SPIE-4013-74

Architecting the Search for Terrestrial Planets and Related Origins (ASTRO)

D.W. Miller, A.V. Curtis, O. De Weck, E. Frazzoli, A. Girerd, T. Hacker, C.D. Jilla, E.M. Kong, B. Makins, and S. Pak Massachusetts Institute of Technology Cambridge, MA USA

SPIE International Symposium on Astronomical Telescopes and Instrumentation 27-31 March 2000 Munich, Germany

Architecting the Search for Terrestrial Planets and Related Origins (ASTRO)

David W. Miller^{*a}, Andrew W. Curtis^b, Olivier L. de Weck^a, Emilio Frazzoli^a, André R. Girerd^a, Troy L. Hacker^a, Cyrus D. Jilla^a, Edmund M. Kong^a, Brian Makins^a, and Sangwoo Pak^a

^aMIT Dept. of Aeronautics and Astronautics, Cambridge, MA 02139

^bMIT Dept. of Mechanical Engineering, Cambridge, MA 02139

ABSTRACT

As a cornerstone in NASA's Origins program, the primary goal of the Terrestrial Planet Finder (TPF) mission is to directly detect the existence of Earth-like planets around nearby stars. This paper presents a process and a software tool, based on a quantitative systems engineering methodology, to conduct architectural trade studies during the TPF mission conceptual design phase.

The TPF mission analysis software (TMAS) package consists of six macro-modules that model the physics and processes that distinguish between competing system architectures, including structurally connected (truss) and separated spacecraft (formation flying) concepts. The macro-modules were selected following an initial qualitative assessment of the most influential system attributes. Each macro-module consists of specialized sub-modules that provide parameterized models for each mission component (subsystems, etc.). This approach provides many advantages, including the ability to perform sensitivity analyses for individual system parameters and the ability to incrementally refine the model components to incorporate altered assumptions, new technologies, and greater design detail. Ultimately, the designs are evaluated by a performance assessment module, which calculates the capability, performance, and cost for each architecture.

Following calibration and validation of the TMAS package using previously developed TPF spacecraft design concepts, the software was used to conduct one dimensional trade studies to evaluate the general trends within the design trade space. Additionally, four multidisciplinary design optimization techniques were used with TMAS to examine how well they converged to the optimal TPF mission design, which was determined to be an 8 aperture (4 meters diameter each with a 30 meter maximum aperture baseline), two-dimensional, structurally connected spacecraft at an operational orbit of 4 AU (see Figure 1). While it is premature to accept this particular design for the TPF mission, TMAS has proven to be a useful tool for evaluating disparate mission architectures based on unified quantitative metrics.

Keywords: Systems Engineering, Terrestrial Planet Finder (TPF), Space Systems Design, Interferometer Trade Studies, Optimization



Figure 1. Optimal TPF Configuration Generated by TMAS

1. INTRODUCTION

As stated in a recent publication by the TPF Science Working Group,¹ "A great deal of effort will be required over the next few years to arrive at a design that optimizes the performance of the entire system while minimizing cost and complexity." This paper describes work performed at MIT to conduct a trade study of mission architectures for the TPF mission using a quantitative systems engineering methodology.² The fundamental objective was to develop a methodology for the comparison of multiple design architectures, including structurally connected and separated spacecraft interferometers. The goal was *not* to generate a single point design that would satisfy the TPF mission requirements, but rather to develop a technique to fairly evaluate the relative merits of intrinsically different design concepts and to identify regions within the trade space that represent the most effective design options. As an implementation of this methodology, TMAS has provided valuable quantitative information during the conceptual design phase of the TPF mission. With the appropriate selection of metrics and application of physical principles and engineering design practices, this methodology can potentially provide beneficial data for other missions.

^{*} Correspondence: Email: millerd@MIT.EDU; Telephone: 617-253-3288; Fax: 617-258-5940

The Generalized Information Network Analysis (GINA) Methodology for Distributed Satellite Systems^{3,4} was selected as the *quantitative systems engineering framework* to evaluate TPF mission architectures. The GINA methodology is based on the premise that satellite systems are information disseminators and can be represented as information transfer networks. Figure 2 provides a summary of how the GINA methodology was applied to develop the TMAS package.

1.	Define the Mission Objective and the Conceptual Design Stage	4.	Partition the Problem
	(CDS) Objective		• Define the design vector and the constants vector
	• Identify the customer and state the mission objective		• Matrix the design vector against the capability metrics
	• Derive top level customer requirements and state the CDS		• Define the modules
	objective	5.	Develop Simulation Software
2.	Transform the Space System into an Information Network		• Develop, code, and integrate the software modules
	Identify the origin-destination pairs in the networkIdentify the four capability quality of service metrics	6.	Explore the System Trade Space • Evaluate system architectures using the system metrics
3.	Develop System Metrics		Apply an optimization algorithm
	• Define the performance, cost per function, and adaptability metrics		

Figure 2. The GINA Methodology Applied to the TPF Mission to Develop TMAS

In the GINA methodology, the capability of an architecture is characterized by four "Quality of Service" parameters that relate to the detection process and to the quantity, quality, and availability of the information processed through the network. These four parameters are signal isolation, information rate, information integrity, and the availability of these services over time.³ Once formulated, these four parameters serve as the minimum instantaneous capability requirements the system must meet to satisfy the customer.

