TPF
Phase 2 Final Architecture Review

Lockheed Martin Team

11-13 December, 2001

San Diego, CA

Introduction

Domenick Tenerelli
Lockheed Martin Space Systems Company (LMSSC)

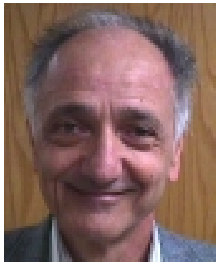
Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

Agenda
(12 Dec 2001)

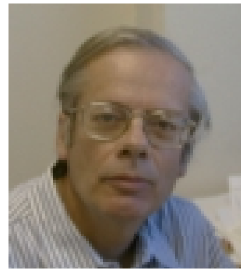
1:15 - 1:30	Introduction	Domenick Tenerelli
1:30 - 2:00	Science	Nick Woolf
2:00 - 2:30	Nulling Interferometery	Phil Hinz
2:30 - 2:50	Optics Design	John Miles
2:50 - 3:00	Orbits	Tom Sherrill
3:00 - 3:10	Thermal Control	Andy Klavins
3:10 - 3:25	Dewar Concept	Dean Read
3:25 - 3:50	**Break**	
3:50 - 4:00	Truss Concept	Tom Connors
4:00 - 4:15	Pointing & Control	Nelson Pedreiro
4:15 - 4:35	System Analysis	Dave Miller
4:35 - 4:45	Formation Flying Technology	Bob Dougherty
4:45 - 4:55	Spacecraft Bus/Flight Ops	Ken Hooper
4:55 - 5:05	TPF Electronic/Ikonos SC	Glenn Butcher
5:05- 5:30	Cost & Summary	Domenick Tenerelli

Lockheed Martin Team


Dr. R. Paulson


Dr. D.Tenerelli


Dr. N. Woolf


Dr. R. Angel


Dr. P. Hinz

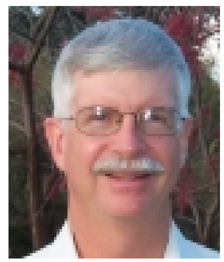

Dr. J. Burge


Prof. J. Westphal


Dr. D. Miller

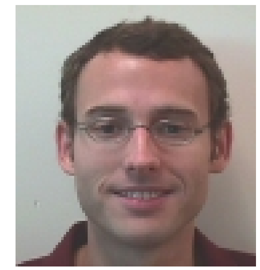

Dr. J. How


Dr. N. Pedreiro


Dr. T. Trankle


R. Doughtery


Dr. T. Sherrill

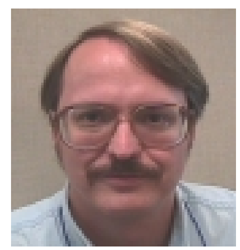

Dr. J. Miles

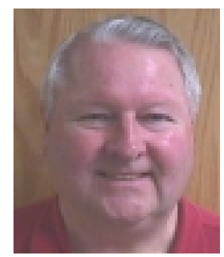

Dr. A. Klavins


T. Connors

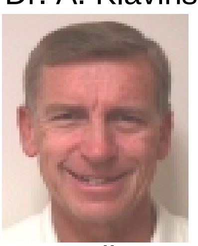

B. Sable


K. Chan


K. Hooper

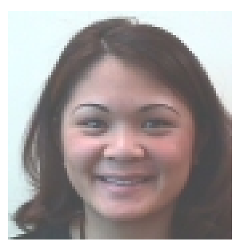

R. Jones

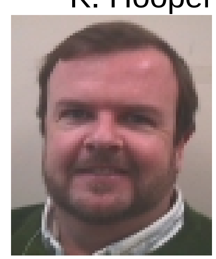

T. McMahon

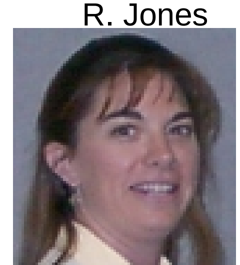

C. Rudiger


S. Utke


G. Painter


J. Tran


G.Butcher


K. Chapman


D. Read

Phase 2 Study Plan

- **PAR Presentation (Recommended Architecture)** — 12/12/00**
- **JPL TPF Architecture Phase 2 Assignment** — 1/15/01
- **Refine TPF Science Requirements & Optical System Concept** — 3/1/01
- **Update Computer Models** — 4/1/01
- **Derive System & Subsystem Requirements** — 7/1/01
- **Perform System Trades & Analyses*** — 9/1/01
- **Define Interfaces & Perform Concept Design** — 10/1/01
- **Present Final Architecture Review** — 12/12/01
  - **Requirements**
  - **Concepts**
  - **Technology**
  - **Cost & Schedule**
- **Phase 2 Final Report** — 3/31/02

*** <u>Analyses</u>:Observatory Geometry & Array Configuration, Optical Layout & Noise Reduction, Optical Beam Transport & Straylight Minimization, Disturbance Effects, Detector Reqmts, Contamination Effects, Cryogenic Component Reqmts, Thermal Design, I&T & Pre-Launch Verification, Orbit & Sky Coverage, Launch Strategy, Operations Scenario & Other Observatory System Analyses; Technology Development Requirements**

**** Task Completion Dates**

Meetings/Telecons-Phase 2

• **TPF Team Telecons**	**Weekly**
• **Program Management Meetings**	**UA & MIT**
• **TPF Mid Term Review (7/01)**	**JPL**
• **TPF Team Meetings**	**UA, MIT, LMSSC**
• **Final Architecture Review (12/01)**	**San Diego**

Exhibit II Science Requirements*
January 7, 1999

General Mission Assumptions	Rqmts	9 m	21 m	40 m	FF	Comment
1. Sky coverage	60%	>90%	>90%	>90%	90%	
2. Mission duration (years)	5	4	5	5	10	
3. Nominal planet is defined as a solid body with Earth radius at 1 AU, T=270 K.						9m mission:Jupiters
4. The planet detection and characterization program will be allocated ~50% of the design mission lifetime with the remainder of the lifetime allocated for general imaging and spectroscopy.						
5. Spacecraft use non-nuclear power sources.						
Planet Detection/Characterization						
1. # of stars (F5-K5) surveyed for planets (R=3, SNR=5)	150	30	44	348	500	
2. Number of scans for CO_2/H_20 (R=20, SNR=10)	30		18	>100	>100	
3. # of scans for Ozone/strong CH_4 (R=20, SNR=25)	5		5	>25	>25	
4. Spectral Band (μ m)	7-17	4-10	7-17	7-17	3-23	Zodiacal light limited
5. Spectral Resolution	20		20	20	100	
6. Maximum distance of ozone detection (pc)	10	10	13	>20	>20	
7. Minimum distance of planet detection (pc)	3		3	3-22	22	
8. Exo-zodiacal dust will be the same as in our own solar system for requirement, up to 10 times the solar system level.						
9. Follow-up (high spectral resolution) surveys are uniformly distributed throughout the volume of the initial survey.						
10. Point source sensitivity: 5 σ, 2 hr at 12 μm, R=3. (μ Jy)	0.3		0.53	0.13		
High Resolution Imaging (TBR)						
1. Imaged objects for 5 year mission	800				1600	(1 object/day)
2. Resolution at 3 μm (milliarcsecond)	0.75				0.75	
3. Band (μm)	3-17				2 to 40	
4. Spectral resolution	3-300				3 to 300	
5. Special purpose spectral resolution (FTS mode) in specified lines					120	
7. Effective minimum baseline for synthetic imaging (m)	100				<50	(interferometric only)
8. Dynamic range in Reconstructed Image	50:1				100:1	

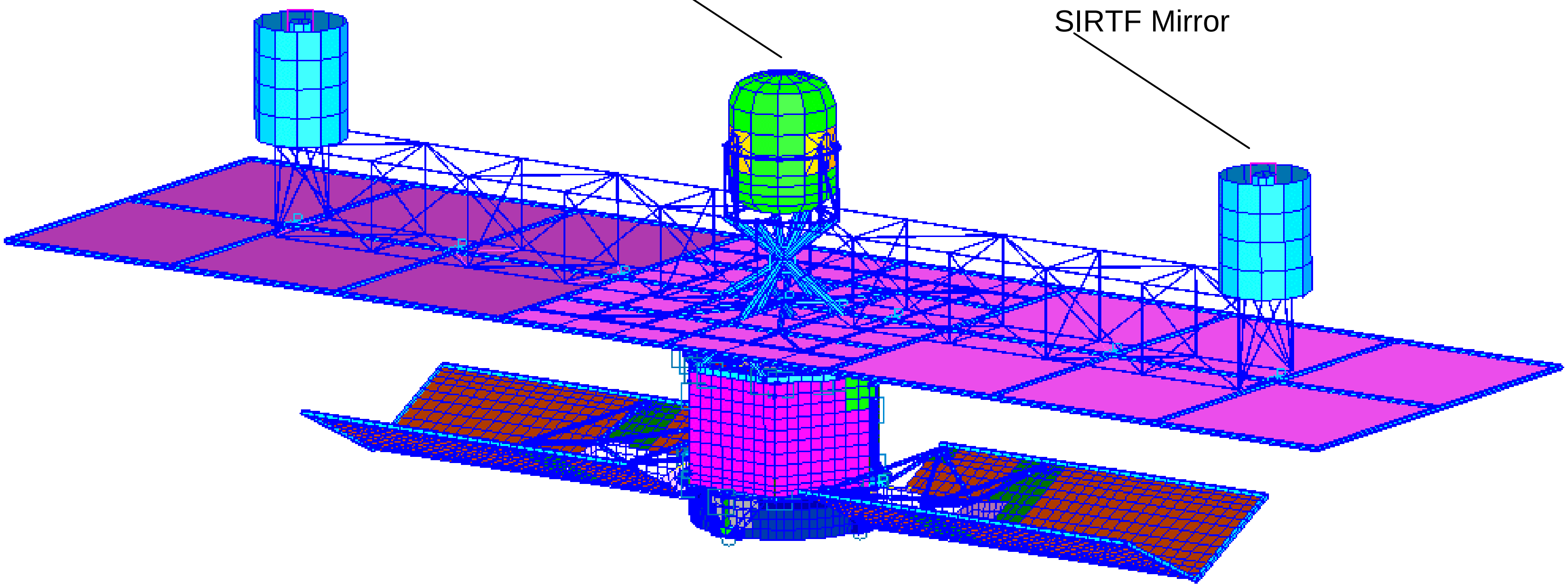
TPF Configurations

Baseline	Telescopes			Science Goals
	Number	Aperture	Temp	
9 m	2	60 cm	60 K	Young Jupiters
21 m	4	1.7 m	40 K-45 K	Earth to 12 pc, O_3, H_2O, CO_2 to 8 pc
40 m	4	3.5 m	40 K-45 K	Earth to 22 pc, O_3, H_2O, CO_2 to 15 pc
Free flyer	4	3.5/6 m	40 K-45 K	Planetary mission goals plus astrophysics

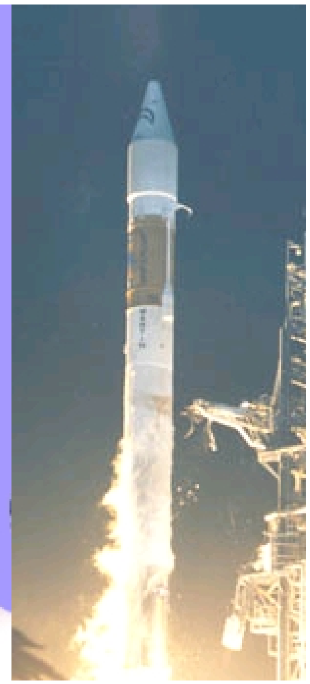
Summary

- Program risk reduction with science rich, low cost, low risk 9 meter SCI development mission launched in December 2006
- Intermediate TPF version (21 meters) identified and costed
- TPF science planetary detection requirements met with 40 meter SCI
- Technology development identified
- Program costs identified for each option
- Free Flyer Interferometer system identified for future TPF missions covers planetary and astrophysics science

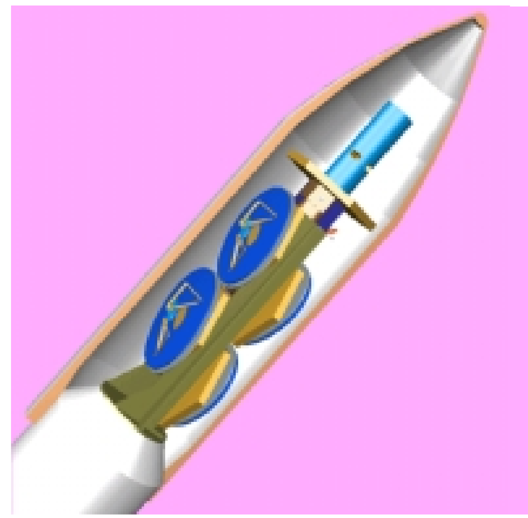
9 m on-Orbit Configuration



Launch Vehicle Options

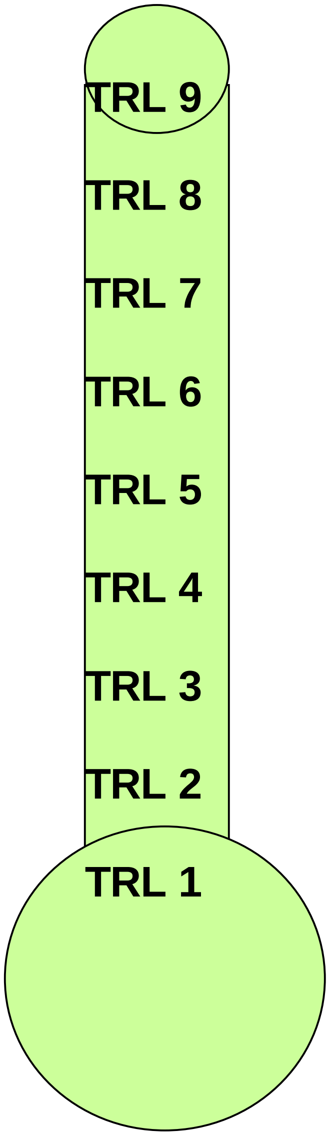


Ariane 5 EELV (HLV-G) EELV (Delta Heavy) Atlas



TPF launch concept

Technology Readiness Levels



- Actual system "flight proven" through successful mission operations.
- Actual system completed and "flight qualified" through test and demonstration (ground or flight).
- System prototype demonstrated in appropriate environment
- System/subsystem validation model or prototype demonstrated in a relevant environment (ground or flight)
- Component and/or breadboard validation in relevant environment
- Component and/or breadboard validation in laboratory environment
- Analytical and experimental critical function and/or characteristic proof of concept
- Technology concept and/or application formulated
- Basic principles observed and reported.

