System Engineering for Spaceborne Optical Interferometers[1]

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Abstract - Spaceborne optical interferometry truly represents uncharted territory – one in which the community developing such missions is still "learning the ropes". This paper is based on a collection of lessons-learned based on related missions including StarLight, a formation-flying stellar interferometry mission that merged with the Terrestrial Planet Finder technology development program just prior to entering phase C/D, the Space Interferometry Mission (currently in phase A), and the Shuttle Radar Topography Mission of 2000 (a radar interferometer which flew in 2000). To first order, optical interferometry missions differ from classical deep-space science missions in several key respects: they are highly distributed systems, they are sensitive to small, cross-coupling error sources, and their operation is very complex. This leads to three unique system engineering challenges associated with implementing such missions: error handling and performance modeling, validation and verification (V&V), and system robustness. With an upcoming suite of interferometry missions approaching the transition from *technology-development mode* to *flight project implementation mode* the time is ripe for a discussion of these challenges and proposed solutions.

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1. INTRODUCTION

There are a number of major spaceborne optical interferometry missions (operating at visible or infrared wavelengths) with reasonably near-term launch dates [1-5].

Table 1 - Near-term Optical Interferometry Missions

Mission	Objectives	Launch
Disturbance Redux System (ST-7 DRS)	Drag-free technology demo	2005
Space Interferometry Mission (SIM)	Exo-planet detection & astrometry	2009
Laser Interferometric Space Antenna (LISA)	Gravity wave detection	2011
Terrestrial Planet Finder (TPF)	Exo-planet detection & spectroscopy	2015
Darwin	Exo-planet detection & spectroscopy	2015

Many other potential near-term and future missions exist in various stages of planning, including wide-field imaging interferometers such as the Space Infrared Interferometric Telescope (SPIRIT) and Submillimeter Probe of the Evolution of the Cosmic Structure (SPECS) and the Micro-arcsecond X-ray Imaging Mission (MAXIM) [6, 7]. All of the above projects are currently (and appropriately) in *technology-development mode*, meaning their focus is on system proof-of-concept in the laboratory along with flight-qualification of selected low-heritage components. These projects will soon undergo a profound metamorphosis as they transition into *flight-project mode*, where the focus will change to producing a robust, deep-space system on-time and within budget. Such transitions are likely to prove challenging given some "cultural" issues that exist in both the interferometry technology and flight-project implementation communities.

To first order, optical interferometry missions differ from more classical deep-space science missions in several key respects: they are highly distributed systems, they are

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sensitive to small, cross-coupling error sources, and their operation is very complex. This leads to three unique challenges in the area of system engineering: error handling and performance modeling, validation and verification (V&V), and system robustness. Performance modeling for interferometers requires a heightened awareness of issues such as errors in the interfaces between constituent models, calibration and characterization testing (and/or modes of operation), and removal of systematic errors. V&V for optical interferometers requires a greater emphasis than usual on things such as requirements validation and model validation and on planning for performance verification (true end-to-end testing is very difficult, resulting in a critical need for a carefully formulated piecewise verification story-board). Finally, ensuring the flight interferometer is robust, both in terms of performance and functionality/operability, places increased demands on performance sensitivity and fault tree analyses.

2. CONTEXT & MOTIVATION

The genesis of this paper began with an invitation for the author to give a presentation on "system engineering lessons-learned for interferometry missions" to the Navigator Program System Engineering team at NASA's Jet Propulsion Laboratory (JPL). The Navigator Program manages the suite of Origins missions led by JPL for NASA which includes projects like SIM and TPF [8].

Some disclaimers are required before proceeding. First, while many of the concepts presented will be applicable to all spaceborne interferometers (including those operating at microwave, sub-millimeter, and X-ray wavelengths) and potentially other complex observational systems such as coronographs, the emphasis here will be on interferometers operating at visible and infrared wavelengths (both white-light stellar interferometers and gravity-sensing laser interferometers). Also, this paper will not describe the fundamental principles of interferometer design as these are already well covered in the literature [9].

This discussion is about *flying* an interferometer reliably for several years in deep-space. These issues will first arise in the Formulation Phase (Phase A) and become critical in the Design, Implementation, & Operations Phases (Phase C/D/E) of a flight project.

The observations offered in this paper are based on lessons-learned from the author's experience as a system engineer on the following related missions:

- Shuttle Radar Topography Mission (SRTM) – earth-looking Interferometric Synthetic Aperture Radar (IFSAR) with a 60 meter monolithic baseline. Flew in 2000. [10]
- Space Interferometry Mission (SIM) – monolithic stellar astrometric interferometer.
- StarLight – formation-flying stellar interferometer (TPF precursor mission) [11]
- Terrestrial Planet Finder (TPF) –formation-flying (or monolithic) nulling interferometer or coronograph
- Kepler – transit photometer not interferometer (but with science issues very similar to SIM, TPF, etc)

Some examples from the latter will be given since the author's most recent experience in applying these lessons-learned is on the Kepler planet-detection mission [12].

The main motivation here: we need to get it right on SIM, TPF, LISA, etal...and it has to be done right on the *first attempt*. We can't afford a "cut and try" approach on billion-dollar plus missions.

3. "CULTURAL AWARENESS"

Before diving into what's difficult about interferometer system engineering, it's worth taking a moment to appreciate the current state of the space-borne optical interferometry "culture".

Most interferometer missions are currently in *Technology Development Mode*. Meaning, their primary goal is "Proof of System Concept in the Lab/Observatory and Qualify Key Components". This focus is quite necessary and appropriate at this stage. However, at some point – typically late in phase A – these projects must transition to *Flight Project Mode*. At which point the goal must change to: "Deliver a ROBUST, integrated flight SYSTEM". Note the emphasis on ROBUST and SYSTEM. We'll come back to these issues later.

So we can expect to see a number of projects transitioning between these modes in the near future. Their success in doing so will be somewhat dependent on their recognition of this transition and their pro-active efforts to facilitate it. The time is ripe for a discussion of these issues and proposed solutions.

Additionally, there is another consideration associated with the project personnel themselves. Many veterans of past flight projects are unfamiliar with the relatively new science and technology of interferometry – they're still learning the key system issues and basic language. Conversely, many interferometer technologists have not worked on a flight project beyond Phase A. As a result, project managers are sometimes unaware of and unsympathetic to the special needs (& extra costs) associated with system engineering for these missions. Technologists may scoff at the need for formal & rigorous system engineering when they've successfully used a "cut-n-try" approach in ground testbeds. The danger here is projects might put too much focus on *invention* at the expense of *delivery*.

However, these sorts of cultural differences are not unusual in areas where large step-functions occur in technology. In the end: both viewpoints and skill-sets are necessary to make the project successful. With awareness and patience, we should be able to blend the two cultures.

3. OPTICAL VS MICROWAVE: DIFFERENCES & USEFUL PARALLELS

There are currently two basic flavors of sparse-aperture interferometry used in astronomy and remote-sensing: optical interferometry and radio/radar interferometry. The distinctions are primarily due to the physics involved at the different wavelength regimes and the science applications of these techniques as discussed below.