Isolation refers to the ability of an information system to isolate and distinguish signals from different sources within the field of view. For TPF, the system's angular resolution, which is a function of the maximum vector baseline between a pair of collectors, among other factors, determines whether or not the telescope will be able to successfully isolate the image of a planet from its parent star. This capability is evaluated by examining the characteristics of the interferometer's transmissivity function.

Rate measures the speed at which an information system transfers information between the sources and sinks in the network. For TPF, the imaging rate is the total number of images the system can produce per unit time. A TPF image is defined as the result of one of the survey, medium spectroscopy, or deep spectroscopy operations that are scheduled throughout the mission.

Integrity is a measure of the quality of the information being transferred through the network. In the case of TPF, the integrity of an individual image is a function of the signal-to-noise ratio (SNR) and the image plane coverage (u-v coverage) used to obtain that image.⁵ TPF architectures with greater integrity will gather data with less ambiguity.

Availability characterizes the instantaneous probability that information is being transferred through the network between the sources and sinks. TPF targets close to the sun, or targets whose imaging needs violate sun avoidance angles within the optical train, reduce the availability of the system. The actual imaging time versus the time to complete other tasks such as calibration and re-targeting, also affects the availability of the system.

2. PARSING THE TERRESTRIAL PLANET FINDER MISSION

The following subsections provide a description of the process employed to define the relevant mission parameters required to perform the desired quantitative analysis. A brief description of the TPF mission is followed by a summary of the three tiered requirements hierarchy used to define the mission. Next is a description of the metrics chosen to evaluate the mission architectures, a qualitative assessment of the trade space, and finally, identification of the six macro-modules of the TPF mission model that were developed to conduct the analysis.

2.1. TPF Mission Description and Requirements

The primary objective of the TPF mission is to detect and characterize Earth-like planets orbiting nearby stars.⁶ This objective requires the capability to detect radiation emitted from extra-solar planets and to be able to discriminate this radiation from that of the parent star. The proposed technique for performing this function is to use a spaceborne

interferometer. By combining the high sensitivity of space telescopes with the sharp detail of a nulling interferometer,⁷ TPF will be able to reduce the glare of parent stars by a factor of more than 10⁶ to see planetary systems as far away as 50 light years. In addition to measuring the size, temperature, and location of planets as small as the Earth in the habitable zones of distant solar systems, TPF will be used to gather spectroscopic data that will allow atmospheric chemists and biologists to study the concentrations of gasses like carbon dioxide, water vapor, ozone and methane to determine whether a planet someday could, or even now does, support life.¹

A secondary application of the TPF is to perform astrophysical imaging of planetary accretion disks and other phenomena. This application introduces imaging requirements that increase the TPF aperture baseline and were not incorporated into this initial study.

The three most critical factors that define the planetary detection performance of the TPF system are:

- Suppression of parent star light (nulling) by a factor of 10^6 over the entire diameter of the star,
- Retention of maximum transmissivity in the habitable zone (0.5 to 3 AU) around a star,
- Maintenance of the spacecraft optics and detectors at dynamically stable and thermally cold conditions to maximize the SNR in the 7-17 μm range.

One of the first activities of this study was to develop the system and design requirements for the TPF mission from the stated science objectives in enough detail to allow for the development of viable competing mission architectures. These requirements are organized into three successively more engineering-oriented levels. The first level, Science Requirements / User Needs, includes a formal definition of the stated scientific objectives of the mission. The second level consists of TPF mission System Requirements derived from the Science Requirements. The third level contains Design Requirements derived from the previous two levels. Figure 3 provides an example of some of the TPF requirements that demonstrates the increasing level of detail from science to system to design requirements.^{2,8}

Science Requirement	Derived System Requirements	Derived Design Requirements
• The mission shall detect each planet by isolating it from its parent star.	 The system shall have a fraction of a milliarcsecond resolution. The system shall suppress the light from a parent star by a factor of more than 10⁶. The system shall have a minimum SNR of 5 for surveying, 10 for coarse spectroscopy, and 25 for detailed spectroscopy. 	 The infrared imager shall have a pixel size less than 30 μm with a 3 μsec/pixel readout time. The optical train shall have a differential path length control of at least λ/6000. The infrared imager shall have less than 2 electrons per second of dark current and at least a 50% quantum efficiency.

Figure 3. Example of TPF Requirements

2.2. Metric Definition

In addition to the capability metrics discussed in Section 1, the TPF mission architectures were evaluated using measures of performance, cost per function, and adaptability per the GINA methodology.³

While the four capability "Quality of Service" parameters measure how well a design architecture meets the capability requirements at any instantaneous point in time, the *performance* metric measures how well the architecture satisfies the mission requirements over the entire life of the mission. For TPF, the total number of images produced during the nominal mission lifetime is the chosen performance metric. This will be the sum of all survey, medium spectroscopy, and deep spectroscopy imaging operations. To assess the lifecycle performance, subsystem failure modes and recovery options must be taken into account. A reliability model for each mission architecture based on Markov models was used to predict subsystem failure rates that would cause either a decreased imaging rate or decreased image integrity.

The *cost per function* metric provides a measure of the cost of an architecture versus its performance. It is a measure of the cost to achieve a common level of performance and includes expected development, launch, failure compensation, and operations costs. For TPF, the cost per function metric is defined as the cost per image, and is calculated by dividing the total cost of the TPF mission by the total number of images it produces over its designed mission lifetime.

