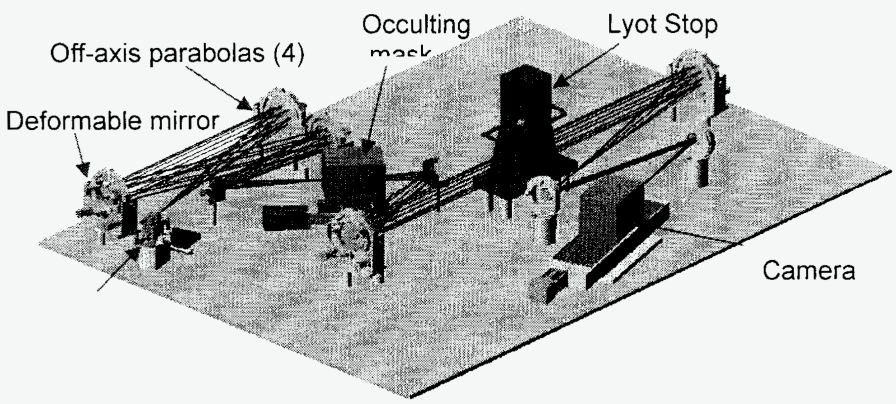

Figure 2. Schematic of the High Contrast Imaging Testbed (Trauger)

The heart of the coronagraph system is the coronagraph sensor assembly where the starlight is suppressed and the wavefront is sensed and controlled. The High Contrast Imaging Testbed is a flight-like-environment exploration of the methods and hardware that will perform these functions. Current performance will be reported at this conference[1]. Masks and stops designs, optical designs, wavefront sensing concepts, and control algorithms are all included in a variety of theories and tests 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. Figure 4 shows the testbed in its vacuum chamber. A series of increasingly mature and robust deformable mirrors have been developed, fabricated, calibrated and

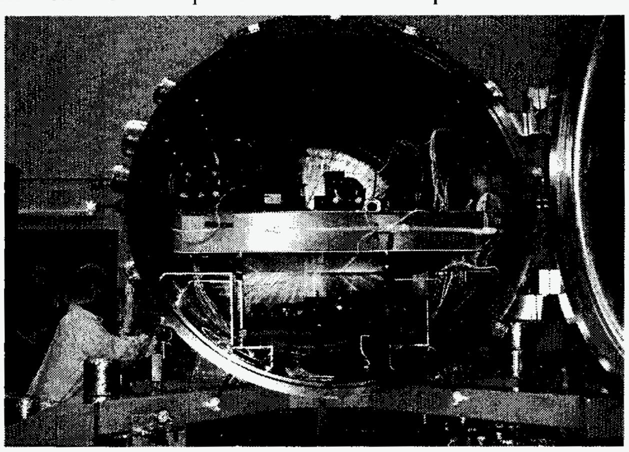

Figure 4. Photograph of High Contrast Imaging

installed to demonstrate precise wavefront control. Current narrow band performance has reached an average contrast of <$1x10^{-9}$ throughout an area of 4λ/D to 10λ/D x ±10λ/D using laser light at 785nm. Current broad band contrast has reached an average contrast <$1x10^{-9}$ over the same area at 785±10 nm.

The HCIT team is currently working to demonstrate <$1x10^{-9}$ average contrast at 785nm in the area between 4λ/D to 5λ/D x ±5λ/D. Following that, the testbed is scheduled to explore alternate mask options and broad band wavelength performance improvements.

2.1.3 Research in Masks and Stops

Development of theories of mask and stop forms, researching candidate mask materials and materials-related influences, modeling light propagation and sensitivity to form errors are areas of research supporting the contrast goal of 10^{-10} required to detect and characterize Earth-like planets[3].

An example of the development of models of light propagation through masks that include electromagnetic field effects that influence polarization and wave band performance is shown in Figure 5. Modeling exercises such as this have helped to understand sensitivities that have lead to the development of requirements for the masks and stops to be used in coronagraph of TPF-C. Modeling and assessing sensitivity has led to development of a promising new mask form called an 8^{th} order mask. Two types of 8^{th} order masks have been built to demonstrate this mask form - using High Energy Beam Sensitive (HEBS) glass and using a deposited aluminum binary representation that is shown in Figure 6. These masks are scheduled for testing next in the HCIT.

