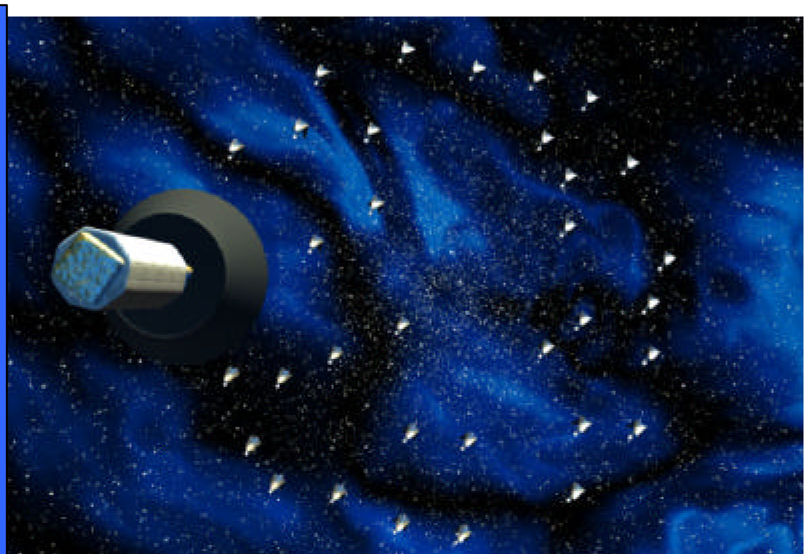
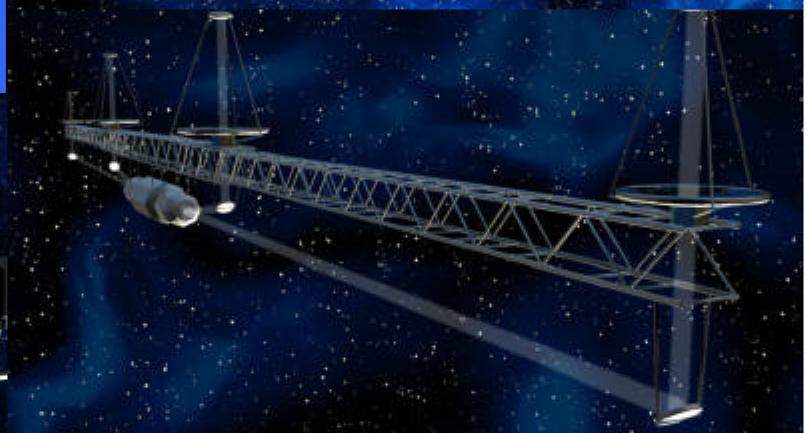
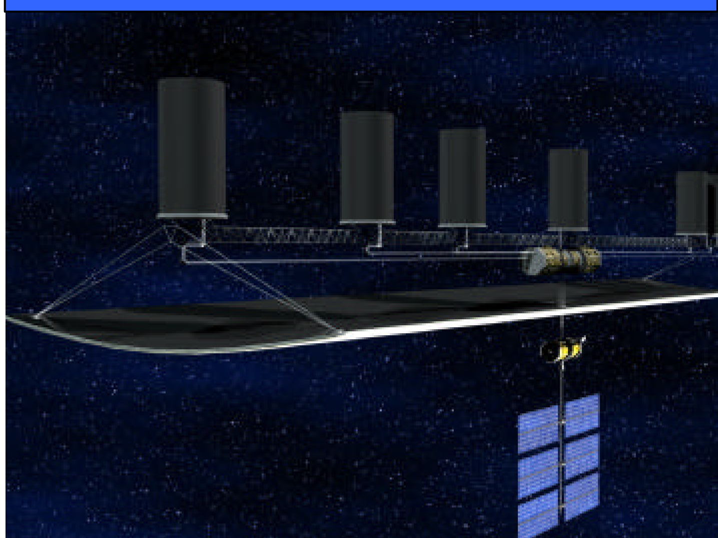
The Boeing-SVS Team Products for the Terrestrial Planet Finder (TPF) Architecture Study Contract

March 2002







Boeing-SVS
4411 The 25 Way
Albuquerque, NM
87109

Questions should be directed to
Ed Friedman
Boeing-SVS
edward.j.friedman@Boeing.com
303 642 8247

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1 Introduction

Boeing-SVS brought together 40 astronomers, planetologists and other scientists from numerous universities and observatories in the United States and France, with engineers and scientists from Aerospace Solutions, Boeing-SVS, Goodrich, Orbital Sciences, Foster-Miller and the University of Colorado. The team revisited the fundamentals of the Terrestrial Planet Finder requirements in an attempt to identify scientific and engineering approaches that would open new parameter space for TPF. Our objective was to develop cost-effective architectural approaches to accomplishing the TPF science.

In a series of group meetings and focus workshops, supported by independent research, the team proposed significant adjustments to the TPF scientific plan and requirements, a change of the TPF program strategy, and several promising new mission concepts.

The reader should note that while a large number of concepts were developed, not all were given the same level of investment. The late introduction of the apodized square aperture (ASA) concept shortened the time available for its development. Therefore, the contract obligation on the part of the Boeing-SVS team was modified by JPL. Therefore, the reader will find that not all topics addressed in the discussion of hypertelescopes are also addressed in the discussion of ASA.

2 Summary of the study results

The team identified the value of a visible wavelength option for TPF. The reflected spectrum region is scientifically critical, and the required spectral diagnostics are available. By exploiting the high angular resolving power achievable with short wavelengths, it is possible to consider TPF mission concepts that are physically similar to other missions under current development, such as NGST.

A true imaging TPF is recommended for its diagnostic power and flexibility in dealing with complex scenes. The potential of such a mission for astrophysics is already strong, so enhancements of the mission for astrophysics are not required or recommended.

To enable TPF mission science, our team explored the techniques of pupil densification, generalized coronagraphy, and pupil optimization.

Implementations of these techniques were proposed: one and two-dimension hypertelescopes, and ASA telescopes. The engineering studies in Phase II showed that these concepts are feasible, in both full TPF missions (capable of delivering all of the TPF science) and in TPF-Lite configurations, appropriate to a staged TPF study. Key technical developments identified in the report will advance the feasibility of TPF and confidence in TPF planning.

3 Phase I – Reviewing TPF Requirements, Evaluating Enabling Technologies and Developing Concepts

The range of available TPF technologies is large. Only a broad view of the science goals and challenges will fully illuminate and prove the possible mission concepts. The Boeing-SVS team's first efforts were directed toward a reexamination of the TPF objectives. We found that the TPF science program is likely to require several types of precursor missions and supporting data. We further concluded that the detection and characterization of earth-like planets could be carried out with several techniques in wavelength ranges from the visible to the mid-infrared.

3.1 A reexamination of TPF requirements

The major steps in accomplishing the TPF science program are; target selection, detection of candidate planets, confirmation of candidates, and characterization of detected planets.

3.1.1 Favorable wavelengths for planet search and characterization

The initial focus of TPF mission studies on the thermal infrared was strongly supported by the favorable contrast ratio between planet and star, and by the valuable selection of diagnostic molecular bands. However, the angular resolution achieved for a given optical instrument size is smaller than for shorter wavelengths, hence a mid-infrared mission must present difficult size and control issues. Further, study of exosystems in emitted thermal light will not reveal precious information contained only in the reflected light.

At the opposite end of the spectral range considered, visible light allows higher angular resolution from a fixed system size. This resolution can be employed to alleviate the further reduced contrast ratio. Availability of well-developed components and conventional optical systems is a potential advantage.

Based on our review of the TPF goals and the expected and possible planetological characteristics, we advocated in December 2001 to the Science Working Group (SWG) the visible-near infrared region for some mission concepts. Following further review, the SWG Biomarkers Subcommittee supported this extension in its report (Des Marais et al, 2001).

3.1.2 Planetology issues

The field of planetology is well developed through study of the solar system. This experience can be a critical guide, provided its relevance is not exaggerated. Exosystems may present familiar or dramatically unfamiliar physical and evolutionary scenarios.

3.1.2.1 Temperature and Energy Budget

The widely adopted criterion for defining a habitable zone (HZ) is the temperature range that allows liquid water. The effective temperature of a planet, the primary temperature indicator available from the mid-infrared spectrum, may not reveal the surface temperature of a planet. For example, the effective temperatures of Venus and Earth are both below the "habitable" range, whereas the surface temperature of the Earth is in the habitable range and the surface temperature of Venus is far above it!

Reflection spectra may reach deeper into dense atmospheres. Detected molecular species and spectral bands may offer a measure of excitation temperature and equilibrium abundances under near-surface conditions. Eventually, both reflection and emission spectra will be required to build up an integrated knowledge of planet diameter, albedo, and energy budget.

3.1.2.2 Biomarkers

The topic of biomarkers has been extensively reviewed in the Des Marais report (2001). An important conclusion is that evidence from a wide range of wavelengths will be important in determining and confirming the existence of earth-like planets, and of their habitability. Wavelengths from the visible through the mid-infrared may be reasonably considered for the TPF mission or for the first in a phased sequence of missions. The visible/near IR wavelengths include a full range of biomarkers; water; molecular oxygen and ozone. We propose a mission that can detect these diagnostics.

3.1.2.3 Secular and Seasonal Variations

As planets rotate about their axes and revolve around their stars, the planets' emitted and reflected light will provide much information about their characteristics. Except in the rare pole-on orbital orientation, as a planet progresses through its orbit, the aspect ratio of the illuminated portion of the planetary disk will change. The detected thermal emission will be the sum of the emission from the illuminated side and the "dark" side. As the ratio of apparent surface areas changes, the total flux and flux ratios will change. This may be interpreted in terms of the thermal capacity and time constant of the illuminated layers. In the reflection spectrum, the illuminated side will dominate the detected flux. Measurements of color and the polarization in reflected/scattered light, and their variation with phase angle, potentially reveal information about the composition of cloud layers.

3.1.3 Detection issues

Given the very low flux level of earth-like planets at the typical distances of nearby stars, there will be a variety of potentially confusing sources. The importance of these, and the time lost on them, will certainly be reduced if planets are common, and heightened if planets are rare.

In estimating the significance of confusion, it is important to consider the likely sequence of observations. In the most general case, we may not know if a star has a planetary system. An earth may not be readily detectable – for the typical system, with an orbit at arbitrary inclination to the line of sight, a planet may be unresolved from the star during part of its year. Thus, a first question will be whether there is a planetary system at all. This will be determined from the presence or absence of planets out to some maximum distance much greater than the diameter of a terrestrial planet orbit.

3.1.3.1 Background stars

Within 30 degrees of the galactic plane, background stars brighter than an earth at 10 pc will appear within the orbit of a standard Jupiter for 1/50 of all candidate systems at 10 microns, and for 1/5 of all candidate systems at 0.5 microns. The apparent relative angular speeds of these stars will overlap the range of apparent speeds of true planets. At least three observations with detections will be required to detect orbital, as opposed to, uniform relative motion. Spectral distributions, however, will be very different and a broad spectral coverage may readily identify stellar objects.

3.1.3.2 Asteroids

Within 10 degrees of the plane of the ecliptic, during a ten hour exposure, we can expect 10 asteroids much brighter than an earthlike planet to pass through the field of view. The apparent speeds will be high, and the response of the detection system to real but transient events must be considered.

3.1.3.3 Galaxies

Faint, distant galaxies will be numerous and the most significant potential source of confusion. This is a motivation for a true imaging TPF, as many galaxies will be well resolved. Unfortunately, some primeval galaxies may have a point-like appearance due to bursts of star formation or other early phenomena. Galaxy spectral distribution may mimic planet spectral distribution. At least three detections will be required to distinguish such sources from planets by apparent motions.