Adaptability is a measure of how flexible an architecture is to changes in design assumptions and mission requirements. In one sense, adaptability may be thought of as the sensitivity, or elasticity, of the cost per function of a particular architecture to

incremental changes in an assumption or requirement. For the TPF mission, potential assumptions that could be altered to measure architecture sensitivity include component costs, fabrication learning curve slopes, and component reliabilities. In another sense, adaptability may be thought of as the flexibility of a particular architecture to adapt to a new set of mission requirements, such as an extension of the mission duration. Another example of flexibility for the TPF mission is the ability of an architecture to transition from a planetary detection mission to an astrophysical imaging mission.

2.3. Trade Space and Model Definition

Prior to the development of specific TPF mission models for quantitative analysis, a qualitative evaluation of the mission requirements and the design options was conducted to identify the parameters that most significantly affect mission performance and cost. The use of a space based nulling interferometer was accepted as the best approach to pursue and no trades with other techniques were conducted. Five interferometer spacecraft configurations (architectures) were considered and two were selected for further evaluation -- structurally connected (truss) interferometer (SCI) and separated spacecraft (formation flying) interferometer (SSI). These architectures include both one-dimensional (linear) and two-dimensional aperture arrangements. The mission orbit, the total number of apertures, and the size of the apertures were determined to be the other top level mission trade parameters that would be evaluated. Together, these top level parameters form the design vector of inputs that define distinct TPF configurations in TMAS (see Section 3.1). Other top level trades such as mission lifetime, target identification and selection procedures, and launch vehicle selection were identified for incorporation into the models for future evaluations. This process also identified numerous subsystem level component and implementation trades that could be incorporated into individual subsystem models.

The matrix in Figure 4 summarizes the relationships between the identified top level trade parameters for the TPF mission (the design vector) and the capability metrics. Each matrix entry provides a qualitative assessment of the influence of the trade parameter on the corresponding metric. For example, as the orbit increases, the imaging rate is expected to increase as the local noise source (the local zodiacal dust density) decreases. Furthermore, the table entries were grouped based on similarity of physical processes into six logical categories that identify the six macro-modules that comprise the TPF Mission Analysis Software -- Environment; Aperture; Spacecraft; Dynamics, Optics, Controls, and Structures (DOCS); Operations; and Performance Assessment (GINA).

Design Vector:	Heliocentric Orbital Altitude	Aperture Topology (SCI vs. SSI and	Number of Apertures (4 to 12)	Size of Apertures (1 to 4 m)
Capability Metrics	(1 to 6 AU)	1-D vs. 2-D)	· · ·	· · ·
Isolation (Angular Resolution)	N/A	SSI allows more freedom in baseline tuning	Fine tuning of transmissivity function	N/A
Rate (Images/Mission Lifetime)	Noise reductions increase rates. Operations delays	SSI power and prop. requirements highly sensitive	Increased collecting area improves rates	Increased collecting area improves rates
Integrity (SNR)	Different local zodiacal emission and solar thermal flux	SCI: passive alignment but complex dynamics	Tuning of transmissivity for exo-zodiacal suppression	Smaller FOV collects less local zodiacal noise
Availability	N/A	Different safing complexity and operational events	Different calibration and capture complexity	N/A
Environment	Aperture Sp	acecraft DOC	S Operations	GINA

Figure 4. Model Con	mponent Identification Matrix
---------------------	-------------------------------

3. TPF MISSION ANALYSIS SOFTWARE (TMAS) MODULES

The following subsections provide an overview and some of the technical considerations that constitute the six macromodules of the TPF Mission Analysis Software. The routines were written in Matlab, with each sub-module representing a modular component of the model that may be independently modified or replaced with alternative components (of higher or lower fidelity) as long as the interface requirements are satisfied. Interface control was accomplished by using an N² diagram to track module and sub-module input and output relationships.⁹ Figure 5 provides an overview of the TPF Mission Analysis Software, which receives its inputs from the design and constants vectors that define the current mission concept and then generates the performance metrics as outputs.

3.1. Design and Constants Vectors

The inputs to TMAS that define each possible mission architecture are described by the design and constants vectors. The design vector contains values for the four top level trade parameters, which have the range of values identified in Figure 4. The constants vector defines other top level parameters, such as the nominal mission design lifetime, the assumed data transmission rate, the observation wavelength, and the minimum acceptable SNR and resolution values for each mode of observation. While the parameters in the constants vector remained unchanged during the current study, they may be easily transferred to the design vector if desired for future analyses.



3.2. Environment Module

The Environment module represents the relevant physics associated with the local space environment around the TPF spacecraft in its

operational orbit. The local space environment influences the thermal, power, aperture size, mission lifetime, and attitude control components of the spacecraft and must be considered when evaluating whether or not the proposed design meets the TPF mission requirements. The solar flux at the operational orbit is one of the major issues for thermal control and is a potential source of power. Therefore, the solar flux information is calculated by this module and is output to the Spacecraft module. The local zodiacal dust density is calculated for use in the Aperture module to calculate image integration times for different aperture sizes. The solar pressure and gravity gradient data output by this module is used by the Dynamics, Optics, Controls and Structures (DOCS) module. When the TPF is close to the Sun, the effects of these two outputs may be significant.

3.3. Aperture Module

As discussed in Section 2.1, the TPF mission will be implemented using a number of apertures operating as an interferometer. Unlike conventional interferometers, the goal of this mission is to null out the parent star at the center of the field of view. This will be accomplished using the Bracewell nulling interferometer concept.⁷ However, similar to any conventional interferometer, the response of the TPF interferometer will be highly dependent upon the locations and the relative sizes of the individual apertures. This module takes into account the external noise sources that can effect the capability of the interferometer to detect a planet and calculates the optimal transmissivity function for the given number of apertures.

