An Infrared Telescope for Planet Detection and General Astrophysics

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ABSTRACT

NASA plans to launch a Terrestrial Planet Finder (TPF) mission in 2014 to detect and characterize Earth-like planets around nearby stars, perform comparative planetology studies, and obtain general astrophysics observations. During our recently completed a TPF Mission Architecture study for NASA/JPL we developed the conceptual design for a 28-meter telescope with an IR Coronagraph that meets these mission objectives. This telescope and the technology it embodies are directly applicable to future Far-IR and Submillimeter space missions.

The detection of a 30th magnitude planet located within 50 milli-arcseconds of a 5th (Visual) magnitude star is an exceptionally challenging objective. Observations in the thermal infrared (7-17 μm) are somewhat easier since the planet is 'only' 15^{m} fainter than the star at these wavelengths, but many severe challenges must still be overcome.

These challenges include:

- Designing a coronagraph for star:planet separations less than or equal to λ/D
- Developing the deployment scheme for a 28m space telescope that can fit in an existing launch vehicle payload fairing
- Generating configuration layouts for the IR telescope, coronagraph, spacecraft bus, sunshade, solar array, and high-gain antenna.
- Providing:
  - Structural stability to within 10 microns to support the optics
  - Thermal control to achieve the necessary structural stability, as well as providing a stable (~30K) thermal environment for the optics
  - Dynamics isolation from potential jitter sources
- Minimizing launch mass to provide the maximum payload for the science mission
- Interfacing to an EELV Heavy launch vehicle, including acoustic and stress loads for the launch environment
- Identifying the key technologies (which can be developed by 2009) that will enable TPF mission to be performed
- Generating a manufacturing plan that will permit TPF to be developed at a reasonable cost and schedule.

Many of these design challenges result in inherently conflicting requirements on the design of TPF. Drawing on our experience with large space telescopes such as the Chandra X-ray Observatory and the Next Generation Space Telescope, we have created a conceptual design for TPF that successfully meets these challenging requirements. This paper describes our solution to these challenges.

1.0 Introduction

This paper describes our conceptual design for a large aperture telescope with an IR Coronagraph that we developed during our mission architecture study for the Terrestrial Planet Finder (TPF) Mission. In addition to its capabilities for planet detection, characterization and comparative planetology, this observatory also has a significant capability for general astrophysics in the 3 to 28-micron spectral region. This architecture is readily scaleable to both larger and smaller apertures, and with minor modifications the present design could also be used at Far Infrared and Sub-millimeter wavelengths.

2.0 The Terrestrial Planet Finder Mission

The TPF Mission is a key element of NASA's Origins program. Now planned for launch in ~2014, TPF is designed to detect and characterize the properties of Earth-like planets in the habitable zones around solar type stars. It will also carry out a program of comparative planetology in a large number of solar systems, studying gas giant and terrestrial planet and debris disks. TPF observing time will also be used to collect important new data of general astrophysics interest.

During its five year mission TPF will search over >60% of the sky for solid bodies with ~ 1 Earth radius and a temperature of ~270K around >150 stars of spectral type F5 to K5. Spectra will be obtained for >5 of the detected objects in the 7-17 micron region, at a resolution of ~20, to look for features due to CO_2, H_20, CH_4 and ozone that could indicate the presence of life. TPF's observing time will be split 50:50 between planet detection and characterization and general imaging and spectroscopy.

3.0 Mission Architectures

During the first phase of our study we examined several different architectures for the TPF mission. These architectures included (1) a >100-meter baseline IR nulling interferometer with a linear array of four 4-meter cryogenic telescopes; (2) a 30-meter cryogenic telescope with excellent mid-spatial frequency figure and a coronagraph with deformable optics; (3) a 30-meter Fresnel telescope with free flying spacecraft for the primary mirror and modules, separated by ~ 6 km; (4) a 100-meter sparse aperture IR telescope with ~100 randomly distributed 2 to 4-meter sub-apertures and a separate spacecraft with the correction optics/coronagraph/sensors located ~500 meters away; and (5) a 70-meter apodized occulter flown in formation with an ~8-meter diffraction-limited visible telescope ~100,000 km away.

From this effort we concluded that (1) the contrast ratio was too severe and the technology development was too challenging for direct detection of Earth-like planets with a visible interferometer; (2) that the contrast ratio in the visible was too severe for the sparse aperture telescope; and (3) that an IR occulter was not practical since the occulter must be very large and very distant from the "camera" telescope.

