System Trades & Analyses

Dave Miller
Massachusetts Institute of Technology
(MIT)

Terrestrial Planet Finder (TPF)
Phase 1 Architecture Study Report
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GINA: Systems Approach to TPF

- **Generalized Information Network Analysis (GINA) methodology**
  - *A systems engineering and architecting methodology, based upon information network theory, that facilitates quantitative comparisons between viable architectures competing to satisfy a mission's needs*

- **Comprehensive Metric Set**
  - ***Capability "Quality of Service" Metrics***
    - Isolation - ability to separate the desired signal from competing signals
    - Integrity - quality of signal characterized by noise or anomalies
    - Rate - throughput of the system
    - Availability - temporal and spatial variability of isolation, integrity & rate
  - ***Evaluation Metrics***
    - Performance - productivity over mission lifetime in presence of failures
    - Cost per Function - mission efficiency: lifecycle cost per performance
  - ***Adaptability - sensitivity analysis***

- **GINA derives these metrics from physics models**

GINA: TPF Metrics Capture

Rate

Integration Time
- Zodiacal Distribution
- Collecting Area
- Detector Noise
- Propulsion Profile

Availability

Operational Efficiency
- Calibration
- Retargeting (slews)
- Deployment Time
- Anomaly Recovery
- Alignment

Isolation

Transmissivity & EE
- No. of Apertures
- Maximum Baseline
- Relative Geometry

Integrity

Signal-to-Noise
- Detector Noise
- Optical Bandpass
- Center Wavelength
- Mirror Surface Quality
- Aperture Diameter
- Thermal Noise
- Zodiacal Noise
- Glint

Performance

Productivity
- Mean time to failure
- Mission Lifetime
- Rate times Availability

Cost

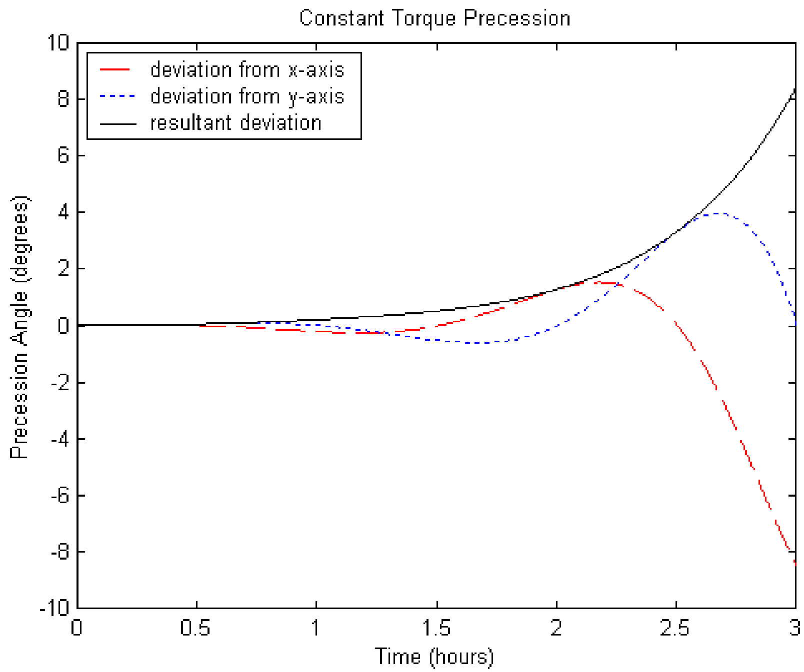
Lifecycle
- P/L - aperture diameter
- Bus - mass & power
- Launch - mass & orbit
- Ops - complexity & orbit
- Learning Curve
- Thermal Shield Develop.

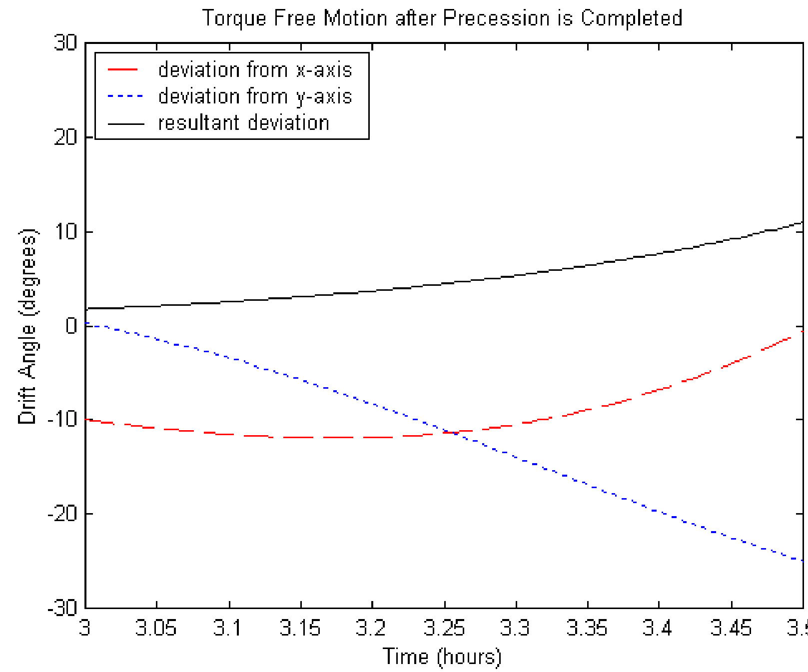
GINA: TPF Metric Matrix

Trades / Metrics	Heliocentric Orbital Altitude (1 to 6 AU)	Aperture Maintenance (SCI vs. SSI)	Number of Apertures (4 to 12)	Size of Apertures (1 to 4 m)
Isolation (Angular Res.)	N/A	SSI allows more freedom in baseline tuning	Fine tuning of transmissivity function	N/A
Rate (Images/Life)	Noise reductions increase rates; Operation delay changes	SSI power and propulsion requirements highly sensitive	Increased collecting area improves rate	Increased collecting area improves rate
Integrity (SNR)	Different local zodiacal emission and solar thermal flux	SCI: passive alignment but complex flexible dynamics	Tuning of transmissivity for exo-zodiacal suppression	Smaller FOV collects less local zodiacal noise
Availability (Variability)	N/A	Different safing complexity and operational events	Different calibration and capture complexity	N/A