The aperture configurations were optimized for imaging an Earth-Sun system located 10 parsecs away at an observational wavelength of 12 μ m. These values correspond to the baseline case study¹ and are in the middle of the specified ranges for the TPF interferometer (5 to 15 parsecs and 7 to 17 μ m). Both values are components of the constants vector used to initiate TMAS (see Section 3.1).

Figure 6 shows the transmissivity function¹⁰ and the output for an example interferometer. From the figure, at $r = 7.5 \times 10^{-4}$ arcsec, the normalized response of the interferometer is less than 10^{-7} , which is very small compared to some of the responses for angular separations greater than 0.1 arcsec. In fact, the response shown here meets the nulling requirement to detect an Earth-like planet orbiting a Sun-like star located 10 parsecs away. The six order of magnitude star light suppression requirement is indicated by the solid box in the figure. The dashed line in the figure represents an area between the surface of the parent star to the 0.5 AU inside limit of the habitable zone. Signals received from this area will be pre-dominantly from the exo-zodiacal cloud surrounding the star. Therefore, it makes sense to also null out this region. Unfortunately, it is almost impossible to null out such a large region using a limited number of apertures while maintaining the desired high transmissivity in the habitable region. Hence, the dashed lines represent a soft constraint where it is preferable to have the interferometer exhibit a low transmissivity.

In this module, a heuristic optimization method called simulated annealing¹¹ was used to determine the best aperture configurations (sizes and locations) as a function of the number of apertures and of the allowable geometry (1-D or 2-D, symmetric or non-symmetric). While heuristic methods cannot guarantee that the solution obtained is the global minimum, in general, they can determine a reasonable solution using much less computational time than complete enumeration.

Figure 5. TMAS Block Diagram



Figure 6. Transmissivity Function and Sample Output

3.4. Spacecraft Module

The Spacecraft module consists of five sub-modules that represent the science payload instruments and the spacecraft bus subsystems that support payload operations. Namely, the five sub-modules are the Payload, Communications, Power, Propulsion, and Thermal sub-modules. The Spacecraft module is responsible for scaling the relative size and power characteristics of the four bus subsystems to optimize the TPF spacecraft design.

The *Payload sub-module* models the four primary components of the TPF payload: the collector mirrors, the optical train, the beam combiner, and the infrared detectors. The payload masses, power budgets, and spatial distributions are estimated in this module based on instrument and materials data collected from various sources^{1, 12} and on engineering judgement. As the required instrument technologies are developed in greater detail, these estimates can be improved.

The *Communications sub-module* calculates the minimum antenna size and mass for a given power, data rate, and orbital altitude. There are four inputs into this module, two of which (orbital altitude and power allocation) are the main system drivers. The outputs from the Communications sub-module are the antenna diameter, the antenna mass, the transmitter mass, and the minimum gimbal distance. The communications equipment is assumed to be collocated with the combiner and the other primary spacecraft systems at the center of a structurally connected interferometer (SCI) or on the combiner spacecraft of a separated spacecraft interferometer (SSI).

The *Power sub-module* chooses the lowest mass power source from the two power sources used in modern spacecraft: solar arrays and radioisotope thermoelectric generators (RTGs). The power system masses are estimated using the average and peak power requirements for the bus and payload subsystems and the mission lifetime, interferometer type, and orbital radius. Solar array, RTG, and battery power, efficiency, lifetime, and mass properties were primarily acquired from published sources.¹² There is a fundamental mass trade between the power system and the other bus subsystems. To minimize mass, the power subsystem tries to drive the power requirements to a minimum, while the other subsystems increase their power requirements to minimize their respective masses. The spacecraft bus algorithm iterates through a reasonable power range to find the equilibrium point between these competing goals.

The *Propulsion sub-module* estimates the mission ΔV requirements and chooses an appropriate attitude control thruster design. The propulsion system provides energy to maneuver the TPF spacecraft between targets and to dump built up momentum. In a separated spacecraft (SSI) mission, the propulsion system must also provide the energy to rotate each collector spacecraft about the combiner, maintaining the spacecraft in constant relative positions. In this case, the Propulsion sub-module is biased to design a system that can sustain continuous low thrust levels.

The *Thermal sub-module* estimates the mass and power of a spacecraft thermal control system to maintain the infrared detector, the optical train components, and the spacecraft electronics at appropriate temperatures. The infrared detector and optical train temperature requirements are derived from the specifications for the instrument sensitivity in the near infrared frequencies. Since the ambient blackbody temperature for the spacecraft is expected to be between 100 and 200 K for the

range of solar orbits under consideration, both cooling and heating capabilities for different parts of the spacecraft will be needed. Using a combined strategy of thermal shields, cryocoolers, and heaters, this module chooses the lowest mass option that satisfies the thermal requirements.

3.5. Dynamics, Optics, Controls, and Structures (DOCS) Module

The Dynamics, Optics Controls, and Structures (DOCS) module¹³ provides the link between aperture physics and the performance modeling in the GINA module. The motivation for this module is to model the difficulties in maintaining nanometer precision optical path length control between the apertures and the combiner of the TPF for SCI and SSI spacecraft architectures. The following paragraphs describe the modules in the order they are executed in TMAS: Structures, Optics Control, ADCS, Integration, and Disturbance Analysis.