During the second phase of the study we elected to perform a more detailed study of the IR Coronagraph described herein, while the Ball Aerospace team studied visible coronagraphs, the Lockheed Martin team studied IR nulling interferometers, and the Boeing-SVS studied a “hyper telescope” and an apodized square aperture telescope.

4.0 IR Coronagraph Design Concept

Our conceptual design for a large aperture telescope with an IR Coronagraph is shown in Figure 1. It draws heavily from our previous work for the Next Generation Space Telescope, with a large multi-layer sunshield that allows the segmented deployable telescope and science instrument module to be passively cooled to less than 30K.

The primary mirror consists of 36 hexagonal panels measuring ~4-meters flat-to-flat, arranged in 3 rings around a central opening. Each panel has a thin, gold-coated composite membrane mirror mounted attached to a composite backing structure by 6 rigid body actuators for tip-tilt-piston control, and 7 figure control actuators for control of low-order figure errors. The mirrors are produced with a low-cost replica optics process. The panels’ areal density is ~5 kg/m^2.

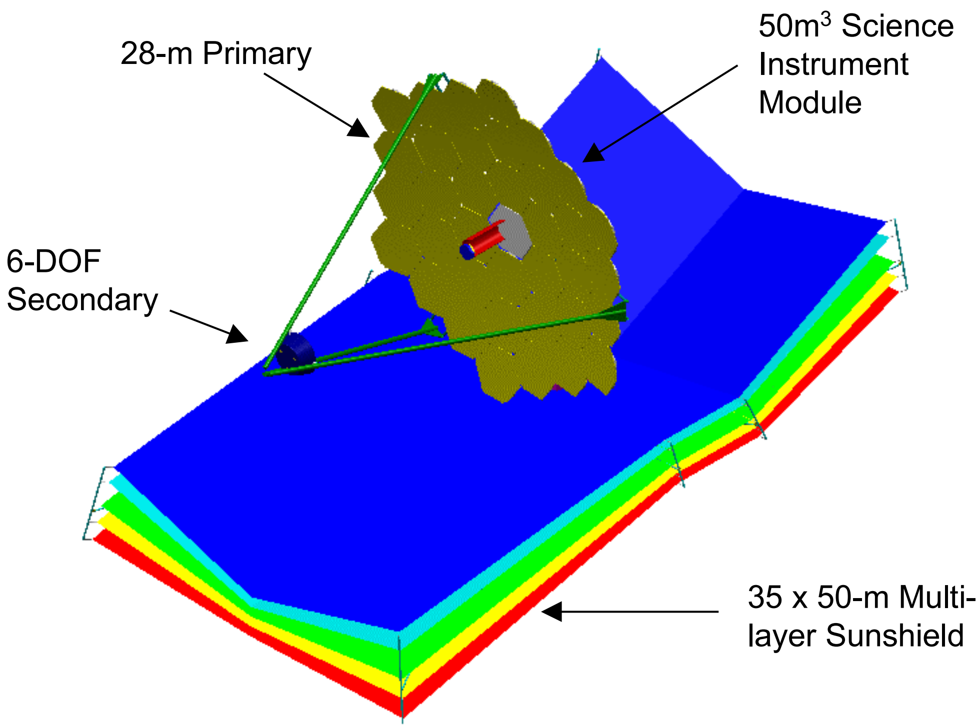

Figure 1. Conceptual Design

A science instrument module (Figure 2) behind the primary houses a coronagraph with an IR imager for planet detection and an IR spectrometer for planet characterization. The coronagraph occupies ~1/3 of the instrument module’s 50 m^3 volume, leaving room for other instruments, such as imagers and spectrometers for general astrophysics observations.

This science payload (telescope plus the SIM) is attached to the sunshade and the spacecraft bus by a deployable mast that also provides thermal and vibration isolation from the ~300K spacecraft with its rapidly rotating gyros and reaction wheels.