3.1.3.4 Confusion with exo-system sources

3.1.3.4.1 An abundance of Planets?

We may hope (and even have reasons to expect) that exo-planet systems may be numerous and richly populated. This could be a source of confusion. Planets may have unexpected orbital characteristics (eccentricity, non-planarity). TPF may study these systems at the limit of detectability, and planets may become visible or invisible as they approach or recede from the star, as their projected angular distance from the star becomes small, or as the orbital phase results in a modulation of their apparent brightness. A series of snapshots, which may not be at optimum intervals due to TPF pointing limitations, may reveal a confusing sequence of planet detections that are difficult to correlate.

3.1.3.4.2 Peculiar Planets

Even in the solar system, planetary rings are ubiquitous among the gas giant planets. They may be common in exo-systems. We can also imagine dust rings around terrestrial planets. The rings of Saturn are comparably bright to the planetary disk. Ring brightness will be modulated strongly by phase angle, and ringed planets could appear “dark” in reflected light in some orbital positions. Seasonal changes in surface albedo (frosts, ices) or cloud cover could similarly modulate detectability in unexpected ways.

3.1.3.4.3 Comets

Comets are not very large or abundant in our sun's habitable zone, but they may have been in the past, and they may be in other systems. Bright comets are comparable to the Earth in integrated flux, and could be confused with planets from a distance.

3.1.3.4.4 Zodiacal Dust Clumps

Zodiacal dust is present in the solar system, and the distribution is significantly structured in both radial and azimuthal directions. Clumping mimics orbital motion and spectral distribution of rocky planets. It may be possible to correctly interpret such signatures from the overall zodiacal light patterns, from spectral features or lack of them, and from correlation with other planet candidates.

3.1.3.5 Candidate exo-systems

It is important to recognize that the habitable zone is defined by the local conditions of stellar type and planetary orbit radius. The apparent angular extent of the HZ, a critical factor in the selection of stars suitable for study, can vary in ways that are not related to the distance from the observatory to the planetary system. A bright star at 30 pc could have a HZ of much larger angular extent than a system with an M star that is much closer.

The detectability of an exo-planet can vary significantly from one TPF concept to another. For example, a sensitivity-limited concept might operate well for nearby M stars (with small HZs) and poorly for distant F stars (with large HZs). Therefore, the TPF SWG recommended that each concept should select the best 150 stars (from a range of spectral types) for each proposed concept. With this science oriented formulation of the requirement, it is not necessary (and is even inappropriate) to compare concepts simply based on performance for a particular test case or to a given distance.

3.1.3.6 Detection criteria

The potential for confusion in exo-planet detection is great – possibly greater than we can appreciate at this time. For this reason, the pattern of observations for confirmation and characterization should probably follow a pattern that might be redundant for a simple system. A number of observations with a number of time intervals, from short to long, may be best suited to carrying out a census of exo-systems and confirming earth-like members. Although the primary scientific goal of TPF concerns terrestrial planets, it is critical to appreciate that the identification and understanding of habitable planets requires the detection and study of complete exo-planet systems. Other components of the system may offer, initially, confusion and eventually supporting diagnostic information on the nature and status of possible terrestrial planets.

The likely difficulty and complexity of exo-planet and TPF studies, and our review of sources of confusion leads us to the conclusion that true imaging systems (classical or aperture synthesis) offer significant advantages for TPF. These advantages include improved discrimination against nearby sources (including binary companions and background stars), improved discrimination against exo-zodiacal light, and diagnostic power in the evaluation of complex images and exo-system configurations and phenomena.

3.1.3.7 Astrophysics

The observing facilities that we recommend to carry out the TPF mission offer true imaging capability, over a significant field of view, with a capability to achieve dynamic ranges appropriate for planet detection. Whether operating in the visible/near-infrared or the mid-infrared (both satisfactory for TPF) these facilities offer extraordinary power for other observations in astronomy and astrophysics. The high dynamic range and high angular resolution combination will be unique and unprecedented. *Within one arcsec from a bright source, TPF will have 3 - 5 orders of magnitude less stray light than NGST*

The accompanying list shows a selection of extra-galactic and galactic topics that will amply exploit the remarkable TPF capability for high dynamic range imaging. Many of these were discussed in our Preliminary Architecture Review contributions.

- Extra-galactic Astronomy
  - What is the nature of quasar host galaxies?
  - How are quasars and starburst galaxies related?
  - Are quasars born in mergers or through other processes?
  - Do orientation effects account for the diversity of AGNs?
  - What determines whether a quasar is radio-loud or -quiet?
  - What is the dark-matter distribution in lensing galaxies?
  - Are damped Lyman Alpha systems protospiral galaxies?
- Galactic Astronomy
  - Differentiate between brown dwarfs and giant planets
  - Determine the mass & luminosities of binary white dwarfs
  - Map the mass loss from Mira variables and AGB stars
  - Observe the changes in outflow symmetries as AGBs age
  - Image the environs of T Tauri and other young stars
  - Study the mass exchange in symbiotic variables
  - Follow the outflow in cataclysmic variables

In our view, the intrinsic TPF requirements, if satisfied with a true imaging system, offer an exciting astrophysics capability. No augmentation or optimization is required for this component of the TPF mission.

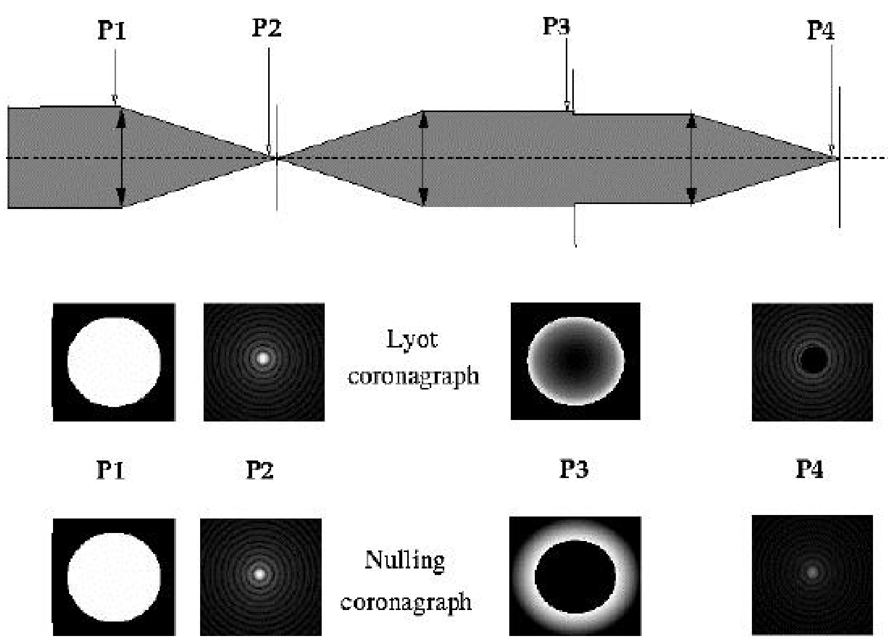
Our philosophy is simple. A true imaging TPF would immediately have outstanding capability for general astrophysics, and could be applied to the many specific programs mentioned above. No enhancement of the mission is required beyond the basic TPF requirements in order to make it astrophysics-capable. This is true for our visible and infrared concepts, and for precursors as well as full TPF implementations, taking into account wavelength ranges, angular resolution, dynamic range, field of view and spectral resolution.

3.2 TPF Enabling Technologies

The essential requirement for a TPF observation is the detection of a faint point source close to a bright quasi-point source. The Boeing-SVS team members undertook a review of techniques for suppressing bright point sources in imagery, and in the course of this review, further refined techniques that they had developed in the past and invented a number of new techniques. In the following, literature references are to team member publications. A list of those papers published during the study follows below.

3.2.1 Coronagraphy and related techniques

Coronagraphy is a well-known but rarely used method for the suppression of a bright source. Classically, it is implemented with a mask in the image plane that blocks the light of the bright



Roddier coronagraph-The phase mask coronagraph compared to the classical Lyot coronagraph.

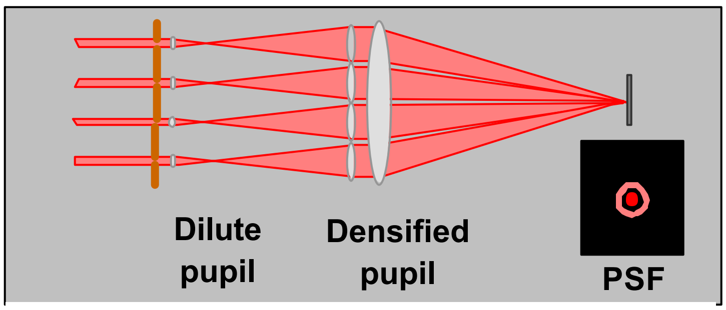
source. A mask in a subsequent pupil plane then blocks the light diffracted from the mask. Strong suppression requires a relatively large mask, of order 3 times the resolution element of the telescope.

Our team members developed several generalizations of classical coronagraphy, based on the use of a phase mask instead of an amplitude mask. The phase mask coronagraph is far more efficient than the classical coronagraph. The mask is transparent, the required size is smaller than the telescope resolution element, and the throughput of the associated Lyot stop is higher.

These phase masks actually allow observation of an adjacent source within slightly less than one resolution element of the suppressed bright source. Variant techniques (circular mask, quadrant mask (Rouan et al, 2000, Riaud et al, 2001), circular mask (Guyon et al, PASP 111, 1321) and phase knife (Abe et al, 2001)) offer additional optional tools.

3.2.2 Hyper telescopes and pupil densification

In the mid-infrared, an affordable TPF would certainly consist of an array of telescopes. The beam combination for telescope arrays can be configured to form a direct, real image. However, except for very high filling factors (nearly a filled aperture equivalent), the point spread function (PSF) will have large, complex side lobes that will interfere with faint source detection. The densified pupil technique was invented to deal with this circumstance. Densification consists of rearranging the pupil so that the spacing between beams is smaller, before forming an image. Quite non-intuitively, this produces a compact, clean PSF but with a reduced isoplanatic field of view. Several techniques were developed to deal with the limitations of this kind of measurement. The hypertelescope has the strong advantage that it can be further developed and generalized to programs beyond TPF, such as Life Finder and Planet Imager.



Pupil densification-Illustration of the pupil densification concept, which produces a compact, high Strehl PSF from a dilute telescope array.

A telescope array can also operate in an aperture synthesis mode, measuring image parameters in the Fourier transform plane. The data can be computer processed to reconstruct the image from the spatial frequencies. Computer processing performs numerically the same step that a lens performs analogically, and in the case of full UV coverage, provides an equally valid image. For TPF, the major challenge of an aperture synthesis array is to develop a concept that enables full coverage of the spatial frequencies with a modest number of telescopes and a reasonably compact configuration.

Our team members identified an optimization procedure and tabulated 2-d and 1-d configurations as a function of the number and size of unit apertures (Guyon and Roddier, 2001).

3.2.3 Pupil optimization

Team members developed the Apodized Square Aperture (ASA) concept (Nisenson et al, 2001) at the first team meeting. A square aperture concentrates diffracted light along orthogonal axes, leaving a greatly reduced diffracted level in the rest of the image plane – the diffraction along the diagonals falls off as R^4. A strong, optimized apodization composed of crossed 1-d apodizing functions perpendicular to the aperture edges further suppresses the diffracted light. Diffraction in the region around the diagonals is down more than 10^8 – the strong suppression of diffraction persists to small inner radius (a few times ? /D) and close to the diffraction spikes.