System Element Maturity

Interferometer	9 meter SCI	21 meter SCI	40 meter SCI
Project Mgmt	9	9	9
Sys Engineering	9	9	9
Telescopes	8/9	7	6 (NGST)
Beam Combining	4	4	4
Detector Cooling	8	8	8
Spacecraft	9/8	9/8	9/8
Electrical Power	9	9	9
Guide & Control	9	9	9
Software	5	5	5
Vibration Control	7	6	6
Truss	9	8	8
Sunshield	7	5 (NGST)	5(NGST)
Contamination	9	9	9
Integration & Test	9	9	9 (Seg tests)
Orbit	6 (SIRTF)	6 (SIRTF)	6 (SIRTF)
Launch Vehicle	9	9	9 (Pkg TBR)
Ground System	7 (SIRTF)	7 (SIRTF)	7 (SIRTF)

TPF
Terrestrial Planet Finder

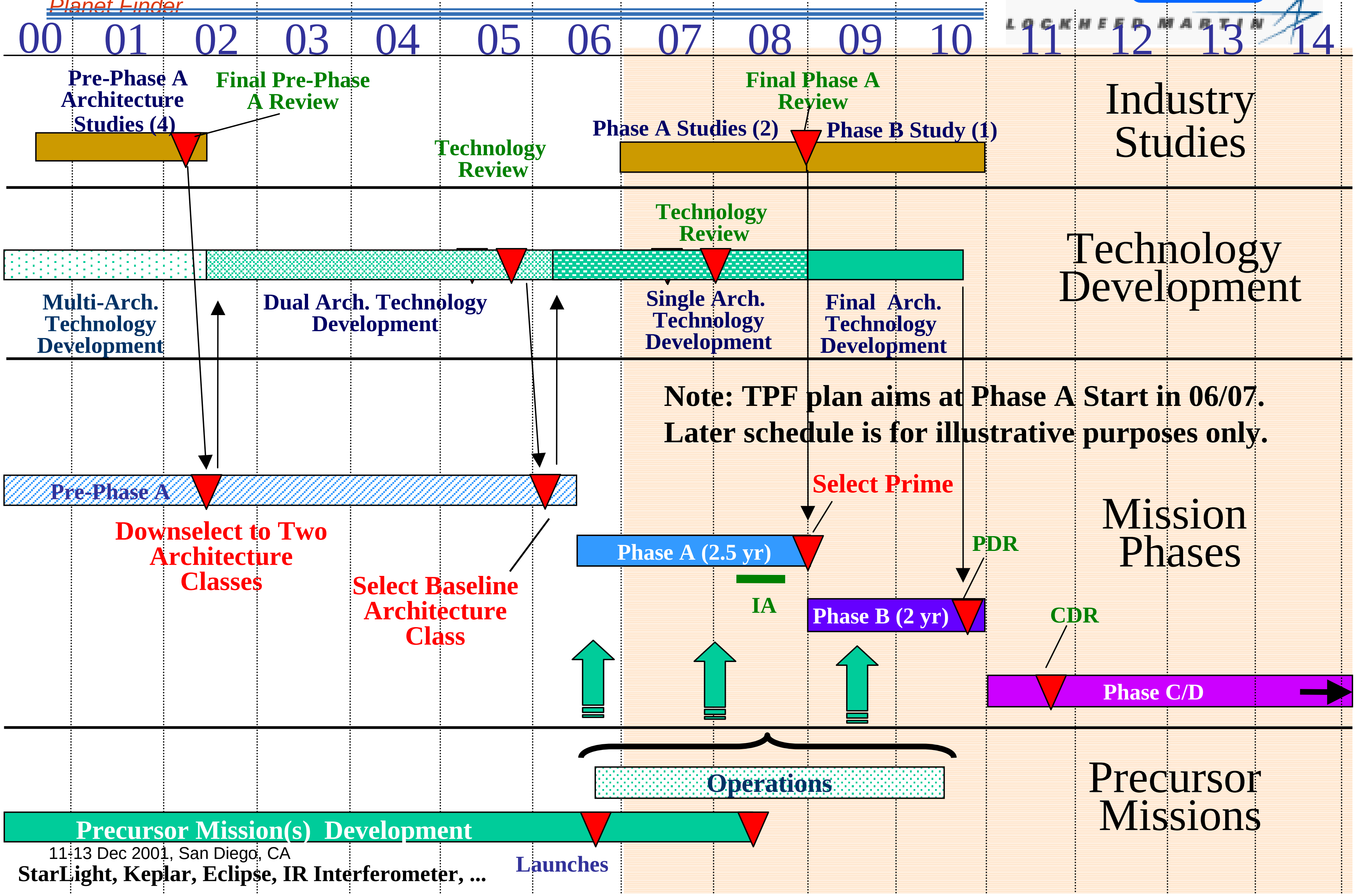
Revised TPF Schedule(JPL)

LMSSC P556045

MIT

BUSEK

LOCKHEED MARTIN



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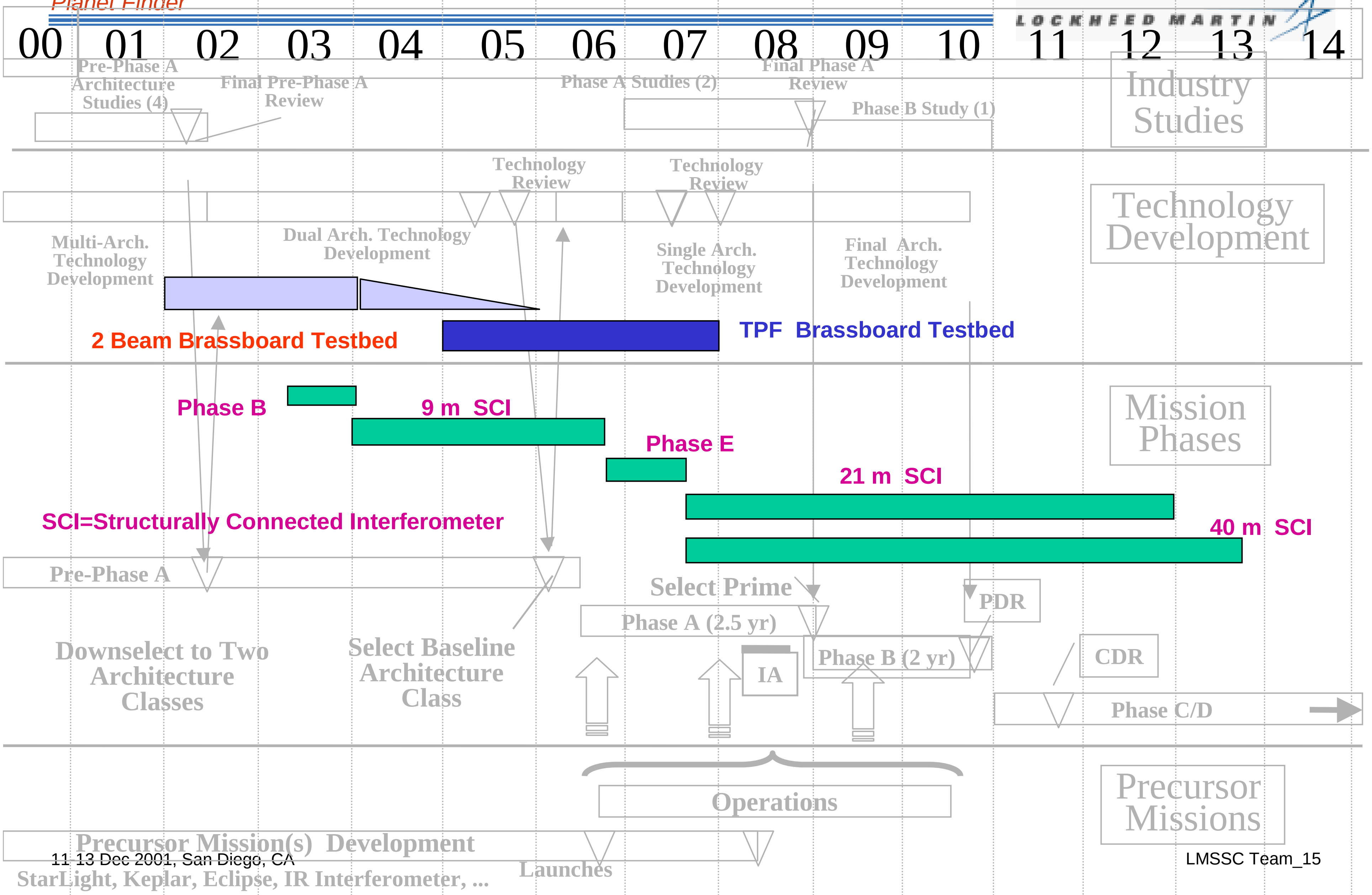
TPF
Terrestrial Planet Finder

Pre-Formulation Phase Study -Final Architecture Review

LMSSC P556045

Lockheed Team TPF Schedule



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Science Issues

Nick Woolf
Steward Observatory, University of Arizona

Terrestrial Planet Finder (TPF)
Phase 2 Review
December 12, 2001

Topics

1)Biomarker study - Our involvement
Science conclusions.

2) TPF data reduction program.

3) TPF nuller variants Navigator Science issues
Science for the variants.

4) What does it take to determine whether a planet is habitable/ inhabited? Which variants do that, at various distances?

5) The general issue of learning about planetary systems, and relationship to potential science precursors.

6) General Astrophysics.

1) Biomarkers Study

- The Lockheed team had 3 members in the 10 member Biomarkers Study:
- David Des Marais - Chaired the sessions and was the sole biologist.
- Jonathan Lunine - edited the manuscript, and was lead writer for section 1.
- Nick Woolf - was the lead writer for the appendix on algorithms for spectral detection, and presented the entire material to the NASA Astrobiology Task Force

Biomarkers Study Conclusions I

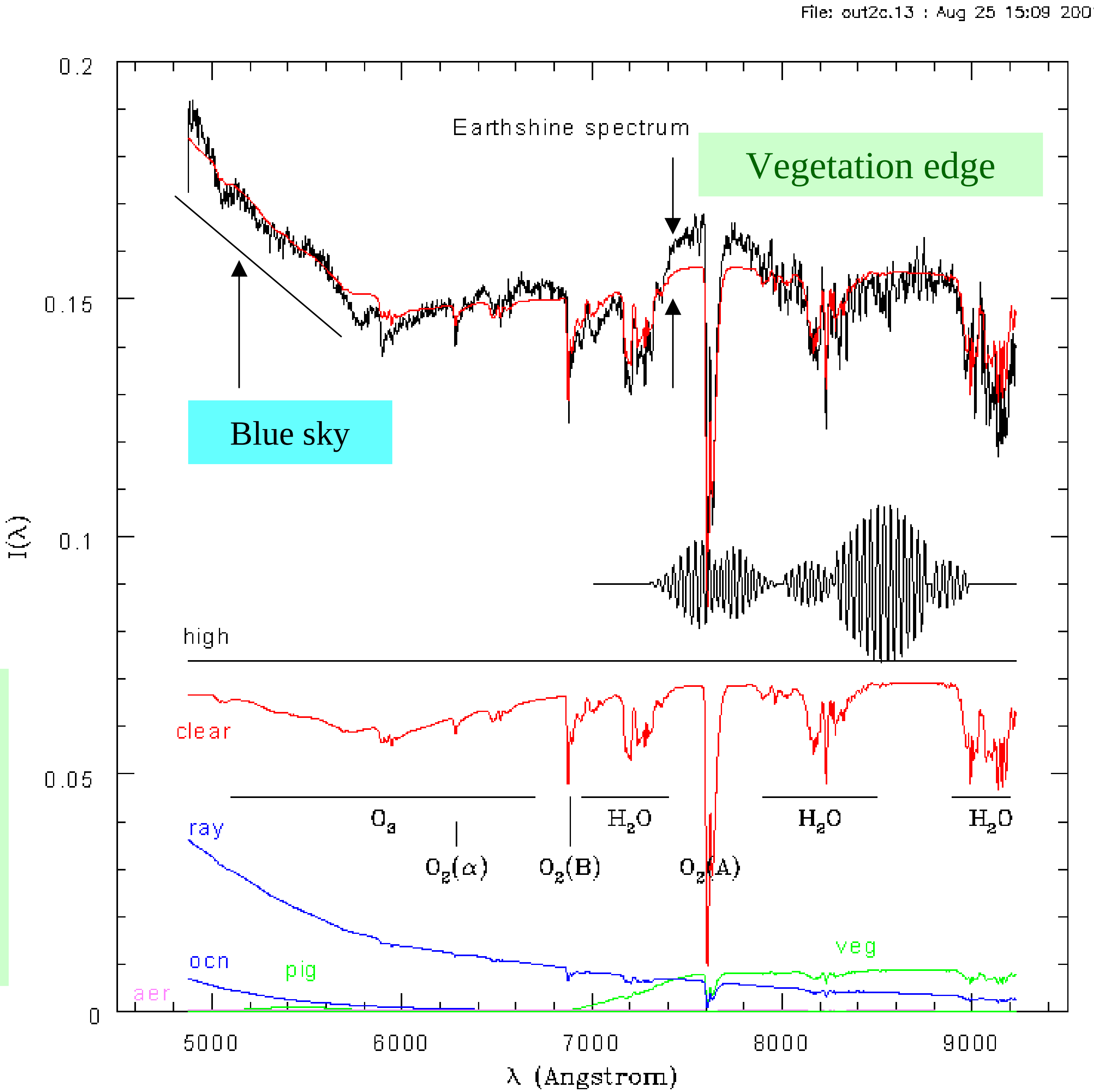
- We need to know surface conditions, not effective temperature - Venus and Earth have similar effective temperatures!
- Excessive cloud will prevent us learning about the surface of planets - except by radio observations beyond our technology.
- Infrared observations can determine planet size and approximate mass, regardless of cloud.
- Infrared can determine surface temperature, for cool (250-300K) relatively cloud-free planets.
- Infrared can determine atmospheric constituents and atmospheric thermal structure, but is poor for measuring abundances.
- Visible molecular band observations are not affected by thermal structure, and so are good for determining abundances.
- There are potential routes for visible determination of surface conditions that need to be tested on actual spectra[which we have since obtained].

Biomarkers Study Conclusions II

- The combination of visible and IR observations is very valuable - neither region will give all the information and either region will require modelling to interpret.
- There is a concern that Earth is a particularly easy planet to interpret from spectral observations, and that other planets, larger or smaller, with more or less insolation may be cloudier and so much harder to interpret.
- Oxygen and/or Ozone is our highest priority biomarker.
- The technological issues that determine whether visible or Mid-IR is easier to observe with appropriate sensitivity is more important than any other scientific priorities than detection of Oxygen or Ozone.

TPF

Terrestrial Planet Finder



Earth spectrum from Earth-shine

The importance of visible observations

- Although we believe that the technology readiness makes it appropriate to start infrared observations first, we want to stress the importance of a balanced program that also includes the development of technology for visible wavelength observations.
- Earths visible spectrum, even at the lowest resolution shows the amount of Rayleigh scattering and so measures the amount of Earth's total atmosphere. Also we observe a signal of the presence of abundant plant life. Even this limited performance provides vital data.

2) TPF-type Interferogram analysis

- C program being developed, (using LINUX).
- Gives numerical results for planet positions.
- Gives numerical results for planet signals.
- Gives numerical analysis for spectra (nearing completion).

- Insert planet brightnesses as a function of wavelength.
- Insert planet positions.
- Insert Gaussian noise of adjustable amplitude.
- Current program is simple, and will require larger arrays and more calculation time to allow more precise positions to be input.

- Principle goals are:

1) To understand the effects of noise on the precision of interferogram reduction.
2) To understand planet-planet interactions in data reduction.

TPF varieties and science

- TPF can be approached gradually through simple devices, initially with a 2 element small nuller, and going to larger devices with 4 elements.
- The science for the TPF nullers varies with the sensitivity of the devices, because the infrared emission from a planetary system is a function of age, whereas the visible radiation stays much the same after star formation.
- One small truss interferometer concept we have developed in an attempt to reduce cost can be used for various scale TPFs.
- It's special advantages include a 55% truss length for the same angular resolution.

Pre-TPF concept options

1) SPF 9m baseline 0.6m ‘scopes (x2). Used for young Jupiters 5-10 microns.

2) Close TPF 21m baseline 1.7m scopes (x4)
Detection of planetary systems and terrestrial planets to 12 pc
Observation of ozone to 8pc

3) Intermediate TPF 40m baseline ~3.5m scopes (x4)
Detection of planetary systems and terrestrial planets to 22pc.
Observation of ozone to 15pc.

4) Free-flying system with 6m telescopes for astrophysics and search around 1000s of stars.