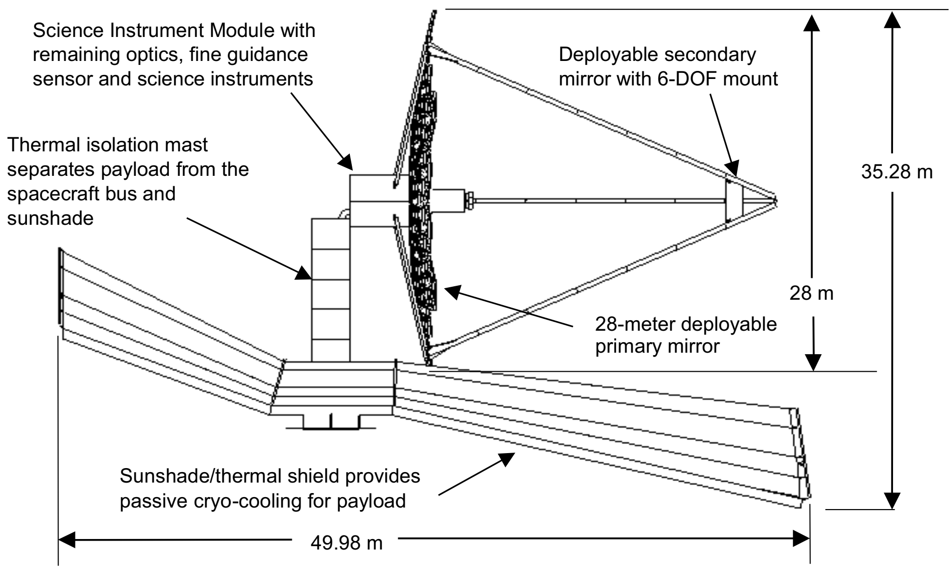

Figure 2. Deployed Observatory (Side View)

The Spacecraft equipment compartment (Figure 3) houses all of the avionics and warm payload electronics. A deployable, non-articulating solar array provides constant electrical power while low gain omni antennas and a high gain dish antenna provide communications with the ground system. Bi-propellant Secondary Combustion Augmented Thrusters (SCAT)s provide propulsion for orbit insertion and station keeping, while hydrazine thrusters provide momentum unloading and backup attitude control. The equipment module has dedicated panels for parallel integration and test. The thermal isolation mast stows in the equipment module's central cylinder.

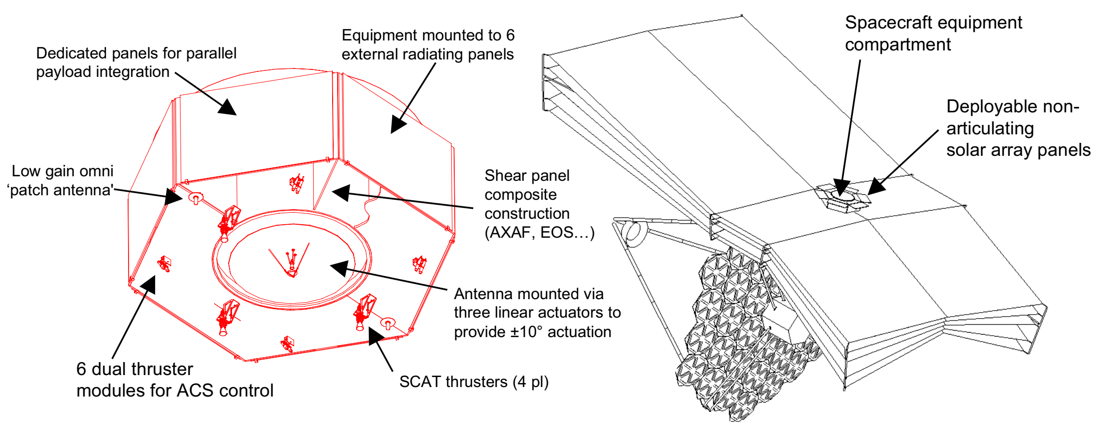

Figure 3. Spacecraft Bus

The entire TPF observatory can be packaged to fit in the fairing of the Delta IV Heavy launch vehicle (Figure 4), which has sufficient lift capability to place it in a transfer orbit to its operational orbit around the L2 point.