The *Structures sub-module* creates dynamic models for the structurally connected (SCI) and separated spacecraft (SSI) interferometer concepts. It uses a generic spacecraft design based on the concept of a central hub, which contains the combiner, the spacecraft bus, and the high-gain communications antenna. The apertures are located in a plane around the hub. In the structurally connected case, a deployable truss connects each aperture with the central hub or with another aperture that is located on the same radial spoke. Each truss and its associated canister are dimensioned based on existing empirical engineering relationships for truss diameter and mass.¹⁴ Using Finite Element Modeling (FEM) methods and matrix algebra, the structural mass, mass distribution, and approximate dynamic characteristics are calculated. Figure 7 shows a graphical representation of a TPF FEM model for a structurally connected, four aperture linear array.



Figure 7. Graphic Representation of a TPF FEM Structure Model (SCI Architecture)

The *Optics Control sub-module* calculates the optics linear sensitivity matrix, which relates the physical displacements and rotations of the combiner and the apertures to the optical performance metrics. Currently, the only optical performance metric examined is the optical pathlength difference (OPD), which can be calculated as a linear combination of the relative displacements of the hub and apertures with respect to each other as shown in Equations (2) through (4). The effect of optical control on the OPD was approximated by passing the optical performance metrics through a low order high pass filter, shown in Equation (5).

$OPL_{ref} = R - z_{ref} + r_{ref} + \overline{d}_{ref} \cdot \overline{u}_{ref} - \overline{d}_o \cdot \overline{u}_{ref}$	(2)	where OPL	- Optical path length
$OPL_i = R - z_i + r_i + r_{ODLi} + \overline{d}_i \cdot \overline{u}_i - \overline{d}_o \cdot \overline{u}_i$	(3)	R	- Distance of the aperture to the reference plane of the incoming stellar wave front
$OPD_i = OPL_{ref} - OPL_i$	(4)	z r	Z position of the apertureRadial position of the aperture
$G_{ODL} = \frac{K_{ODL}s}{s + \omega_{ODL}}$	(5)	d u	 Displacement vector of the aperture Unit normal vector along aperture radius

Figure 8. Optics Sub-Module Key Equations

To provide the nulling performance needed for planet detection, the relative geometry of the TPF apertures and other optical instruments must be maintained within very small tolerances. To satisfy this goal and to allow for the limited bandwidth and dynamic range of available sensors and actuators, a layered control system is employed. With the Optics Control sub-module responsible for the final nanometer scale control, the *Attitude Determination and Control System (ADCS) sub-module* provides the coarser, centimeter scale control between apertures. The main purpose of the ADCS is to stabilize rigid body motions and to reject disturbances at low frequencies. This is achieved by sensing the current attitude (and relative position in the SSI case) using an appropriate suite of sensors and providing control torques and forces using thrusters and angular momentum control/storage devices. The ADCS subsystem design is strongly coupled with the spacecraft configuration, and with other subsystems, such as the propulsion subsystem. The ADCS sub-module characterizes the achievable performance in the face of the worst-case environmental disturbances and the spacecraft disturbances injected into the system by the ADCS actuators themselves (namely, the effects of static and dynamic imbalances in the Reaction Wheel Assemblies).

The *Integration sub-module* assembles an integrated dynamic spacecraft model based on the outputs from the Structures, Optics Control, and ADCS sub-modules. The integrated model is represented in LTI state space form and can be used for the subsequent dynamic performance analysis. The integrated model contains the structural plant, the ADCS, and the optical controllers, as well as the linear sensitivity matrix that relates the physical degrees of freedom of the structural system to the performance metrics of interest (see Figure 9).



Figure 9. TMAS Integrated Dynamics Model Block Diagram

The *Disturbance Analysis sub-module* models disturbances as Power Spectral Densities (PSDs) and evaluates their effect using the integrated spacecraft dynamic model derived in the Integration sub-module. The RMS phase error caused by a disturbance can be calculated with Equation (6) if S_{ww} and G_{zw} are known.

G_{zw} - Transfer function from disturbance to performance output	$\sigma_z^2 = \frac{1}{\pi} \int_0^\infty G_{zw}(\omega) S_{ww}(\omega) G_{zw}^H(\omega) d\omega $ (6)	where
---	--	-------

Figure 10. RMS Phase Error Calculation

Another way to observe the effects of disturbances is to examine the 2-D plots of the transmissivity function. The left subplot of Figure 11 shows the effect of reaction wheel imbalances that where obtained from a test case. The transmissivity function has four symmetric lobes (fringes of peak intensity visible as vertical white lines in the left figure) and the suppression of starlight meets the specification of 10^{-6} out to the star diameter. The right subplot demonstrates the effect of scaling up the wheel imbalances by a factor of 10. This could occur if the wheels are poorly balanced or if a ball bearing fails during operations. The effect on the resulting transmissivity function is dramatic. First, one pair of fringes is being washed out by the vibrations. Second, the nulling of the starlight at the center of the image is no longer meeting the requirements. Clearly, the SNR (integrity) is reduced. In the nominal case, the σ_{OPD} (average) is 76 nm. It is 762 nm in the second case, which corresponds to roughly $\lambda/16$. For non-interferometer systems, such a wavefront error might be acceptable, but for TPF, it clearly is not.