TPF Truss options

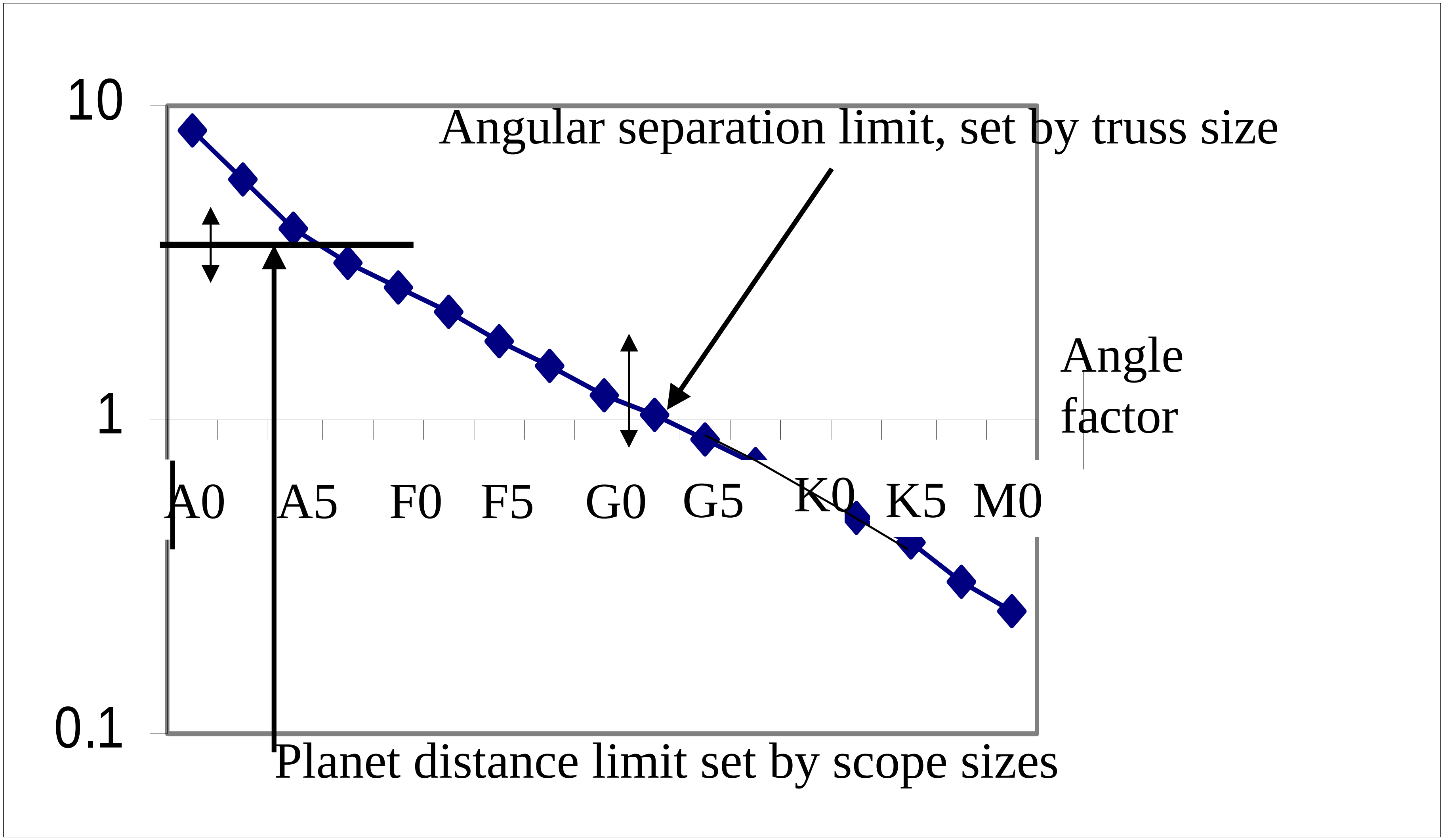
4-element Double Bracewell nullers

Overall length	Short baseline	Long baseline	θ_1/θ_2 short, arcsec 10μm	θ long arcsec
40m	11.2m	28m	0.089/0.060	0.036
21m	6m	15m	0.167/0.11	0.067

Effect of spectral type

Type	ZAMS magnitude	L/LO	Distance possible	Volume surveyed
A0	0.1	69	8.3	575
A2.5	0.9	33	5.75	191
A5	1.7	15.8	4.0	63
A7.5	1.7	10.5	3.2	34
F0	2.6	6.9	2.6	18
F2.5	3.0	4.8	2.2	10.5
F5	3.4	3.3	1.8	6.0
F7.5	3.85	2.2	1.5	3.2
G0	4.3	1.4	1.2	1.7
G2.5	4.65	1.05	1.02	1.07
G5	5.0	0.76	0.87	0.66
G7.5	5.4	0.52	0.72	0.38
K0	5.8	0.36	0.60	0.21
K2.5	6.25	0.23	0.49	0.12
K5	6.7	0.16	0.40	0.06
K7.5	+7.25	0.095	0.31	0.03
M0	+7.8	0.062	0.25	0.015

Effects of Scopes and truss sizes



Candidate Stars

Star closer than 10pc

Planet @ Earth temperature, no closer than 0.1 arcseconds (stretched to 0.09 for 61 Cyg B)

Name	mbol	parallax	planet separation	Type	Comment
1) ε **Eri**	3.50	.310	.18	K2V	
2) **61CygA**	4.66	. 287	.11	K5V	- comp. 27"
3) **61CygB**		.287	.09	K7V	- comp 27"
4) ε **Indi**	4.14	. 276	.13	K4-5V	
5) τ **Ceti**	3.50	. 274	.18	G8V	
6) **40 Eri**	4.26	.198	.13	K1V	- WD 83"
7) **Altair**	0.90	.194	.60	A7IV-V	
8) σ **Dra**	4.56	.173	.11	K0V	
9) η **Cas**	3.44	.168	.19	G0V	- comp.12.5"
10) **82 Eri**	4.25	.165	.13	G5V	
11**)** δ **Pav**	3.52	.164	.18	K2V?	- sub-giant
12) **Fomahault**	1.26	.130	.50	A3V	
13) **Vega**	0.03	.129	.90	A0V	
14) 61 **Vir**	4.70	.117	.105	G6V	
15) ζ **Tuc**	4.23	.116	.13	G2V	
16) χ 1 **Ori**	4.41	.115	.12	G0V	
17) δ **Eri**	3.42	.111	.19	K0IV	- subgiant
18) γ **Pav**	4.27	.109	.13	F8V	
19) κ **Cet**	4.81	.109	.10	G5V	
20) β **Com**	4.26	.109	.13	G0V	

Notice the scarcity of late K stars!

The science rationale for SPF

1) The dynamical structure of newly formed planetary systems and the potential for retaining terrestrial planets in habitable zones,

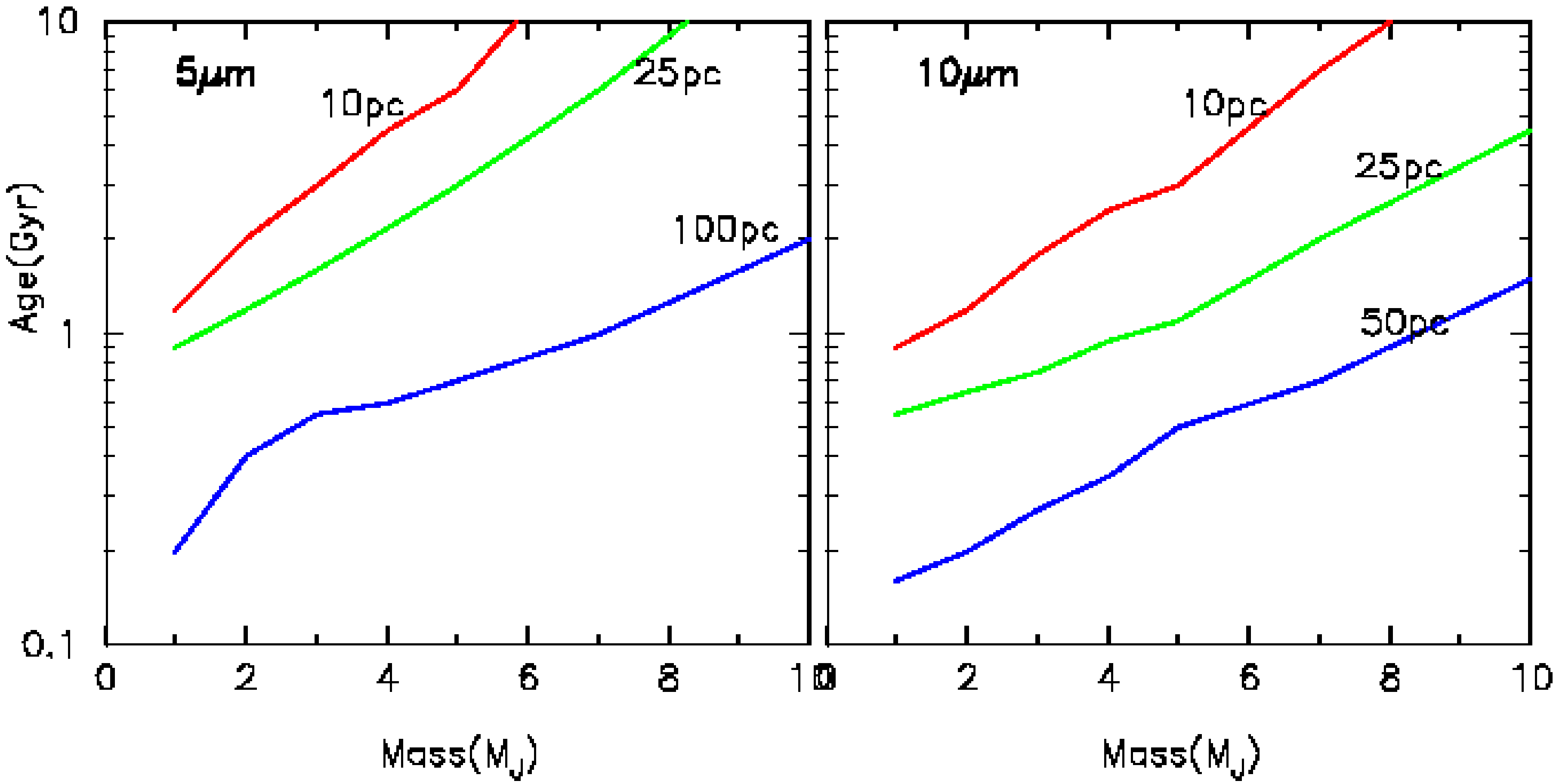
2) The origin of diversity among extrasolar planets,

3) The evolution of multiple planetary systems, and the internal structure and contraction history of gaseous giant planets.

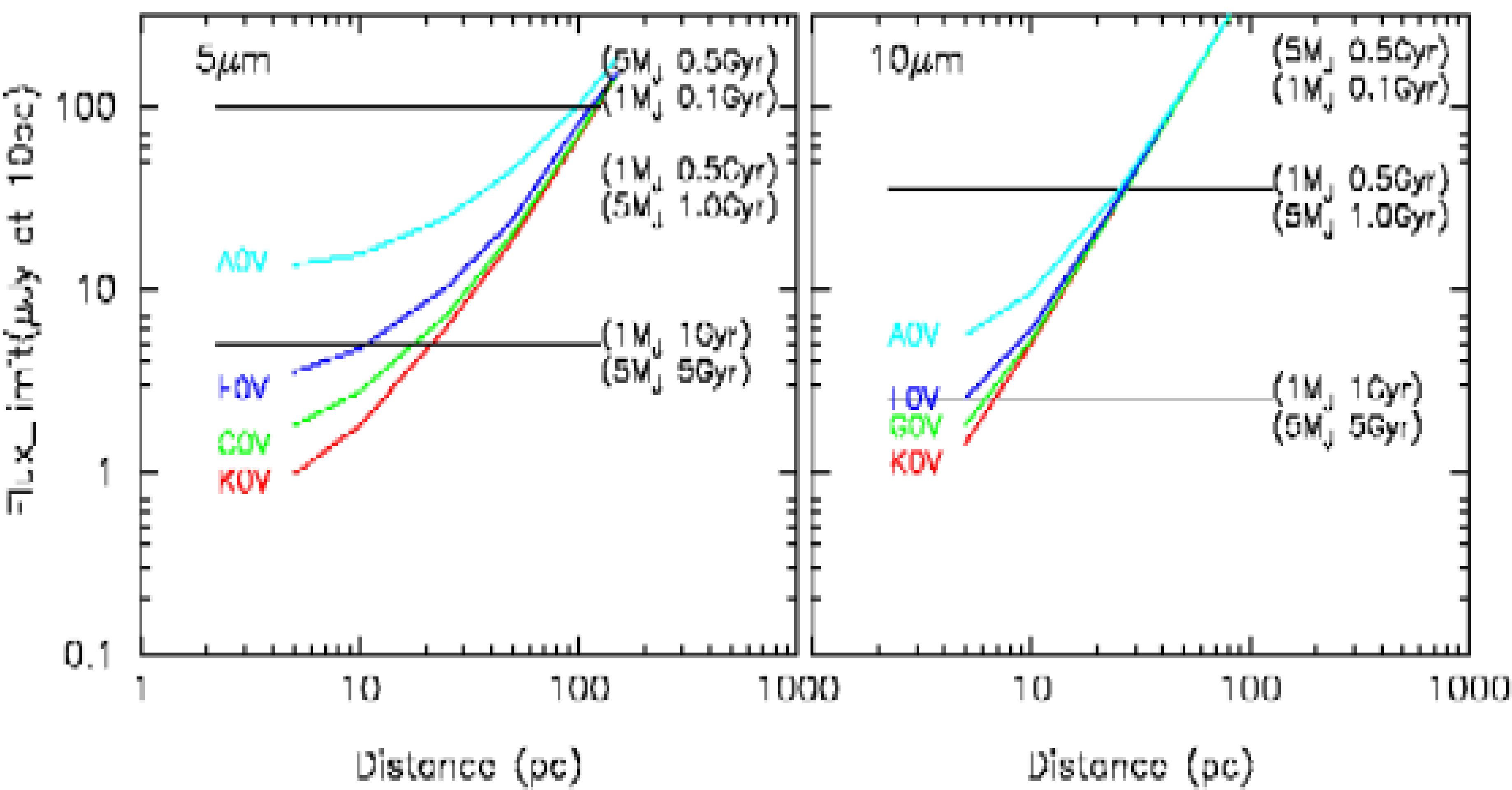
Young Planetary Systems

- Jupiters are warm
- 5 micron emission in the opacity window can be measured.
- Zodiacal glow is unimportant (at least for the solar system).
- Planets can be seen to large distances.
- Device concept (SPF) is two 0.6m mirrors separated by 9m. Simplest possible nuller.

SPF Planet detectability as a function of age and mass



Flux limits at 10pc (μJy). Variation with spectral type and distance of primary star



What could SPF see?

- Beyond the local region, out to 100 pc, there are several young clusters, associations, and star forming regions which include many young stars. Even at these distances, young Jupiter-mass planets are sufficiently bright to be detectable by the nulling interferometer proposed here. For example, at the Hyades (45pc away, ~6.5 10^8 years old). The range of detectable angular resolutions is adequate for resolving all planets with orbital radii between those of Jupiter and Pluto. Clusters and associations have independently derivable ages, and so these planet masses can be inferred from their luminosities, and astrometric measurements are not needed.

- These object/angular resolution ranges will not even be available to NGST. Even if NGST were to be fitted with a 5 micron coronagraph, coronagraphs only operate outside ~3 times the diffraction core size. Thus SPF will be observing objects ~5 times closer to their star than NGST could observe, and the projected sensitivity is several times higher than projected for LBT (which would have the required angular resolution), because of the reduction in thermal background).
- Note however that LBT can initiate studies of this type.

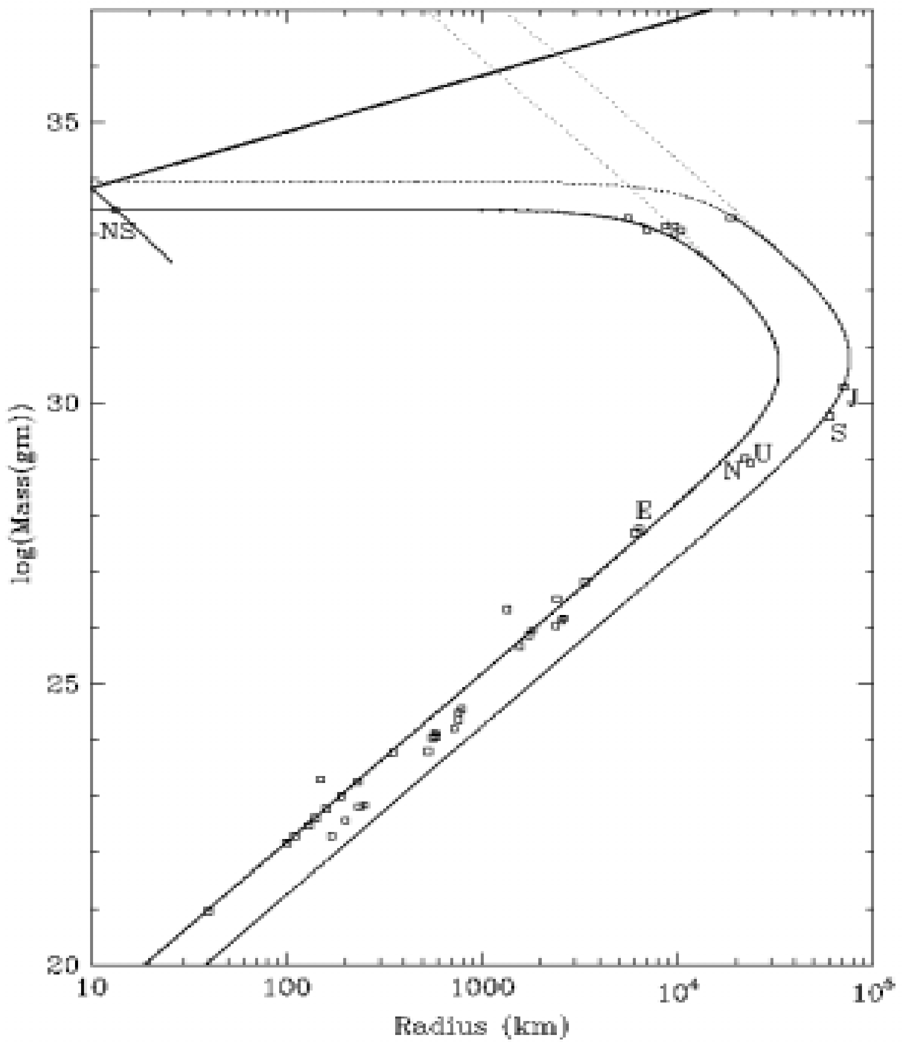
Comparison of 21m and 40m with Ref. design

Science Goal of an earth at 10pc	4x3.5 m (1 AU)
Detect Planet Spectral Resolution (R)=3 12 µm observation Signal to Noise (SNR)=5 (Size and Temperature)	2.0 hr
Detect Atmosphere R=20 /SNR=10 CO_2, H_2O	2.3 day
Habitable? Life? R=20/SNR=25 O_3 ,CH_4	14.7 day

Science Goal of an earth at 8pc [15pc]	1-1-1-1 4x1.7m (1AU) [3.5]	1-2-2-1 4x3.5 m (1 AU)
Detect Planet Spectral Resolution (R)=3 12 µm observation Signal to Noise (SNR)=5 (Size and Temperature)	4 hrs	0.8 hr
Detect Atmosphere R=20 /SNR=10 CO_2, H_2O	4.6 days	0.96 day
Habitable? Life? R=20/SNR=25 O_3	29.4 days	6 days

Science Goal of an earth at 12pc [22pc]	1-1-1-1 4x1.7m (1AU) [3.5]	1-2-2-1 4x3.5 m (1 AU)
Detect Planet Spectral Resolution (R)=3 12 µm observation Signal to Noise (SNR)=5 (Size and Temperature)	20. 5hr	4.1 hr

Planet mass-radius relationship



5) Cost per System Observed

- TPF goals were set in a rapidly developed Origins plan, and at a time where knowledge of the frequency of planetary systems was incorrectly derived from observations by Campbell et al.
- The actual frequency of planetary systems with near-circular orbits like the solar system could range from very common, with one around every few stars, to relatively rare, with one or none accessible.