Aperture | GINA | Operations | Controls | Environment | S/C Bus

Propulsion Models: Island 3



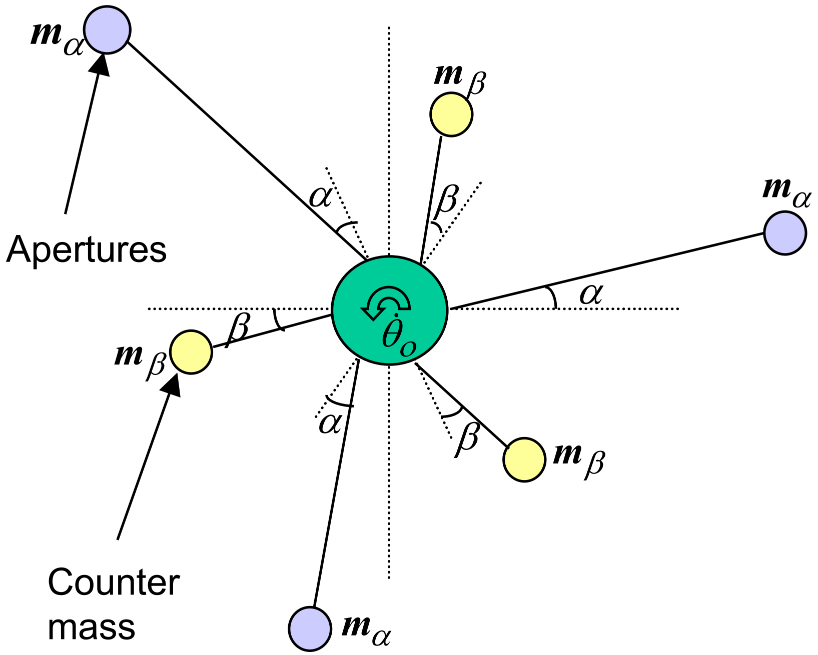


- To slow the constant torque precession down to the order of hours, a M ~ mN-m to μN-m is required.
  - *I = 300k kg-m^2, ω = 1rev / 2 hrs M =10 μN-m for 3 hours*
  - *I = 750k kg-m^2, ω = 1rev / 8 hrs M =0.5 mN-m for 1 hours*

- Moments are minimal (“not a excessive fuel burden”) and precession is not time limited easily within 6 hour noted in TPF book.
- Inadvertent precession and subsequent control may be the fuel driver for precession

Tether System

Pendulum Mode

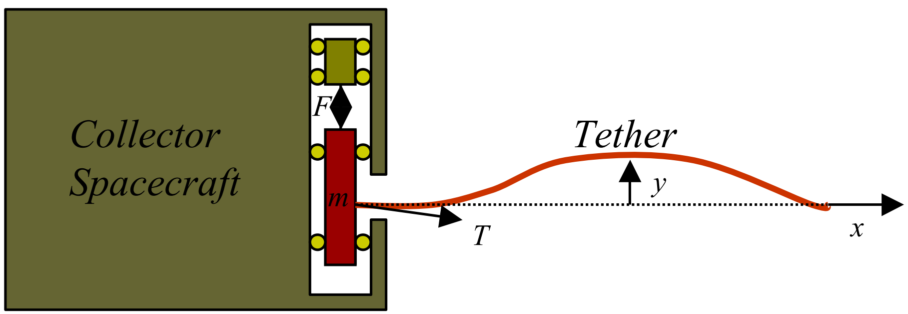


•The tether system dynamics may be linearized assuming constant hub rotation rate

• The linearized system is controllable when actuating hub torque and tether tension

•No propulsion on the apertures is necessary

Cable Vibration Mode



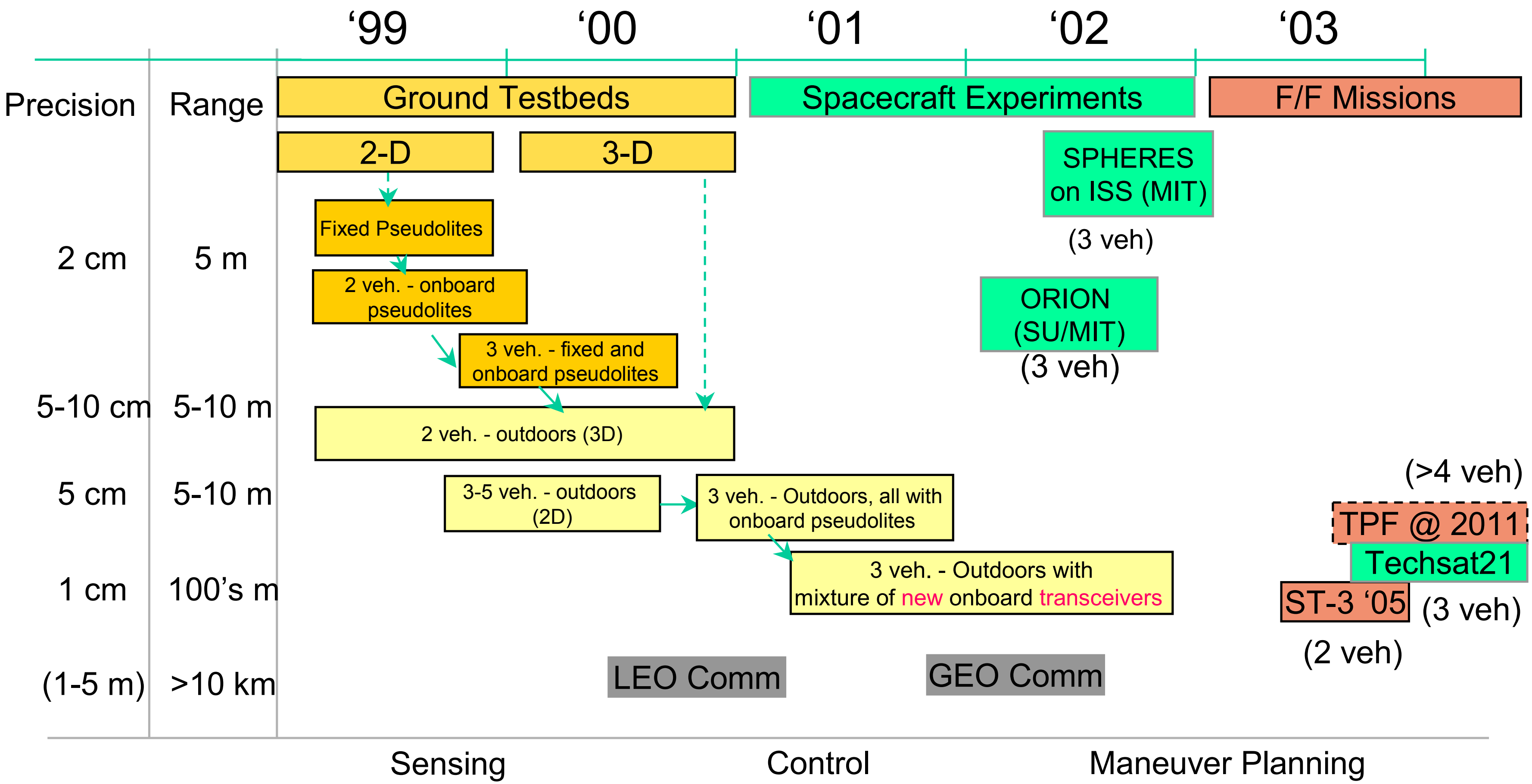
•Tether vibrations can disturb the stability of the optical train and therefore need to be controlled