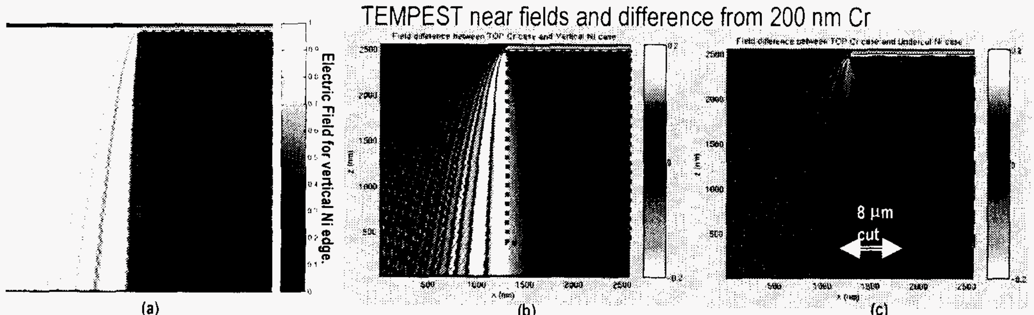

Figure 5. Modeled electromagnetic propagation past a mask structure - TEMPEST software (Ceperley)[2]

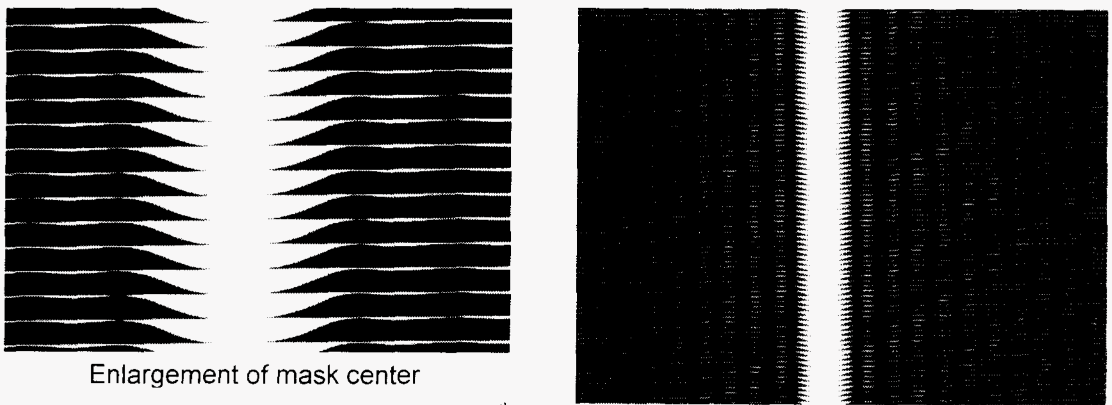

Figure 6. Microscope photographs of an 8^{th} order binary mask – black is clear and white is an aluminum layer (Hoppe and Balasubramanian)

Materials research[4] has focused on careful measurement of material properties and influences on the mask performance. This research is expected to lead to mask solutions that increase the bandwidth of performance and polarization tolerance of future masks.

2.1.4 Modeling Efforts

The TPF Coronagraph will rely heavily on modeling and analyses throughout its mission lifecycle, thus developing models, validating them, and implementing them 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.

Development of on-orbit performance models includes modeling the thermal and dynamic responses of the observatory during operation in space and will be covered in section 3.0 describing the observatory design. These models are tied to optical performance models that represent the propagation of the wavefront through the perturbed surfaces, including diffraction, polarization, mask and stop effects and optimization algorithms for the deformable mirrors. Broad band wavelength effects are being added.

In parallel, several modeling tools are used to model the performance of the HCIT. SPICA[5] is a science-based code used to understand the HCIT performance and develop control algorithms for the deformable mirror. MACOS[6] is an optical engineering tool capable of interfacing with MATLAB scripts and NASTRAN that is being used to duplicate the code developed using SPICA so that the HCIT