Figure 11. Demonstration of "Washout" Effect Due to RWA Noise

3.6. Operations Module

Operations costs comprise a significant portion of total mission costs, especially over long duration missions like the TPF. They are sometimes considered "hidden" costs since they accrue over time, unlike big-ticket items such as development, construction, and launch. Traditionally, operational issues are relegated to the tail end of a spacecraft design process, and rarely influence the decision criterion of key system trades that they directly affect. This is not to imply that operations crews do not attempt to optimize their efficiencies throughout the mission, but rather that some spacecraft are inherently more difficult to operate than others. Higher operational difficulty leads to larger costs. Therefore, the inclusion of operations costs and improved discrimination between alternate designs.

Operational issues also affect the TPF design trade in an important area besides cost. Dissimilar TPF configurations generate different rates of anomalies along with varying anomaly response times. While not directly affecting cost, the anomaly frequency and response capability influences overall system performance by impacting the availability of the telescope to collect images. This is important in scientific missions with an established design life, but traditionally has not been captured during early system studies. Thus, the inclusion of operationally-derived adjustments to TPF performance indices contributes needed fidelity to the design trades. The key equations used to represent operational complexity and mission inefficiency are shown in Figure 12.



Figure 12. Operations Module Key Equations

The Operations module also includes two sub-modules to evaluate mission parameters and costs associated with the launch and transit phases of the mission prior to the nominal data gathering operations phase. The *Launch sub-module* uses a lookup-table to choose an appropriate launch vehicle based on the estimated total (wet) mass of the TPF spacecraft.¹⁵ The *Orbit sub-module* performs ΔV and flight time calculations based on Hill's transfer method for 1 AU orbits and on Hohmann's transfer method for other orbits.

3.7. GINA Module (Performance Assessment)

The final module in TMAS is the Performance Assessment module, which employs the GINA methodology³ to evaluate alternative mission designs. First, this module calculates the four capability "Quality of Service" parameters (defined in Section 1) for the proposed TPF design – angular resolution, the time required to complete an image in each mode of operation (Equation 9), the total signal to noise ratio, and the predicted availability of the spacecraft. These parameters represent the minimum instantaneous capability requirements the system must meet to satisfy the mission requirements. Second, Markov reliability modeling techniques are used with failure rate and degraded operational capability data to estimate the total number of images that are expected from the proposed design over the mission lifetime (Equation 10). Third, the total mission cost is calculated by summing the contributions from the payload, the spacecraft bus, the launch vehicle, and the operations support costs. Finally, the cost per function metric used to compare mission designs is calculated as the average cost per image.

$$\tau = \left[SNR_n \sqrt{\left(\mathcal{Q}_{leak} + \mathcal{Q}_{LZ} + \mathcal{Q}_{EZ} + \mathcal{Q}_{dark} + \mathcal{Q}_{planet} + \mathcal{Q}_{flat}\right)} / \mathcal{Q}_{planet}\right]^2 \qquad (9)$$

$$Total \# Images = \int_{74}^{256} \sum_{i=1}^{n} C_{si}P_i(t)dt + \int_{325}^{51} \sum_{i=1}^{n} C_{mi}P_i(t)dt + \int_{314}^{565} \sum_{i=1}^{n} C_{di}P_i(t)dt + \int_{366}^{547} \sum_{i=1}^{n} C_{si}P_i(t)dt + \int_{366}^{547} \sum_{i=1}^{n} C_{si}P_i(t)dt + \int_{314}^{565} \sum_{i=1}^{n} C_{si}P_i(t)dt + \int_{316}^{566} \sum_{i=1}^{n} C_{si}P_i(t)dt + \int_{314}^{565} \sum_{i=1}^{n} C_{si}P_i(t)dt + \int_{316}^{506} \sum_{i=1}^{n} C_{si}P_i(t)dt + \int_{316}^{1004} \sum_{i=1}^{n} C_{mi}P_i(t)dt + \int_{316}^{1004} \sum_{i$$

Figure 13. GINA Module Key Equations

Prior to use as a tool to evaluate different mission designs, TMAS results were validated using independently developed preliminary TPF mission designs proposed by Ball,¹⁶ TRW,¹⁷ and Lockheed Martin.¹⁸ The results of evaluating each of these design configurations using TMAS were compared to the TPF system parameters generated by the contractors. When discrepancies were found, they were addressed by first examining the assumptions made by each team and then by modifications to TMAS if necessary. The goal of this verification process was to gain confidence in the results produced by TMAS, not to make the output parameters exactly match those from the other designs.

Overall, the validation test cases proved the validity of TMAS and gave the team confidence in its results. The parameter comparisons primarily involved subsystem mass and power estimates. Figure 14 shows the validation data for the comparison between TMAS data and the

4. TMAS VALIDATION



Figure 14. Sample TMAS Validation Results (TRW SCI)

Structurally Connected Interferometer (SCI) conceptual design developed by TRW.¹⁷ In this case, the significant discrepancies between the two estimates concern the spacecraft structure and the power and propulsion subsystems. The primary reason for these differences is that the TRW design minimized mass using an ultra lightweight truss and lightweight solar concentrators. The TMAS modules account for certain technological advances, but use more conservative assumptions than those made by TRW. Additionally, the propulsion subsystem in the TRW design includes the orbit transfer propellant while the TMAS estimate does not.

5. TMAS RESULTS

The first results from the TMAS were obtained by conducting one-dimensional (one parameter) trade studies of potential TPF mission architectures. These results provide insight regarding the sensitivity of the performance metrics to the mission design parameters. They also provide an opportunity to gain further confidence in the TMAS models by exercising the full range of input parameters to expose potential modeling deficiencies. Table 1 shows the baseline values and value ranges for the four components of the design vector. The one-dimensional studies were followed by a complete enumeration of the TPF design space to identify the optimal configuration and then by an evaluation of optimization methods to determine their capacity to efficiently search the design space and converge to the best mission architecture.