•Tether vibration is fundamentally governed by the wave behavior of a string under tension

•One option for controlling tether vibration is impedance matching

- -Vibrations in the tether are absorbed by the matched termination
- -The collector spacecraft is undisturbed since the control force is generated by reacting against the extra mass

Formation Flying Roadmap



SPHERES - software maturation for close proximity formation flight, rendezvous and docking
ORION - demonstration of CDGPS relative navigation and formation flying control algorithms in LEO

Mature Technology on ISS

- ISS provides a laboratory in the space environment
  – *Use as facility for maturing component technologies*
  – *Infrastructure ((up)downlink, video, crew operation, power, coarse pointing,etc.) is provided*
- The MIT MACE facility (STS-67, STS-106 to ISS) is maturing system identification, multi-channel control, & slewing

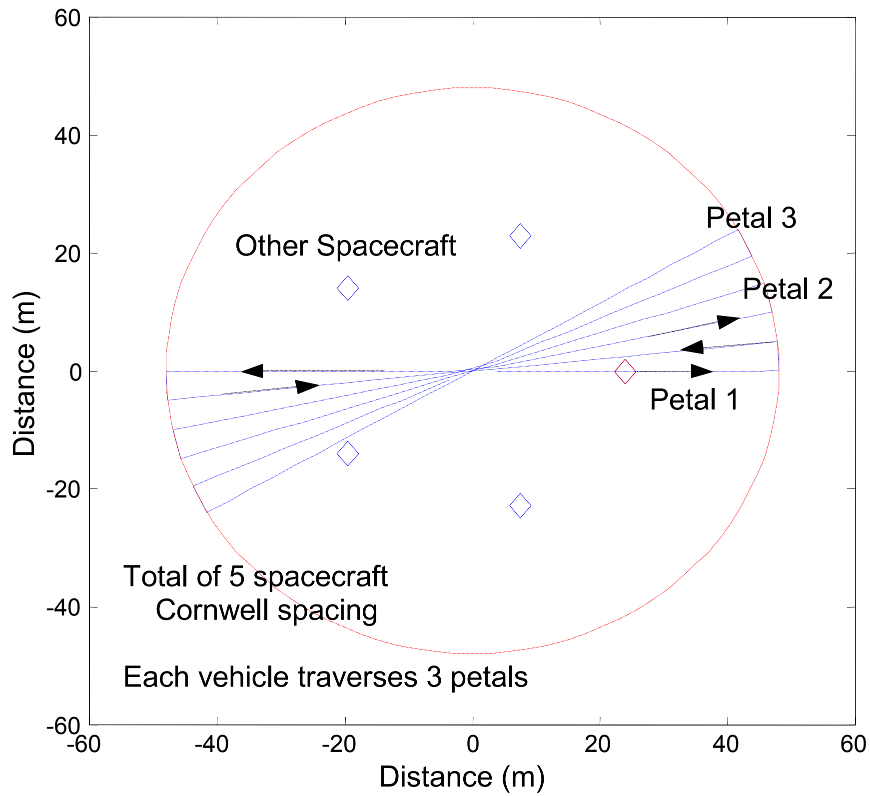
- The SPHERES facility (ISS-9a in 5/02) matures formation flight and autonomous rendezvous

(click to play)

- Benefit of space laboratories demonstrated by MIT's MODE & MACE having more reflights than first flights

SSI Imaging Approach

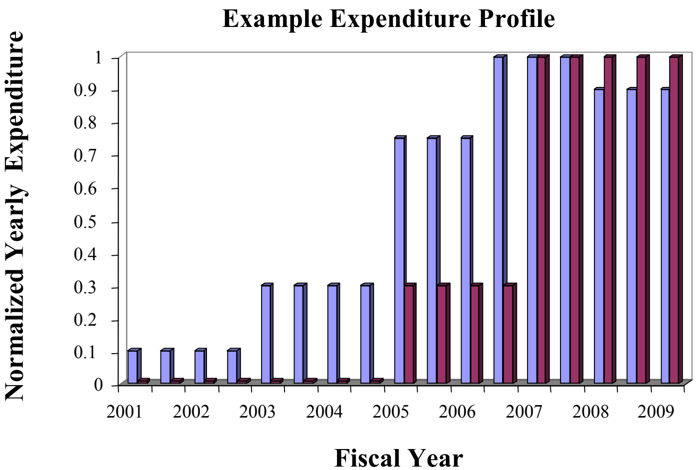
- Satellites arrayed in Cornwell pattern
  - *3 to 6 spacecraft*
- Assumes "drift through" imaging
- "Petals" used to maximize length of rectilinear motion
  - *center ⇒ far edge ⇒ along far edge ⇒ back to center ⇒ near edge ⇒ along near edge ⇒ back to center*
  - *small turn & then start next petal.*
  - *ΔV only required to steer at edges and to change heading for next petal*