Note, Fizeau interferometers involving masked single apertures are not included in this discussion. Also note, while techniques are being developed for use at other wavelengths (namely sub-millimeter and X-ray for the earlier referenced SPECS and MAXIM missions) these systems do not yet have the maturity of visible, infrared, and microwave space interferometry missions[13]. However, we can expect such missions in the future and the lessons discussed in this paper apply to them as well.

3.1 Interferometric Techniques

1. Optical interferometry (visible & infrared regime)

   Two sub-types, stellar interferometers and gravity-wave interferometers.

   a. Stellar interferometers: obtain white-light fringe visibility amplitude &/or phase measurements on flux from target stars with an emphasis on detecting and characterizing extrasolar planets via one or more of the following methods:

   - Astrometry – a 3-interferometer, "parallel" configuration with a nearly co-linear, monolithic baseline is employed to indirectly detect planets by observing the gravitational wobble induced on their host star. Two interferometers produce fringe measurements on bright guide stars while the third interferometer produces fringe measurements for a number of offset science stars. The relative delays in fringe phase between the interferometers combined with precision (pico-meter level) baseline metrology allow reconstruction of angular separation between the science stars and an astrometric reference grid to high precision. SIM will provide astrometric precision of a few micro-arcseconds (μas) over 5 years enabling detection of 10 earth-mass (Me) planets in the habitable zones of stars at distances of about 10 parsecs (pc).

   - Nulling – a 3-interferometer, "series" configuration (outputs of two interferometers feed the inputs of the third interferometer) is used to project an achromatic nulling fringe pattern on the plane of the target planetary system such that the star light is suppressed by the null and planets can be detected by rotating the interferometric array about the line of sight to the star and observing the resulting visibility amplitude modulation as planets move in and out of the fringe pattern. They can either be a monolithic or formation-flying architecture. One possible architecture for TPF will use this technique to produce null-depths of 10E-6 at 10 μm, enabling detection of earth-size planets in the habitable zones at 15 pc.

   - Synthesis imaging: the 3-baseline nulling configuration described above is used to acquire fringe visibility amplitude and phase measurements at discrete baseline orientations and lengths such that the complex uv-plane is sampled. Aperture synthesis (inverse Fourier) techniques developed by radio astronomers are then applied to generate a synthetic image of planetary systems and other objects of astrophysical interested with a resolution proportional to λ/B. Clearly, a large and variable baseline is desirable so formation-flying architectures are preferred. A formation-flying TPF operating with a 1km baseline in astrophysics imaging mode could achieve resolutions of about 2 milli-arcsecond (mas).

   b. Laser Interferometric Gravitational Observation (LIGO): precision laser heterodyne metrology measurements of large baselines and drag-free gravitation reference sensors are used to measure the small displacements of proof-masses associated with the passage of gravity waves. LISA will achieve acceleration noise levels of 3E-15 $ms^{-2}Hz^{-1/2}$ (for f = 10E-2 Hz and lower) by measuring 5 million km baselines to a precision of 10 pm and controlling spacecraft-body positions relative to their internal proof-masses to an accuracy of 10 nm (drag-free sensors).

2. Radio/Radar interferometry (microwave regime)

    a. Interferometric Synthetic Aperture Radar (IFSAR or InSAR): active microwave fringe visibility phase measurements used for moderate resolutions imaging, polarimetry, and elevation mapping of planetary surfaces. There are three common architectures and operational modes for such interferometers:

- Single-pass monolithic baseline
- Single-pass formation-flying baseline
- Repeat-pass (single spacecraft)

(note: in this context "single pass" means only one pass is required to generate a fringe measurement – meaning an interferometric baseline exists in a spatial sense as opposed to a temporal sense for the repeat-pass method - in all cases, repeated fringe measurements from different look angles improve the accuracy of the solution)

    b. Very Long Baseline Interferometry (VLBI): passive microwave fringe visibility amplitude & phase measurements of astrophysical sources from widely separated radio antennas to perform aperture synthesis imaging (uv-plane coverage provided by the Earth's rotation for ground- based arrays or by maneuvering spacecraft for space-based arrays).

3.2 Differences Between Optical & Microwave

Admittedly, there here are significant differences in the between the two basic techniques, primarily associated with:

a. direct vs indirect fringe generation
b. sensitivity to mechanical positions

Radio and radar interferometers operate by independently detecting signals from two antennas and combining them a posteriori for indirect fringe generation. This method involves heterodyne receivers which experience shot noise from their local oscillators - about 1 photon per Hz of bandwidth [14]. While this is acceptable at microwave wavelengths, the local shot noise grows with frequency such that it dominates the source shot noise and detector noise at visible and IR wavelengths (400 nm to 30 μm). So optical (Michelson) interferometers employ direct detection - in which the two beams are combined using a beam-splitter with the resulting fringe sampled by a single detector. This approach results in a system whose accuracy is properly limited by the source shot noise and detector noise as opposed to the shot noise of some optical local oscillator.

Also, while visible wavelengths result in a 10,000-fold improved spatial resolution over that available in the microwave regime, this also means an equivalent increased sensitivity to opto-mechanical tolerancing and geometry. These factors require precision angular (mas level) and linear metrology (nanometer level) and high-bandwidth (few kHz) real-time control of Optical Path Delay (OPD), intensity matching, etc to acquire and track the fringe.

On the flip side, VLBI and IFSAR operate primarily in the microwave (cm – mm) regime, which does not preclude a posteriori fringe generation by heterodyne mixing. However, this requires large data-rates/volumes (typically a few hundred Mbps) and precision time-correlation associated with the independent data channels. Also, only modest baselines and antenna surface metrology (μm to mm scale) and no appreciable real-time control are required. However, radio and radar antennas are typically much larger than optical apertures for an equivalent visible instrument and thus suffer from larger external disturbances (even if they have reduced sensitivity to them).

3.3 Useful Parallels

Yet despite these differences, there are two common areas of synergy between the optical and microwave regime that can be mined for common lessons-learned:

1) The problem of fringe acquisition in the presence of high delay-rates is common to both VLBI and formation-flying stellar interferometers. This similarity was applied to fringe detection algorithm design on the StarLight mission.

2) Geometrical issues associated with tying the interferometric baseline to a global reference frame are common to both DEM-producing IFSARs and wide-angle stellar astrometry. The two missions that come to mind in this context are SRTM and SIM.

The point here is some cross-pollenization is definitely possible. SIM and TPF have acquired this recently is the form of key team-members hailing from the VLBI and IFSAR communities.

5. UNIQUE CHALLENGES FOR INTERFEROMETRY MISSIONS

While all deep-space missions are challenging, optical interferometers are uniquely challenging in the following areas:

1. They're highly distributed systems
2. They suffer from small cross-coupling errors
3. They're very complex to operate

Each of these issues is explored briefly below to provide an appreciation for why they result in unique system engineering challenges.