Table 1. Design Vector Parameters Baseline Values and Value Range

Design Vector Parameters	Baseline Value	Value Range
Orbit	1 AU	1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6
Aperture size	2 m	0.5, 1, 1.5, 2, 2.5, 3.0, 3.5, 4.0
Number of Apertures	4	4, 6, 8, 10, 12
Interferometer type	Linear Symmetric (SCI & SSI)	Structurally Connected, Separated Spacecraft,
	-	(also Linear vs. 2D Aperture Array and
		Symmetric vs Asymmetric Array)

The Orbit trade study confirmed that the total number of images, the spacecraft mass, and the total mission cost tend to increase as orbit increases. With the other design vector parameters held constant, the number of images reaches an asymptote at an orbital radius of approximately 3 AU, outside of which the noise contribution of the local zodiacal dust becomes negligible compared to other noise sources. The same number of images is expected for both SSI and SCI architectures with the same number and size of apertures. SSI architectures generally have greater total mass and cost than SCI architectures, for the aperture baselines of up to 120 meters considered, due to the individual spacecraft bus components weighing and costing more than the truss components. Since the total number of images is the same for both SSI and SCI architectures when only the orbit is changed, the total cost per image is lower for the SCI cases. Figure 15 shows that the lowest cost per image occurs at an orbital radius of 2.5 AU. Unfortunately, 2.5 AU is located in the asteroid belt, so future work is required to determine if this orbit is feasible for TPF.



Figure 15. Orbit Trade Study Results

With the constraint that all apertures were the same size, the *Aperture Size trade study* showed expected increases in the total number of images and in the total mission cost as the diameter of the apertures was increased. The number of images increases as a result of the shorter image integration time required to achieve a desired SNR with larger apertures. However, since a (fixed) finite time interval was assumed to occur between imaging passes to reconfigure the spacecraft, the increase in the number of images asymptotically approaches a maximum, calculated as the mission duration divided by the reconfiguration interval. When the other parameters were held at their baseline values, the lowest cost per image occurred when the aperture diameter was 3.5 m for the SSI case and 4 m for the SCI case. Of the four design vector parameters, aperture size proved to have the highest relative importance, i.e. the cost per image performance metric was most sensitive to variations of the aperture size compared to the other design vector parameters.¹⁹ Figure 16 shows the large variation in both the number of images and the cost per image when only the aperture size was varied.



Figure 16. Aperture Size Trade Study Results



Figure 17. SSI Number of Apertures Trade Study Results

The *Number of Apertures trade study* confirmed that spacecraft mass and total mission cost increase as the number of apertures increases. However, while the total number of images initially increased as expected, it began to *decrease* for the highest number of aperture cases due to increased mission complexity. This result was most noticeable for the SSI case (see Figure 17) since the level of complexity of maintaining a constellation of spacecraft in formation flight was assumed to be higher than maneuvering a structurally connected payload.

Another interesting result from the Number of Apertures trade study was that SSI architectures produce more images than SCI architectures except for the minimum case of four apertures. This difference is attributed to the capability of the separated spacecraft architecture to better utilize the remaining apertures (especially odd numbers of apertures) by reconfiguring the array into a new geometry when the Markov reliability model indicates that at least one aperture has failed. However, since the cost of SSI mission designs was also higher than for SCI mission designs (see below), the increased number of images did not result in a lower cost per image.

The *Interferometer Type trade study* showed that the cost and mass of SSI designs are generally higher than for SCI designs for the aperture baselines of up to 120 meters considered for planetary imaging. With such relatively short baselines, the potential mass, complexity, and cost savings of multiple spacecraft versus one spacecraft with long trusses was not fully realized. One-dimensional (linear) aperture configurations produced a greater total number of images than two-dimensional designs for both SSI and SCI architectures when the other design vector parameters were held at their baseline values. The combined effect of these trends was that the SCI one-dimensional architecture generated the lowest cost per image. However, this trend turned out to be an example of a local phenomenon and is not representative of the region around the optimal solution, which contains two-dimensional designs.

From a complete enumeration of all 640 possible design vectors, the optimal solution to the design problem was found to be a structurally connected two-dimensional configuration located at 4 AU with eight collector apertures, each of which is 4 meters in diameter, and a maximum aperture baseline of 30 meters (see Figure 1). This TPF architecture minimized the cost per image metric at a value of \$469.6 thousand per image.

Four *multidisciplinary design optimization* (MDO) techniques were investigated as methods to identify the minimum cost per image TPF configuration in the entire multi-dimensional trade space without conducting a TMAS analysis of all possible configurations.¹⁹ The four MDO techniques tested were Taguchi's method²⁰, simulated annealing¹¹, a pseudo-gradient search, and single variable axis exploration. The best solution obtained from each technique after evaluating only 7.3%-7.8% of all possible solutions was compared to the true optimal solution obtained from complete enumeration. While the simulated annealing, pseudo-gradient search, and single variable axis exploration algorithms all found the true optimal solution at least once over ten trials, the simulated annealing technique was the most consistent at finding good configurations since it is the method least likely to "get stuck" at local minima.