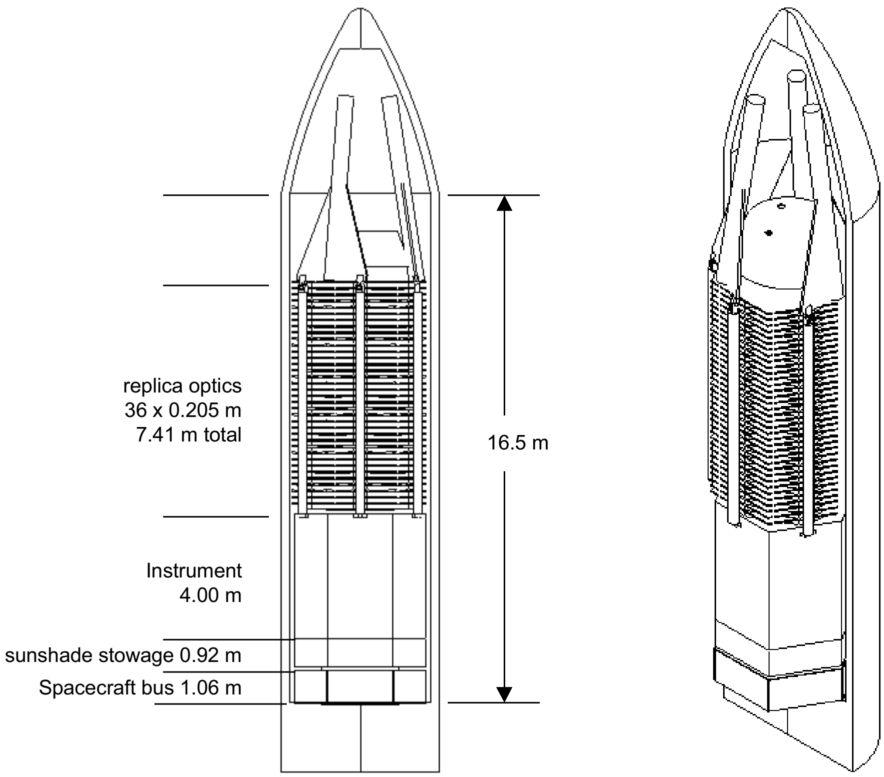

Figure 4. Observatory Stowed in 73.5 foot Delta IV Heavy Fairing

5.0 Deployment

After separation from the launch vehicle's upper stage the spacecraft's solar array panels are deployed, followed by the Optical Telescope Assembly (OTA) and the Thermal Isolation Mast (TIM). The OTA deployment begins with the extension of the telescoping secondary mirror support struts. The struts then hinge in the middle and rotate outward at their point of attachment to the Science Instrument Module (SIM), providing clearance for deployment of the primary mirror. The primary mirror panels are deployed using the approach proven by TRW's highly successful High Accuracy Reflector Demonstration (HARD) Program in the early 1990's. Figure 5 shows how HARD reflector panel stack is raised, rotated, and lowered so that the bottom panel can be latched into place. For TPF this process is repeated until all three rings (36 panels) have been deployed. The secondary support struts are then straightened and latched to the periphery of the primary mirror (see Figure 2). The tertiary mirror, deformable mirror and central baffle that have been stowed in the instrument compartment are then deployed into position with a telescoping mechanism. The final step in the deployment is deployment of the sunshade, using proven mechanical deployment technology developed for large RF antennas.

TPF's 11 deployment systems with 68 elements are not much more complex than those on our Tracking and Data Relay Satellites (TDRS) with 8 systems and 45 elements that deployed perfectly on all 6 flight systems. [In our over 40 years of experience in the design, integration, verification and flight operation of spacecraft deployments we have deployed 672 systems with 1920 elements with a 100% mission success rate].