5.1 Highly Distributed Systems

Unlike most planetary probes consisting of one or many small science instruments operating somewhat independently on a spacecraft bus, interferometers are essentially one big instrument. And unlike other large space-borne observatories based on filled-aperture telescopes, monolithic interferometers in their operational configuration reach lengths of tens of meters and formation-flying interferometers consist of multiple spacecraft operating in an array 100's to 1000's of meters across. The fact that such systems are too large to launch in an operational configuration means they typically involve many deployments. The result is a system that is physically LARGE and connected loosely at best - both in a structural, electrical, and thermal sense. This unfortunately means interferometers are very effective "disturbance antennas".

Interferometers are also very distributed in that they typically have many steps in their "signal processing chain" (i.e., photons encounter many optical surfaces in series, distributed across a large area - each experiencing perturbations before reaching the detector).

Another issue associated with being a large, distributed system is fault tolerance. Building redundancy into such a system is difficult given the large number of opto-mechanical elements, many of which are actively driven. Some redundancy can be provided with optical switchyards and backup components but such methods require additional mass and cost and can actually lead to reduced reliability.

5.2 Small Cross-Coupling Errors

Due to the short wavelengths and sensitivity to small motions, optical interferometers must accommodate error sources that are well below the detection threshold of other missions.

At the scale of nanometers and picometers, EVERYTHING affects fringe acquisition and tracking and/or baseline metrology! A partial list of examples:

- Micro-dynamics in structures
- Thermal changes on milli-Kelvin scales
- Micro-seismicity (Lenz's law)
- Small angle errors due to (tiny) lever-arms
- Actuator-induced jitter

The latter point is a two-way street: motion of delay-line actuators perturbs pointing control system performance and vice-versa. So an interferometer can be *self-polluting* in terms of disturbances.

Given the tendency of interferometers to act as disturbance antennas and their sensitivity, systematic errors typically lurk everywhere. Even when suppressed by real-time or post-processing techniques, *systematic error are never removed – only reduced* by some finite amount. Accounting for such residuals is critical.

5.3 Operational Complexity

The need for precision external pointing control, internal alignment and beam-shear control, and OPD control results in:

- many nested control loops
- many sensors & actuators
- multiple "hand-offs"
- high-bandwidths and ranges of motion

Likewise, fault-protection promises to be very complex in that all interferometers must accommodate the difficulties in redundancy management mentioned earlier and formation-flyers face the additional challenge of accommodating sophisticated autonomous functions such as collision avoidance, constellation initialization, and prevention of constellation "evaporation". Finally, for formation-flying architectures, basic intra-constellation communication is non-trivial (including control coordination due to latencies and different command and control topologies – see Figure 1).

Given the above differences between interferometry missions and classical deep-space missions, implementing the former requires the system engineer to successfully meet the challenges in the following areas:

a. Error Handling & Performance Modeling
b. Validation & Verification
c. Robustness

In the following sections, the potential pit-falls of each area are provided along with recommended solutions.

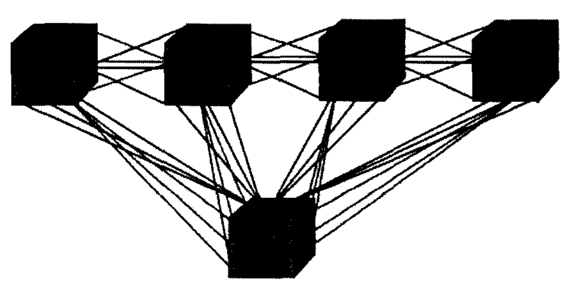


Figure 1- Constellation Control Complexity (ex: TPF)

6. ERROR HANDLING & PERFORMANCE MODELING

System level error budgets and models sometimes contain holes in the form of wrong assumptions about "negligible terms". In any well-designed experiment, the total instrumental noise is comparable to the noise inherent in the physical process being measured. So identification and suppression of systematic errors is key to meeting this requirement. This may sound obvious but recall that we're dealing with a regime that defies our everyday experience on other deep-space missions.

For example, consider the recently launched Gravity Recovery and Climate Experiment (GRACE) mission that involves measuring distances between proof-masses on two formation-flying spacecraft to a precision of a few microns in order to sense accelerations at the 1E-10 $ms^{-2}Hz^{-1/2}$ level [15]. During ground testing of their precision accelerometers, the GRACE team noticed an unexpected acceleration that appeared to be correlated with heater limit-cycling. Despite the fact that the heaters were designed to be magnetically-compensated, several months of investigation revealed the cause to be "micro-seismicity" produced by Lenz's Law (magnetic fields from heaters inducing eddy currents in an adjacent aluminum panel, resulting in a significant acoustic wave in the panel) [16]. While this did not result in a problem for the non-conductive flight configuration, it's a good example of how we can be surprised by subtle effects. Considering the fact that ST-7 DRS and LISA will have sensitivities 3 and 6 orders of magnitude greater than GRACE, respectively, it's logical to assume we will be surprised again as the technology pushes into new performance regimes.

When error budgeting we sometimes wave our hands at error sources that *seem* negligible based on engineering intuition and past experience. However, in dealing with interferometers, one must be rigorous in identifying ALL conceivable errors sources and explicitly listing them in related error-budgets. Even if the source is truly negligible compared to other terms, this systematic approach minimizes the potential for surprises. Projects should develop, maintain, and peer-review a master list of error sources (including those deemed "insignificant").

The potential pit-falls in dealing with error sources in complex interferometer systems include:

a. Performance modeling errors
b. Calibration & characterization
c. Systematic error correction

6.1. Performance Modeling Errors

Performance modeling in this context includes all simulation, modeling, and error-budgeting of overall system performance for the interferometer. Depending on the application, these models/budgets can address top-level parameters as astrometric (angular) precision, fringe visibility amplitude and phase, null depth, OPD control accuracy, pointing accuracy, etc.

Given the highly distributed yet cross-coupling nature of interferometers, true end-to-end performance models are almost always required. Such end-to-end models frequently rely on a number of independent models whose inputs and outputs are woven together into a (hopefully) seamless whole. Such components might include optical prescription models, OPD and pointing control models, signal processing chain/detector models, thermal models, structural models, astrophysical models, etc with simulation of disturbance sources such as optical alignment, beam-shear, jitter, and jitter using Monte Carlo techniques. Assigning model development and validation responsibility to independent analysts without providing adequate coordination is asking for trouble in the form of inconsistent assumptions and holes in the interfaces.

The SRTM project suffered from not having an end-to-end model and having insufficient model definitions in general. This resulted in additional efforts to resolve model interface issues as well as fundamental disconnects between the radar error budgets and metrology error budgets associated the spectral nature of the observables. This contributed to an under-sampled mode of the 60 meter mast supporting the interferometer. While this error was a second-order effect, its impact on the final data produce was significant and required major, unplanned post-processing to reduce.

When architecting an end-to-end model, it is preferable to have some overlap at the interfaces between two models such that consistency checking is enabled. Likewise, a common set (database) of input parameters should be shared by all constituent models, rather than independent parameter sets for each model. Figure 2 depicts these concepts.