The combination of square aperture and apodization offers the potential to develop a TPF that is remarkably similar to a conventional telescope. The strong apodization results in a configuration that is very forgiving to deviations from the ideal square aperture and not very sensitive to wavefront errors at the aperture edge (where they are hardest to control). Numerical techniques can be employed to synthesize or complement pupil apodization (Aime et al, 2001).

3.2.4 Observational Techniques

The TPF will only be possible with very high wavefront quality. Any residual wavefront errors will appear as a speckle pattern in the focal plane. Recently, it has been understood that the speckle pattern – a microscopic effect – may be stable in the presence of macroscopic changes. If this pattern is stable, it can be subtracted out. This exciting area continues to develop rapidly. For example, it has only recently been understood that a low-order expansion of the wavefront error reveals simplifications to the speckle pattern (Boccaletti et al, 2002). Part of the pattern is correlated with the diffraction and is anti-symmetric, and part is associated with the diffuse halo and is symmetric. These relations can be exploited to calibrate and correct for speckle structure in the image post-processing. Our team members (Guyon et al, BAAS 197, 5209) have also demonstrated, on the Gemini 8meter telescope, suppression of long-lived speckle by telescope rotation.

3.2.5 Published papers

- *Snapshot coronagraphy with an interferometer in space*, Boccaletti, A. et al, 2000, ICAR **145**, 628.

- *Refined laboratory simulations of dark-speckle coronagraphy*, Boccaletti, A., Moutou, C., and Abe, L., 2000, Astronomy and Astrophysics Supplement **141**, 157.

- *First images on the sky from a hypertelescope*, Pedretti et al, 2000, Astronomy and Astrophysics Supplement **147**, 285.

- *Speckle Symmetry with High-Contrast Coronagraphs,* Boccaletti, A., Riaud, P. and Rouan, D., 2002, Publications of the Astronomical Society of the Pacific **114***,* 132-136.

- *The Four-Quadrant Phase-Mask Coronagraph. I. Principle*, Rouan, D. et al, 2000, Publications of the Astronomical Society of the Pacific **112**, 1479.

- *The achromatic phase knife coronagraph*, Abe, L., Vakili, F., and Boccaletti, A., 2001, Astronomy and Astrophysics **374**, 1161.

- *Interferometric apodization of rectangular apertures. Application to stellar coronagraphy*, Aime, C., Soummer, R., and Ferrari, A., 2001, Astronomy and Astrophysics **379**, 697.

- *Stellar coronagraphy with a redundant array of telescopes in space: The multiple mask coronagraph*, Aime, C., Soummer, R., and Lopez, B., 2001, Astronomy and Astrophysics **370**, 680.

- *Direct exoplanet imaging possibilities of the nulling stellar coronagraph, Guyon, O., and Roddier, F., 2000,* SPIE **4006***, 377.*

- *Aperture Rotation Synthesis: Optimization of the (u, v)-Plane Coverage for a Rotating Phased Array of Telescopes*, Guyon, O., and Roddier, F. 2001, Publications of the Astronomical Society of the Pacific **113**, 98.

- *Detection of Earth-like Planets Using Apodized Telescopes*, Nisenson, P., and Papaliolios, C., 2001, Astrophysical Journal **548,** L201.

- *The Four-Quadrant Phase-Mask Coronagraph. II. Simulations*, Riaud, P. et al, 2001, Publications of the Astronomical Society of the Pacific **113**, 1145.

- *Total Coronagraphic Extinction of Rectangular Apertures Using Linear Prolate Apodizations,* Aime, C., Soummer, R., and Ferrari, A., 2002, Astronomy and Astrophysics (submitted).

3.3 TPF Concepts

In Phase I, the Boeing-SVS team studied several concepts. Three of the concepts are telescope arrays. Arrays of the sizes that are required for a mid-infrared TPF (many tens of meters) could be either connected with a structure or free flying. Up to some size, a connected structure should be less expensive. Since the TPF targets require different angular resolutions, a free-flyer array may offer valuable flexibility. One of the team goals was to determine if a connected array would be viable and cost-effective for TPF.

One filled aperture concept was evaluated. The team goal in this case was to show that a visible wavelength, filled aperture concept could achieve the TPF science.

For each proposed mission concept, the rejection of the bright star was approached differently, using techniques developed by team members specifically to enable exo-planet detection.

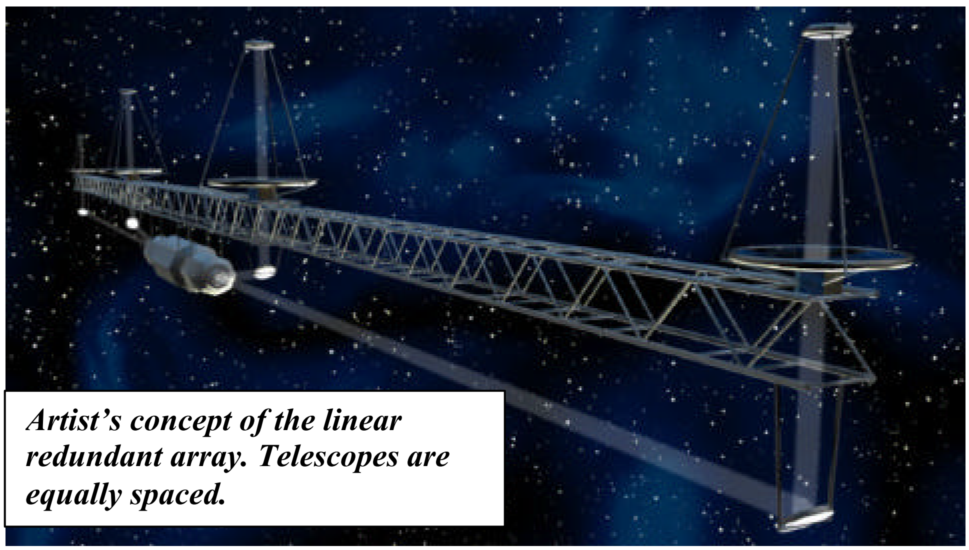
3.3.1 Linear redundant connected array

A linear array offers a good combination of compact structure and high angular resolution. With complete redundancy (equal spacing between unit telescopes), the side lobes of the PSF fall on top of one another. The central source and all of the side lobes can then be nulled with a multiple phase mask coronagraph tailored to the side lobe spacing (Aime et al, 2001). Due to the inherent

1-dimensional symmetry of the array, spectral dispersion along the orthogonal axis offers a natural solution to the chromaticity of the mask. The phase knife coronagraph is well suited to this application (Abe 2001).

For low filling factors, the redundant array does not offer complete coverage of the spatial frequencies. Image reconstruction is achieved through tomographic and related techniques. The redundant array could be implemented in visible or infrared spectral regions. The concept was not developed to the point of simulating TPF measurements. However, modeling of the optical rejection performance indicated that the required dynamic range was within reach.

3.3.2 Laser-trapped mirror



Artist's concept of the linear redundant array. Telescopes are equally spaced.

The laser trapped mirror concept employs appropriately shaped beam launchers projecting tunable laser beams in opposite directions to produce a system of paraboloidal fringes. Exploiting a phenomenon similar to the commercial technique of "optical tweezers", reflective particles are trapped on the fringe. The trapping of particles in the laboratory has demonstrated that the particles "self organize" due to photon scattering. Cyclic tuning of the laser wavelength is expected to collapse the particles to the zero fringe.

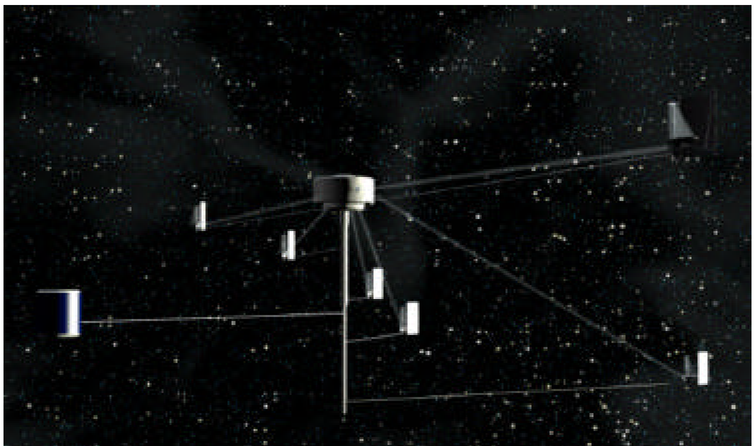
A major strength of the concept is the opportunity to deploy very large apertures with low mass (100 milligrams of reflective material per square meter). The cost of scaling up in size is very low. However, much basic work remains in order to understand the properties of "optical matter". The team recommends further work on laser trapping, in the hope that it will eventually mature to a stage of readiness for a demonstration in space.

3.3.3 2-d Non-redundant connected array

For complete coverage of spatial frequencies, a non-redundant or minimally redundant array offers the most efficient configuration. In Phase I, we studied a 2-dimensional non-redundant array. The method adopted for rejection of the bright star exploits several of the techniques described above. This concept was developed as a continuation of work begun by team members several years before the Phase I contract.

The light from the unit-telescopes is combined, with rearranged pupils, to provide a nearly filled densified pupil, which is then apodized. This pupil forms an image. A coronagraph phase mask and subsequent pupil stop reject the bright star with high efficiency.

The pupil is then rediluted to its original configuration, and used to form a real image. This image has the complex PSF of the original pupil. The image is formed on an array detector. As the telescope rotates about the line of sight, snapshot images are recorded with short exposures (short enough to avoid blurring the spatial information). The Fourier transform of each image yields the spatial frequency components of the snapshot. Since the telescope configuration is known, the spatial frequency data can be filtered to reject noise outside the domain of real spatial information.



A concept for a 2-d non-redundant array, to be configured for operation as a hypertelescope with pupil densification.

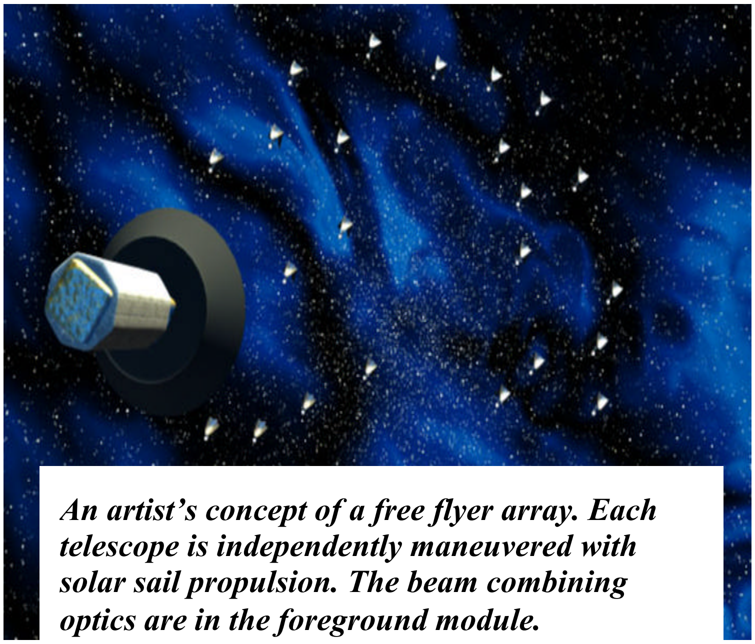
A set of images at consecutive rotational angles gives the complete spatial frequency coverage for image synthesis. The de-rotated images can be processed to derive the image of the stellar leakage (from an imperfect mask, pointing errors, aberrations, etc) for improved dynamic range.

The non-redundant array provides robust data with a high degree of internal diagnostic information for calibration and compensation.