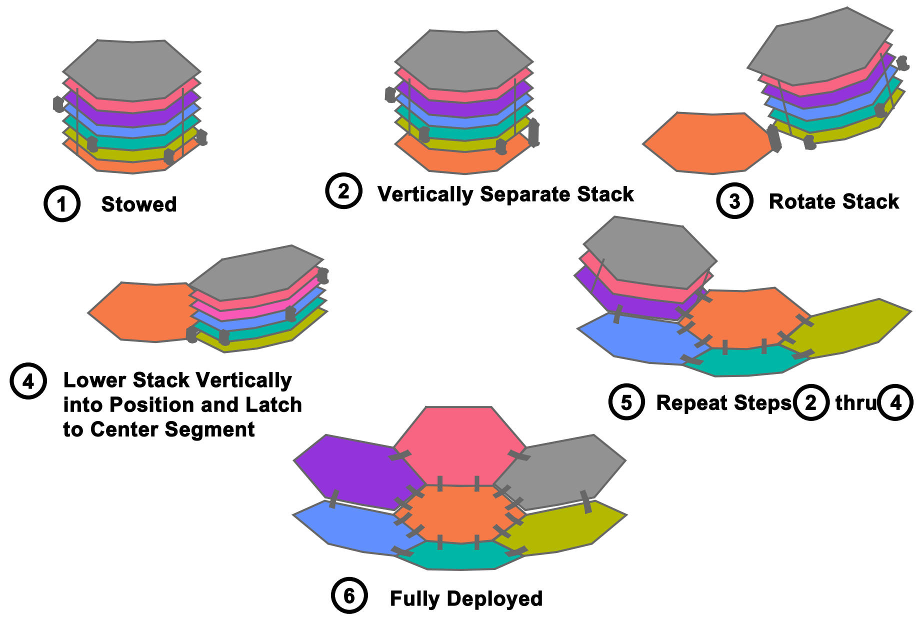

Figure 5. HARD Reflector Deployment Sequence

6.0 Telescope Design

The OTA (Figure 6) is a three-mirror anastigmat (TMA) with a fourth (steerable and deformable) mirror that provides fine pointing and wavefront error correction. The off-axis in field, on-axis in aperture design provides excellent stray light control and well corrected aberrations in the focal plane with residual spot sizes <0.038 x diffraction limit at 7 μm over a 2.4 x 7.2 arcminute field of view. The F/20 optical system provides a plate scale of 0.367 arcsec/mm at the telescope focal plane.

The OTA image quality requirement is diffraction limited at 7 μm (with a goal of 3 μm). In order to minimize scattered light the surface roughness requirement is <10 nm rms (with a goal of 3 nm). The IR coronagraph requires correction of spatial frequencies from ~0.8 to 98 cycles/diameter. Our actuator density study show 7 figure actuators are ample for correcting low order deformations such as RoC, astigmatism and trefoil, and we can use global influence functions to control low-spatial frequencies from 0.5 to 10 cycles/dia. The residual is corrected by the DM with ~200 actuators/dia.

The TMA system wavefront error due to actuator residual errors, static wavefront errors, launch induced errors and on-orbit thermal/structural errors (with contingency) is ~980 nm rms (0.14λ at 7 μm). After correction with the DM the mid-spatial frequency wavefront error is predicted to be 3.69 nm rms.

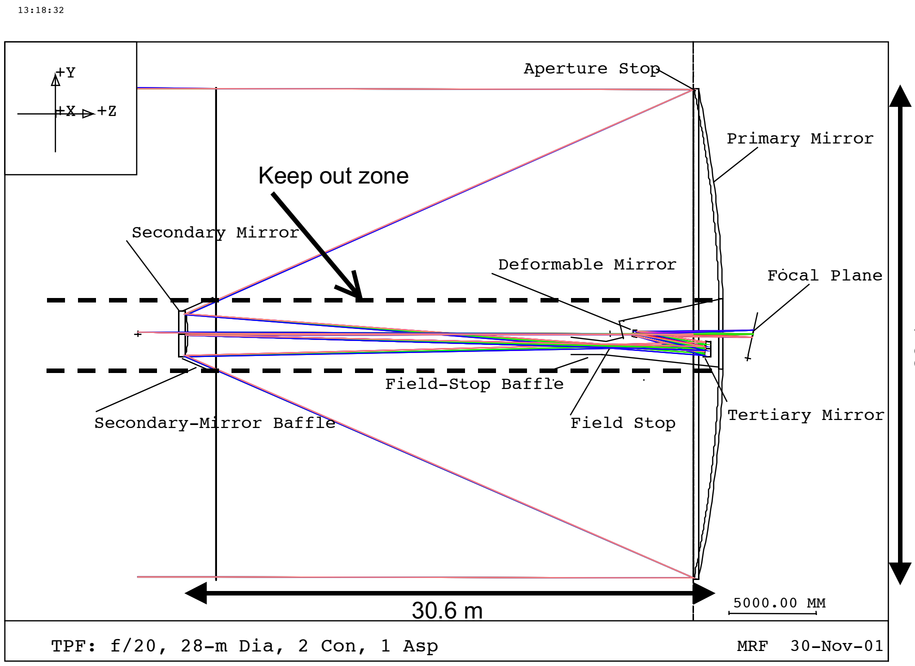

Figure 6. Optical Telescope Assembly Layout

7.0 Science Instruments

Figure 7 lists the science instrument characteristics, including the coronagraph, guide star sensor and the (optional) mid-IR camera/spectrometer. Figure 8 shows the coronagraph's optical layout, including the occulting spot, Lyot stop and the imaging camera. The Fast Steering Mirror is used to correct for jitter-induced line-of-sight pointing errors. These errors are sensed with a quad cell that receives the starlight reflected off the back of the occulting spot. A filter wheel selects the bandpass that reaches the imaging system focal plane and other wheels hold a variety of occulting