Figure 18. TPF System Trade Space Cost Per Image Results

The plot on the left in Figure 18 illustrates the full trade space for the TPF mission with lines of constant cost per image indicated. The zoom-in plot on the right shows the location of the true and Taguchi optimal solutions. All four techniques converged to the region in the trade space with the best solutions on the basis of the cost per image metric after evaluating

less than 8% of the total trade space. While complete enumeration guarantees optimality and was possible in this case, the exponential growth rate in the number of design options as a function of the design vector size makes these optimization techniques an attractive alternative for large problems.

6. CONCLUSIONS

TMAS has proven to be a useful tool for evaluating TPF mission architectures based on unified quantitative metrics. By incorporating a modular architecture, TMAS can be incrementally refined and updated to contain the appropriate level of modeling detail for each subsystem. As implemented, TMAS captures the essential physics and heuristics for all aspects of the TPF mission architecture, including areas often neglected, such as operations. Through the use of the GINA methodology, TMAS permits comparison of significantly different mission architectures (structurally connected vs. separated spacecraft) using quantitative, comprehensive metrics. Finally, TMAS can be combined with multivariable optimization techniques to more quickly identify the best candidate mission designs for detailed analysis and to evaluate the sensitivity of the output metrics to changes in the design parameters.

While the TMAS package is specifically tailored to evaluate TPF mission designs, it is an example of a new methodology for performing quantitative comparisons of intrinsically different design concepts that satisfy the mission requirements. With the appropriate selection of metrics and application of physical principles and engineering design practices, this methodology may be applied to other missions to aid in the selection of the most effective mission architectures.

ACKNOWLEDGMENTS

The authors would like to thank Professor Walter Hollister, Dr. Joyce Warmkessel, Dr. Raymond Sedwick, and Colonel Pete Young for their guidance and assistance during this project.

REFERENCES

- ¹ Beichman, C. A., Woolf, N. J., and Lindensmith, C. A., ed., *The Terrestrial Planet Finder (TPF): A NASA Origins Program to Search for Habitable Planets*, JPL Publication 99-003, 1999.
- ² Curtis, A., et al. *ASTRO: Architecting the Search for Terrestrial Planets and Related Origins*. MIT Space Systems Laboratory. SERC #6-99, 1999.
- ³ Shaw, G. B., "The Generalized Information Network Analysis Methodology for Distributed Satellite Systems," PhD Thesis, MIT Department of Aeronautics and Astronautics, 1998.
- ⁴ Shaw, G. B., Miller, D. W., and Hastings, D. E., "Development of the Quantitative Generalized Information Network Analysis (GINA) Methodology for Distributed Satellite Systems," Journal of Spacecraft and Rockets, AIAA, 2000.
- ⁵ Kong, E. M. and Miller, D. W., "Optimization of Separated Spacecraft Interferometer Trajectories in the Absence of a Gravity-Well," Proceedings of the SPIE International Symposium on Astronomical Telescopes and Instrumentation, Paper No. 3350-13, Kona, Hawaii, March, 1998.
- ⁶ Beichman, C. A., A Road Map for the Exploration of Neighboring Planetary Systems, JPL Publication 96-22, 1996.
- ⁷ Bracewell, R.N., and Macphie, R.H., "Searching for Non Solar Planets," *Icarus* 38, p. 136, 1979.
- ⁸ Makins, B., et. al., "TPF Mission Requirements Document," MIT Course 16.89, Space Systems Engineering, 1999.
- ⁹ Boppe, C. W., "Integrated Product Process Development," 16.870 Aerospace Product Design course notes, 1997.
- ¹⁰ Mennesson, B. and Mariotti, J. M., "Array Configurations for a Space Infrared Nulling Interferometer Dedicated to the Search for Earthlike Extrasolar Planets," *Icarus* 128, pp. 202-212, 1997.
- ¹¹ Kirkpatrick, S., Gelatt, C. D., and Vecchi, M. P. "Optimization by Simulated Annealing," *Science*, Volume 220, Number 4598, 1983.
- ¹² Larson, W.J. and Wertz, J.R., Space Mission Analysis and Design, 2nd Edition, Microcosm Inc. Torrance, CA., 1992.
- ¹³ Gutierrez, H., "Performance Assessment and Enhancement of Precision Controlled Structures During Conceptual Design," PhD Thesis, MIT Department of Aeronautics and Astronautics, 1999.
- ¹⁴ AEC -- ABLE Engineering Company, ABLE Deployable Articulated Mast (ADAM) Technology Manual, 1999.
- ¹⁵ Isakowitz, Steven J. International Reference Guide to Space Launch Systems, 2nd Edition, AIAA, Washington, DC, 1995.
- ¹⁶ Noecker, C., et al., "Ball TPF Study," Ball TPF Conceptual Design Report, 1997.
- ¹⁷ Wehner, M., Johnson, L., Kroening, K., and Moses, S., "TRW Terrestrial Planet Finder Study," *TRW TPF Conceptual Design Report*, 1997.
- ¹⁸ Francis, B., et al., "Lockheed Martin TPF Final Review," Lockheed Martin Missiles & Space TPF Conceptual Design Report, 1997.
- ¹⁹ Jilla, C. D., Sedwick, R. J., and Miller, D. W., "Application of Multidisciplinary Design Optimization Techniques to Distributed Satellite Systems," Proceedings of the AIAA Space Technology Conference, AIAA-99-4632, Albuquerque, NM, September, 1999.
- ²⁰ Ross, P.J., Taguchi Techniques for Quality Engineering: Loss Function, Orthogonal Experiments, Parameter and Tolerance Design 2nd Edition, McGraw-Hill, New York, 1996.