Contrast Simulation of TPF-C System with Static Figure Errors

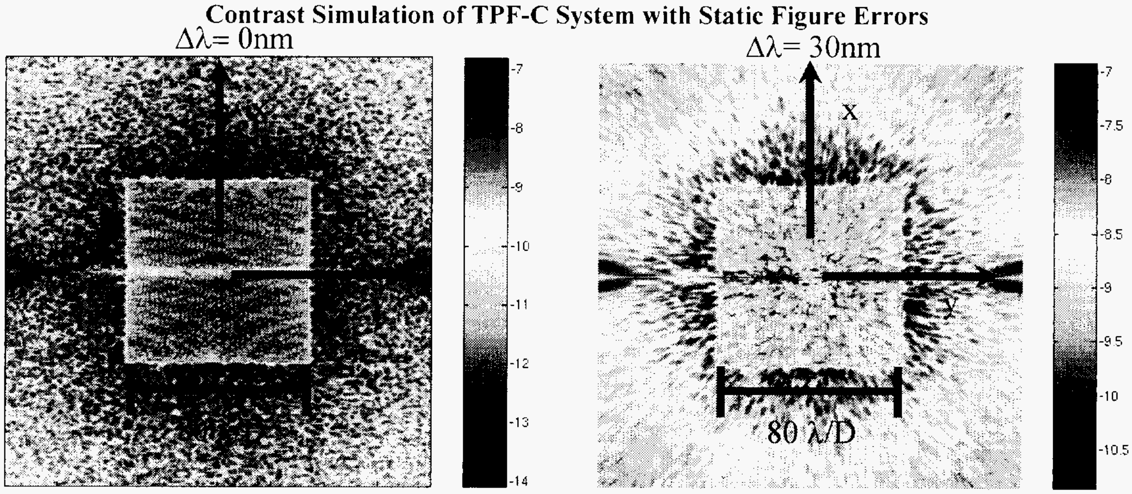

Figure 7. MACOS model of the TPF-C coronagraph contrast development including static figure errors at single wavelength and 30 nm bandwith.[7] (Palacios)

models are validated, then interface with the thermal and dynamic codes to represent the system response to perturbations. Figure 7 shows a MACOS representation of the TPF-C coronagraph performance at single wavelength on the left and broadband wavelength on the right.

Also under development is a fully integrated modeling tool that simulates under a single computational code the thermal, mechanical, control and optical performance of the flight system. This tool (a fully upgraded version of IMOS [Ref. 3]) has structural evaluation, 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 end-to-end sensitivity and optimization abilities. This tool is currently being used to run simple trade studies for the TPF-C modeling team.

Modeling process verification and validation will be performed on the HCIT and testbeds that are envisioned as the mission progresses. Currently, SPICA can be considered as being validated on the HCIT since its predictions are traceable to HCIT performance. The MACOS model of the HCIT is still under development, but will be eventually be validated on the HCIT. Currently, its analytical diffraction predictions are verified both through verification of 1-D propagation problems for which there are derivable solutions and through comparison of results to SPICA generated results. The upgraded IMOS tool is being verified through derivable solution text-book problems.

2.1.5 Alternative Starlight Suppression Testbeds

Three additional methods of starlight suppression are being supported by TPF-C. A test bed has been developed Princeton University to design, analyze, fabricate and test pupil plane masks. A test bed has been developed as a joint effort of NOAO and University of Hawaii to build and study a pupil re-mapping concept. Finally, a testbed has been developed to use visible light and interferometric techniques to create a null over a star enabling imaging of orbiting planets.

3. TPF CORONAGRAPH DESIGN DEVELOPMENT

Table 1. Preliminary Science Requirements (Lawson)

Key Parameter	Requirement	Goal*
Star types (main sequence)	F through K	
Habitable zone	0.7 to 1.5 AU scaled $L^{0.5}$	
Orbit phase space	Semi-major axis: uniform inclination: uniform eccentricity: 0–0.35	
Number of core stars to be searched	35 core stars	
Completeness per core star	90%	
Number of additional stars to be searched	(Not specified)	130
Completeness per set of additional stars	(Not specified)	90% integrated over the ensemble of 165 stars (core and additional)
Minimum planet area	1/2 Earth area	
Geometric albedo	Earth	
Flux ratio	At least 3 broad wavelength bands;	
Spectral range	0.5–0.8 m	0.5–1.05 m
Spectral resolution	70	140
Characterization completeness	50%	
Giant planets	Jupiter brightness at 5 AU, 50% of stars	
Average (Maximum) tolerable exozodi	3 (10) zodi	

*Stated in addition to the requirements already noted.

The TPF-C design team is responsible for creating a configuration of the TPF coronagraph mission, to analyze it, determine its performance, and to make systems trades. The connection between the technology development and the design team is the performance model and sensitivity matrix that are used to create an error budget[8] of allowable perturbations. The design concept has gone through one design concept cycle called the Minimum Mission Cycle Its purpose was to determine if an observatory could be developed that would be able to create the stable thermal and dynamic environment needed to maintain the coronagraph performance to meet minimum science requirements. This was able to predict adequate performance and is documented in a report[9] that was released April 22, 2004. The next cycle, called Flight Baseline 1, is currently in its analysis phase and is due to be completed in October 2005. It addresses nominal science requirements and explores the internal instrument concepts. More detail is included in all areas. It does not include any active temperature control system modeling – instead heater locations are held at constant temperatures for analysis. These temperatures will be varied to understand the influence of their stability to define requirements for the next cycle: Flight Baseline Cycle 2. This cycle is scheduled to be defined by the end of October 2005, and will address active temperature control systems and further explore instrument accommodation. This cycle will be followed by Flight Baseline Cycle 3 where more instrument detail will be added, and optimization will be applied to ensure the design meets the performance requirements.

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 the Space Interferometer and LISA Missions; and some of the spacecraft isolation schemes developed by industry for James Webb Space Telescope.