	λ (μm)	IFOV (mas)	FPA size (pixels^2)	FOV (as^2)	Comments
Guide Camera (Guide *and* Wide Field / Acquisition modes)	3-5	10 *and* 60	1024	10 *and* 60	HgCdTe likely. Run fast enough to drive the mirror for guiding. Baseline a magnification Guiding Mode. Could be separate units for Mode and Wide Field Acquisition Mode. Based NGST science instrument and guider.
IR Coronagraph	7-17 (5-28)	20	512	10	Base on Eclipse testbed heritage. Filter wheel spot wheel to optimize detection based on type & expected separation; dispersive gratings for low resolution spectra for
IR Imaging Camera / Spectrometer	5-28	60 or 30	1024 or 2048	60 or 120	Largest available Si:As detector. Dual filter CVF, grisms, spectrometer pickoff are all options. Base on NGST MIR camera, and spectrometers.
Optional: Vis/NIR Imager	0.5-5	15	4096 (NGST based)	60	InSb or HgCdTe detector as used for NGST. driven by figure errors of primary mirror. wavelength cutoff driven by mirror

Figure 7. Science Instrument Characteristics

spots and Lyot Stops that enable the coronagraph to optimize its characteristics for each target. Not shown here is the folding flat that feeds a spectrograph similar to the SIRTF Infrared Spectrometer short wavelength, low-resolution module with a micro-shutter device to select the portion of the image that contains the object to be observed.

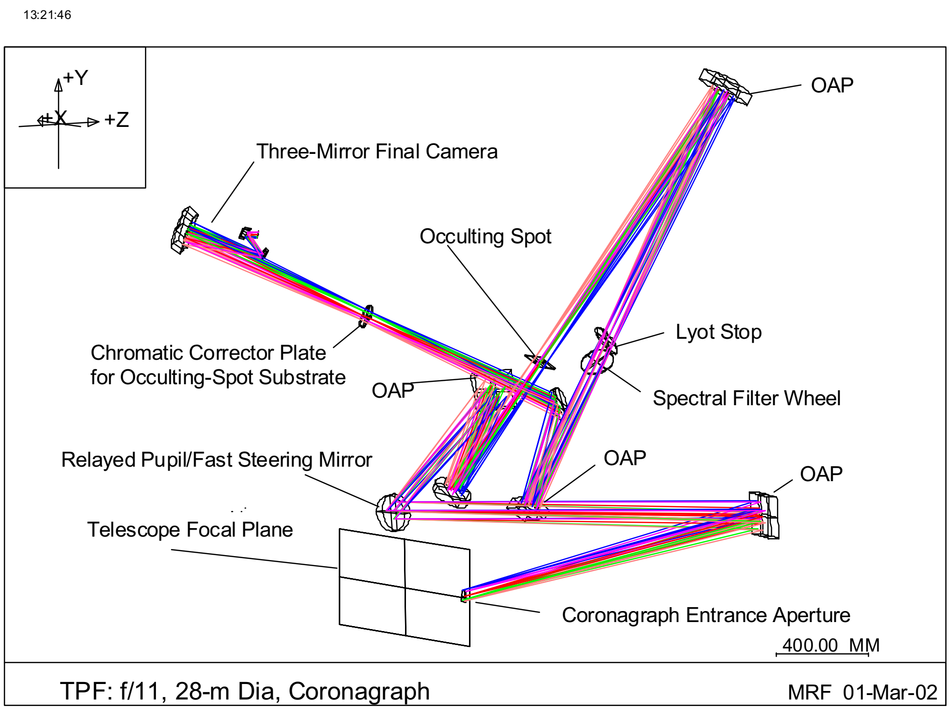

Figure 8. Coronagraph Layout

8.0 Planet Detection and Characterization Performance

Figure 9 summarizes the expected performance of our IR coronagraph for the planet detection, including the input parameters to our performance model and the values