In Phase, I the team studied a connected non-redundant 2-d hypertelescope array. The array was constructed on a truss, or connected with spars and tethers. Simulations of the star rejection and optical/numerical image processing showed that the technique could yield the required dynamic range and sensitivity with modest total collecting area.

3.3.4 2-d Free flyer array

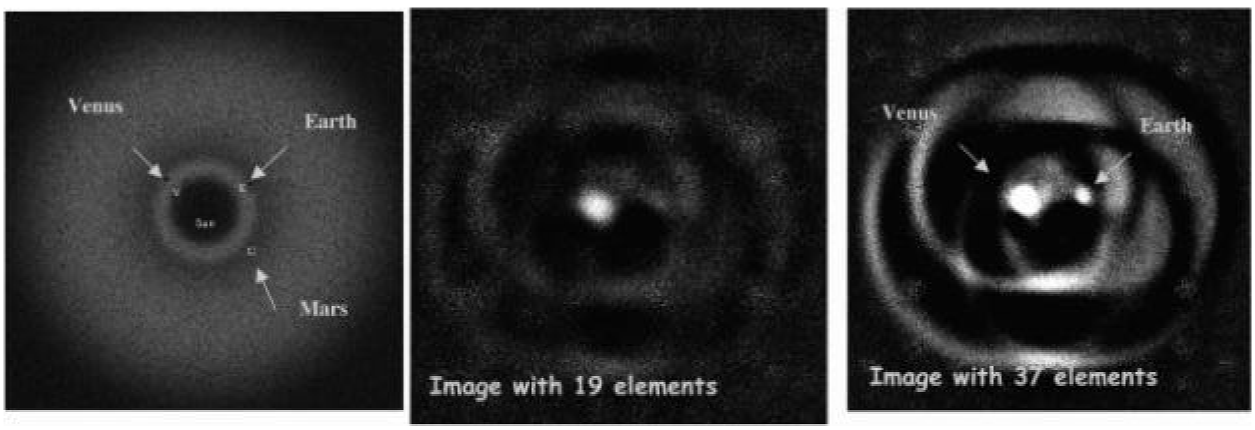
A free-flying array offers great flexibility. Members of the team continued investigation of a family of free flyer hypertelescope concepts that they had developed for several years (e.g., Labeyrie et al, A&AS 118, 517). The concepts are characterized by a substantial number of free-flying telescopes (nominally 37 in an extensively modeled configuration). With this number of telescopes (or more), pupil densification yields a field of view that is directly useful for TPF and astrophysics, without the re-dilution employed for a smaller number.



An artist's concept of a free flyer array. Each telescope is independently maneuvered with solar sail propulsion. The beam combining optics are in the foreground module.

The central problem of free-flying telescopes is maneuver and control. Solar-sails and laser metrology are recommended, and team members described possible configurations, metrology and control schemes.

An intriguing option for free-flyers is the availability of alternate beam combining and instrument stations, optimized for different wavelengths. Instrument design was developed primarily in the visible, including wavefront correctors for use with spherical primary segments, coronagraphic star suppression, and multiplexed spectroscopic detection.



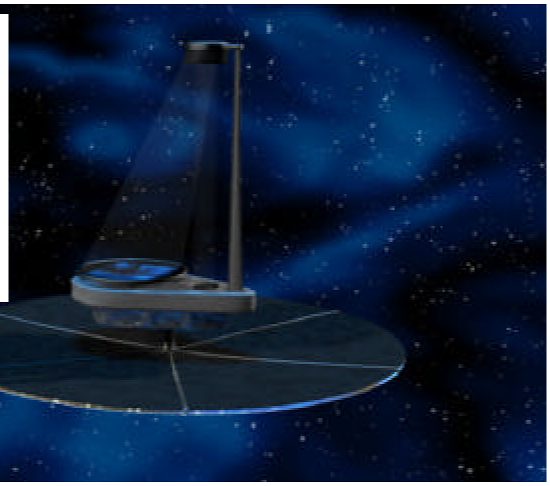
Simulated detection of exo-planets with both 19 and 37 aperture hypertelescopes. Noise levels and PSF are based on models of the optical performance. The left panel shows the simulated solar system.

Numerical simulations of image formation with the 37 aperture densified pupil array shows that the required TPF sensitivity can be achieved with modest unit-telescope apertures.

The free-flying hypertelescope array requires development of several challenging technologies, but is the least constrained in ultimate potential performance, as the unit apertures, the number of apertures and the array size can all be scaled up with little conceptual change.

3.3.5 Apodized square aperture

The combination of aperture shape and apodization that we call the Apodized Square Aperture is distinctly different from array configurations. It is a filled aperture telescope. The cleanest implementation employs an off-axis primary, so that the pupil is free of diffracting edges. Otherwise, it looks and acts much like a conventional telescope. The preference for a filled aperture leads us to naturally propose implementation in the visible, where the required angular resolution can be achieved with reasonable size telescopes.



Artists conception of square aperture telescope and spacecraft. The spacecraft and telescope are protected from sunlight by a disk-shaped sunshade

The ASA concept relies on a high quality wavefront to provide high dynamic range. In the simplest implementation, there is no exotic star suppression device. The bright star simply falls on one region of the image plane and the faint source on another. Laboratory demonstrations with test sources exploring the appropriate dynamic range show that this actually works. The relative simplicity and low cost of the demonstrations encourages us that the path to a TPF implementation may be relatively quick and trouble-free. A nearly conventional telescope also promises fewer spacecraft, control developments, and a straightforward application to astrophysics observations.

The ASA is surprisingly tolerant of low and very high frequency wavefront errors that "scatter" light into the image core or to the far wings. However, it requires very tight control and stability of the mid-spatial frequencies.

3.4 Team Evaluation and Prioritization of Concepts

The Boeing-SVS team determined that the most promising concept for rapid development and deployment as a TPF is the Apodized Square Aperture, operating in the visible. This concept was the team's first choice for study in Phase 2 of the contract.

The team's second choice was a Non-Redundant Linear Array, operating in the mid-infrared. This array fully satisfies the TPF requirements and offers a powerful technique for generalization and future exploitation in much more difficult programs, such as Planet Imager.

3.5 TPF Strategy

At the beginning of our study, the TPF mission carried a large burden for both planet discovery and study. Following our review of the science requirements, the available technology and the possible concepts, the Boeing-SVS team recommends that the TPF study of terrestrial planets be considered as a possible series of missions, in which initially simpler and less expensive surveys would precede the full planet characterization required for TPF. In this view, such precursor missions as Starlight, SIM and Kepler would lead into perhaps two TPF missions covering initial identification, visible and infrared photometry and spectrometry.

A serious impediment in our TPF design was lack of knowledge of the frequency of candidate planets in the habitable zone. This necessitated designing to a worst case in which it might be necessary to search to 15-20 pc or more to find terrestrial planet systems (hence the SWG requirement to survey 150 stars). For resolution-limited concepts, this leads to large telescopes or structures (to achieve the requisite angular resolution) and high costs.

Scientific precursor missions will refine the requirements. Kepler can return data on the statistical occurrence of candidates among typical field stars. This data would be most effective when combined with a survey for nearby systems with giant planets in the outer regions where they formed. Detections would be strong evidence of "normal" planetary systems that had not been disrupted by inward migration. This could be carried out by SIM. A TPF Lite, such as a 2 meter aperture ASA, could combine technology development and demonstration with the critical survey of hundreds of nearby stars for gas giants. With this kind of information, it may be found that a significant number of terrestrial planets can be studied within 10 pc – or that it is necessary to go much further!

QuickTime™ and a
GIF decompressor
are needed to see this picture.

Illustration of dynamic range of ASA. Brightness ratio 10^9, with several levels of wavefront aberration.

In our view a sufficient characterization of habitable planets will require estimation of surface temperature, which will be difficult to accomplish without reflected light measurements (to constrain albedo) and thermal measurements (to constrain effective temperature and diameter). In order to observe both reflected light and thermal emission, it is natural to consider a series of TPF missions for detection and increasingly refined characterization. Furthermore, a mission series can pursue these topics and others more systematically and in-depth than a monolithic TPF concept.

Potential astrophysics programs, such as those described above, can be addressed at significant levels with TPF Lite missions.

4 Phase II – Investigation of Two Leading Concepts

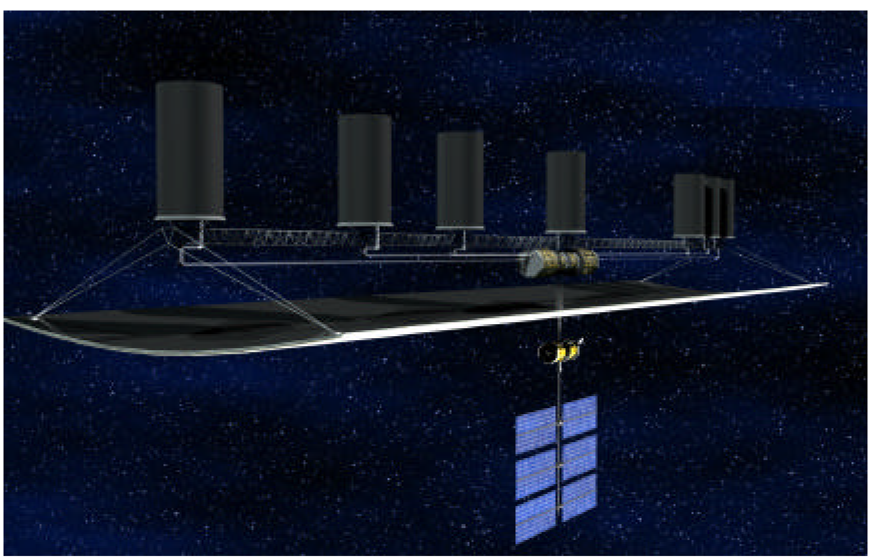
JPL instructed the Boeing-SVS team to study a hypertelescope in Phase II. Since we believe that an apodized square aperture may be much simpler and closer to realization, the team undertook a smaller study of ASA concepts.

4.1 TPF Mission Requirements

The TPF SWG reformulated the TPF mission statement for Phase II, opening the field to visible as well as infrared missions, deleting the requirement to detect terrestrial planets to a given distance, and substituting the requirement to search any 150 stars fitting certain criteria. Thus, each concept could be independently optimized for the fundamental science goals rather than an implied technical requirement. On the basis of this mission statement, the Boeing-SVS team developed point designs for the hypertelescope and the apodized square aperture, determined an appropriate design reference mission, and computed the required observing time. In the last few months of the contract, a detailed performance evaluation task was specified, with a star list and set of required observations. The concept missions were evaluated for the specific requirements, and the results, presented below, show that both approaches studied can accomplish the TPF science, plus at least equal time for astrophysics, within a mission life of 5 years.

4.2 NRLA

At the Phase I review, the Preliminary Architecture Review, the major questions about the hypertelescope concerned feasibility and cost. In order to approach these issues from the conservative side, and settle the issues clearly in favor of feasibility, a new array configuration was developed – a 1-d Non-Redundant Linear Array, or NRLA. Preliminary study had strongly indicated that in the dimensions required for TPF, a connected structure would be more economical than free-flyer telescopes, and this configuration was investigated.



Artist's concept of the NRLA, showing the non-redundant layout of the OTAs and the sun shade.

The NRLA fully develops the 1-d and 2-d hypertelescope technology, and accomplishes the full TPF mission in the mid-infrared.

For the point design, a telescope separation of 100 meters was adopted. This is on the high end of the range required for angular resolution, but in order to address possible questions about scaling the size up, we preferred to tackle a greater rather than a typical size.