The design team is chartered to develop a design that will meet a set of science requirements that are being developed. In the meantime, the team has been working towards meeting the science requirements shown in Table 1.

3.1 Flight Baseline 1 Design

In 2004, a design was developed called Minimum Mission Design that was aimed at meeting minimum science requirements and taking a first-time look at a concept that might produce an environment stable enough to permit starlight suppression close to the star by a factor of 10^{-10} that is required to detect planet light in the habitable zone. This design is reported in Jet Propulsion Laboratory document: "JPL D-28535 Terrestrial Planet Finder Coronagraph Minimum Mission Baseline Design and Analysis Report." Though the model developed was simplified, analysis indicated that a successful mission is feasible. In addition, the exercise created performance models and sensitivity matrices that led to an error budget. Also developed was an approach for coordinated modeling between different modeling tools that allowed smooth transfer of data between disciplines. Using this cycle of data from model to model, the team was able to determine the impact of thermal and dynamic perturbations on contrast – the performance metric. This process has been applied to the current design – called Flight Baseline 1.

Table 2. Mission and Spaceraft Choices (Lisman & Feher)

	Parameter	Value	Comments
Mission	Duration required/goal	5/10 years	Resources for 10 years
	Orbit	L2	Direct trajectory
	Field of Regard	Sun angles > 95°	Potential earth/moon/planet constraints
	Required ΔV	60 m/s	
	Launch Energy (C_3)	-0.69 km^2/s^2	
	Launch Vehicle	EELV	
	Launch Fairing	5 m diameter	limits primary mirror short axis to ~3.5 m
	Launch Mass	9200 kg	
	Time to reach operating orbit	109 days	
	Ground Station	34m DSN Ka-Band	
	Downlink Data Rate	64Mbps	
Spacecraft	EOL Power	3kW	provided by solar arrays
	Reaction Wheels	6 Goodrich wheels	
	Propellant	242 kg Hydrazine	
	Thrusters	12 20N	
	Hi Rate Downlink Frequency	Ka-Band	avg duration 2.5 hours per day
	Engineering Downlink Frequency	X-Band	
	Uplink Frequency	X-Band	
	Transmitter Power	50W	
	Hi Gain Antenna	43dB	0.5m patch array

The Flight Baseline 1 (FB1) design differs from the Minimum Mission Design (MMD) in many ways. Firstly, the design team expanded to include more Goddard Space Flight Center personnel focusing on the Telescope Assembly, more Northrup Grumman Space Systems personnel focusing on the deployable sunshade, more Lockheed Martin Space Systems Company personnel focusing on spacecraft to payload isolation and systems engineering, and more Ball Aerospace & Technologies Company personnel focusing on science modeling and systems engineering. This expansion enabled more detail to be included in the design, but also required instruction to accomplish the modeling transfer process that was developed during the Minimum Mission exercise described above.

The technical differences between MMD and FB1 are, in brief: an orbital change from Earth trailing to Lissajous halo orbit at L2; different telecom; improved sunshade and sunshade deployment; added electronics details; improved telescope with much more detail including thermal control, laser metrology implementation, and mirror mounting schemes; improved instrument assembly with much more detail including placeholder instruments, passive thermal control, improved thermal enclosure. The new FB1 concept is described below.

3.2 TPF Coronagraph Flight Baseline 1 (FB1) Mission and Spacecraft Description

Table 3. First Cut Mass & Power Estimates for FB1 (Lisman & Feher)

MASS **Component**	**Mass Est(kg)**	**% of Total Mass**	**POWER**	**Power Est (W)**	**% of Total Power**
Payload	5540		**Payload**	1049	51.2
Telescope	3440	43.5	Telescope & thermal control	664	32.4
Payload Support Subsystem	1508	19.1	Payload and thermal control	156	7.6
Starlight Suppression Subsystem	412	5.2	Starlight Suppression Subsystem	87	4.2
Planet Detection Camera	10	0.13	Planet Detection Camera	2	0.1
Planet Characterization Spectrometer	20	0.3	Planet Characterization Spectrometer	40	2.0
General Astrophysics Instrument	150	1.9	General Astrophysics Instrument	100	4.9
Spacecraft	2374	30.0	Spacecraft	1000	48.8
Total Launch Mass	7914		Total Power	2049	
Launch Vehicle Capability	9200		Available EOL Power	3000	
Launch Margin	**1336**		Power Margin (W)	**951**	
Launch Margin (%)*	**14.4**		Power Margin (%)*	**32**	

*Defined as (LV Capability-Total Estimate)/Launch Capability

Mass reduction in work

*Defined as (Available Power-Total Estimate)/Available Power

The mission choices for the FB1 design provide the frame work that defines the FB1 observatory requirements. These choices are not considered to be technology drivers – in fact, an attempt was made to stay within the limits of existing technology where possible so that resources at this phase of the project could focus more on areas that require technology development or non-heritage engineering. The choices for both the mission and the spacecraft for this observatory are listed in Table 2.