Example shows 3 petals for 1 of 5 spacecraft

Operational Concept: Staged Deployment

- Staged deployment of smaller structurally connected spacecraft
  - *Each spacecraft is an identical "Jovian Planet Finder" with the first one acting as a precursor mission*
- Advantages of staged deployment
  - *Start mission sooner since the technology is already available to affordably build and fly the first stage or precursor*
    - Precursor can collect useful scientific (i.e. narrowing down the search field for TPF candidate stars) and engineering (i.e. operating an interferometer at the eventual location of TPF) data
      - *Any science or engineering data from the precursor can drive subsequent upgrades to future segments*
  - *Cost is spread out and risk is reduced by using acquired experience to direct future expenditures*
  - *By end of staged deployment have the ability to do both imaging and detection of Jovian and Terrestrial planets*



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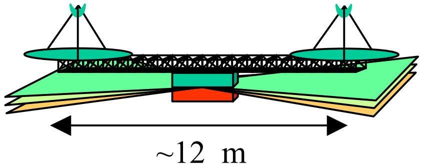
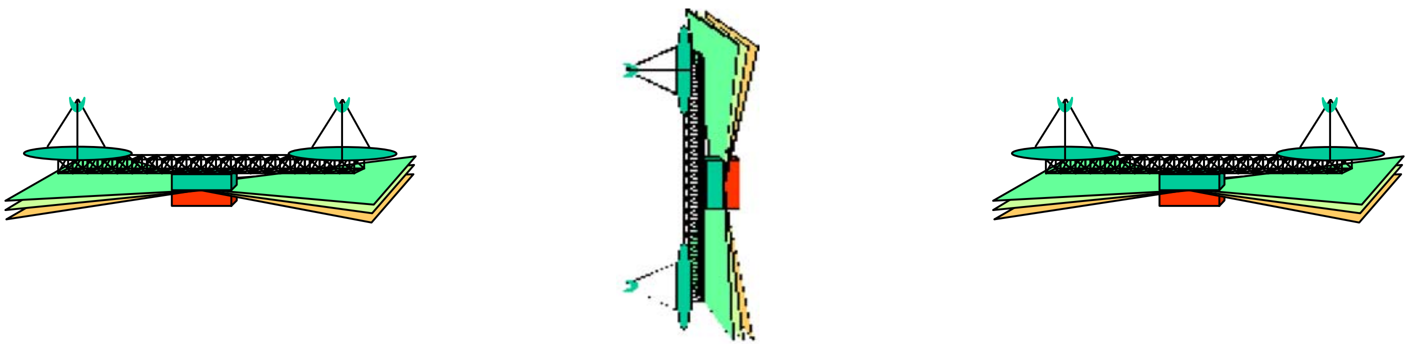
Operational Variations: Staged Deployment

- Base segment (i.e. precursor)

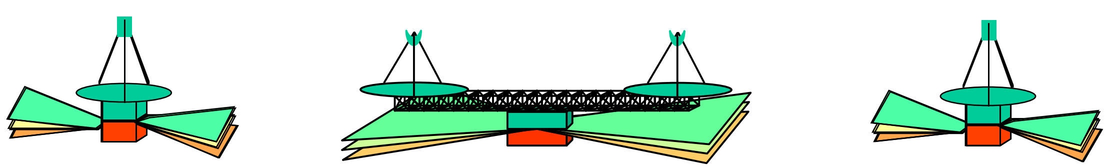


- Operational variations include, but are not limited to:

Staged deployment of identical modules



Addition of middle module to be used as a combiner/collector



Identical components in each module

Planning for Staged Deployment

- Technological development needed
  - *Relative metrology between modules*
  - *Inter-module beam control*

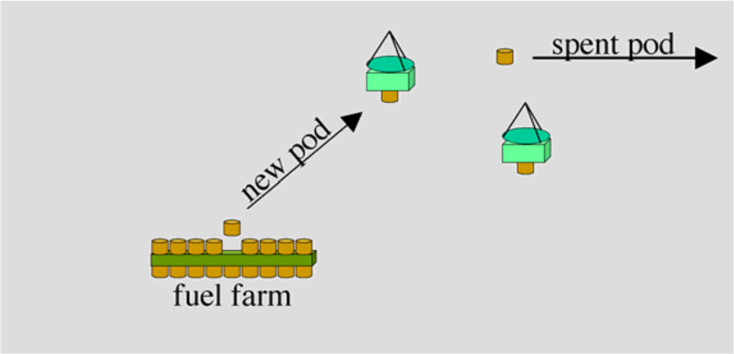
- Planning for future interfaces
  - *Formation flight*
  - *Docking: Permanent docking or ability to both dock and undock modules*
  - *Electro-magnetic control*