4.2.1 Heritage

The NRLA exploits Fourier image synthesis, a technique that is used effectively in the radio/microwave (with telescope arrays), and in the infrared (with aperture masking). Optical interferometric beam combination, with path control and phasing, has been implemented at many optical telescope arrays, though Fourier synthesis with optical arrays is in its infancy. Hypertelescope design studies have been carried out by several groups including the Observatoire de la Cote d'Azur, Observatoire de Haute Provence and the University of Hawaii with both lab and telescope demonstrations. The Goddard Space Flight Center Fizeau Testbed will include a pupil densification experiment. NRLA is scalable to future, larger and more powerful architectures.

4.2.2 Derived Requirements

The combination of unit telescope size, number and spacing were selected to provide full UV coverage, with a small redundancy at low spatial frequencies. This is achieved with 3 meter telescopes. These give more than enough collecting area, and in a smaller (lower angular resolution) array the telescopes could be smaller and/or fewer in number. The telescopes are specified as off-axis to reduce diffraction and leakage of stellar light through the coronagraph.

The NRLA despins, repoints (typical repointing angle less than 20 degrees), spins up, and settles in under five hours. Pointing and optical path control errors must be low in order to keep stellar leakage small and constant.

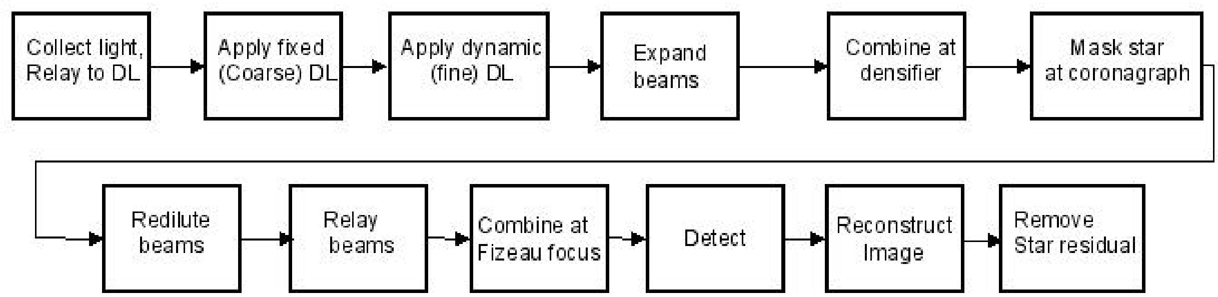
4.2.3 How the NRLA Works

The NRLA employs *pupil densification* to form a compact, real image of the star. In order to form a stigmatic image, the beam arrangement must be scaled according to the Golden Rule (preserving the telescope arrangement). However, for the special case of an on-axis point source, this requirement may be violated. In the NRLA, the linear pupil arrangement is shuffled into a hexagonal pattern, giving a compact, high-Strehl image. (Note that the optics are carefully designed to ensure equal polarization states on all beams). In this image plane, coronagraphic nulling removes most of the stellar photons. Pupil expansion (restoring the Golden Rule) and re-imaging provide the image (and its Fourier components) with stigmatic full UV coverage in 1-d along a single position angle from a single snapshot image. Additional snapshot images during rotation by 180 degrees provide full 2-d UV coverage. De-rotation of the snapshot images provides the high signal-to-noise stellar light residual map. Inversion of the Fourier components yields the image. The final noise level is set in practice by the photon noise associated with the residual stellar leakage through the coronagraph.

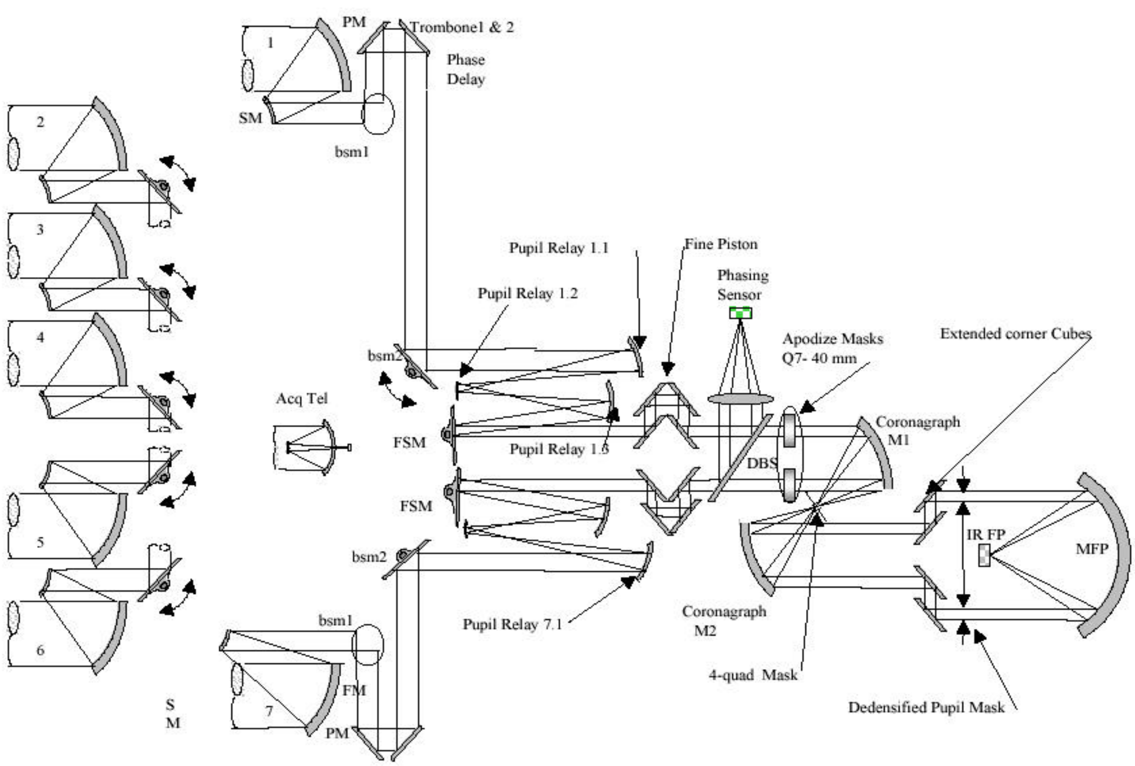
4.2.4 NRLA Design Details

4.2.4.1 Optical Design

The point design specifies an off-axis, 3 meter Mersenne telescope. These telescopes are feasible with existing technology. Each telescope has an associated star finder. The optical design provides coarse optical path equalization by layout. There is a fine delay line in each optical arm. Piston and tilt errors are detected from visible light split off at the densified pupil.



A block diagram for the NRLA, showing the major functional steps.



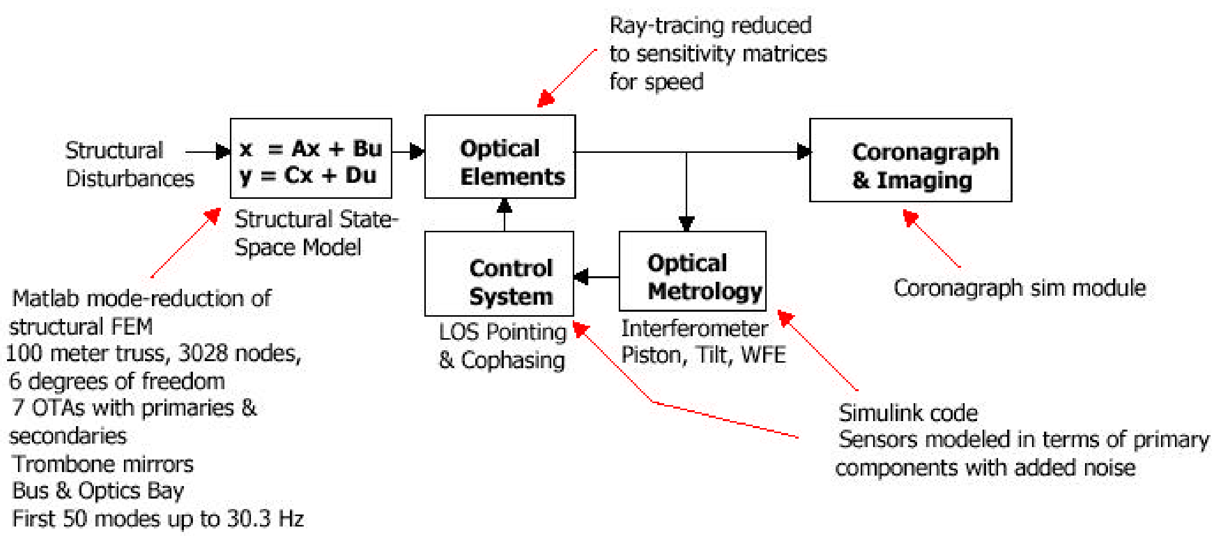
The optical layout of the NRLA. Seven telescopes are shown, but the beam paths for only two are followed through to the final image plan

A single mirror forms an image with the densified pupil and then reimages the densified pupil to the de-densified pupil plane. The coronagraph is small and can be built as a compact, stable unit, thoroughly tested on the ground.

4.2.4.2 Mechanical design and opto-mechanical modeling

The NRLA is based on a connected structure, which is to be assembled in low Earth orbit (LEO).

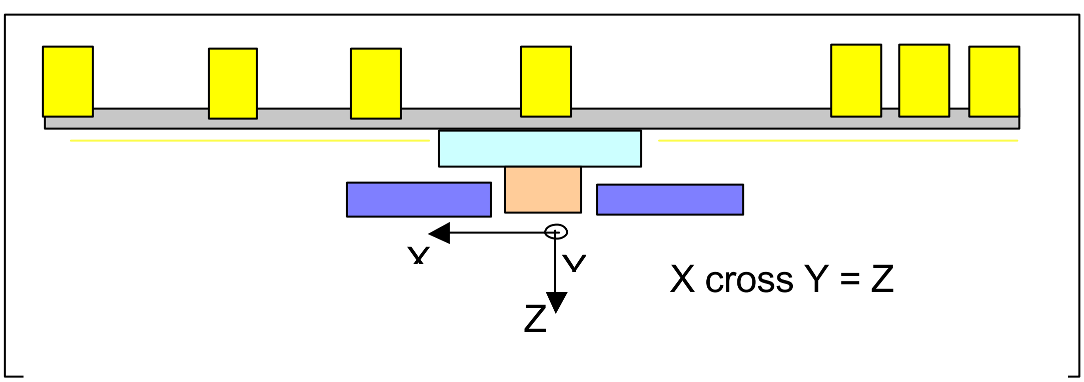
The computer model of the NRLA combines MATLAB, Simulink, Zemax and stand-alone C



Block diagram of the model used in predicting the performance of the NRLA.

code.