Another way to avoid interface errors between models is

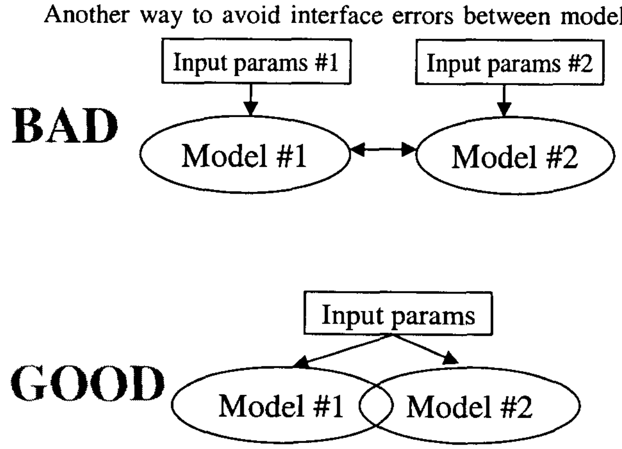


Figure 2 - Model Interface Architecture

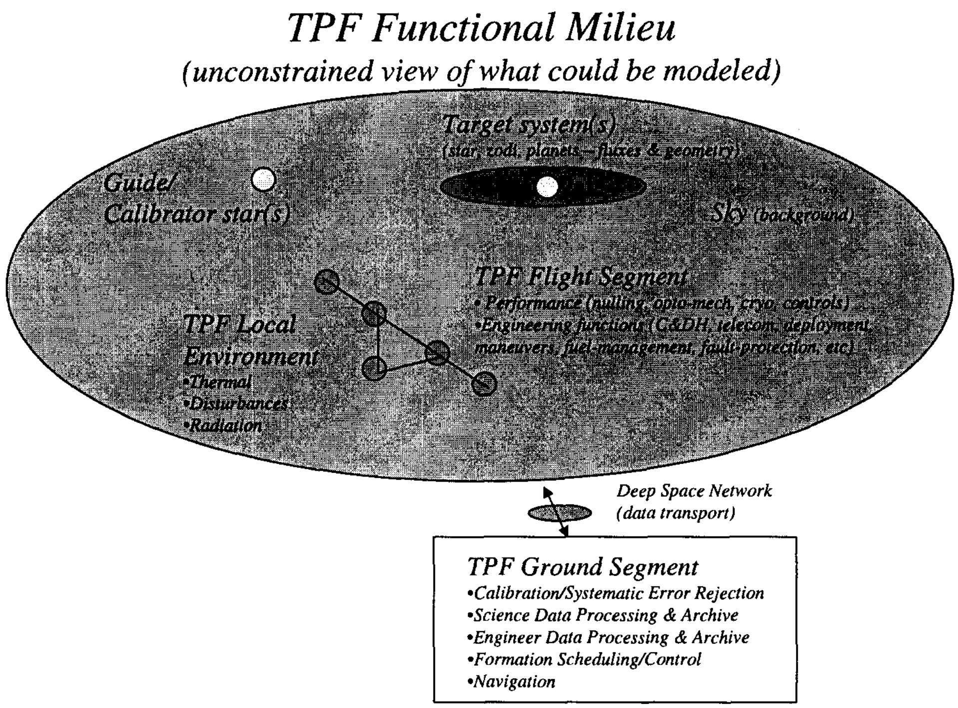


Figure 3 – Model "Functional Milieu" concept (ex: TPF)

to use a systematic approach to design the end-to-end model architecture and develop a modeling plan for implementing and validating it early in the project life-cycle.

6.2. Calibration & Characterization

The process of determining the magnitude of various systematic errors includes characterization and calibration testing. These efforts (at a component and system level) allow the system engineer to validate models and ensure error budget entries are realistic. This is an iterative process beginning in Phase B of a project (with testbeds and prototype hardware) and in continues well into Phase E (in-orbit checkout).

6.3. Systematic Error Correction

Being aware of systematic errors is an important first step. Knowing what to do with that knowledge is even more important. In some cases, systematic errors can be ignored in others they must be removed. Deciding how to categorize these involves a systematic study of how the uncompensated systematic errors can affect overall performance.

For example: in many detectors, bias due to dark-current is a systematic error that must be reduced to avoid swamping the star signal but the shot-noise associated with the dark current cannot be removed and thus must be budgeted along with other random noise sources.

The following *cautions* are in order when dealing with systematic error modeling and correction:

- There's no such thing as "total systematic error removal" (residuals in the form of measurement or algorithm errors always exist...the question is, are they significant?)
- Many, but not all systematic errors are common-mode (spatially correlated with other signals). In other words, a systematic error can be uncorrelated spatially but may be temporally correlated (e.g., thermal drifts). These distinctions should be explicitly identified when listing error sources.
- Colored noise with long time-constants can masquerade as either simple white-gaussian noise or DC biases on short time-scales (e.g., they can represent significant drifts/ramps on longer time-scales)

6.4. Planning

Interferometer missions can follow a structured approach to architecting, implementing, and managing the above efforts by generating the following products:

a. Performance Modeling Plan
b. System Performance Book
c. Characterization/Calibration Plan

The Performance Modeling Plan should be developed in early Phase A and identify what model/simulation/error-budget capabilities are needed (in terms of functions & accuracy), how the end-to-end modeling environment will be architected, who does what, etc. This plan is key to properly staffing and estimating the appropriate costs for the modeling effort. Without this structured approach, projects risk an ad-hoc development of models, resulting in overlap, gaps, and cost-overruns.

The following suggestions on architecting a Performance Modeling Plan are offered:

1. The most important step: making the effort to plan it - do this in phase A
2. Keep the big picture in mind - periodically step back and compare the scope of the modeling program against the mission's "functional milieu" – it's important to explicitly identify what is being simulated and what is not [see Figure 3]
3. Recognize that a system is a "3 dimensional" entity in the following sense and should be modeled as such:
    a. "width" – End-to-End nature of the Project System (flow of "stuff" from front end of Flight Segment through back end of Ground Segment)
    b. "height" – top-to-bottom (or vice-versa) nature of system performance (error budgets must identify all significant error sources in a coherent fashion)
    c. "depth" – time or phases in the project life cycle (recognize that models/simulations will evolve over time to serve different purposes)
4. Finally, balance "what you want" with "what you need" and "what you can afford"

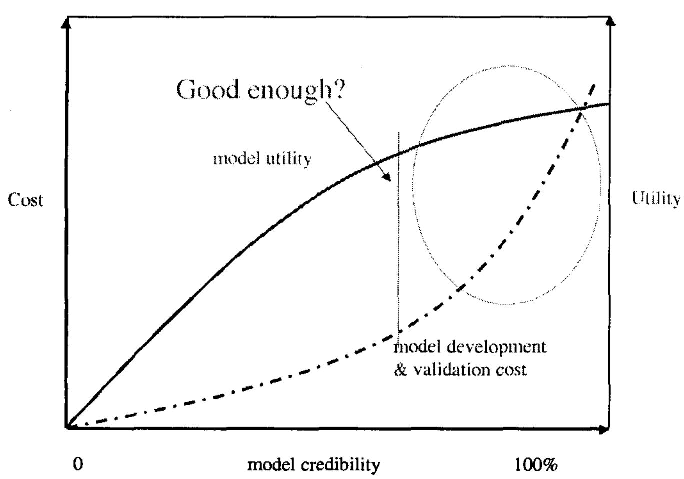


Figure 4 - Model Cost vs Credibility vs Utility

For example, the typical relationship between model cost, utility, and credibility is depicted in Figure 4 [17]. A system engineer may ask the question: is 60% model credibility (accuracy) good enough? Increasing the credibility to near perfection (99.99%) will likely produce a relatively small improvement in utility but involves a substantial model development cost. How much improvement is warranted? The answer to these questions depends on the ultimate use of the model and its criticality in the overall project risk equation.