- The question is whether the goal of a first TPF mission to look for Earth-like planets around ~150 stars is an appropriate starting goal. We need to know how the cost per system changes with the number of systems observed. We need to know how the required technology level changes with the number of systems observed. We need to assess how that technology can be achieved.

Cost per observation Telescopes I

- In a homogenous universe, the number of objects of a particular type increases as the cube of the distance explored. $N=kd^3$.
- If all spacecraft last the same amount of time, and N objects are observed, the time available for each is : $t = T/N$.
- There are two cases:
  - A)All photons are from the source (adequately deals with coronagraphs at visible wavelengths).
  - B)There is a constant background flux limiting the observations (adequately deals with Mid IR observations.

- Case AThe same number of photons are required for an observation of any system. And the rate photons are collected increases with mirror size D^2, and decreases with distance d^2. $P=Q\ D^2/d^2N$, Q is a constant. So , for the same number of photons collected P, D^2/d^5 must be held constant. Thus the relationship between D and N is D is proportional to $N^{5/6}$.The cost of a telescope will increase with diameter to some power. On the ground, costs increase as ~D2.7. Assuming this applies to space, Cost varies as $N^{2.25}$.

Telescopes 2

- Case B
- The noise is independent of mirror diameter. The signal-to-noise varies as D^2/d^2. The observing time per object is proportional to d^4/D^4.
- D varies as $dN^{0.25}$. Or D varies as $N^{7/12}$. Again if cost varies as D2.7, the cost varies as $N^{1.575}$.

- Overall the cost increases as N to some power greater than 1, so the cost increases per object observed.

1) There is a premium on observing the fewest number of objects.
2) It is cost effective to start with the least sensitive device that can fully explore the needed technology, and test it on a small number of objects.

Cost per observation, Trusses and Free Flyers

- The length L needed for an interferometer truss to resolve planets will increase with d, so L is proportional to $N^{1/3}$.
- If the cost to launch a truss increases as L^3, which seems plausible as a starting point, then the cost of a truss will be proportional to N. Thus the truss cost per object is likely to be constant.
- Free flyer costs have a start-up price which is likely to be large, but once achieved, there is no obvious increase in price with N for the free-flying component.
- However, for both of these, the telescopes will be major expenses. So for free-flyers, the advisable starting size is where the telescope costs are comparable to free-flyer start-up.
- For trusses, the advisable start-up size is that which permits observing a small number of objects.

How well does the proposed architecture meet the primary goals of TPF?

a) Can it detect Earth-like planets around a statistically interesting number of stars during the nominal mission duration, in less than half of 5-year mission?

Answer:

The detection of Earth-like planets at Primary Goal #1 with fixed baseline interferometers requires resolution of ~35mas. This is possible with a 40m baseline interferometer using the new shorter configuration. It is also possible to do this with a free-flying interferometer. The performance of 4x 3.5m mirrors is discussed in the TPF book.

How well does the proposed architecture meet the primary goals of TPF?II

b)Does it cover wavelengths that are indicative of 1) the presence of an atmosphere, 2) habitability, and 3) extant life?

Answer: The presence of an atmosphere is shown minimally by the 15micron CO_2 band.

Extant life can be seen in the 9.7micron O_2 band which is capable of showing lower oxygen levels on the planet than for any other band.. Habitability is indicated by temperature, surface gravity and liquid water. The temperature is found independently of bands by the ratio of the continuum emission at 12 and 9 microns. Water is seen at 17-17.5 microns in the depression of the long wavelength end of the CO_2 band. The surface gravity is found from the strength of the IR emission which, when compared with the temperature determined above gives the planet area. This is compared with a sharply defined mass-radius relationship for planets to give the surface gravity.

Other Architecture issues

Can the architecture provide information on full range of objects and structures in the planetary systems being studied (e.g. Giant planets, Exo-zodiacal dust clouds, etc) ?

Answer: One valuable feature of the IR interferometer variants of TPF is that they obtain information about all components of the planetary system- including their spectra - in a single observation. The angular limit of the observations is set by signal-to-noise concerns, and can be appreciably larger than the Airy disk of the individual telescopes.

General Astrophysics

What is the potential of this architecture for general astrophysical observing?

Answer: The long range potential for interferometer architectures is to provide angular resolution that is not available with a filled aperture. There is also a need for both interferometers on trusses and free-flying interferometers to cover the full range of baselines necessary for astrophysical objects at IR or visible wavelengths.

However, the specific devices for the first planetary studies do not fit well with the requirements for general astrophysics. There is a substantial saving in time and money by making the first interferometer on a truss.

Astrophysics II

How would the requirement for a general astrophysical capability affect the facility (e.g. complexity, additional instruments, target limitations, mission lifetime)?

Answer: The high precision requirements for a TPF are such that, if they are met, it will be possible at lower expense to build a larger and more sensitive device of the same kind with more normal specifications for general astrophysical observing.

The tightness of the requirements for all TPF variants are such that the imposition of additional constraints would be inadvisable.

Continued

Astrophysics II cont'd

Also, the appropriate extent of a program that is for the first time investigation the properties of other planetary systems is likely to more than fill the available time of a first mission lifetime. Nonetheless, provided that additional instruments, fuel, pointing systems etc. are provided, it would in principle be possible to use a free-flying interferometric TPF for other tasks.

The requirements for a truss TPF are in general sufficiently different - one requires a highly non-redundant array for astrophysics, and a highly redundant array for planetary system studies, that the trusses should be optimized for one or the other but not both.

Suite of Missions ?

Question: Does the proposed architecture have a natural scientific precursor of more limited scope? List scientific goals, legacy to TPF, mission size (by cost or analogy).

Answer: The Self-luminous Planet Finder is a natural scientific precursor that can also bring all the technology needed for truss interferometers to TRL7.

The science goals are to look for young Jupiters around stars including early F and A stars, and at distances from their stars corresponding to the range of Giant Planets in the solar system.

Cost is less than $300M.

Possible Missions

Self-luminous Planet Finder

Young planetary systems with Jupiters at >0.08 arc seconds.

E.g. 8AU from star @ 100pc.

Close Terrestrial Planet Finder

Earths as close as 0.08 arcsec for T and O_3.

As close as 0.11 arcsec for CO_2 and H_2O

Core program to 8pc. Extended program to 12pc.

Intermediate Terrestrial Planet Finder

Earths as close as 0.045 arcsec for T and O_3.

As close as 0.062 for CO_2 and H_2O.

Core program to 15 pc. Extended program to 22pc.

Extended program only measures temperature and size.

From TPF book appendix A

Table A3. Interferometer Observing System	
Baseline	75 m
Telescope Apertures	1.8:3.5:3.5:1.8 m (1 AU) 1.1:2.2:2.2:1.1 (5 AU)
Telescope Temperature	40 K(1 AU) 35 K(5 AU)
Telescope Emissivity	0.1
Spectral Resolution	20
Net Efficiency (Optics*Detector*Beam)	0.04
Deepest Null	10^{-5} (1 AU) 10^{-6} (5 AU)
Phase Center Pointing Jitter	0.25 milli-arcsec
Detector Dark Current	5 e^{-}/s
Detector Read Noise	1 e^{-}
Flat Field Error	10^{-5} (1 AU) 10^{-4} (5 AU)

TPF
Terrestrial Planet Finder

From TPF book Appendix A

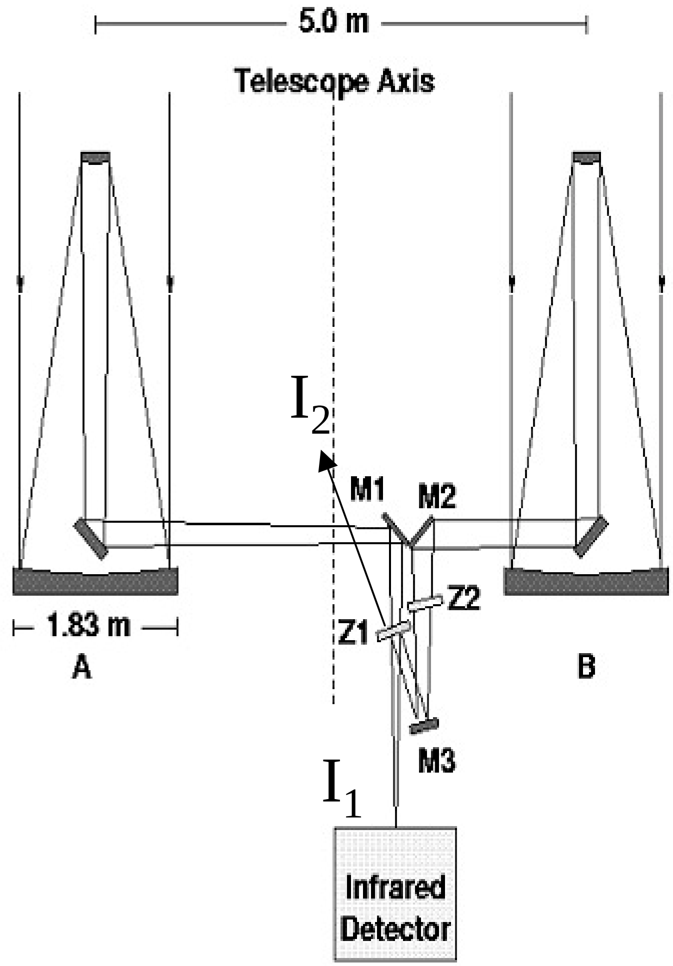
Table A.4. Signal and Noise Sources at 1 and 5 AU		
Signal (Photo-Electrons) R=20, $\tau=10^5$ s at 12 μm	2 m (5 AU)	3.5 m (1 AU)
Planet @ 10 pc	0.008×10^6	0.025×10^6
Exo-Zodiacal Background	0.71×10^6	2.15×10^6
Local Zodiacal Background	0.10×10^6	8.56×10^6
Nulled Star Leakage	0.04×10^6	1.16×10^6
Dark Current	0.50×10^6	0.50×10^6
Total Counts	1.35×10^6	12.4×10^6
√(Counts)	1.16×10^3	3.52×10^3
Flat*Counts	0.14×10^3	0.12×10^3
Noise	1.17×10^3	3.52×10^3
SNR (Signal/Noise)	7.0	7.1

Nulling detection of planets

Philip Hinz
Steward Observatory, University of Arizona

Terrestrial Planet Finder (TPF)
Phase 2 Review
December 12, 2001

MMT- an example of nulling optics



What do we see in the images?

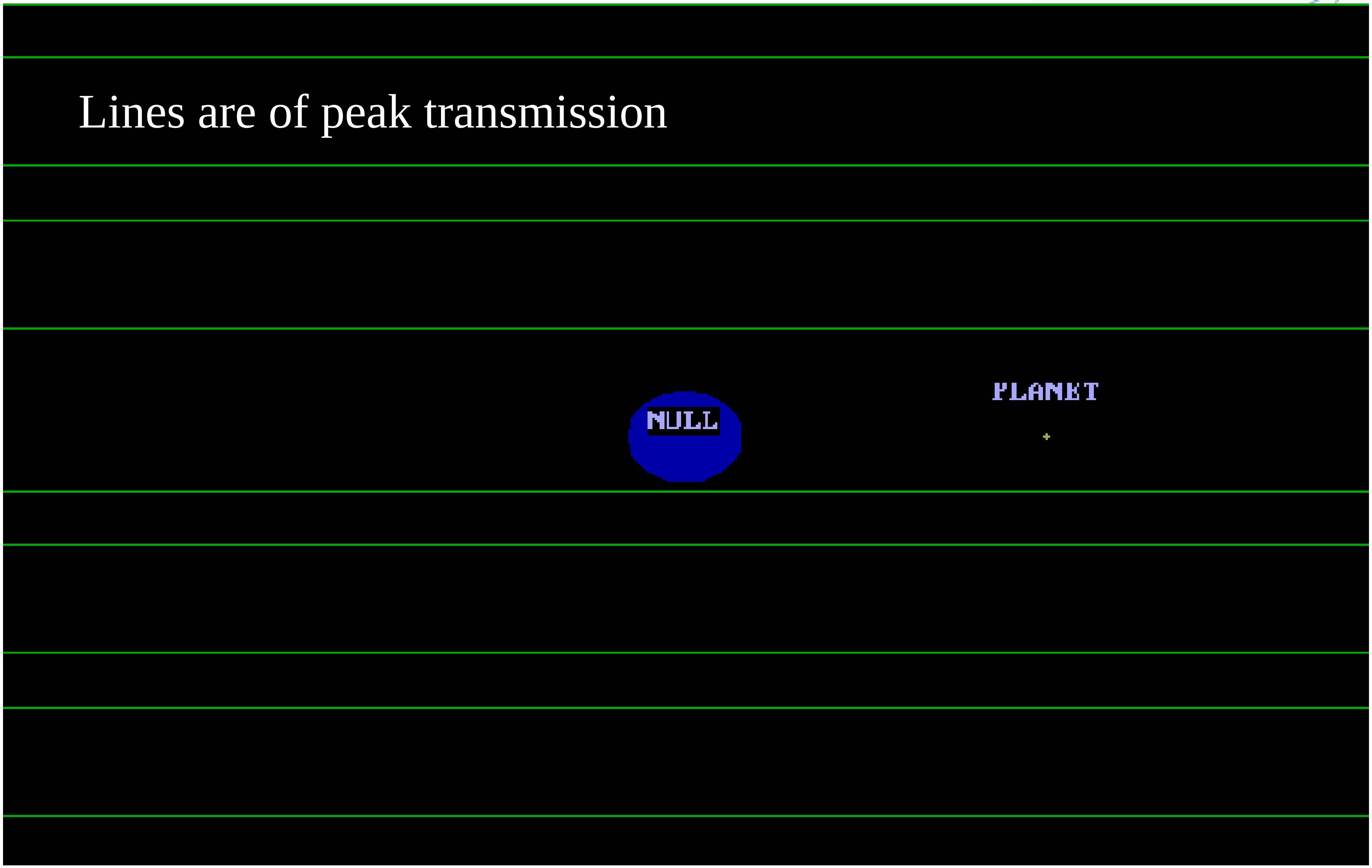
- I_1 and I_2 are out of phase, so that if the phase shift is correct (and we look in monochromatic light), we will see a star in one image, and not at the other.

- However the phase shift is position dependant on the sky, so we see straight line sinusoidal transmission fringes crossing the sky in one image, and complementary transmissions in the other image. These transmission fringes are closer spaced than the Airy disk. An entire Airy pattern is visible or invisible dependant on the exact position of the object with respect to the fringes.