The truss buckling stiffness is constrained by the need to boost it to L2 after assembly in LEO. The loads analysis identified reaction wheel assembly (RWA) disturbance of the truss (a bending

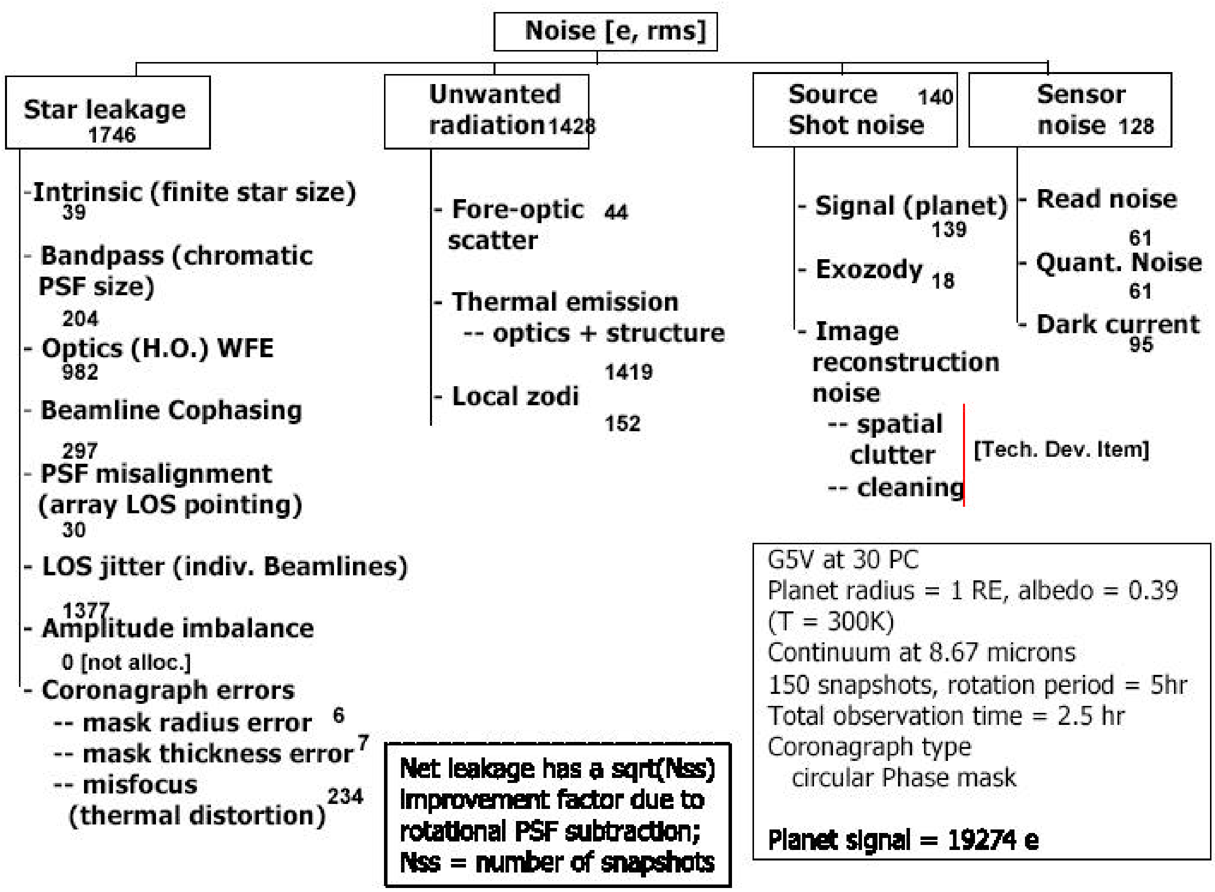


The layout of the NRLA, showing the relative sizes of the OTAs, the truss web, spacecraft bus and solar panels. NOT TO SCALE

mode >0.06 Hz) as the primary design driver. The selected point design truss geometry is triangular with a 1 meter bay dimension, fabricated from 6 cm diameter tubing with 2.5 mm walls and 15% parasitic node mass. The truss mass is 966 kg, and the lowest vibrational mode 0.14 Hz.

The requirements are determined by the slew and settle constraints. The structural disturbances are simulated consistent with braking after repointing. Then the time is measured until the control system is able to reacquire interference fringes and stabilize the piston and pointing.

The model is used to create empirically derived scale factors for some elements of the error budget. The planet detectability as a function of the RMS wavefront error determines the wavefront error budget. In turn, the error budget for sensors and control and structural parameters is determined by their simulated effect on the wavefront error. Other error budget components are derived analytically. The error budget includes both interferometer and coronagraph performance in the presence of spacecraft disturbances.



Error budget for the NRLA

All terms are reduced to detected electrons RMS. The dominant terms are the thermal photon noise associated with the thermal background, and the photon noise from the star leakage due to pointing jitter.

4.2.4.3 Thermal design

The thermal shield is 22 by 122 meter. It is based on the NGST six layer design, although four layers may suffice depending on the final decision for the maximum wavelength of operation. The shield permits sun angles allowing 15% instantaneous sky coverage and 71% total sky coverage. Cryogenic mechanisms will be required for two fast steering mirrors and two fine optical delay adjustments per telescope, plus a rotating filter wheel. Tolerances in the coronagraph assembly will be tight, requiring maximum of 1 K radial gradient and 0.5K longitudinal gradient.

Outgassing of materials can be expected to generate deposition on cryogenic surfaces, including the telescope primary mirrors. Mitigation options include periodic warming of optics and on-telescope monitoring.

4.2.4.4 Packaging, launch and orbit

NRLA is a complex spacecraft and instrument. We propose astronaut-aided assembly/deployment in LEO. The NRLA launch requirements are driven by volume (130 cubic meters stowed). The mass budget is 9900 kg, plus 20% allocated margin.

Three launches (2 STS and 1 Delta IV-H) accommodate the mission. Functionality at the sub-system level could be fully validated, and in gravity gradient attitude, limited interferometric tests can be carried out.

After verification of functionality, NRLA would be lifted from earth orbit to L2 with a series of 30 burns. A disposable upper stage based on the Centaur-G is suitable. The Delta-V for L2 halo orbit insertion is only five m/s, and could be supplied with small chemical or electrical thrusters.

The thermal parasol deploys after L2 insertion. Note that the thermal shield acts as a solar sail, producing potentially 0.1 m/s Delta-V per year.

4.2.4.5 On-orbit operations

For typical repointing maneuvers, the momentum to be imparted and later removed is 80 n-m-s. With chemical thrusters, the propellant consumed would be approximately 0.01 kg. Several thruster options were considered. The L2 insertion, maintenance and science maneuvering fuel requirements would total in the range 35, 150 or 400 kg (for hydrogen resistojet, hydrazine and nitrogen).

Momentum wheels offer an option. The ISS moment gyros can store 4700 n-m-s but propulsion will be needed for desaturation.

Data downlink, assumed X-band DSN compatible, can be accommodated with a 1meter high gain gimbaled antenna, and one 8 hour session per week, or 2 omni-directional antennas with an 8 hour session per day.

Power budget is 2585 W. Considering efficiency and five year degradation, with 30% margin, a solar array area of 10 m^2 will be required.

4.2.4.6 Cost estimate

With full cost accounting, the estimate for NRLA total life-cycle costs is $2.8B (FY 2002 dollars). Note that the costs are dominated by launch, due to the large volume of the telescopes and the connecting structure. A smaller configuration (considered below) would have proportionately lower launch costs.

Space Segment	$517M	18.3%
Launch Segment	$2.0B	70.7%
Ground Segment	$130M	4.6%
Mission Ops and Data Analysis	$167M	5.9%
Education and Public Outreach	$14M	0.5%
Total	$2,828M	

4.2.4.7 Technology development

The team presented a detailed technology development program at the Final Architecture Review (FAR), leading to technical readiness levels of 5-7 by 2012. What follows is a summary of that report.

NRLA offers great promise for planet detection, if an appropriate campaign of technology development can be mounted and maintained. Some of the technology will be inherited from related programs. Particularly, SIM will provide mature technologies for nanometer and picometer metrology, modeling technology for a large dilute aperture system and NGST will have experience with the design and operation of a large thermal shade at L2. In addition, NRLA can expect to benefit from work now under way at Goddard Space Flight Center on a laboratory demonstration of densified pupil technology. Since NRLA is a candidate for a human/robotic assembly option, the current work under way in construction and modification of ISS will be of benefit as well.

Technologies specific to hypertelescopes must be developed as well. Among these, the most important are the development of suitable modeling tools that deal with the combination of interferometric and coronagraphic methods used in NRLA. It is also important to prove the approach for integration of a hypertelescope with a spectrometer. Laboratory testing of such a concept seems essential. Therefore, the technology program must include efforts that will lead to the ability to manufacture and integrate phase masks with performance features consistent with the needs of NRLA. We expect to go through a series of design and fabrication stages before this can be mastered. Laboratory testing of a phase mask in an NRLA-like testbed is required to demonstrate the successful integration of this essential technology.

Because NRLA is a large, very low density spacecraft and structure, we propose that a demonstration flight of essential deployment, assembly and mechanized components be undertaken. This risk reduction flight would provide an opportunity to validate models of critical functions and subsystems, as well as develop a range of experience with 0G environments that cannot be obtained on the ground. Additional technology developments are required to assure that the on-orbit precision optical integration and test can be successful. This might include 0G testing on the risk reduction flight test or in experiments conducted on ISS.

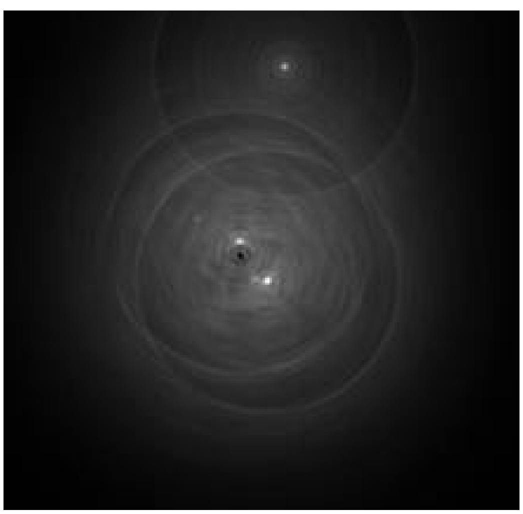
It has already mentioned that NRLA will benefit from experience gained on the SIM program. However, some of the interferometric components of NRLA do not have a counterpart on SIM. These include cryogenic IR delay-line actuators. A series of development cycles, plus 1G thermal-vacuum testing of these devices will be required.

4.2.4.8 Performance

The NRLA can accomplish the TPF mission with a large margin in observing time. After the final architecture review, the team was asked to study the NRLA performance for a particular set of TPF observations. The challenge was to survey the easiest 150 stars (selected from a longer list) with one visit to each star.

4.2.4.8.1 Alternate concepts

Two NRLA versions were examined: the point design (100 meter baseline, 7 apertures), and a small NRLA (39 meter baseline, 4 apertures) – in each case the unit telescope apertures were 3 meter.



Simulated image from the NRLA 100 meter concept, showing detection of five planets in a solar system analog. This simulation includes spacecraft dynamical perturbations of pointing and optical path control. The figure shows the type of image NRLA would provide of an exo-system. This is derived from the opto-mechanical model described above. The central star has been fully suppressed on axis. A small amount of stellar light leaks past the coronagraph, and is modulated by the Fourier synthesis in a complex way, giving a streaky halo pattern. This halo is an effective PSF, and can be partially suppressed by deconvolution, which has not been employed here. Jupiter, Venus and Earth are readily visible. Mars and Mercury are also faintly detected.

The 100 meter NRLA completed 150 stars in 1900 hours, including repointing time. The 39 meter NRLA can only observe 121 of the targets (due to lower resolution) and the time required is 3870 hours. Thus, in both cases, a number of pointings per star, required to detect candidate planets, would take of order 1 year, leaving ample time for confirmation and characterization of candidates.

4.2.4.8.2 Spectroscopic analysis

In addition to searching for and confirming candidate exo-planets, TPF will characterize some of the detected planets with spectroscopic measurements. We have examined a representative case – an earth at 20 pc orbiting a K5V star, with solar exo-zodi level. The time to scan the carbon dioxide and water bands (required resolution R=20, SNR=10 from Exhibit II) will be less than 50 hours per band at all wavelengths (7 to 15 microns). For measurement of molecular oxygen (required R=20, SNR=25 from Exhibit II) the integration times will still be less than 50 hours per band for wavelengths less then 12 microns (the ozone is near 9.5 microns). These integration times permit the minimum number of characterizations specified in the Design Reference Mission (DRM) within the five year mission, with large margin, and 50% TPF fraction reserved for astrophysics.