An estimate was gathered for all the observatory required electronics. The required mass, volume and power were calculated as well. When the solid models of the entire mission were developed, an early exercise was to calculate the launch mass of the mission. Table 3 shows the first cut mass and power estimates for Flight Baseline 1. The first-cut mass that is represented does not meet an acceptable margin for launch, and mass reduction studies are underway – first by understanding better what stiffness is required and modifying model parameters, then lighter approaches will be incorporated for the next design cycle: Flight Baseline 2. The estimated power is below the estimated end-of-life power from the solar panels with adequate margin.

The observatory is designed to examine stars in nearly the entire anti-sun semi hemisphere – a 5° margin is included. The field of regard includes all stars located in the cone defined as greater than or equal to 95° away from the sun. As the observatory travels around the sun, this field-of-regard will sweep the entire sphere of the universe, allowing observation of all star targets of interest during nearly 5 months of the year. During each star observation, the observatory will point at a star target. Once the dynamics are stabilized, the observatory will collect light. Using adaptive optics, the wavefront errors will be reduced until the starlight is suppressed adequately and an image will be taken. Next the observatory will "dither" about its pointing axis by 30 degrees. Once the dynamics are stabilized, the observatory will take an image in this new position. This image will be subtracted from the previous image to eliminate residual light scattered from the observatory (which will all move with the dither). Any planets present would then be detectable. Because the primary mirror is oblong, it is most sensitive along its long axis. In order to completely study the habitable zone around a star, the long axis has to be rotated to positions that are ±60° away from the starting point. This is accomplished by a "roll" along the pointing axis. At each new roll position, the adaptive optics are reset and then the image gathering is repeated, including the dither. With a 30° dither around 60° roll positions, the total angular rotation around the target direction axis is ±75°

This observational scenario defines the thermal environmental perturbations that need to be addressed. The observatory must be stable enough between dither maneuvers to retain precise optical wavefront stability. After each roll, the wavefront correction is reset, so stability between roll positions is not as critical.