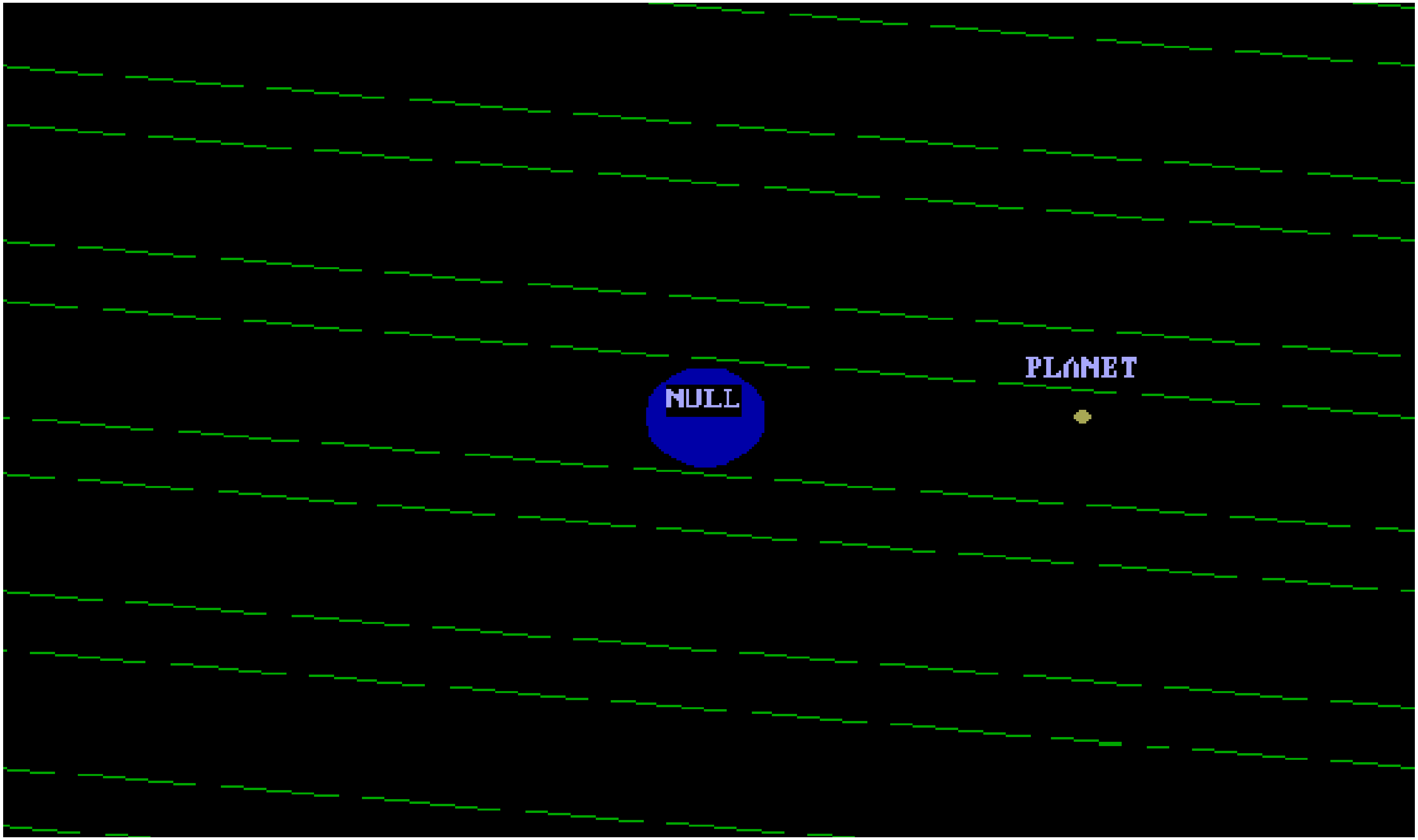
Data taking

- The interferometer output is dispersed into a spectrograph, and interferometer data is obtained in each spectral channel.
- The interferometer is slowly rotated, and data is taken while the device is within a small range of rotation angles.
- The number of steps at which data must be taken is set by the largest radial distance at which data is taken, and the shortest wavelength observed. From simulations, the most rapid rate of signal fluctuation is found, and the necessary angular range for which this signal will not be severely smoothed.
- The phases must match at the null

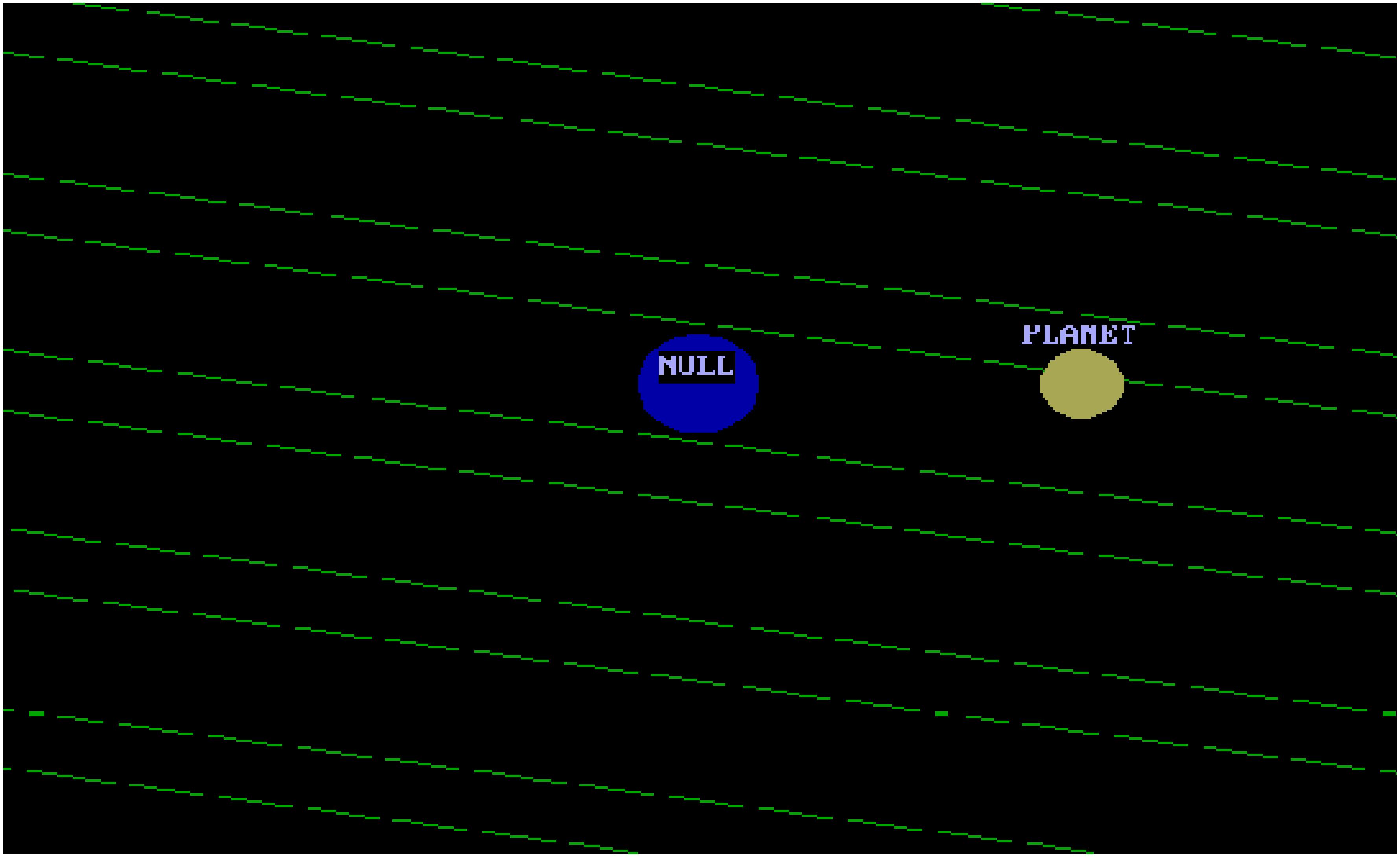
Monochromatic data taking



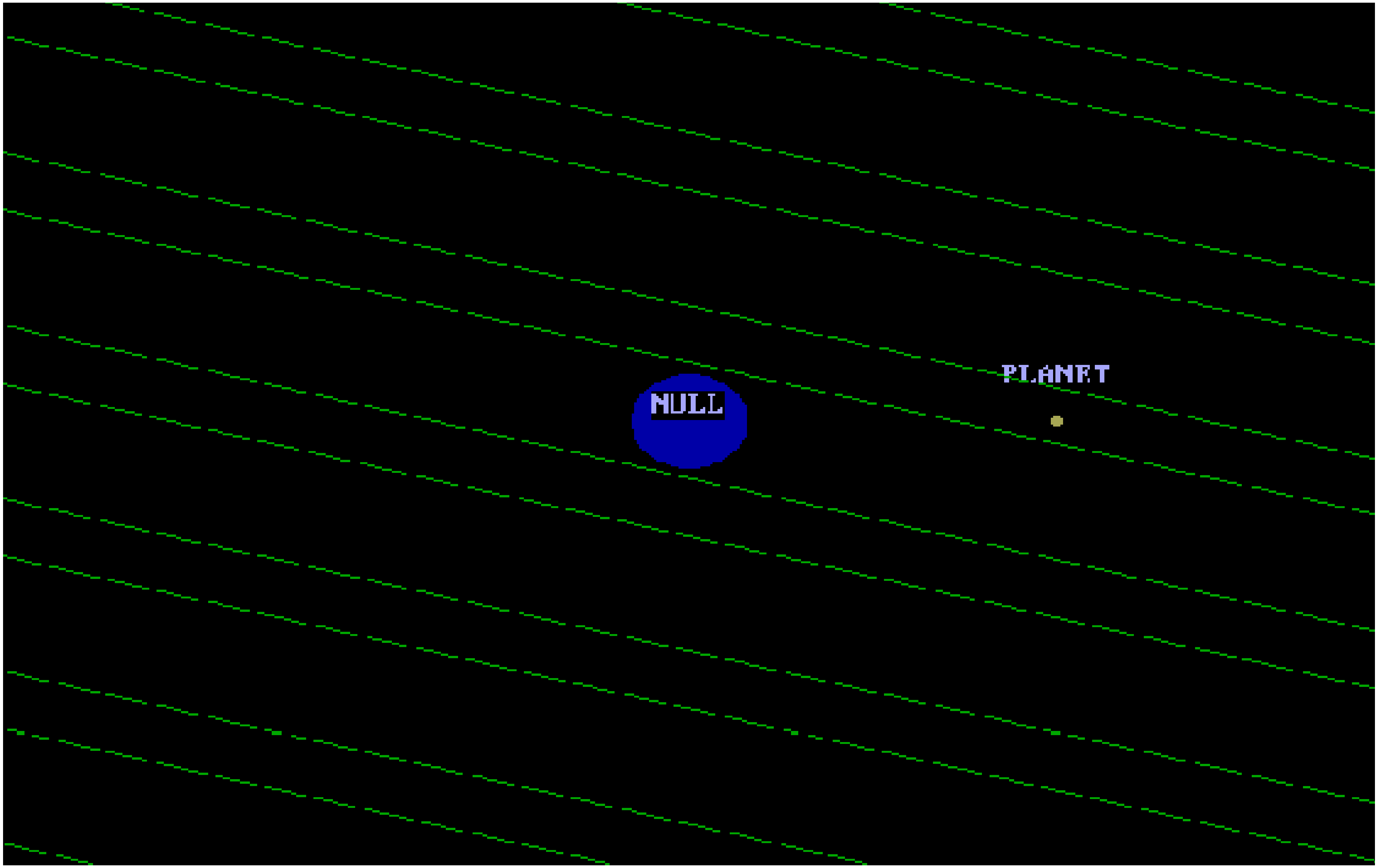
The Interferometer fringes rotate with the interferometer



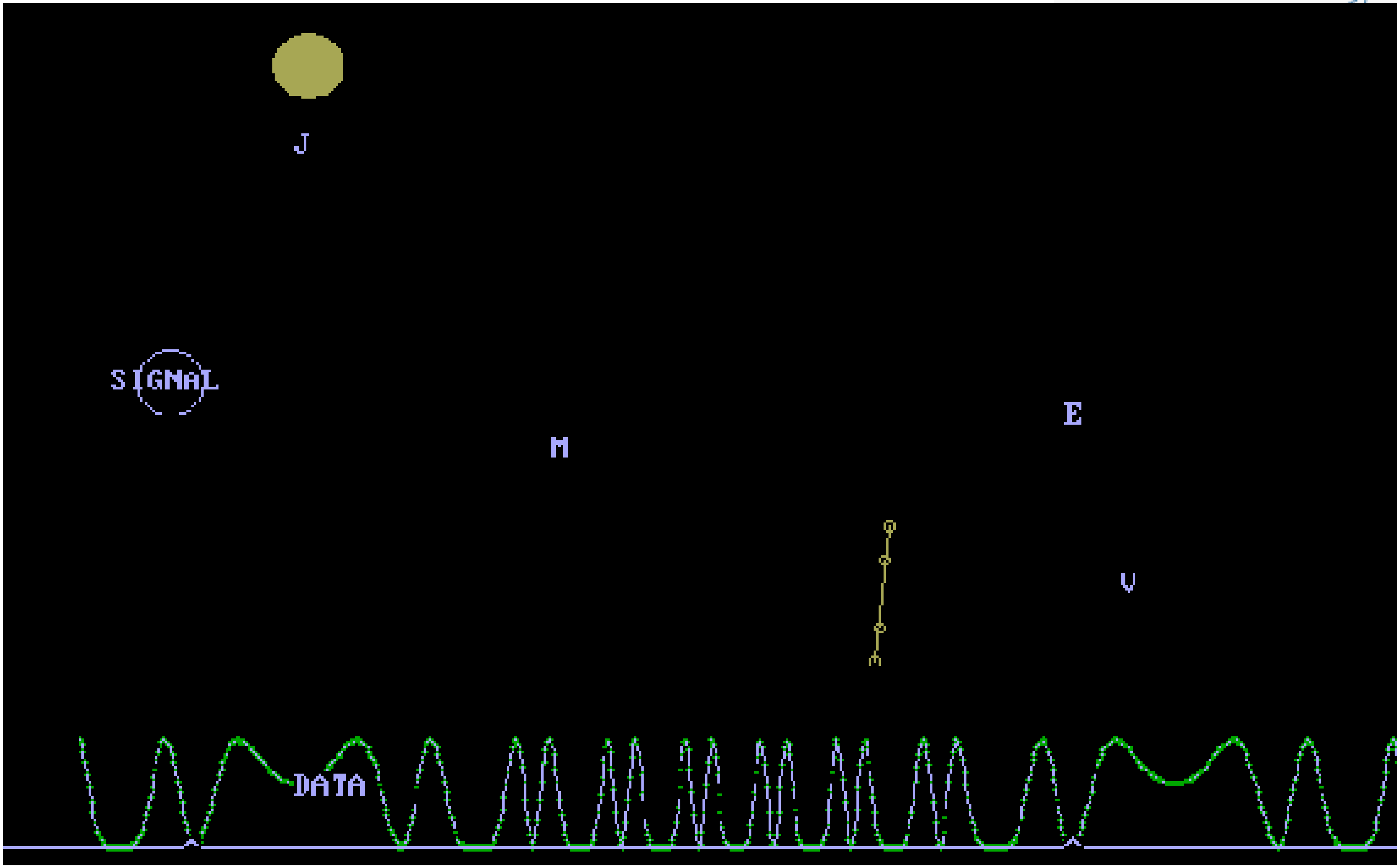
As a maximum passes across the planet...



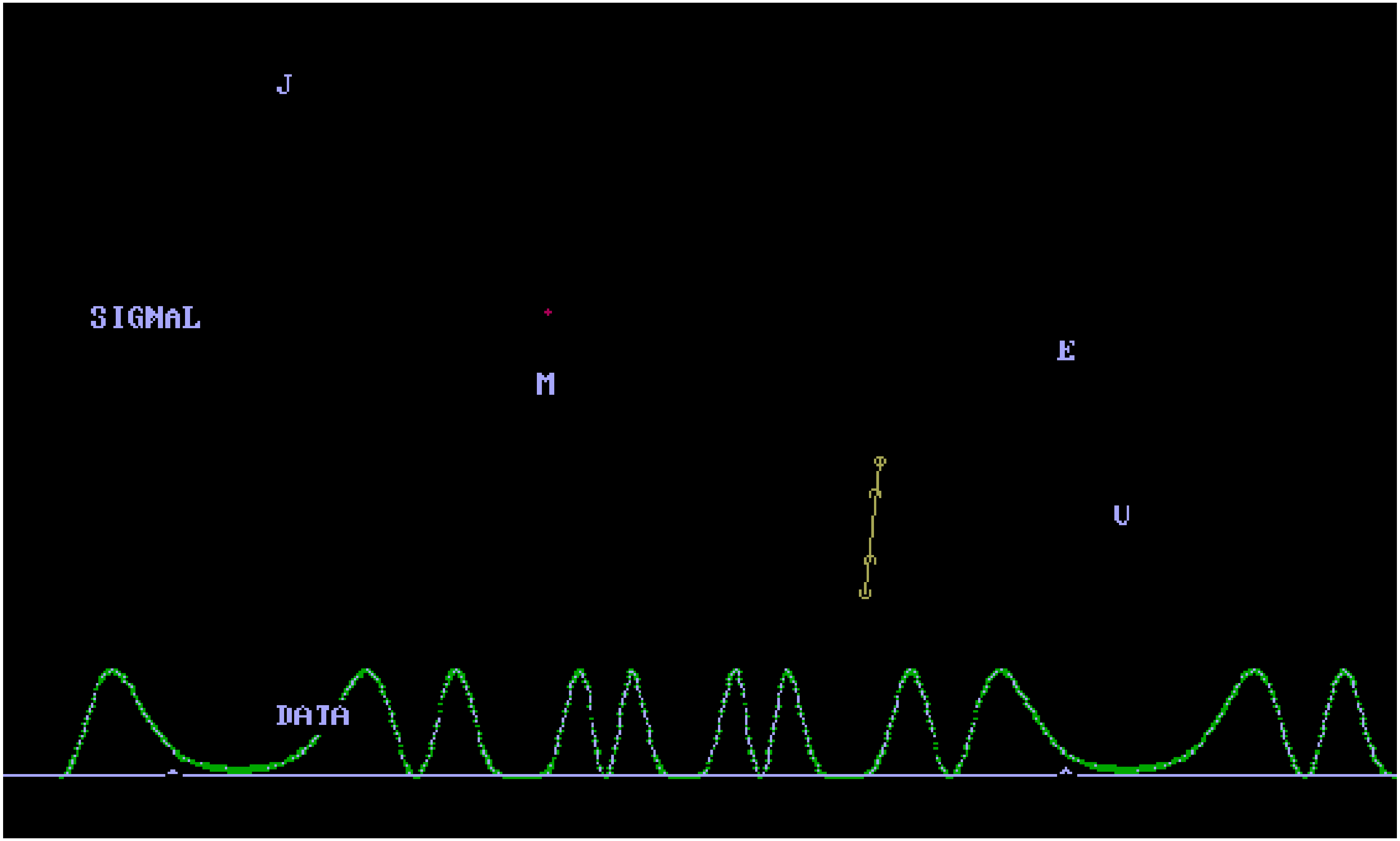
And then moves on...