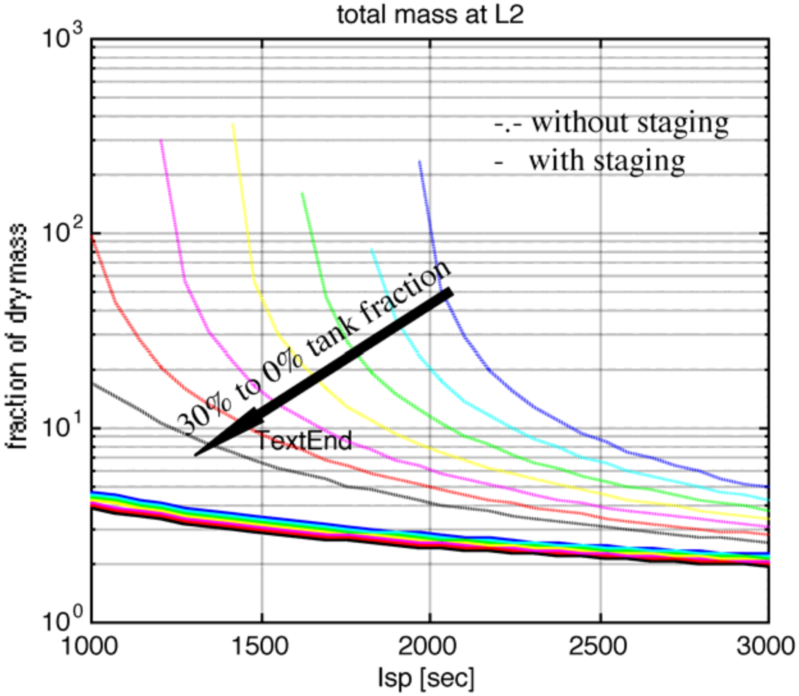
- Precursor needs technology to interface with future modules that would not be used or needed in first stage of mission

- Reliability - precursor will begin to fail before other modules

Fuel Replenishment: Imaging

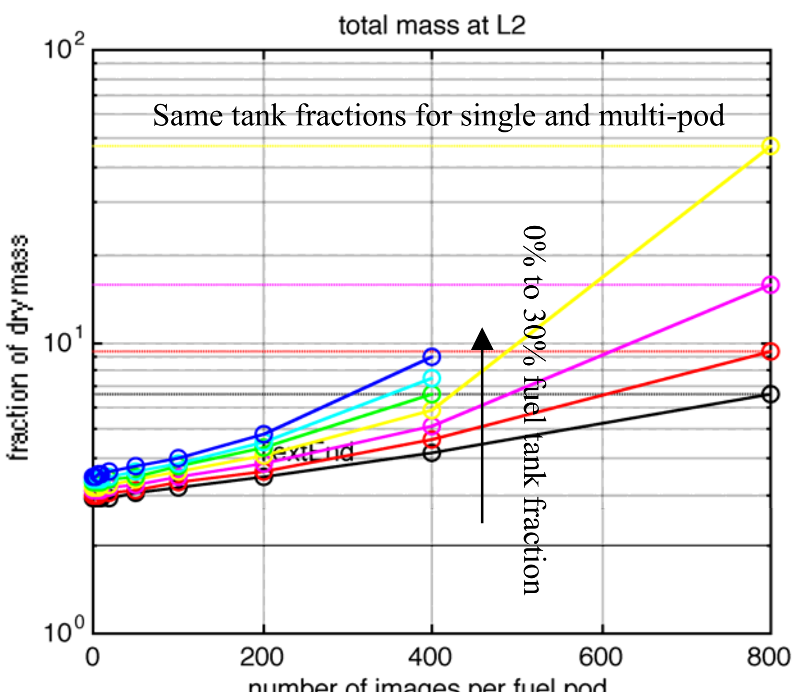
- If replenish SSI fuel via auto docking (eg. Orbital Express), can reduce fuel required for imaging
- Illustration shows pod departing fuel farm to replace spent pod on S/C
- Plot shows ratio of total mass per S/C at operational orbit with and without staging
  - *Total mass includes payload, bus, fuel tankage, and fuel*
  - *Staging results for one pod per image per spacecraft (eg. 800 pods)*
  - *Realistically, one pod should support several images*
  - *High I_{sp} will not support accels needed for one image per day*
- Could also replenish cryostats