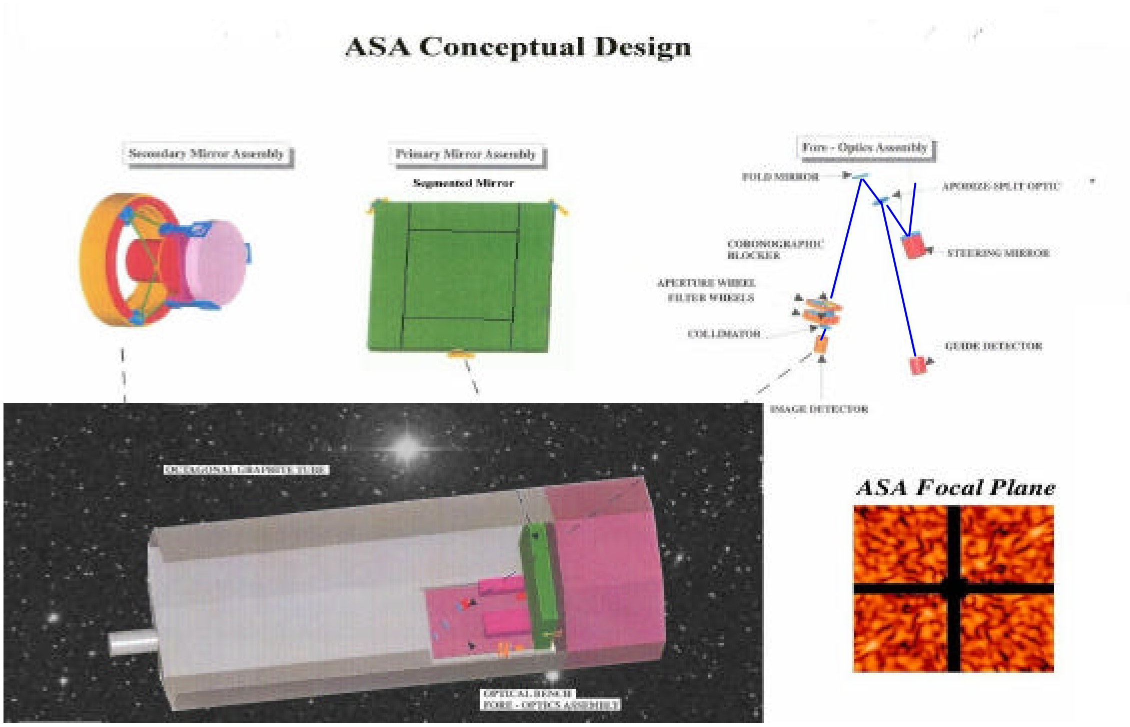
The sensitivity, imaging capability and field of view of the NRLA (both 100 meter and 39 meter versions) are well suited for the suite of astrophysics described in the Phase I report. The coverage of the mid-infrared spectral region is suited to detection of both hot structures (stars and stellar systems) and cool material (dust, cool companions), and to measurement of molecular bands in stellar, circumstellar and interstellar gas.

4.2.4.9 Conclusions

The NRLA has significant potential for planet detection and study, and can perform the TPF mission, including general astrophysics. It can be developed using reasonable technology advances, which are extrapolations of current technology. It is a scalable concept, flexible enough to adapt to changes in TPF programmatic needs. It prepares a technology path to free-flyer hypertelescope arrays – only an imaging array can respond to the long-range need for a planet imager.

4.3 Apodized Square Aperture

By operating in the visible spectral region, the TPF mission can employ a relatively conventional telescope, though with special optimization and design features. In fact, the recommended ASA configuration is comparable in size to NGST. Consequently, the focus of the Boeing-SVS study



ASA conceptual design

was on critical technical issues that are distinct from conventional or NGST telescope designs. These involve primarily wavefront quality and diffraction.

4.3.1 Laboratory tests

Early in the Boeing-SVS study, team members undertook a laboratory demonstration of the ASA. This was considered advisable in view of the dramatic performance gain expected from an intrinsically simple configuration.

The test, with only a few thousand dollars worth of parts, within a few weeks produced detection of simulated planets, separated by six times ?/E, at dynamic range of $>1x10^9$. Note the distinction between the diameter of a circular telescope (usually abbreviated as D) and the size of the edge of a square aperture, E. The results were readily achieved in spite of various non-optimal choices in the experiment design. These results confirmed the calculations of performance, which were then extended to TPF mission simulations.

The lab demonstration employed small optics (of a few centimeter aperture). An extension to larger optics, more representative of large telescope optical polishing technology, is recommended and planned. Demonstrations at ground based telescopes equipped with adaptive optics are also contemplated.

4.3.2 Modeling results

Numerical modeling of ASA performance has been carried out by two team members employing independent models, and checking on one another's results, in order to confirm accuracy and validity. Modeling has been pursued at several increasingly sophisticated levels, beginning with simple clear apertures and ideal surfaces, extending to apertures with realistic surface irregularities following power law descriptions with breakpoints based on practical experience, and amplitudes representing various levels of optical tolerancing. Diffraction from boundaries due to segmentation has been included in recent calculations.

Models shows that the ASA produces a low diffraction level over a large fraction of the focal plane, particularly in the coronagraphic region near the PSF core. Further work has established the optimum apodization for best suppression of diffraction in the critical region.

Images of point sources by optical systems with aberrations (no matter how small the aberrations) produce an image halo with a structured, spotty appearance. The spots are called speckles. They introduce an image irregularity that modulates the PSF that would be produced by the ideal pupil. In ground-based imaging, the wavefront aberration (even with adaptive optics) is dominated by atmospheric turbulence, and averages out with integration times longer than the atmospheric time constant.

While speckle is wavelength dependent, close to the PSF core, in the critical region, the speckle blurring with bandwidth is modest and strong speckling is present with the bandwidths we specify for TPF measurements.

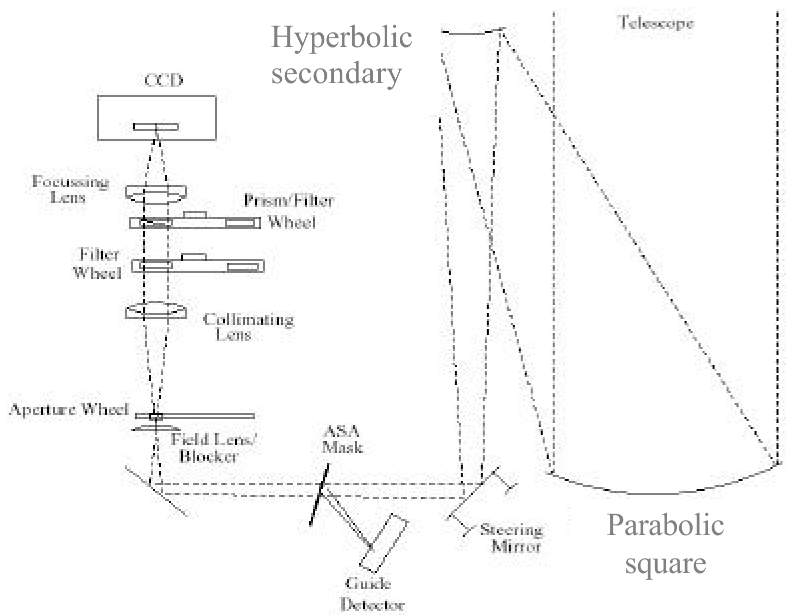
We have discovered that in the approximation of only weak wavefront error (which certainly applies to a TPF measurement), the halo speckle pattern is centro-symmetric. It may be possible to exploit this relationship, allowing PSF calibration, even if the speckle configuration drifts with time. However, preliminary modeling shows that the speckle pattern is invariant with changes of low order aberrations and is insensitive to thermal instability in the optics. Even significant shifts of optical components leave the speckle nearly invariant. In a spacecraft, a well-designed system will have a very stable speckle pattern. With a combination of these and other techniques, we have high confidence that the speckle pattern can be calibrated and subtracted out accurately.

Our simulations have also shown that most of the PSF is actually dark, and speckling produces a significant fraction of very dark pixels. This suggests several possibilities for increase in the sensitivity for TPF measurements. In the initial search, multiple exposures with a small roll of the spacecraft between will move any planets from pixel to pixel. An optimum weighting of the exposures in the final image will take advantage of the dark speckle regions. Once a planet is detected, it can be placed on a dark pixel for spectroscopy. The reduced bandwidth employed for spectroscopy will produce even darker speckles, reducing both halo photon noise and any residual uncorrected speckle noise. We note that study of speckle in high dynamic range imagery is still developing, and additional useful results are possible.

The potential gains, taking advantage of the dark speckle regions, were *not used* in estimating the ASA performance; hence, these constitute an additional design margin.

4.3.3 ASA Design Rationale

Our concept for an ASA employs a filled aperture telescope. In view of the strong dependence of cost on aperture size, the team looked very carefully at the size required in order to accomplish the DRM. By considering the most difficult of the easiest 150 candidate stars, this was determined to require study of habitable zones as small as 75 mas. Averaging over orbital inclinations and phase, we determined that planets must be detected at separations as small as 63 mas if they are to be detected at least 50% of the time.



A conceptual optical layout of the ASA

The selected aperture edge size is E = 8 meters. Simulations show that at 50 mas radial distance, the star leakage at 500 nm is below 10^{-8} over a 45 degree segment around each diagonal. Based on available launch vehicle capacities, the ASA point design must have a segmented primary. The requirement for spectroscopy will be fulfilled with a simple prism spectrograph behind a focal plane aperture. All spectra will be recorded at the maximum required resolution, since no excess noise will be recorded for photon limited measurements. The full spectral range will be recorded in each exposure.

4.3.3.1 Concept

Wavefront quality and small wavefront phase error are critical. The figure shows a concept that has three surfaces before the blocker. These surfaces must satisfy strict surface quality requirements. The blocker removes the diffraction spikes from the image. Only standard optical tolerances are required after the blocker, and this is where the filter wheel and prism are located.

In many instrument and spacecraft issues, the ASA follows the precedent of NGST so that detailed ASA solutions are best deferred pending NGST development. Primary mirror deployment, in particular, can profit from NGST and DoD experiences. By operating in the visible, the ASA avoids many of the thermal requirements of IR systems. Sunshades could be used, to achieve good thermal stability, but an MLI design may be satisfactory. The baseline orbit is L2. The sun avoidance angle is 90 degrees. Typical slews are 17 degrees.