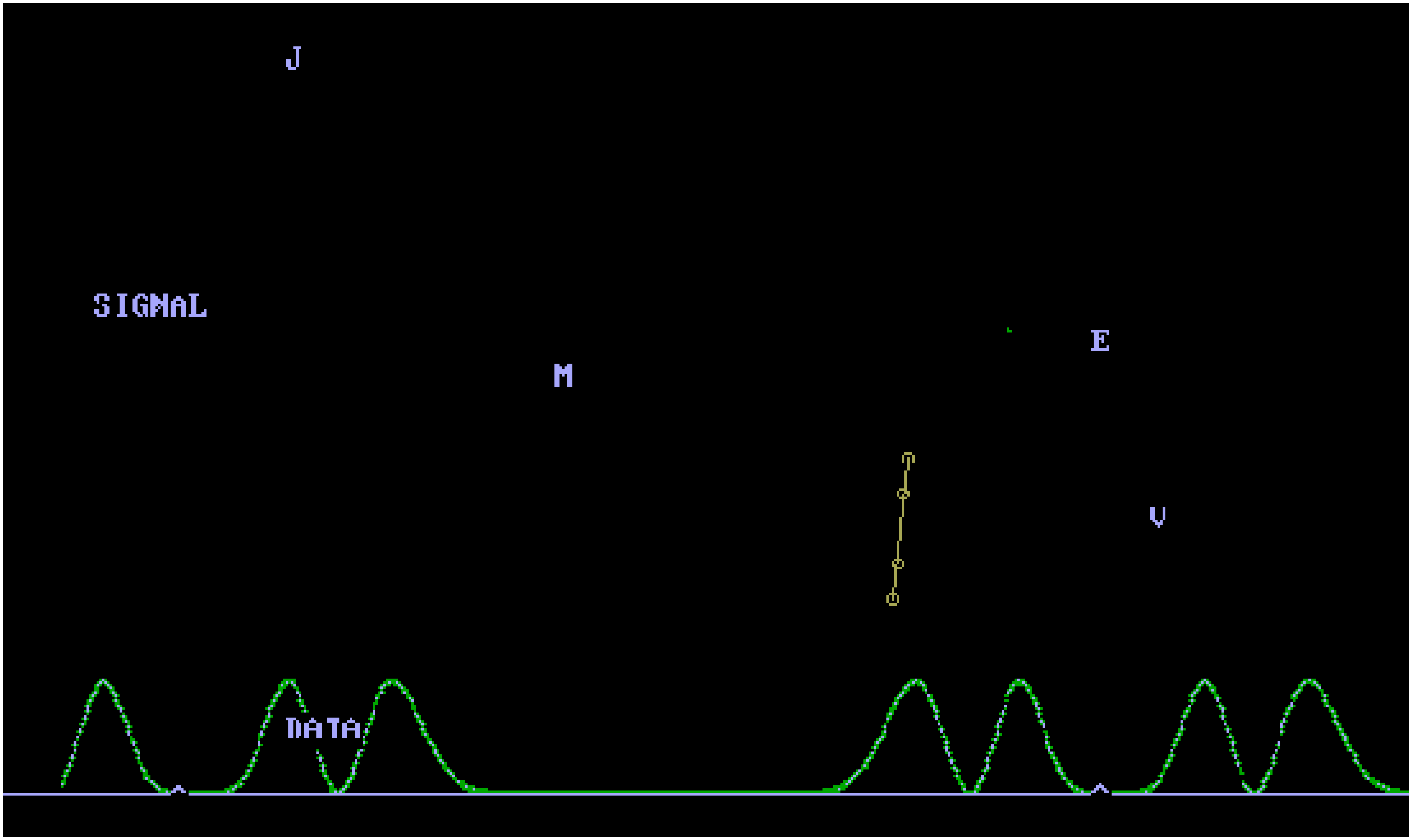
Signal from Jupiter alone



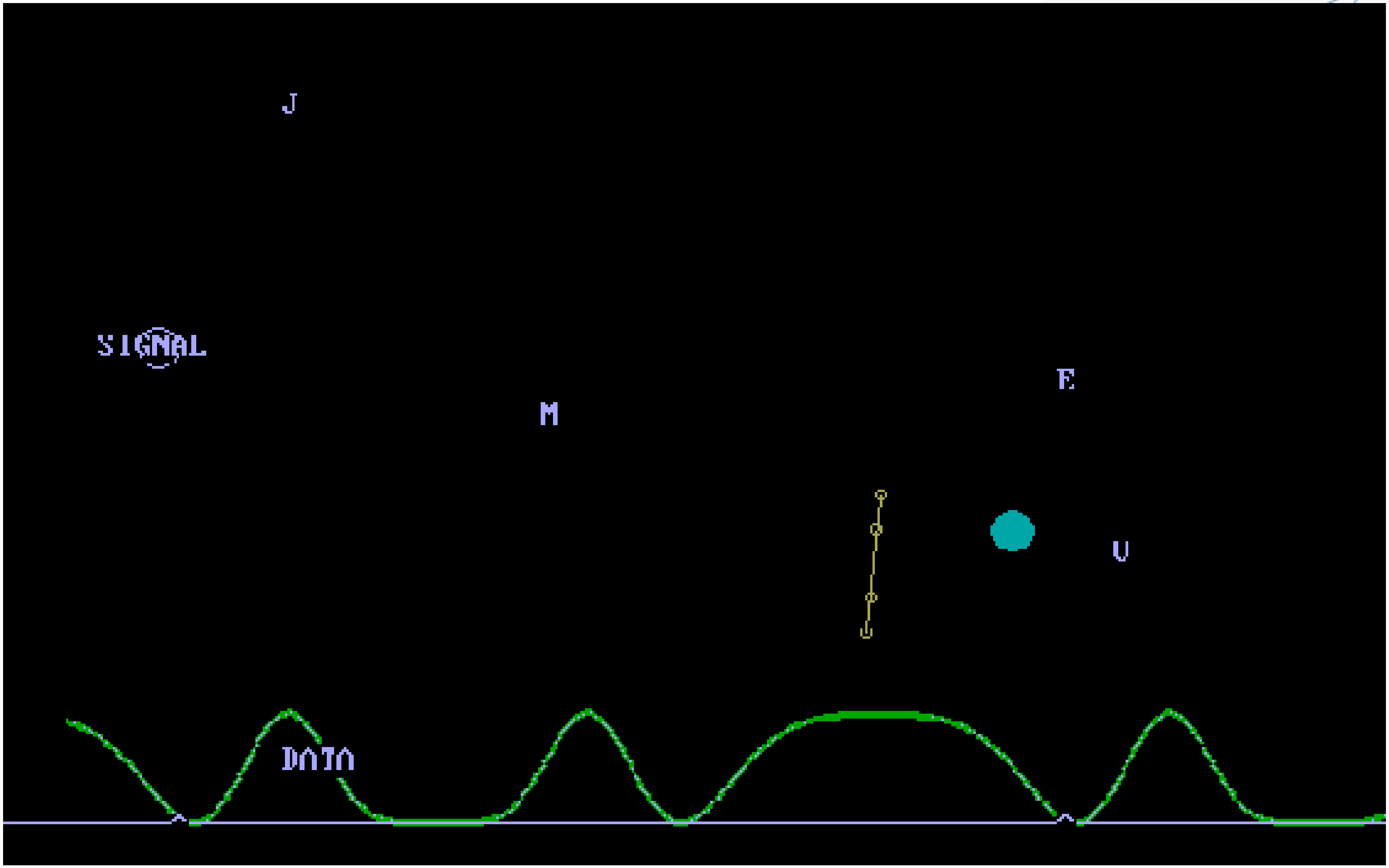
Signal from Mars alone



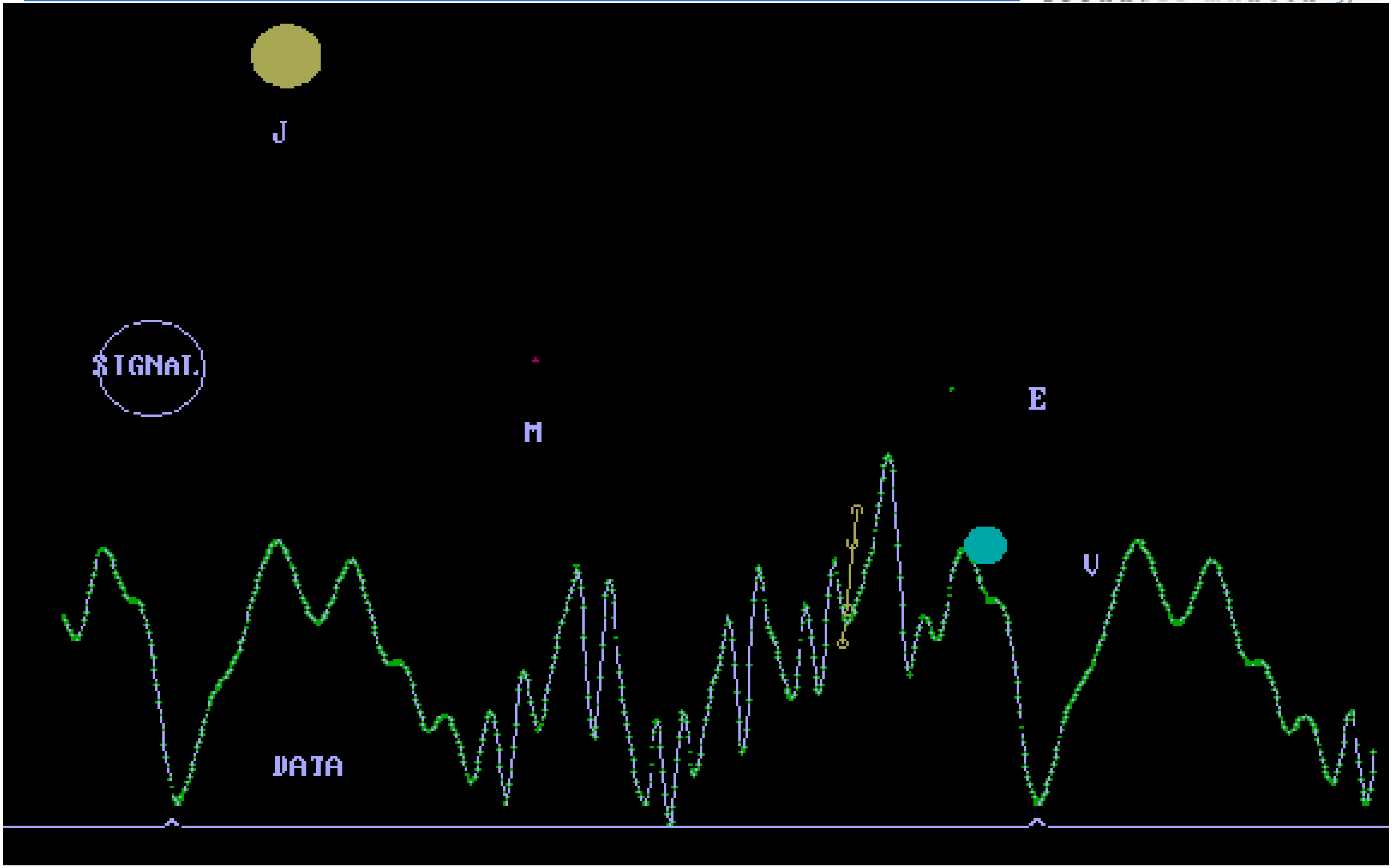
Signal from Earth alone



Signal from Venus alone



All planet signals together



Numerical Analysis of Nulling Data

- Data array consists of a 2-d array: Signal versus wavelength versus interferometer position angle.
- Reduction consists of starting with the signal that would be produced by 1 planet of unit intensity at every wavelength, and calculating its suite of arrays if it were placed at every posible radial and azimuthal position. This suite of arrays is multiplied by the data array, and the result summed for each planet position.
- The brightest planet position is found from this. It may be iterated for a more precise position. Then, for this position, the amplitude at each wavelength is found by iteration. This is the spectrum of the brightest planet. Its suite of signals is subtracted from the data array, and the next brightest planet position is found etc.

Spectral Reduction test (no noise)

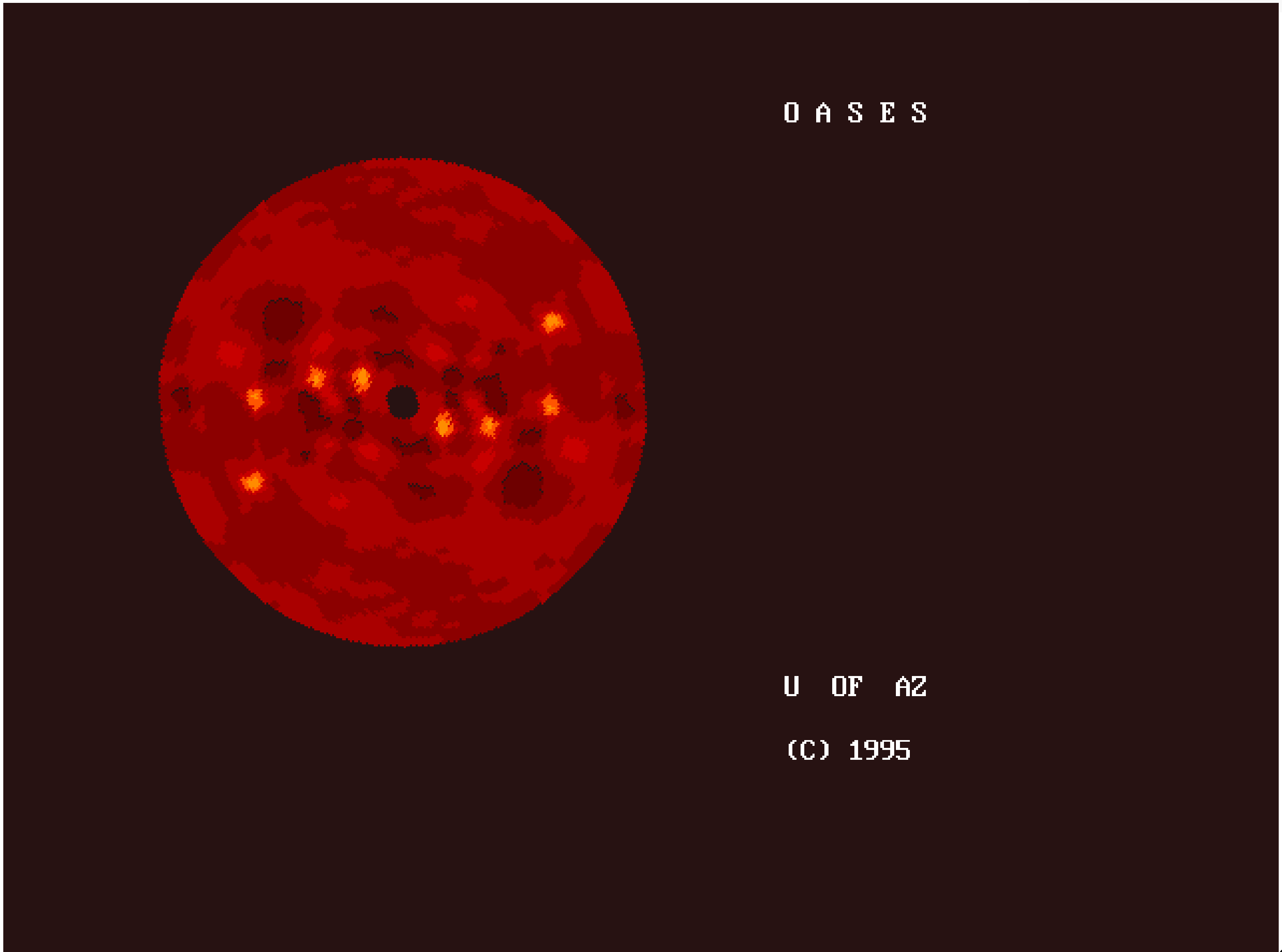
Signal	Calculated	Error
2.760000	2.757500	0.0025
1.470000	1.468750	0.0013
0.630000	0.630625	0.0006
2.700000	2.702500	0.0025
0.780000	0.780625	0.0006
1.200000	1.200625	0.0006
0.780000	0.780625	0.0006
2.160000	2.161250	0.0013
1.080000	1.080625	0.0006
0.330000	0.330312	0.0003
2.040000	2.041250	0.0013
2.010000	2.011250	0.0013
2.460000	2.4587501	0.0013