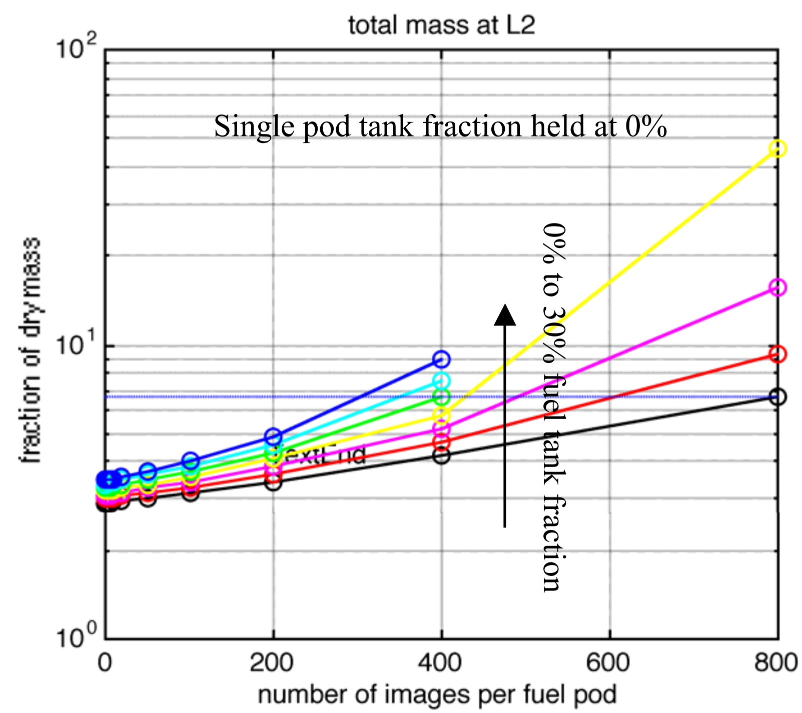




Fuel Replenishment: Imaging

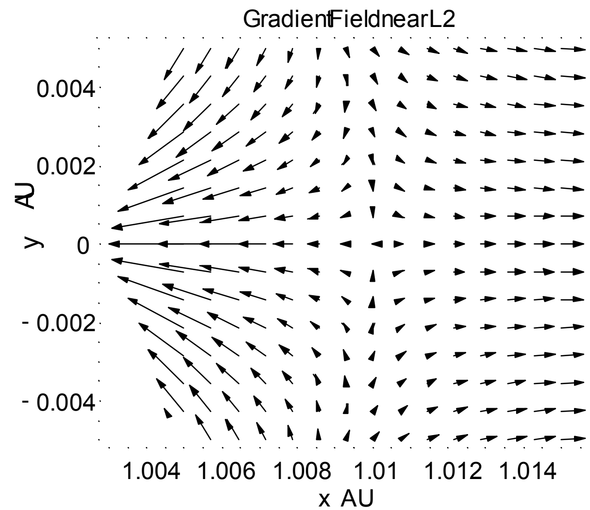
- Increasing number of images per fuel pod reduces mass savings
  - *Assuming 800 images (0.88 images/day), I_{sp}=1500 sec, B=825m, full uv-coverage out to B/2, 4 apertures each 4m diameter, 40 transits, 0.44m/s, 35m/s/image*
- High fuel tank fractions (>15% for I_{sp}=1500 sec) cannot use one pod
- Trade exists: 800 pods per S/C too complex, one fixed pod too massive
- Good compromise would be one pod for 100 images
  - *Saves x2 to x5 in total mass, need 8 pods per S/C, 32 total*

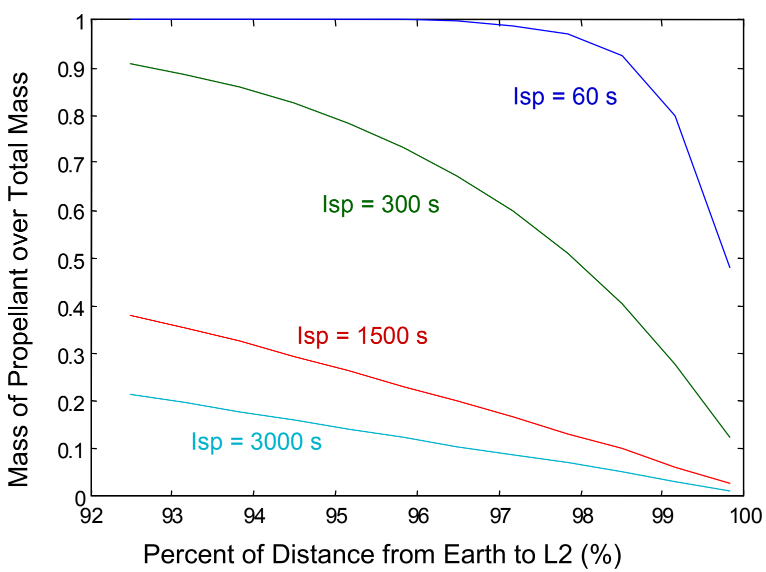


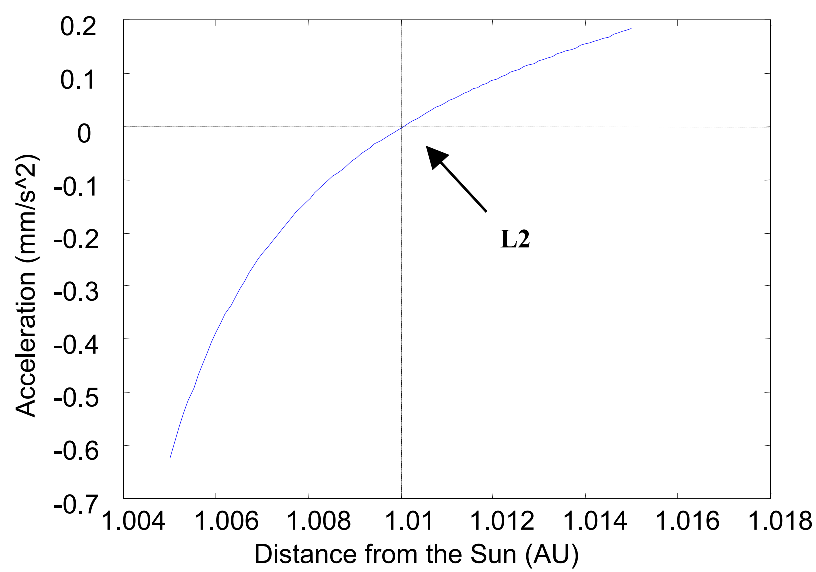


Earth to L2 trade: Orbit model

- Orbit model verifies the L2 instability, but doesn't consider halos.
- Accelerations are on the order of 1/100 mm/s^2 at 100% occultation, where solar pressure is on the order of 5/100 μm/s^2 x a/M.
- **3200 m/s required to go from LEO to halo orbit around L2**
  - ***Only 250 m/s required to go from halo orbit around L2 to L2 itself***







Reliability Optimization (I)

- **Motivation:**
  - *To determine at the conceptual design level how to improve the reliability of a system as complex as TPF most cost effectively.*
- **Options:**
  - *Improve the reliability of individual components/spacecraft*
  - *Add redundancy*