The System Performance Book describes how the models work, their components, and interfaces. It also provides the rolled-up, official performance assessments of the system during phase C/D/E.

The Characterization and Calibration Plan describes what needs to be measured, how to do it, by whom, when, and what will be done with the information (knowledge and/or control). This is a very important product as it specifies what measurements must be done pre-launch (driving requirements on GSE and test plans) as well as *in-flight*. The latter often drives functional requirements on the flight system (e.g., the need for the spacecraft to perform certain maneuvers and/or the addition of extra fiducials and sensors to support interferometer calibration).

7. VALIDATION & VERIFICATION

While *Validation and Verification* is a critical function for all deep-space missions and is treated in detail elsewhere in the literature [18], some aspects are particularly important and difficult on interferometers and are presented here, namely:

1. Validation of requirements
2. Validation of models

The main objectives of a V&V program are:

a. Validate requirements in phase A/B (prove our requirements will meet the Need before building the thing)
b. Validate models – ongoing (prove our mission-critical models reflect reality)
c. Verify the as-built system in phase C/D (prove what we built meets the requirements we wrote)
d. what we built truly meets the Need and is ROBUST)

Validation is ALWAYS tricky on projects because it makes us think "out of the box". How will the system respond if X happens? Will the system do what we want in flight, considering nobody's ever done this before? The latter point is particularly important since there are many different ways to implement interferometers and one must take care to select the best method for the application at hand. An example of this was a major trade-study done by the SIM project several years ago to select between two fundamentally different architectures: "SIM Classic"and "Son of SIM" (Figure 5). Since both architectures were theoretically capable of meeting the driving objectives there could exist two different sets of requirements – "which set is most correct" is a very important question to ask in that case.

Verification is more complex on interferometers than other missions because we typically cannot do end-to-end tests on the flight system – rather, "piecewise verification".

7. 1 How to architect a V&V Program

As with Performance Modeling, the first step in implementing a successful Validation & Verification program is to expend some effort into early *planning.* Projects should develop a V&V Plan (draft in Phase A, final by PDR) that illustrates how the four aspects of V&V discussed above will be addressed.

The V&V plan plays a critical role in identifying *mission critical models* – defined as those models to be used for "verification by analysis" (things that can't be demonstrated by test). Such things should be captured in story-board format that identifies how each link in the V&V chain is covered. With the mission-critical models thus highlighted, the system engineering team can ensure they are rigorously validated prior to use in verification.

As discussed above about modeling, system engineers should recognize the 3 dimensional nature of the project system when architecting the V&V program – looking at

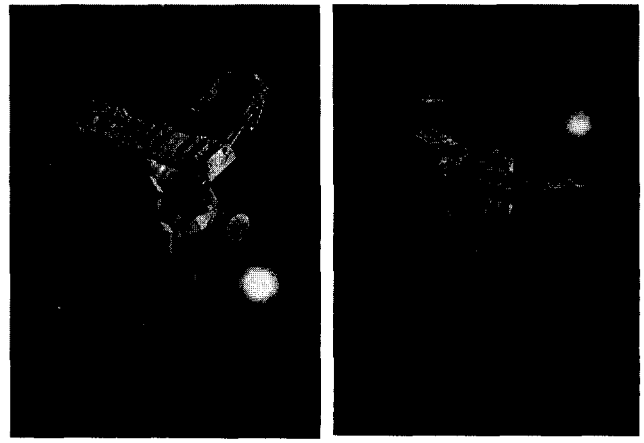


Figure 5 - Two Versions of SIM

the problem from three different perspectives typically yields a good integrated picture. Finally, use the V&V plan to help balance what's desired with what's needed. Projects have freedom to tailor the program as needed but a detailed plan is required to make intelligent choices between cost-management and risk-mitigation.

Figure 6 depicts the architecture of a generic V&V program.

7.2 Requirements Validation

As shown in Figure 6, the draft set of mission requirements should be validated before proceeding with detailed system design, implementation, and ultimately, verification. System engineers can create a validation matrix to help track validation of requirements (just as