calculated to a precision better than 0.1%

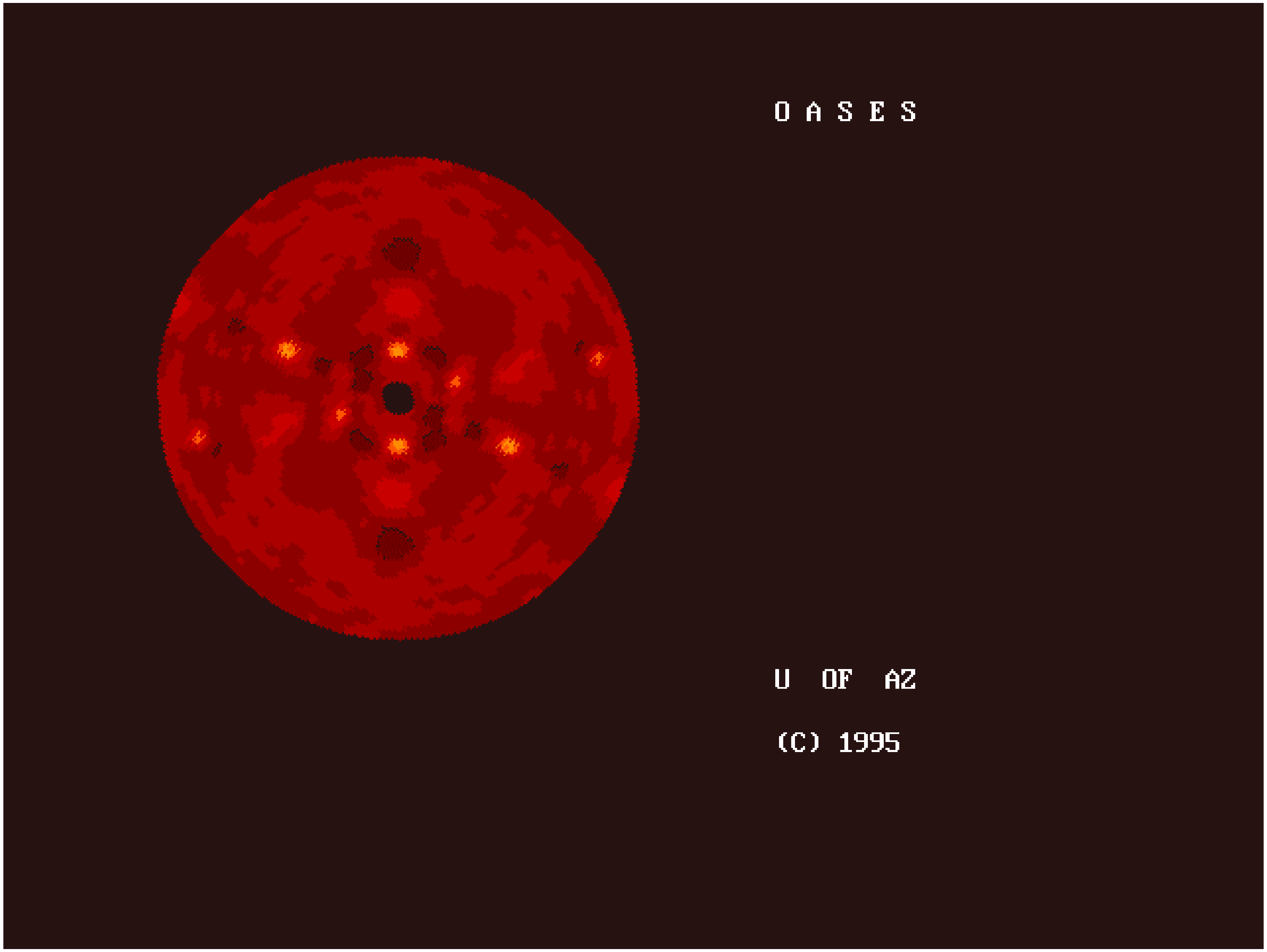
Analysis of Data to make an image

- Data array consists of a 2-d array: Signal versus wavelength versus interferometer position angle.
- The data array is cross correlated with the suite of arrays corresponding to a planet at every possible position . The cross correlation amplitude is then plotted at each position.
- Color maps are also possible by using selected wavelength regions of the data array.
- Some pseudo-planets may appear, corresponding to radial distances of 1/2 and double the true planet distance.
- Also there is spurious noise due to side-lobes.

Planet system picture from interferometer data (simulation)



After planets have revolved



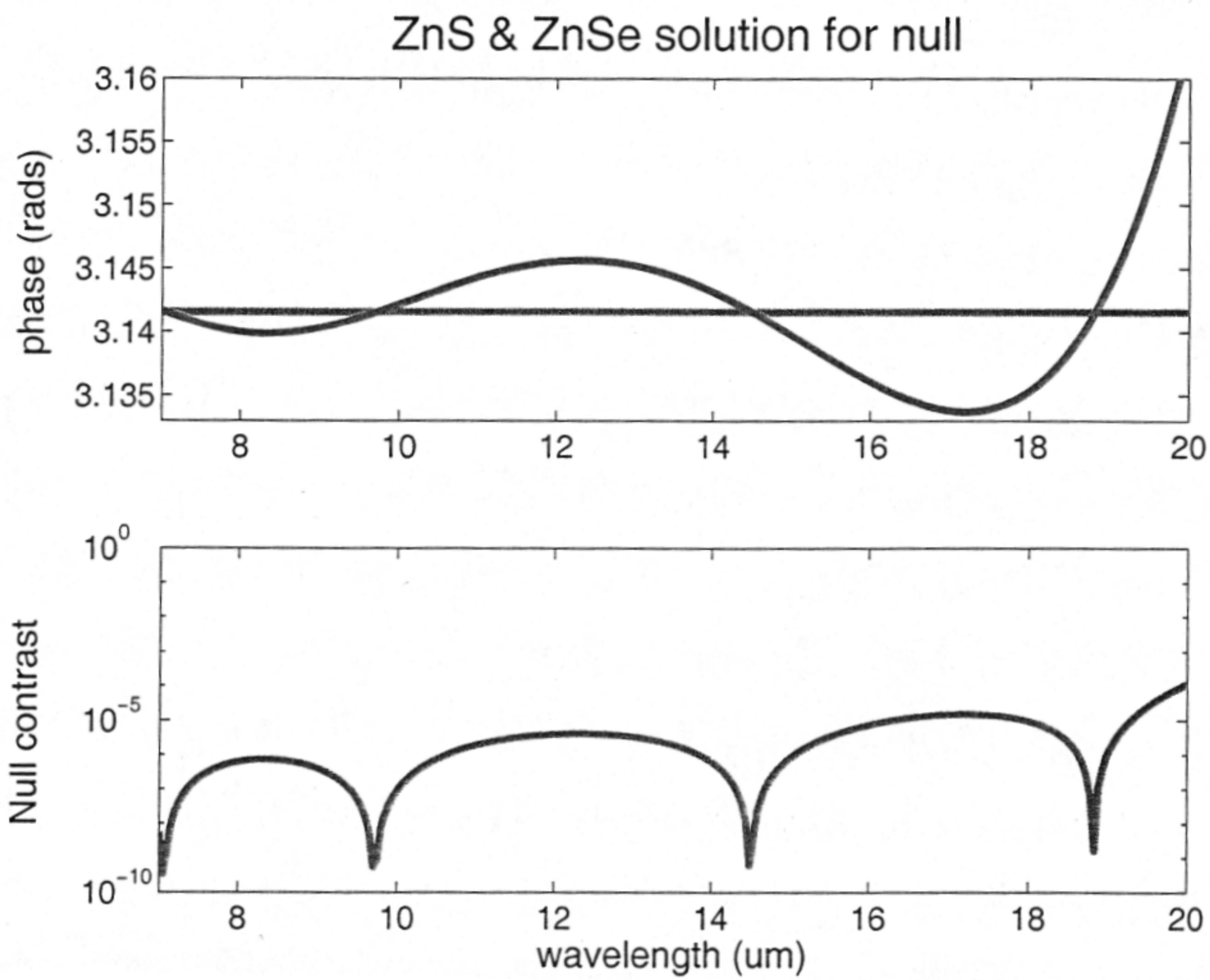
Phase shifting for white light

We need the star to have a phase shift of 180 degrees independent of wavelength.

Options are:

1) to use the phase shift at reflection
2) to use the phase shift at going through focus
3) to use a combination of dielectric plates and vacuum path to obtain a phase shift independent of wavelength through the desired band, but to have 50:50 transmission at a different band, where the phase can be monitored, yet there is totally common path through the region of interference.

Use of phase plates for broad band null



Interferometer dimensions

- From peak transmission to transmission minimum at right angles to the transmission fringes on the sky, the angular spacing is $\lambda/2s$, where s is the separation of the apertures.

Precursor

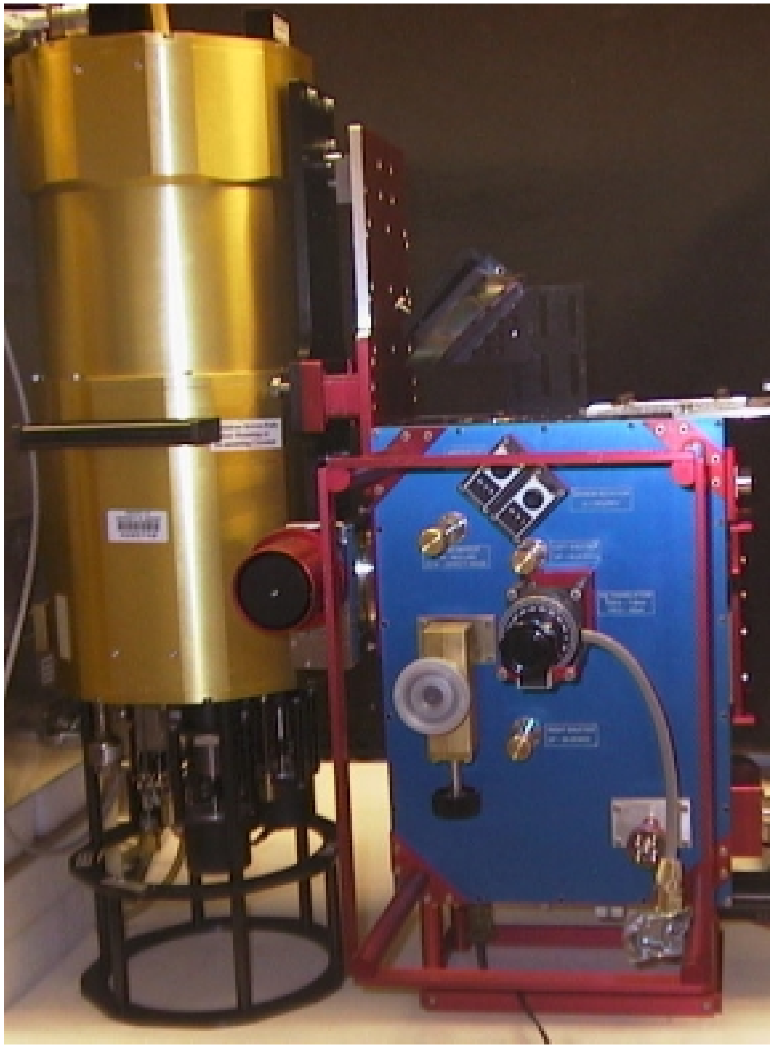
For λ = 5 microns, s= 9 meters,

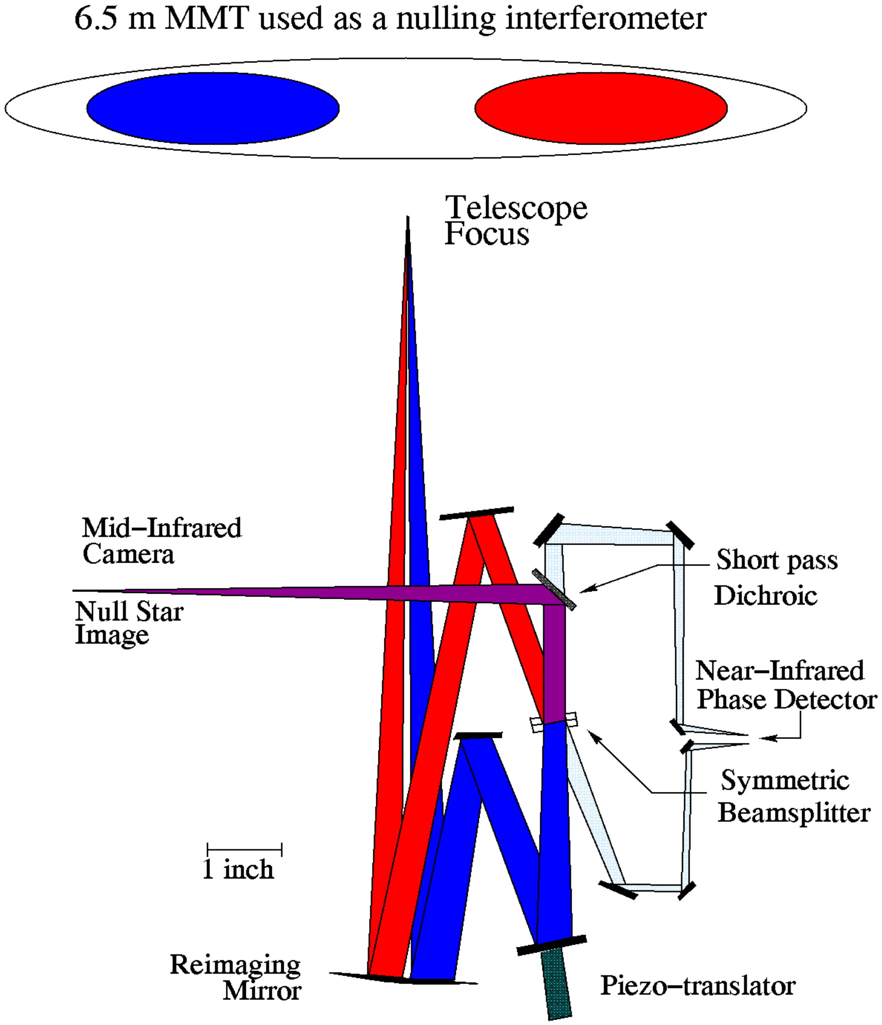
the closest angular separation is 0.055 arc seconds. But for this 2mirror device we use the second fringe.

TPF (40 m baseline)

For s= 29 meters, the separation is 0.036 arc seconds.