Optimization Formulation

$$Max\ (1-(1-R_M)^M)(1-(1-R_L^4)^{\binom{L}{4}})$$

Subject to

$$MC_M + LC_L + X_{RM} + X_{RL} \leq B$$

$$M \geq 1$$

$$L \geq 2$$

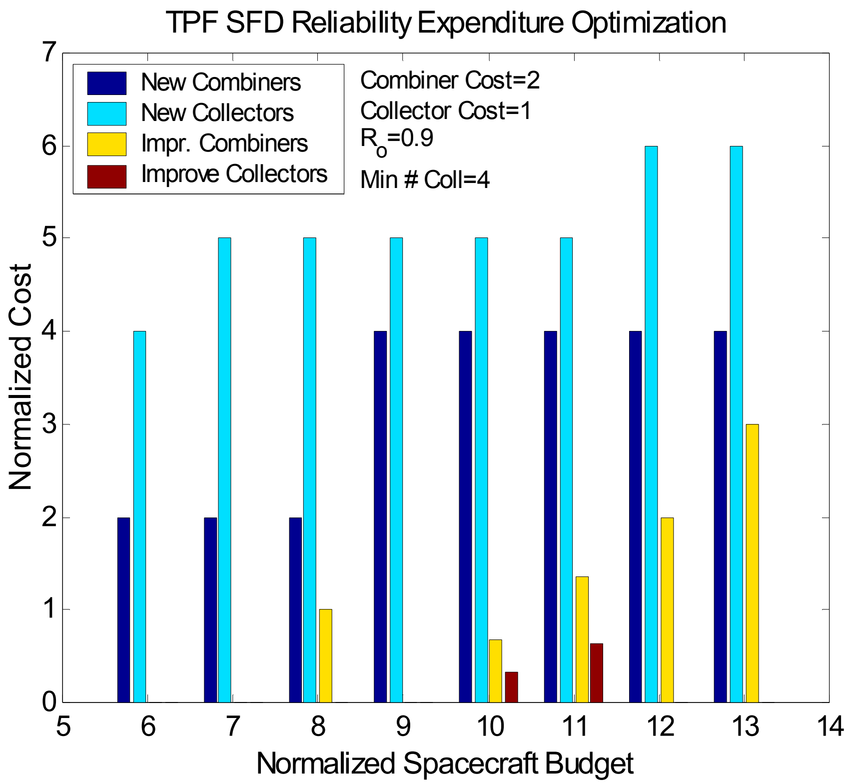
$$M, L\ integer$$

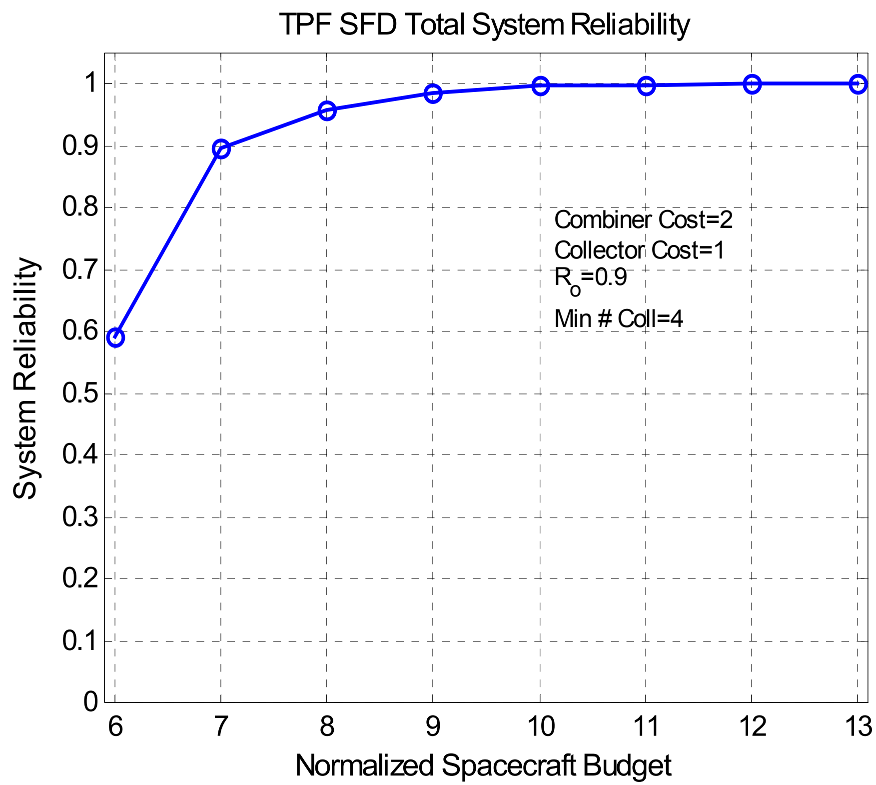
$$X_{RM}, X_{RL} \geq 0$$

$M=$	# combiner s/c in array
$L=$	# collector s/c in array
$X_{RM}=$	\$ spent on improving the combiner s/c reliability above it's baseline value
$X_{RL}=$	\$ spent on improving the collector s/c reliability above it's baseline value
$R_M=$	combiner s/c reliability
$R_L=$	collector s/c reliability
$C_M=$	combiner s/c cost
$C_L=$	collector s/c cost
$B=$	total s/c budget

Reliability Optimization (II)

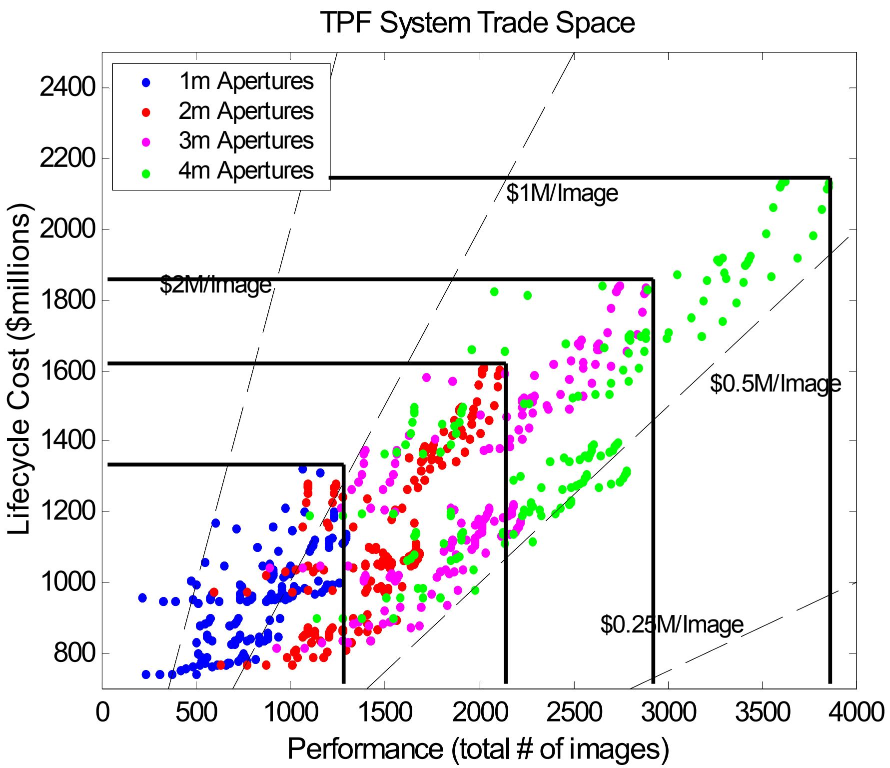
- Result: Tells the systems engineer where to invest limited resources to most positively benefit system reliability.