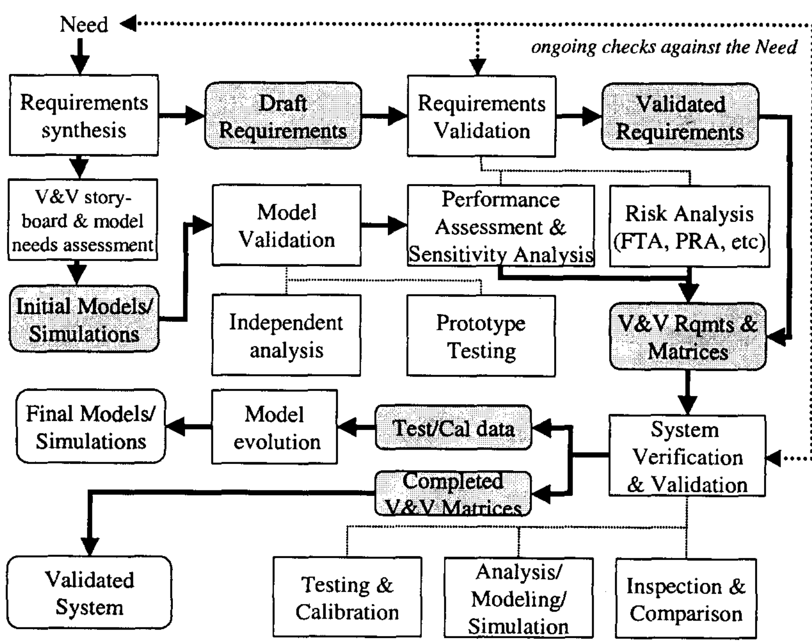


Figure 6 - Validation & Verfication Program Architecture

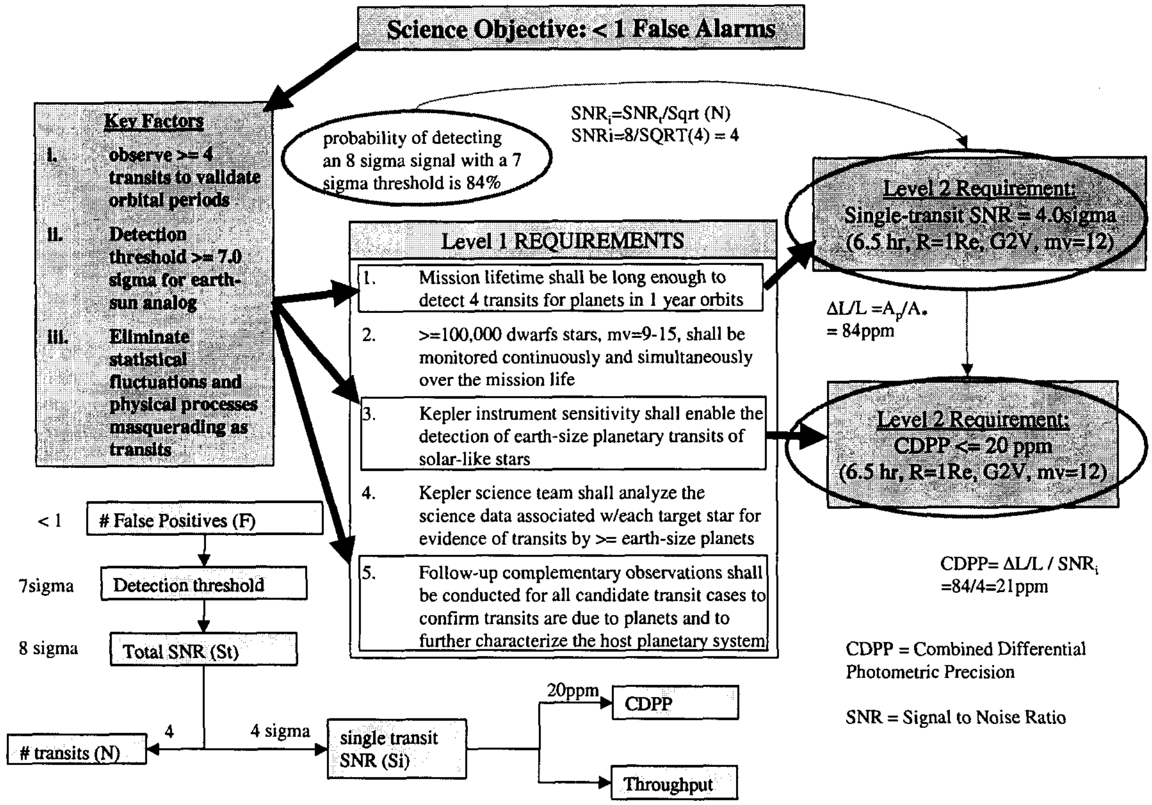
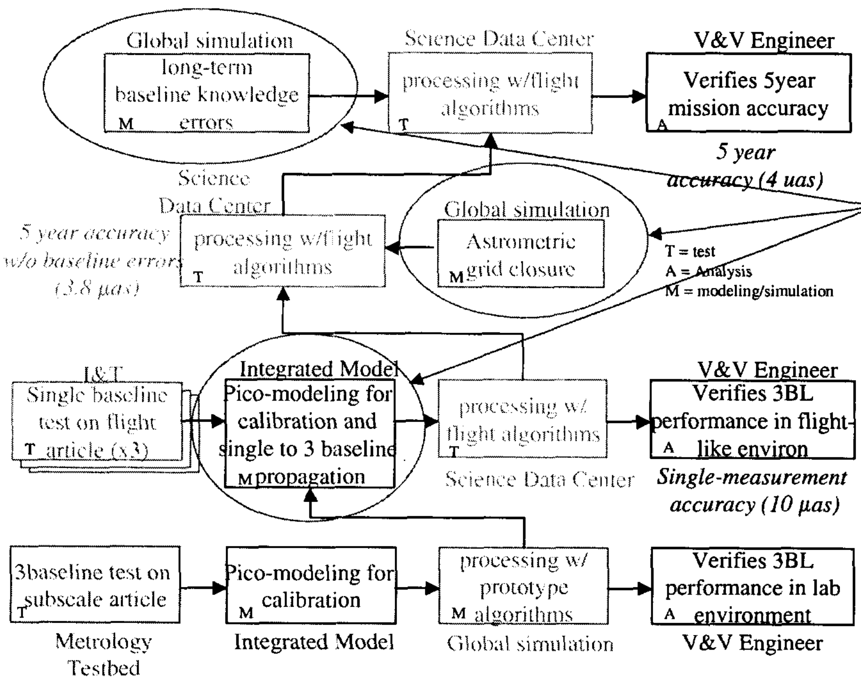


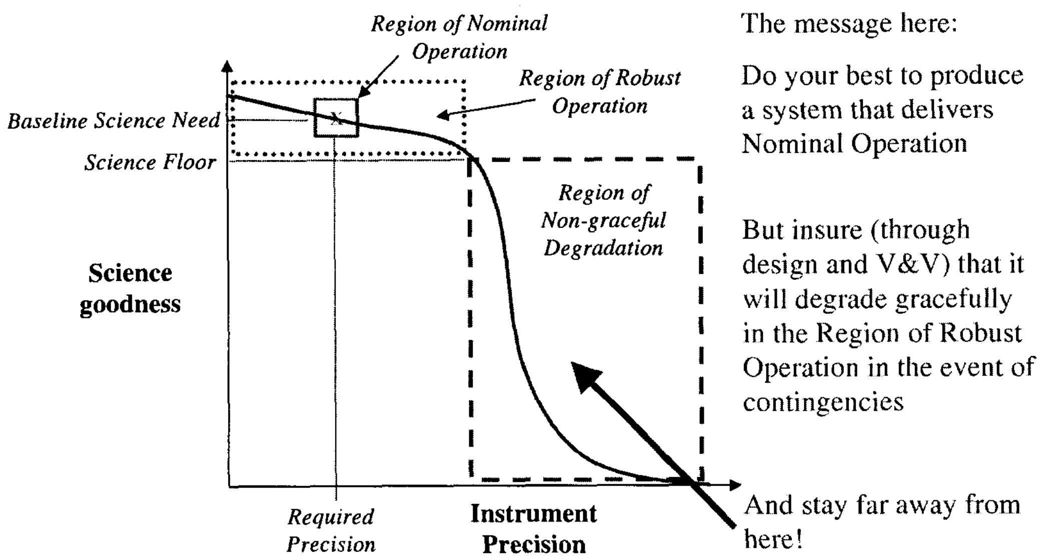
Figure 7 –Trace Analysis concept (ex: Kepler)

verification matrices are used during verification). The validation matrix should indicate how each requirement is validated (i.e., via analysis/modeling, similarity, proto-type test, etc). As always, when trying to balance risk-management with available resources, the system engineer should focus on the "tough nuts" (unique and/or challenging requirements) for rigorous validation and de-emphasize formal validation of the more mundane



Key point - create story-boards early in project identify *mission-critical models/ simulations*

Figure 8 – Astrometric Verification Storyboard concept (ex: SIM)



*this is an idealized example in which the system has been cost-optimized such that the science floor intersects the knee in the curve – clearly, we'd like some buffer

Figure 9 - Performance Robstness concept

requirements as needed.