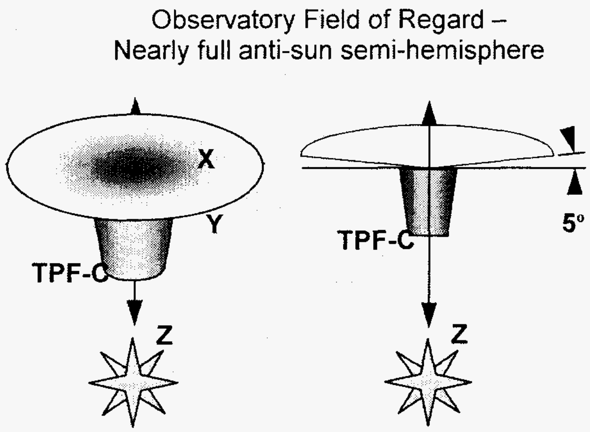

Figure 8. Field of Regard

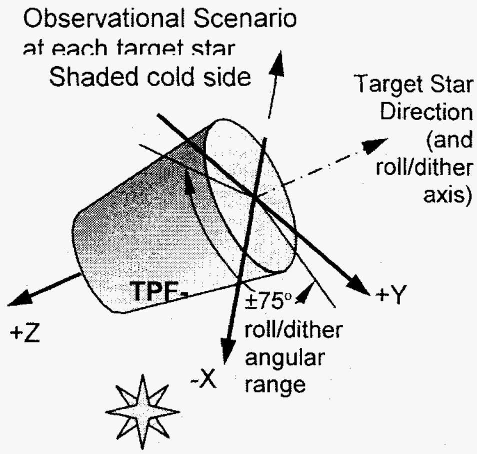

Figure 9. Observational scenario

3.2.1 Flight Baseline 1 Description

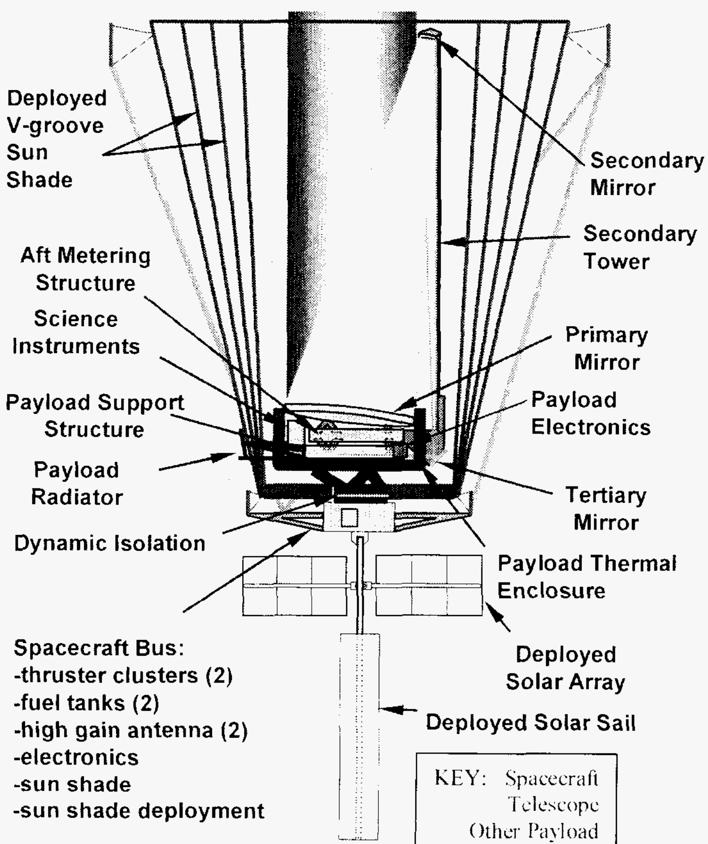

Figure 10. Flight Baseline 1 Schematic

Figure 10 shows a schematic of the design concept. The payload is surrounded by a large deployable conic shaped v-groove sun shade which insulates the payload from the changing sun angles during the observational scenarios. The conic shape was chosen to maximize the opportunity to view target stars multiple times during one year so that planets will have time to orbit into a favorable position out from behind the star. The sunshade is structurally attached to the spacecraft through deployable arms and booms, so any dynamic snaps or warping of the sunshade structures will be filtered through the spacecraft before reaching the sensitive payload. The back end of the conic sunshade consists of flat layers –one per shade layer - that span the space between the spacecraft and the payload.

The optical path enters the telescope baffle and reflects off an 8m x 3.5m elliptical off-axis parabolic primary mirror. The light next reflects off the secondary mirror, towards a tertiary fold mirror that directs the beam into the coronagraph starlight suppression assembly. A pick-off mirror sends the outer portion of the beam to a general astrophysics instrument.

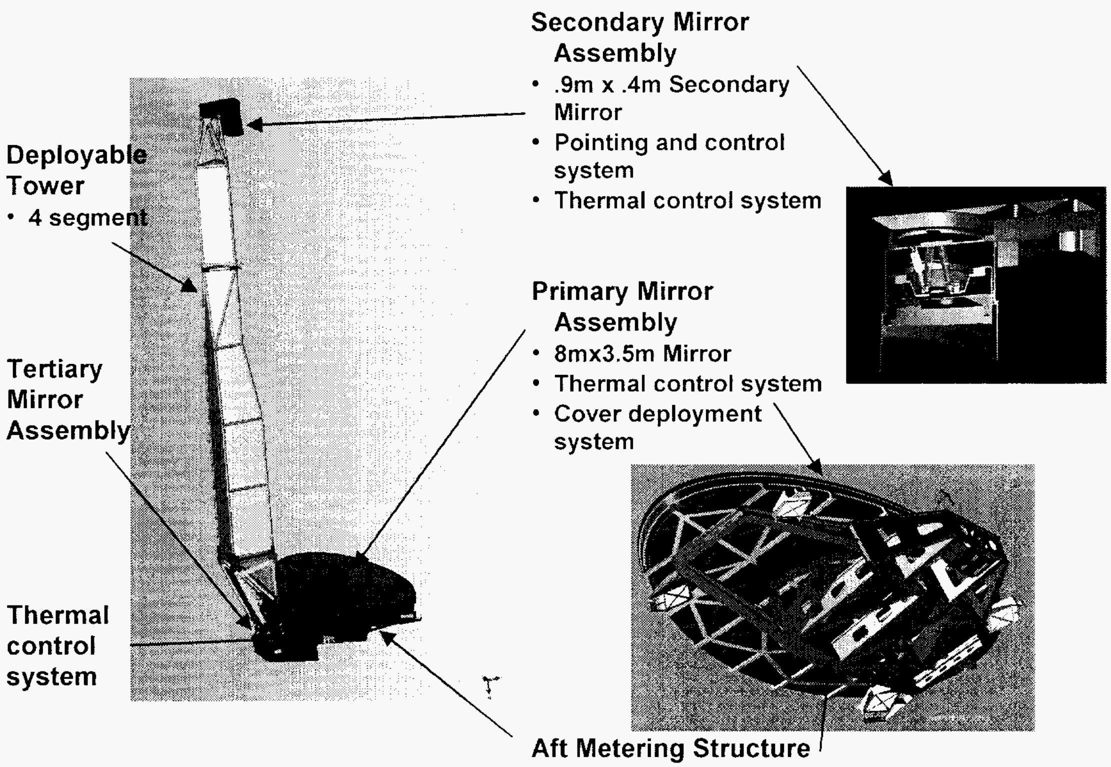

Figure 11. Optical Telescope Assembly (Engler and Guzak)