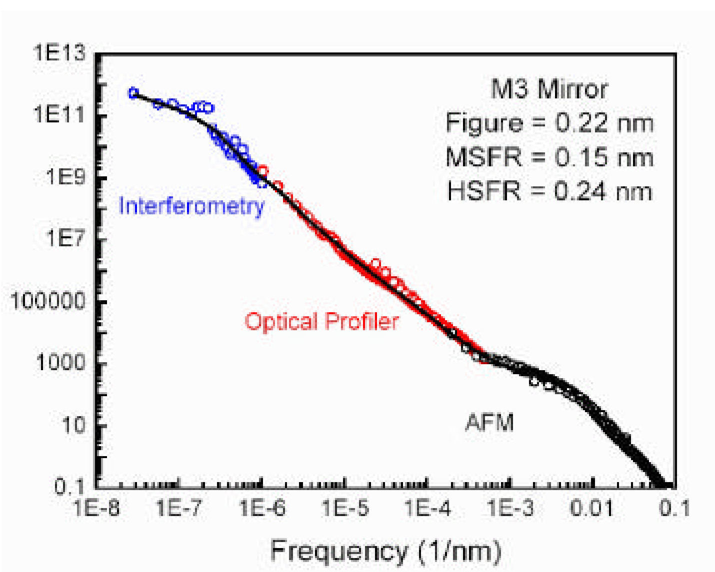
4.3.3.2 Derived Requirements

4.3.3.2.1 Optical surface quality

The required wavefront quality is described in terms of a power spectrum for mirror surface error with several breakpoints. Four distinct spatial frequency domains can be identified. Low spatial frequency range (LSFR), or figure error, 0 to 3 cycles per aperture (c/a) can be controlled by primary mirror actuators, deformable mirrors and corrector elements (DM/CE). The coronagraphic spatial frequency range (CSFR), 3 to 100 c/a, and can also be controlled by DM/CE actuators. The mid-spatial frequency range (MSFR), from 10^2 to 10^4 c/a, called ripple, is not actively controllable, but is correctable with fixed phase plates. The high spatial frequency range (HSFR), or surface micro-roughness, $>10^4$ c/a, is also not actively controllable, and not correctable, but is an intrinsic characteristic of the optical surfaces. Of these, the CSFR is the most critical for ASA, as it scatters light into the halo in the region in which planets will be sought.

Our current error budgets require the primary mirror surface figure to be 0.35 nm RMS over the CSFR. The LSFR can have errors of 1.17 nm RMS. The MSFR error can be 4.0 nm RMS, and the HSFR error 1.0 nm RMS.

This is a difficult surface requirement. However, surfaces of this quality have been produced in the past – in small optical components, in x-ray telescope mirrors, in lithography optics. Mirrors in 150 to 200 mm sizes, for extreme ultraviolet lithography, achieve MSFR surface quality significantly better than one nm RMS, as illustrated in the figure. No conventional telescope has been built to these specifications. Vendors tell us, however, that optical quality approaching this level should be available for conventional telescopes. Before, there has been no substantial demand for it.



Measured PSD of the M3 substrate surface. For each spatial frequency range, the area under the PSD curve is used to determine the rms value of the roughness.

In the ASA point design, it is assumed that the required tolerances can be achieved by a combination of fabrication, stabilization, fixed compensation, and possibly active or adaptive control. The ASA surface accuracy performance risk has several mitigation paths: primary element polishing to low surface error, a static corrective surface, an active corrective surface, or a phase mask.

The area of in-flight wavefront sensing and control to appropriate wavefront tolerances is a topic highlighted for technical development.

4.3.3.2.2 Apodizing Mask

Simulations with varying levels of pupil amplitude error show that random amplitude errors up to 1% generate scattered light levels less than 10^{-10}. The apodization masks produced for the team's ASA laboratory tests have amplitude variations of less than 0.2%, hence this is not expected to be a major performance issue.

4.3.3.2.3 Segmentation

In devising a segmentation layout for the ASA, it is necessary to avoid structures that will diffract additional flux into the planet detection zone. Segment gaps should be parallel to the primary edges, and segment sizes should be either small (to diffract preferentially to large angles) or large (to diffract light mainly to very small angles). The layout adopted employs large, rectangular segments, and the gaps are in the outer part of the pupil where the reduced transmission of the apodizing mask contributes to the suppression of additional diffraction. The gaps must be no more than 0.1% of the aperture diameter – a comfortable 8 mm.

4.3.3.2.4 Thermal stability

The thermal stability requirement is most stringent if very high optical wavefront quality is to be achieved and observations exploit a low Q value (ratio of planet to halo). In that case, temperature drift in the primary mirror must be less than 0.2 K, drift of the deformable mirror (if one is used) less than 2.5 milliKelvin, and drift of the optical bench less than 1K.

4.3.3.2.5 Pointing stability

The spacecraft body pointing must remain stable to 100 mas over integration periods up to approximately 3 hours.

Pointing jitter, as corrected by the fast steering mirror (FSM), must be stabilized within one milli arcsecond. Though an advance on current spacecraft-payload performance, 1 mas is about 1/10 of a pixel, and in TPF measurements, a bright on-axis star is always available to the star tracking sensor for FSM control.

4.3.3.2.6 Spacecraft structure

Most technical challenges for ASA are being addressed by other, prior, missions, including launch to and operation at L2, heliocentric orbit, reliability of performance predictions by integrated models, and operation of large optics in space.

Precision deployment and performance of deployed structures and structural quieting technologies, to ensure optical performance, are the essential ASA structural issues that need flight validation.

4.3.3.3 Optical design

The parent optic of the off-axis primary is a f/1 ellipse. The secondary is an off-axis hyperboloid. The selectable apodizer is implemented with a transmissive mask. Reflection from the apodizer goes to the LOS sensor. The high reflectivity of the mask in the outer parts of the pupil ensures a strong and representative control signal for the FSM. Then comes the fast steering mirror. It folds the beam behind the primary mirror for compact packaging.

The Cassegrain field focus that follows is then reimaged by an ellipsoidal tertiary mirror through an intermediate pupil image. This may be used for a fixed wavefront-correcting surface, fabricated to introduce path differences to compensate for the measured, as-fabricated optical surfaces. It could also be the site of a deformable mirror, operated in either an active or adaptive correction mode. A transmissive phase mask for correction of fixed wavefront errors could also be introduced into the beam.

The field mask blocks the core of the parent star and deflects it to a light trap. Multiple field masks are on a rotary mechanism so that they may be selected in conjunction with the apodizer. In spectroscopic characterization mode, the field mask introduces an aperture to isolate the planet under study from the rest of the halo.

After the field mask, the light is reimaged through a set of selectable filters and/or prism to the focal plane. Among other purposes, the filter wheel selects the optimum wavelength bands required to reduce observing times on planets at different angular separations from their parent stars.

A Lyot mechanism with selectable stops lies at the intermediate pupil image before the filter wheel.

4.3.3.4 Performance

Performance of the ASA for carrying out the TPF survey is based on a value of Q, the ratio of the light received from the distant planet and the diffracted or scattered light from its parent star. In this case, we use a Q of 0.01. Various strategies can be adopted to optimize the search. By adjusting the search wavelength, the halo level at a given radial distance can be optimized (reducing the wavelength reduces the diffraction halo (due to increased resolution). This increases the scatter due to figure error, and the number of required rotational positions may increase from 2 to 3. A survey of 150 stars (one visit each, with an appropriate number of rotations to cover the image space) would require about 7000 hours (or 6000 hours with optimization of the search wavelength for tight and wide habitable zones). This is about 0.8 years.

A single-point performance example has been specified, consisting of an earth-like planet at maximum elongation in a solar system analog at 15 pc. The detection time (SNR=5) would be 21 hours (500-700 nm bandpass) for three measurements separated by two re-orientations.

As a representative example of the observing time required for spectroscopic characterization of a detected planet, we consider the case of an earth-like planet at 10 pc. The proposed observation is a spectrum over the interval 500-1000 nm with a spectral resolution of 70 and an integration time of 92.5 hours. (In data reduction, the spectral resolution is reduced numerically to optimize the detection of each spectral feature.) With this spectrum, the water features at 710-730, 810-820 and 910-970 would be detected with SNR of 2.4, 2.1, and 9.7, respectively. The molecular oxygen features at 680-700 and 760-770 nm, and the ozone feature at 530-660 nm, would be detected with SNR of 1.25, 3.3, and 5.0. (Each species is detected with SNR>=5 for at least one spectral feature, as required in Exhibit II. The lower SNR features will be useful in constraining abundances in model fits to the complete spectrum.)

For consistency with our report at the Final Architecture Review, the point design as studied here employs the Jacquinot apodization. More recently, team members have discovered an optimized apodization, which improves performance in the critical planet detection zone. Additional sensitivity gains also should be available by optimizing observations to exploit a priori knowledge about speckle characteristics. In spectroscopy, gains of ten in speed are possible. Neither apodization nor speckle gains have been incorporated into the performance model reported here.

Revising the point design to operate at a higher value of Q would provide improved performance. We believe that the assumed value of 0.01 represents a good compromise, offering adequate sensitivity in a system likely to be affordable in the next decade.

4.3.3.5 Conclusions and Recommendations for further study and technology development

The ASA provides extremely high dynamic range with conventional technology extended somewhat from current instruments but within reach. The required technology is primarily in optical fabrication and wavefront control. In the former area, vendors are optimistic for rapid and significant improvements. In the latter, intense development is already underway for ground-based telescopes and DoD applications. The ASA can perform all of the TPF requirements. Our team believes that an ASA is the quickest path to a successful TPF-Lite or to a full TPF mission.

The ASA is a robust concept. Performance risks have several mitigation options. The requirements can be met by various combinations of instrument parameters. Underperformance in surface quality can be compensated with increased aperture size or integration time. Active or passive wavefront control are other options. Integration times may be significantly reduced by exploiting dark speckle techniques or improved apodization. Specific features that make ASA robust include insensitivity to piston errors in the primary mirror segments, small number of mechanisms, non-cryogenic operation, tolerance of low order wavefront errors, and symmetric and stable character of the speckle pattern.

The team recommends further study in the following areas: manufacture of an 8 meter segmented mirror, optical surface mid-frequency RMS errors in large segmented mirrors, segment edge finish and edge matching, full and sub-aperture testing, apodizer manufacture and characterization, and field occulter manufacture and characterization.

The essential technology for ASA is production of optics with suitable surface quality in the critical spatial frequencies. Alternatively, we require success from correction technologies like adaptive optics or holographic plates. It will be important to motivate the optics industry to develop capabilities that may have few other applications, including solutions that allow deployed optics and evolution of a capability to assemble and test optics on orbit.

5 Recommendations

The Boeing-SVS team has studied in depth two families of TPF concepts – a hypertelescope array (the NRLA) operating in the mid-infrared, and an apodized square aperture (ASA) operating in the visible/near-infrared. Both concepts are excellent candidates for TPF. Both can carry out the full TPF survey and characterization program, including detection of water or carbon dioxide and oxygen or ozone. The ASA can be implemented in a size and configuration that resembles NGST, and can be developed as a continuation of the NGST technology thrust. The ASA could be deployed in a single launch, and could be technology-ready and affordable within the near future. The NRLA is scalable to far larger and more powerful missions foreseen for the future, including Planet Imager. Both ASA and NRLA are true imaging telescopes so they satisfy the TPF requirements and offer a powerful astrophysics capability without the need for augmentation. Owing to the strong scientific need for exo-planet studies in both the thermal emission and the reflected light regions of the spectrum, the NRLA and the ASA offer complementary potential.

The Boeing-SVS team recommends continued development of the technology for ASA and NRLA, with the expectation that either, or both, can be candidates for flight as a full or 'Lite' TPF missions.

Abbreviations

AGB	Asymptotic giant branch (star)
ASA.	Apodized square aperture
c/a	cycles per aperture
CE	Corrector element
CSFR	coronagraphic spatial frequency range
DoD	Department of Defense
DRM	Design reference mission
DSN	Deep space network
FAR	Final Architecture Review
FSM	fast steering mirror
FY	Fiscal year
HSFR	high spatial frequency range
HZ	Habitable zone
IR	Infrared
ISS	International Space Station
L2	Lagrange point 2
LEO.	Low earth orbit
LOS	Line of sight
LSFR	Low spatial frequency range
MSFR	mid-spatial frequency range
NGST.	Next Generation Space Telescope
NRLA.	Non-Redundant Linear Array
pc	parsec
PSF	Point spread function
RMS	root mean square
RWA	Reaction wheel assembly
SIM	Space Interferometry Mission
SNR	signal to noise ratio
STS	Space transportation system
SWG	Science working group
TPF.	Terrestrial Planet Finder