In validating *each* requirement, the system engineer must ask the following questions:

1. Is it complete? (no holes or confusion)
2. Is it correct? (meets the ultimate need)
3. Is it achievable? (within project scope)
4. Is it verifiable? (can be tested &/or modeled)
5. Is it robust? (far from "cliffs")

The latter point, robustness, means that the system's ability to meet its performance and functional requirements degrades gracefully in reasonably off-nominal scenarios. These concepts will be discussed in more detail in the following section but from a requirements validation perspective it's important to understand "is this requirement written such that our as-built system will operate in the flat portion of the performance/functionality curve"? System engineers must ensure the requirements don't result in a brittle design.

As for completeness and correctness, to answer these questions the system engineer must perform a *requirements trace analysis* to study them versus the driving Need. An example of this is shown in Figure 7 for the Kepler Mission, in which two of the driving level 2 mission requirements (SNR and photometric precision) are validated in terms of completeness and correctness by tracing them back to one of the top-level science objectives (< 1 false positive).

7.3 Model Validation

From the 1998 Mars Polar Lander Mishap Report: *"...the propulsion system, employed analysis as a substitute for test in the verification and validation of total system performance...end-to-end validation of the system through simulation and other analyses was potentially compromised in some areas when the tests employed to develop or validate the constituent models were not of an adequate fidelity level to ensure system robustness"*[19].

Repeated lessons-learned in the space community point to the need for rigorous validation of mission-critical models – those used in "verification by analysis" to span gaps in a project's test program. This is even more critical for interferometers for the simple fact that they are notoriously difficult to test in an end-to-end sense on the ground. Figure 8 depicts a draft verification "story-board" for SIM astrometric performance. The critical models used to span gaps in the verification program are circled. This warns the SIM team that those models must be rigorously validated before use. The Project V&V Plan should include such story-boards to identify mission-critical models early in order to structure a validation program for them. Also note, system engineers should plan for the evolution of models over the project life-cycle. As illustrated in figure 6, model fidelity should improve incrementally as the design matures and test results are obtained.

As for how to validate models, there are many techniques for doing so but the following represent the major categories [18]. Note that using multiple methods to validate a single model in a complementary fashion is often warranted to gain confidence.

1) Face Validation: review model results by subject-matter experts – do results "seem believable"?
2) Peer Review: review model itself (equation/code) for correctness
3) Functional Decomposition & Test: piece-wise testing of individual code modules (inject test inputs and examine outputs)
3) Empirical Validation: compare model results with those from a test of the real system or some analog

8. SYSTEM ROBUSTNESS

As introduced in the last section, the concept of robustness should be considered as part of requirements validation. However, since robustness must likewise be considered when designing and testing the system, it is discussed here as a separate topic.

For interferometer missions, robustness involves the following focus areas:

1. Remote Operation & Autonomy
2. Grace Degradation & Risk Analysis
   - Performance (science sensitivity to mission)
   - Functional (fault-tolerance)

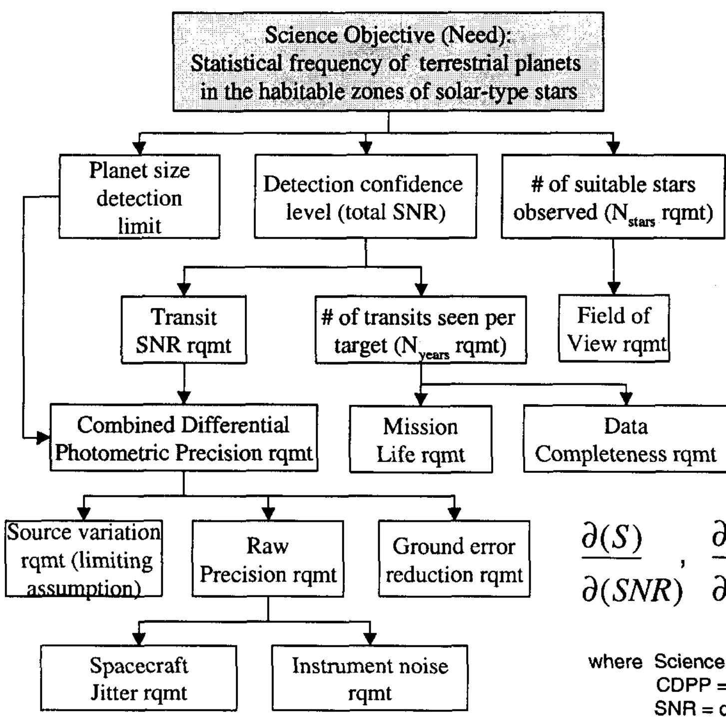
8.1 Remote Operation & Autonomy

When we're working in the testbed (or observatory) environment we usually have ready physical access to the interferometer in order needed to tweak things and make it work. However, that's not an option if the interferometer is parked at L2 or a heliocentric orbit 0.5 AU from Earth! In-orbit checkout aside, successfully obtaining routine science observations from a complex system like an interferometer in an autonomous fashion represents an unprecedented challenge.

This is a detailed discussion in its own right, but the point being: system engineering should recognize this as a major focus area and assign resources accordingly. Devising the proper requirements and design for operability and testing to ensure robustness will require concentrated effort over the life of the project. It is recommended that the project assign an "operability/autonomy" engineer to head this effort. They should report to the project system engineer and work closely with the team chiefs for fault protection, flight software, mission design, mission operations, and the science team.

8.2 Graceful Degradation and Risk Analysis

We're blazing new trails with spaceborne interferometers –so there's a moderate risk they won't work exactly as predicted in flight. This means the system design must be robust to adverse changes in performance and



system engineer must understand the science sensitivity to key mission parameters – use *Merit Functions* to assess "partial derivatives of Science Goodness"as functions of these parameters

$$\frac{\partial(S)}{\partial(SNR)}, \frac{\partial(S)}{\partial(CDPP)}, \frac{\partial(S)}{\partial(N_{stars})}, \frac{\partial(S)}{\partial(N_{years})}$$

where Science goodness S = f(CDPP, SNR, Nstars, Nyears)
CDPP = combined differential photometric precision
SNR = detection signal-to-noise ratio
Nstars = number of stars observed
Nyears = number of years observed

Figure 10 – Merit Function concept (ex: Kepler)

functionality due to "unknown unknowns" - also known as the concept of *graceful degradation.*

8.2.1. Performance Robustness & Analysis

To ensure graceful degradation from a performance perspective, the system engineer must understand the science sensitivity to key mission parameters in order to:

- Manage margins (share the pain between different project elements and components)
- Identify "soft spots" that warrant additional attention to beef-up
- Ensure the system design doesn't put us near any "cliffs" in terms of performance

The latter concept is illustrated in Figure 9.