Parameter	Value	Units
Primary Mirror Diameter	28	m
Number of Hexes	36	
Wavelength	10	microns
Integration time	2	hours
Pixels in FOV	512	
IFOV (per pixel)	0.0250	arcseconds
Distance of Star	24.2	parsecs
Overall optics thruput	0.6150	Read from optics
Spectral Resolution	5	λ/ Δλ
Maximum single t_exp	901	seconds (NGST)
Pixel size	30	microns
Instrument temperature	10	K
Optics Temperature	50	K
Exo-zody (factor * Earth)	1	0.1 - 10x

Detector Parameters (from Detector worksheet)		
Dark current 1	30	electrons/sec
Read noise 1	100	electrons
QE 1	0.407	Si:As
Optics emissivity 1	0.1	

Occulting Spot Parameters		
Spot FWHM	80	mas
Attenuation	8	10^x
Lyot stop atten	1.00E-02	on diffraction
Apodized Lyot?	0	1=yes, 0=no

System Parameters		
Mirror panel vibration alloc.	3	mas
LOS error allocation	3	mas

Case	Time to SNR = 5 for R=5, λ=10 μm
Earth @ 10 pc	2.4 hours
Phi2Pav @ 24.2 pc	71.2
DYEri @ 5 pc	0.4
HIP 48113 @ 18.4 pc	12
71 Ori @ 21.1 pc	73.5
HIP 92549 @ 26.1 pc	783 hours, or 101 hrs @ 8 μm, & 17.6 hrs @ 8 μm w/ 60 mas occulting spot

Multiple occulting spots and filters required for detection mission

"Average" integration time per target is estimated to be ~20 hours

Figure 9. System Performance for Planet Detection

assigned to them. We assumed the occulting spot has a log-Gaussian form with its transmission increasing from 10^{-8} at the center to 10^{-4} at a radial distance of 0.04 arcsec (40 mas) and unity at 120 mas. This sharp increase in transmission enables the instrument to detect planets at radial distances of order ~λ/D, i.e.: at ~50 mas at 7 μm and ~70 mas at 10 μm. As shown in Figure 10, at 10 μm, for a solar-type star at 10 parsecs, the background signal from scattered and diffracted starlight is still ~10^4 greater than the signal from an Earth-like planet. Nevertheless, by PSF fitting and/or subtraction of images with different roll angles, it should be possible to detect the planet at a radial distance of 100 mas with a SNR= 5 and λ/Δλ=5 in ~0.8 hours. This integration time increases to ~2 hours at a radial distance of 80 mas and ~5 hours at 70 mas. The integration times to obtain spectra with λ/Δλ=20 and SNR=10 for planet characterization are a factor of ~18 longer.