The primary mirror is mounted semi-kinematically with a hexapod to an aft metering structure (AMS). Behind the primary mirror, the AMS supports a set of heaters for maintaining the primary mirror at temperatures close to room temperature.

The secondary mirror is mounted on a long deployable tower 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 tertiary mirror also is mounted on a strut system to the AMS with adjustment available for one-time on-orbit calibration. The laser sources for laser metrology between the primary mirror and the second mirror are also mounted on the AMS. The laser metrology system consists of six laser beam assemblies that will provide continuous feedback on the secondary mirror position. This will be used to adjust out relative thermally induced motions between the primary mirror and the secondary mirror. The optical telescope assembly is shown in Figure 11. The aft metering structure mounts through three bi-pods to a payload support structure (PSS).

The coronagraph starlight suppression assembly, all instruments, most of the payload electronics, and thermal control hardware mount to the PSS. The thermal control hardware is both passive and active. Heaters maintain room-temperature conditions. Heat pipes conduct heat from the electronics to a "warm" radiator. Heat pipes also conduct heat from the instrument detectors to a "cold" radiator. The entire lower portion of the payload is surrounded by a thermal enclosure mounted to the PSS. The PSS attaches to the spacecraft through three bi-pods. Figure 12 shows the Science Payload assembly excluding the telescope and the spacecraft assembly.

On the spacecraft side of the interface, at the end of each bi-pod, dynamic isolation is provided – either passively or using an active isolation system. Both options were analyzed. In addition, the spacecraft, shown in Figure 13, carries thruster clusters, orbit maintenance fuel tanks, communications antennas, and reaction wheels. The sunshade mounts off of deployable arms and booms. The solar panels and solar sail are also mounted on the spacecraft with deployable structures.

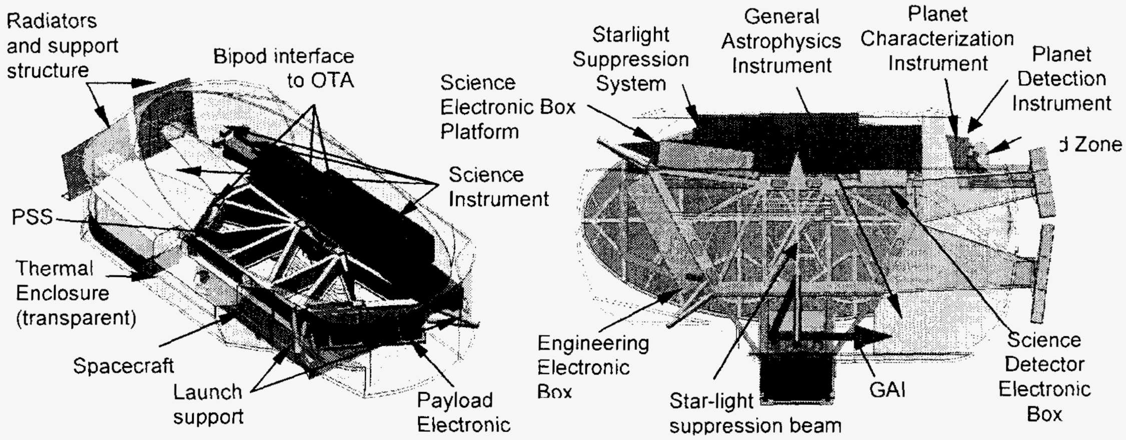

Figure 12. Science Payload excluding Telescope (T. Ho)