This results in the need to use the following techniques for sensitivity analysis:

–Monte Carlo simulations to assess things like jitter and misalignment
–"Merit functions" to assess the performance partial derivatives

An example of the latter concept (taken from the Kepler planet-detection mission) is illustrated in Figure 10. This shows how the overall "science goodness" varies with respect to the driving mission performance requirements – alternatively, "what's the partial derivative of the science goodness with respect to the mission parameters?". This provides the science team and system engineer with a powerful tool for assessing performance robustness and guiding trades to manage risk.

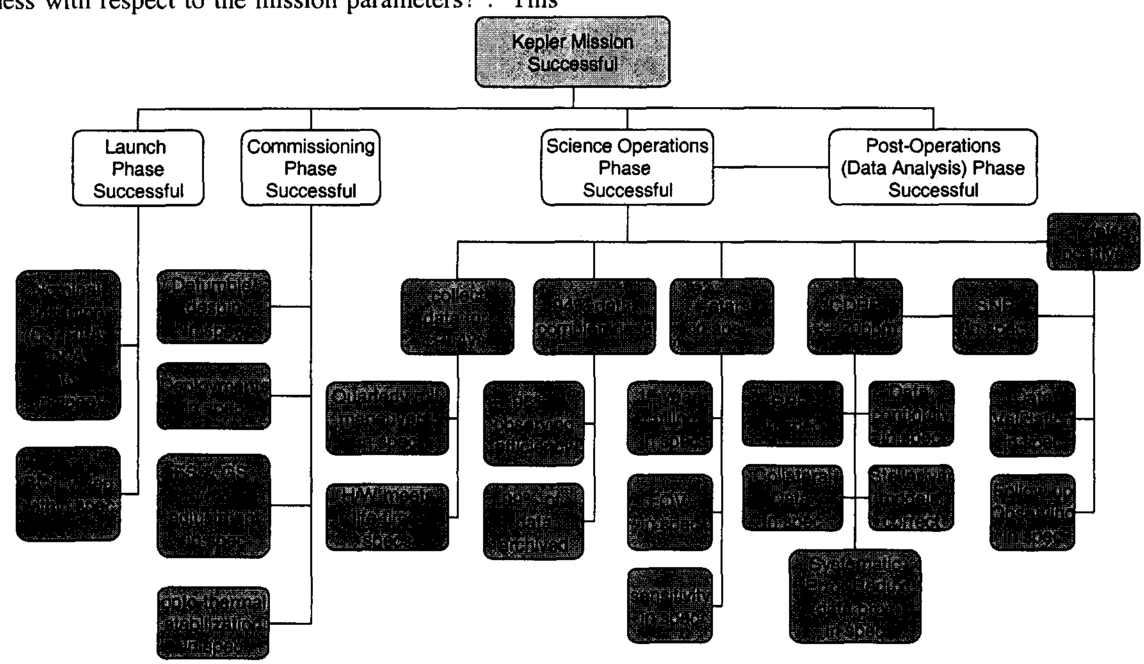
Also, the results of these performance sensitivity analyses should be used to guide system-level performance testing. The system response to conditions beyond the nominal but with the *region of robust operation* as described in Figure 9 should be assessed.

8.2.2. Functional Robustness & Analysis

With regards to graceful degradation, in addition to performance robustness we need *Functional Robustness.* Some useful tools for identifying areas of functional weakness include:

- System Level Fault Tree Analysis (FTA) – Which elements/functions are most critical?
- System Level Probabilistic Risk Analysis (PRA) – What is the relative "softness" of different elements/functions?
- Interface-level Failure Modes, Effects & Criticality Analysis (FMECA) – Insure that faults are contained.
- Assembly-level Worst-Case Analysis (WCA) – Insure system robustness to stressing conditions

Note that PRA is a useful adjunct to FTA. However, a caution: with PRA one can get bogged down trying to go



Note: "in spec" for activities in this context means they meet performance specifications and are on schedule

Figure 11 - Mission Success Tree concept (ex: Kepler)

too deep. PRA is more useful when we focus on mission/system level and key elements rather than detailed decomposition. In other words, use it to highlight areas of relative softness rather than trusting in an "absolute" estimate of overall mission reliability – the accuracy of such global estimates are nearly impossible to verify.

As system engineers, one of the most powerful weapons in our arsenal is the Fault Tree Analysis (FTA) – unfortunately, its use is rather hit-or-miss among projects (most do FTA for individual mechanisms but not at the system level). For instance, the 1998 Mars Polar Lander (MPL) Mishap Investigation Board report found: *"No **system-level**[2] FTA was formally conducted or documented...The greatest value of system-level FTA is to identify, from a top-down perspective, critical areas where redundancy (physical or functional) or additional fault protection is warranted*"[19]. Likewise, the Mars Climate Orbiter (MCO) mishap investigation noted that a key contributor to that mission loss was: *"Absence of a process, such as fault tree analysis, for determining 'what could go wrong' during the mission"*[20].

There are various ways to start a mission-level FTA effort but one technique is to first create a "project success tree" to describe what must happen to make the mission successful (Figure 11). One can then invert it to create a fault tree [21].

Finally, the results of fault-tree and similar analyses should also be used as part of the project's test program, particularly identifying scenarios for stress testing (both on the flight article and in system testbeds).

9. SUMMARY

In closing, the unique technical challenges of interferometers result in three areas of particular concern to system engineering:

–Error Handling & Performance Modeling
–Validation & Verification
–System Robustness

While the space interferometry community is still learning how to do these missions, by explicitly targeting the above areas for additional attention we can mitigate the associated risks. Perhaps the single greatest contributor to success in such complex endeavors is to expend some real effort in early project definition phases *planning* these activities.

[2] Emphasis mine.

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BIOGRAPHY

Riley Duren received a BSEE in 1991 from Auburn University. He also studied graduate-level astronomy and physics at the Florida Institute of Technology and UCLA. He is currently a Senior Member of the Technical Staff at Caltech's Jet Propulsion Laboratory (JPL) where he serves as Project System Engineer for NASA's *Kepler* mission. *Kepler*, the 10th Discovery mission, is scheduled for a 2007 launch and is designed to determine the frequency of earth-sized planets in the habitable zones of solar-type stars using precision transit photometry. Prior to joining JPL Riley worked for NASA's Kennedy Space Center on shuttle payload integration and test. During his 15 years at JPL and NASA, he has been involved with 10 flight projects with tasks spanning system engineering, integration and test, and mission operations. Most recently, he has played lead roles on a number of spaceborne interferometry missions such as StarLight (formerly ST-3), the Space Interferometry Mission (SIM), and the Shuttle Radar Topography Mission (SRTM). He is also involved with the Terrestrial Planet Finder (TPF) mission as a peer-reviewer for various aspects of the Interferometry Technology Development Program. His interests include the search for extra-solar terrestrial planets and developing the missions that enable such searches.