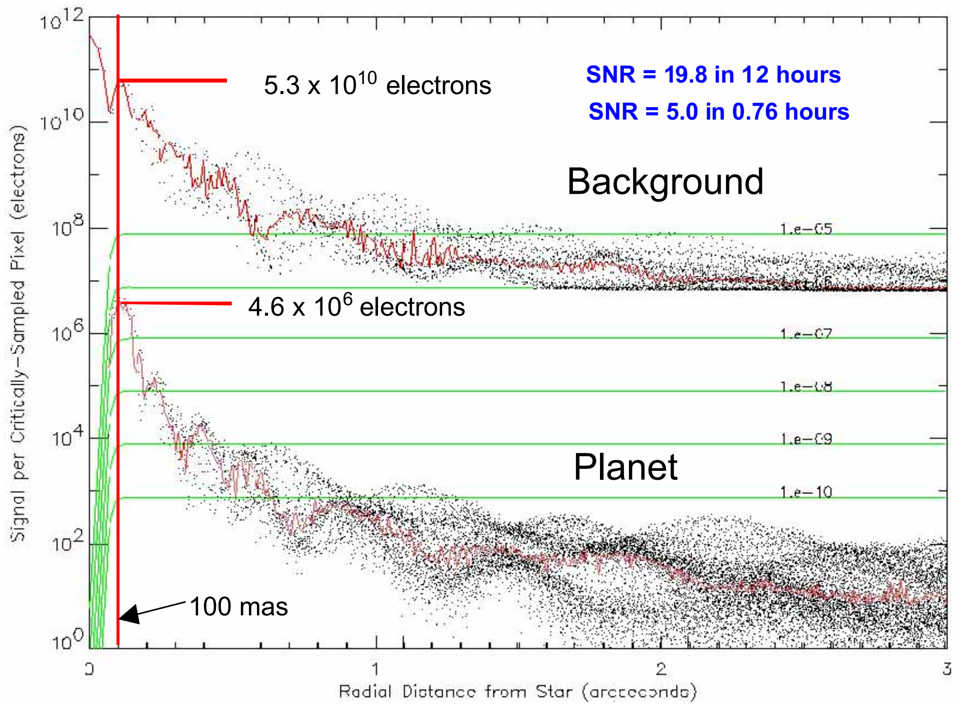

Figure 10. Observed counts per Pixel for a 12 hour Integration

9.0 General Astrophysics Capability

TPF also has a great power for general astrophysics. With an angular resolution of 63 mas at 7 μm, a collecting area of ~490 m^2, a 2.4 x 7.2 arc minute field-of-view, and an average mirror temperature of 21K (and a maximum of 35K) it is well suited for observations in 3 to ~50 μm region. [Since thermal radiation from the spacecraft is the dominant heat source, additional thermal shielding could lower the optics temperature into the 10-15K range]. As shown in Figure 11, TPF's point source sensitivity would be ~10^2 times greater than NGST, ~10^4 times greater than SIRTF, and 10^7 times greater than SOFIA. In particular, TPF could obtain a 5σ observation of a 25-day period Cepheid at J-band at 750 Mpc in ~6 hours; measure IR surface brightness fluctuations at several gigaparsecs; get light curves and spectra of Type Ia supernovae at Z=3; and image super starclusters at Z=19 at an SNR of 10 in 6 hours; study disks and outflows around protostars and disks jets in active galactic nuclei; and obtain spectra of faint galaxies and other faint SIRTF and NGST discoveries.

- TPF point source sensitivity compared with other IR Observatories for
  - Integration time = 10,000 sec
  - Resolution ($\lambda/\Delta\lambda$) = 5
  - Signal to Noise = 5σ
- The 4-m and 8-m NGST and the 28-m TPF telescopes are assumed to have optics with an equilibrium temperature of 35K and emissivity of 0.05
- The zodiacal light background limits NGST and TPF sensitivity for λ<15μm

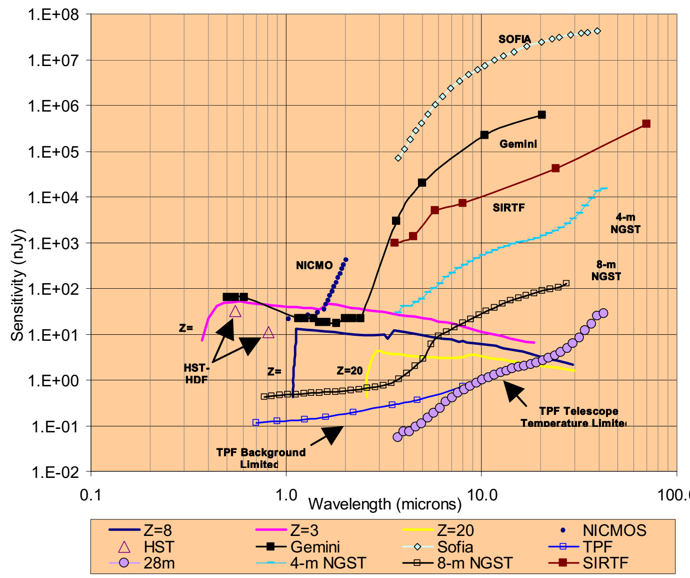

Figure 11. TPF Point Source Sensitivity Compared to Other Observatories

10.0 Key Technologies

The key enabling technologies for our IR Coronagraph are large lightweight optics, high-contrast imaging technologies, large format Si:As detectors, large IR filters and broadband transmissive substrates. Most of these technologies are already being developed for other missions such as NGST, but additional effort is required. Many other NASA programs require similar technologies, including FAIR, SPIRIT, SUVO, Life Finder and Planet Imager. These technologies are currently at TRL 2 or 3. No breakthroughs are required to develop them for TPF, however, just a good engineering effort with reasonable funding.

11.0 Cost and Schedule

The next 4 years of the TPF program will be devoted to technology development, precursor mission(s) development, and pre-phase A studies of two architecture classes leading to selection of a single architecture class in 2006. Two 24-month phase A studies initiated in 2007 will precede downselection to a single prime contractor, followed by a 24-month Phase B and 48-month Phase C/D development effort. We currently envision launch in December 2014. At the TPF Final Architecture Review in December 2001 the four study contractors presented life cycle cost estimates that ranged from ~$1.2B to $1.9B in FY'02 dollars.

12.0 Acknowledgements

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