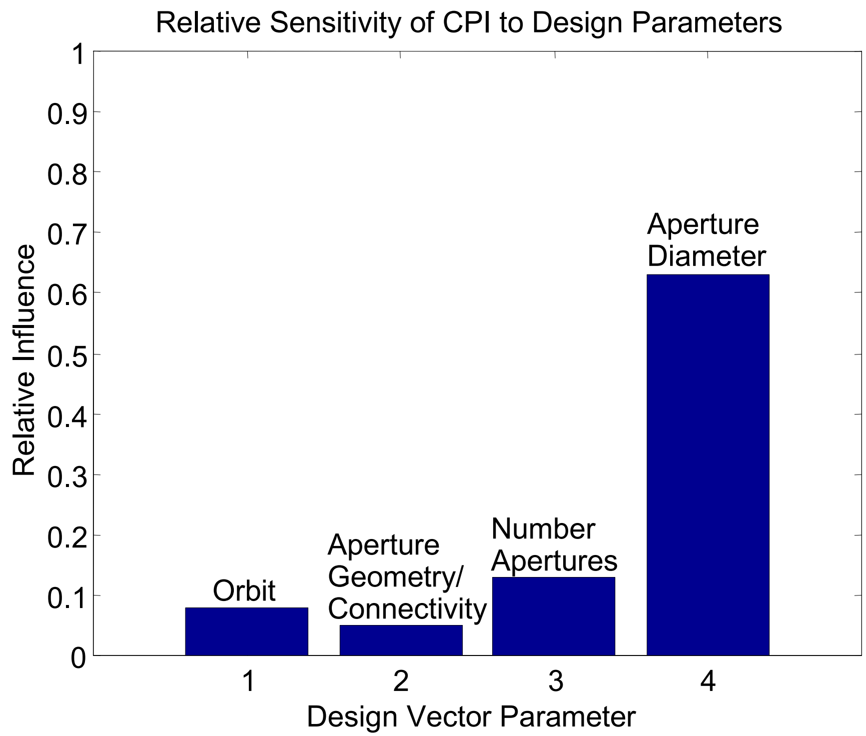




Cost vs Performance: ANOVA Results

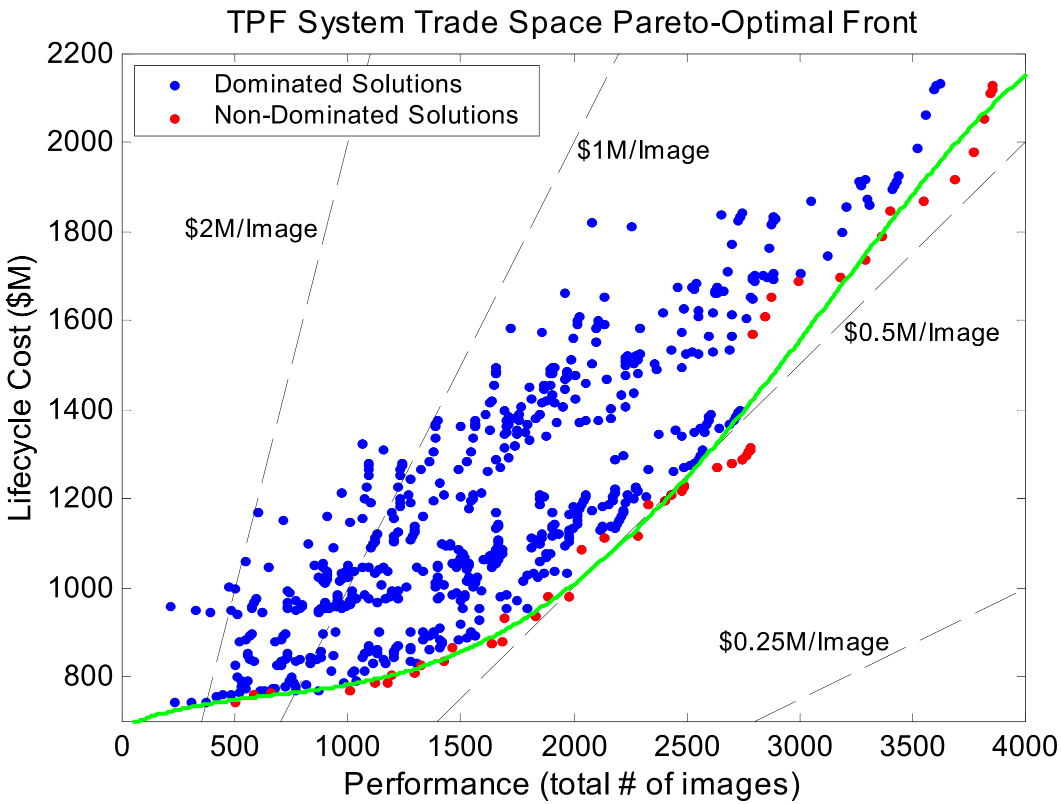
- Aperture diameter exerts by far the greatest influence on the Cost Per Image (CPI) metric for TPF.
- ANOVA may be applied to other design variables to yield insight into technology investment strategies and recommendations.





Cost vs Performance: Optimal Front

- True systems methods handles *trades*, not just a single metric. In real world systems engineering problems, one has to *balance* multiple requirements while simultaneously trying to achieve *multiple* goals.



Observations:
Along this boundary, the systems engineer cannot improve the performance of the design without also increasing lifecycle cost.

This boundary quantitatively captures the trades between the TPF design decision criteria.