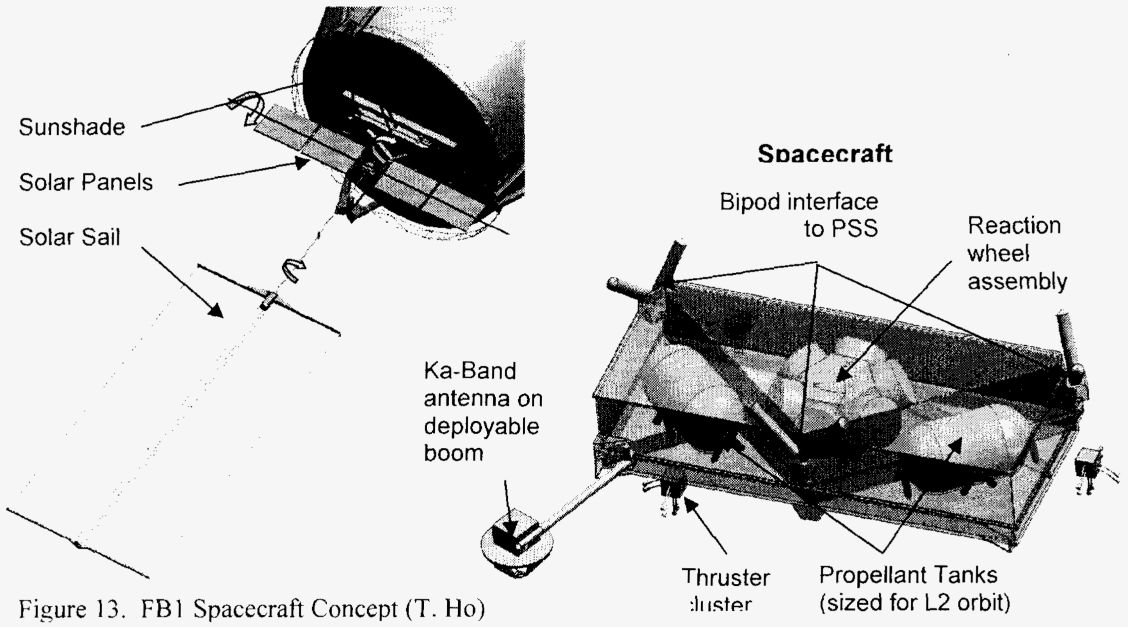

Figure 13. FB1 Spacecraft Concept (T. Ho)

The final important part of the design is how it will stow into launch configuration. The volume constraints of the launch shroud pose significant design limitations. Figure 14 shows the FB1 observatory stowed in its launch shroud. The Sun shade folds up and is tucked behind the payload around the spacecraft. The secondary tower folds along 4 joints to fit pointed vertically along side the primary mirror. The Solar Panels and Solar Sail fold up under the spacecraft, and the antenna arm folds alongside the spacecraft. Launch latches and launch support structure all release and fold away from the observatory upon deployment.

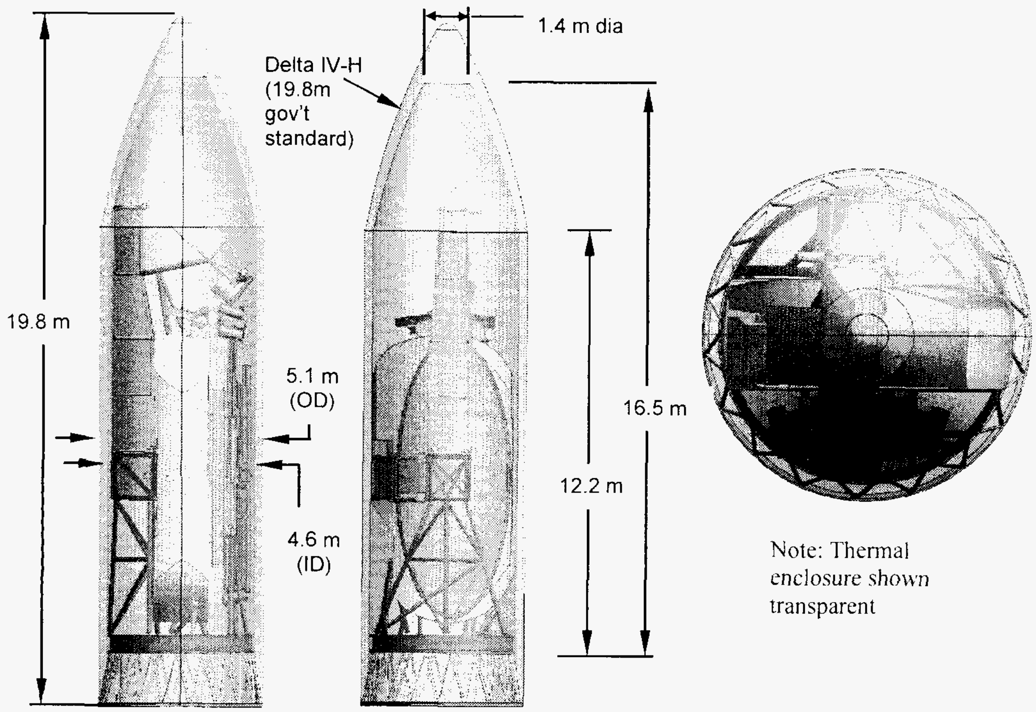

Figure 14. Flight Baseline 1 Launch Configuration (T. Ho)

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