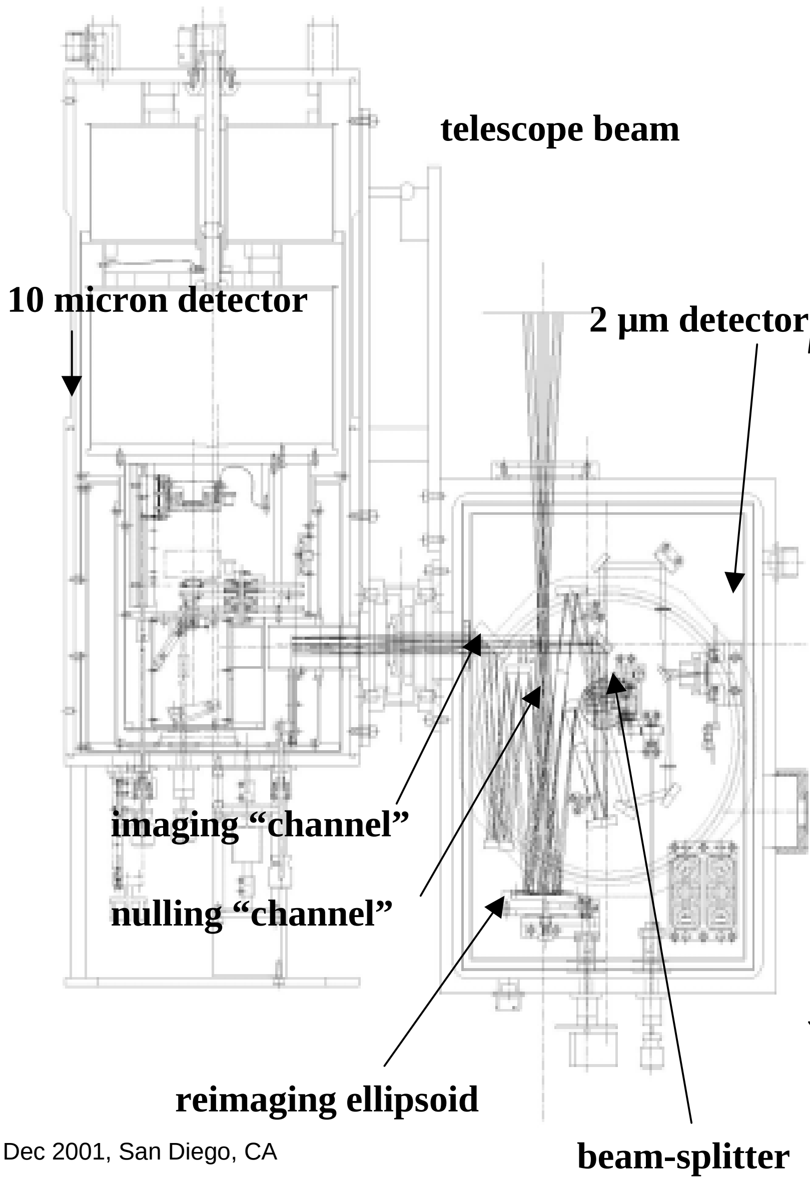
Bracewell Infrared Nulling Cryostat (BLINC) and Mid Infrared Array Camera (MIRAC)





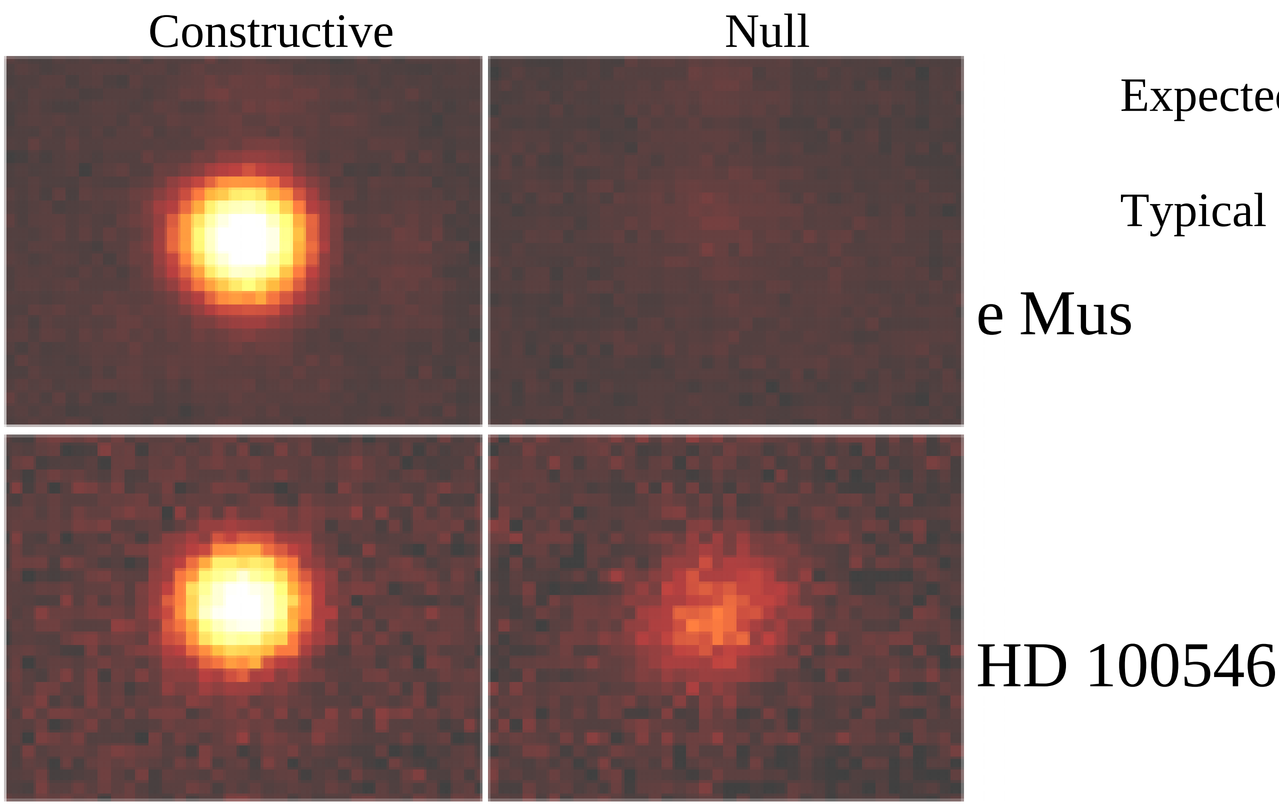
Optical layout of the BracewelL Infrared Nulling Cryostat (BLINC)

BLINC drawing & innards



TPF
Terrestrial Planet Finder

At Magellan 6.5m Observations: Nulling



Expected Null from model: 70%

Typical Null on a point source: 10%

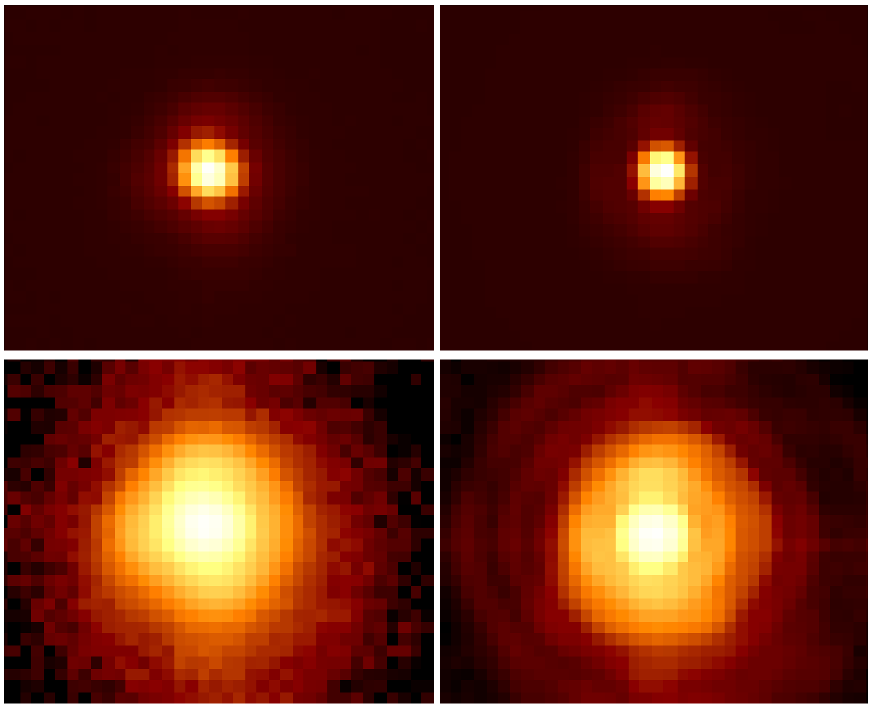
wavelength (μm)	PA	Null
10.3	103	48%
11.7	103	42%
10.3	13	40%
11.7	13	36%

TPF
Terrestrial Planet Finder

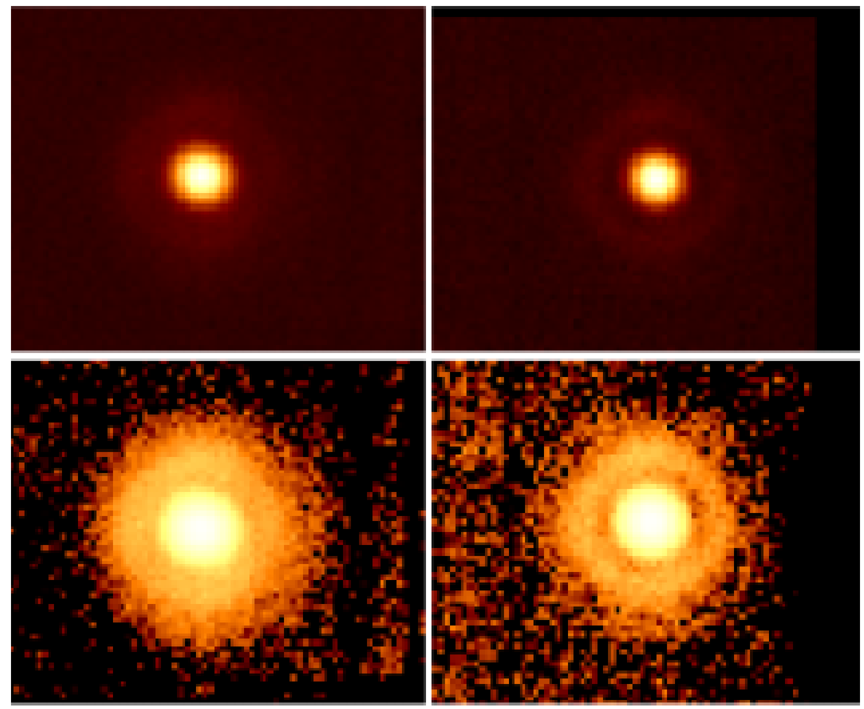
A MIT BUSEK LOCKHEED MARTIN

Observations:Imaging

11.7 µm



24.5 µm



linear

log

HD 100546 (1 arcsec) e Mus

HD 100546 (1 arcsec) e Mus

FWHM: 0.52” 0.42” 0.92” 0.86”

Disk is marginally resolved at both wavelengths

For Space: Intensity balance needed

- If two beams of slightly different intensity are combined, then the null depth will be limited.
- Combine beams of intensity 1 and 1+ x (arbitrary units)
- The amplitudes are the square root of the intensities 1 and 1+0.5x.
- The sum amplitude is 2+0.5x the difference amplitude is 0.5x
- The sum intensity is 4+2x and $0.25x^2$
- The ratio of sum to difference is 4/0.25x = $16/x^2$.
- Thus for a null of 10^{-4}, (sum/difference=10^4) x= 4%.
- For 10^{-5}, x=1.26%

Phase precision needed

Let two amplitude unity beams be out of phase by an angle

$$2\pi + \theta.$$

Then there will be an out of phase sum amplitude of 2 sin ($\theta/2$).

For small signals this is θ. Thus the ratio of the sum intensity to the out of phase intensity is 4: θ^2.

The phase angle θ corresponds to a physical displacement of

$\sigma = \theta\lambda/2\pi$. So if the ratio of in phase intensity to out of phase is

X, X= $4\lambda^2/(2\pi\sigma)^2 = \lambda^2/\pi^2\sigma^2$

So $\sigma = \lambda/\pi$ sqrt(X)

Examples 10^{-4} null at 7 microns σ= 22.3 nm

10^{-5} null σ= 7.1nm

Nulling factor required

- The purpose of nulling is to reduce the photon noise associated with the star. Therefore there is no photon noise benefit in reducing the null below a level where other sources of radiation become significant.
- For the Sun, a first maximum at the Earth would still transmit zodiacal glow 200x Earth at 10 microns, or 2 10-5 of the star.
- There is also the solar system zodiacal glow, whose relative contribution will vary with telescope size and star brightness.

  For 3.5m telescopes and a 16pc star the contributions are:

  7 µm $1.1\ 10^{-6}$, 10 µm $1.7\ 10^{-5,}$ 20 µm $5\ 10^{-4}$
- Overall there is a benefit from a null better than 10^{-4}, but no substantial gain from a null better than 10^{-5}.

Sample Nulling Requirements

Total area	8µm	9	10	14	20	24	28µm
2.27 sq.m	37,300	17,500	8,400	1225	272	124	82
3.14 sq.m	51,880	24,260	11,640	1698	377	172	113

- The upper line refers to **4x 0.85m** (SIRTF) mirrors.
- The lower line refers to **4x 1m** mirrors.
- The nulling factors are for the nulled starlight to be 1/2 the solar zodiacal glow for a solar star at 8 pc, 2x the glow for a solar star at 4pc.
- Similar numbers would correspond to **4x 2m** mirrors and a star at 16pc.
- The nulling demands get tighter if one tries to get the full advantage on a closer star. If the nulling does not get tighter, there is still a time benefit as $1/(\text{distance})^2$. Similarly one can make observations at short wavelengths - but without the maximum possible sensitivity.

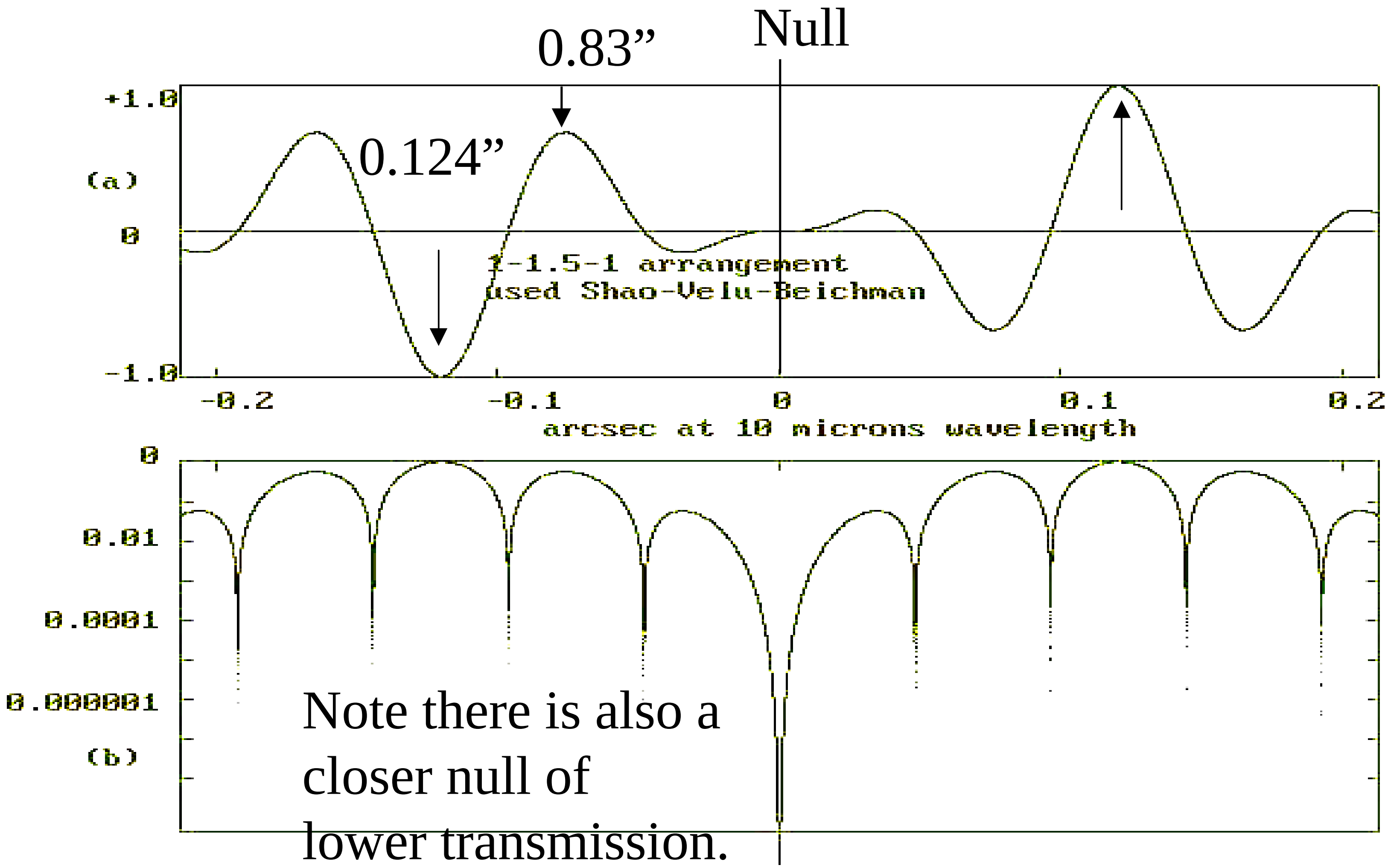
Post-observation correction of the null

- It is necessary to observe a planet fainter than 1/200 of the nulled star. Therefore there is a need either to hold the null very precisely, or to know how it has changed, and to correct for it. This alternative is preferred.
- A change in phase corresponds to the null line moving over the star. For example, If there is a 10m spacing interferometer and the null changes by 10nm, the null moves across the star by 0.2milliarc seconds. Typically a star observed by such an interferometer will have an angular diameter of 2 milliarc seconds, and unless the null is very flat, the leak will change.
- However, since phase will be constantly measured, it will be possible to bootstrap a correction for each wavelength for how the null changes with phase. That is, we can make corrections from the servo system error signal.
- And because phase is measured more frequently than signal, there will be two corrections determined, one for the high frequency phase amplitude, and another for the low frequency phase error.

Precision of Null information

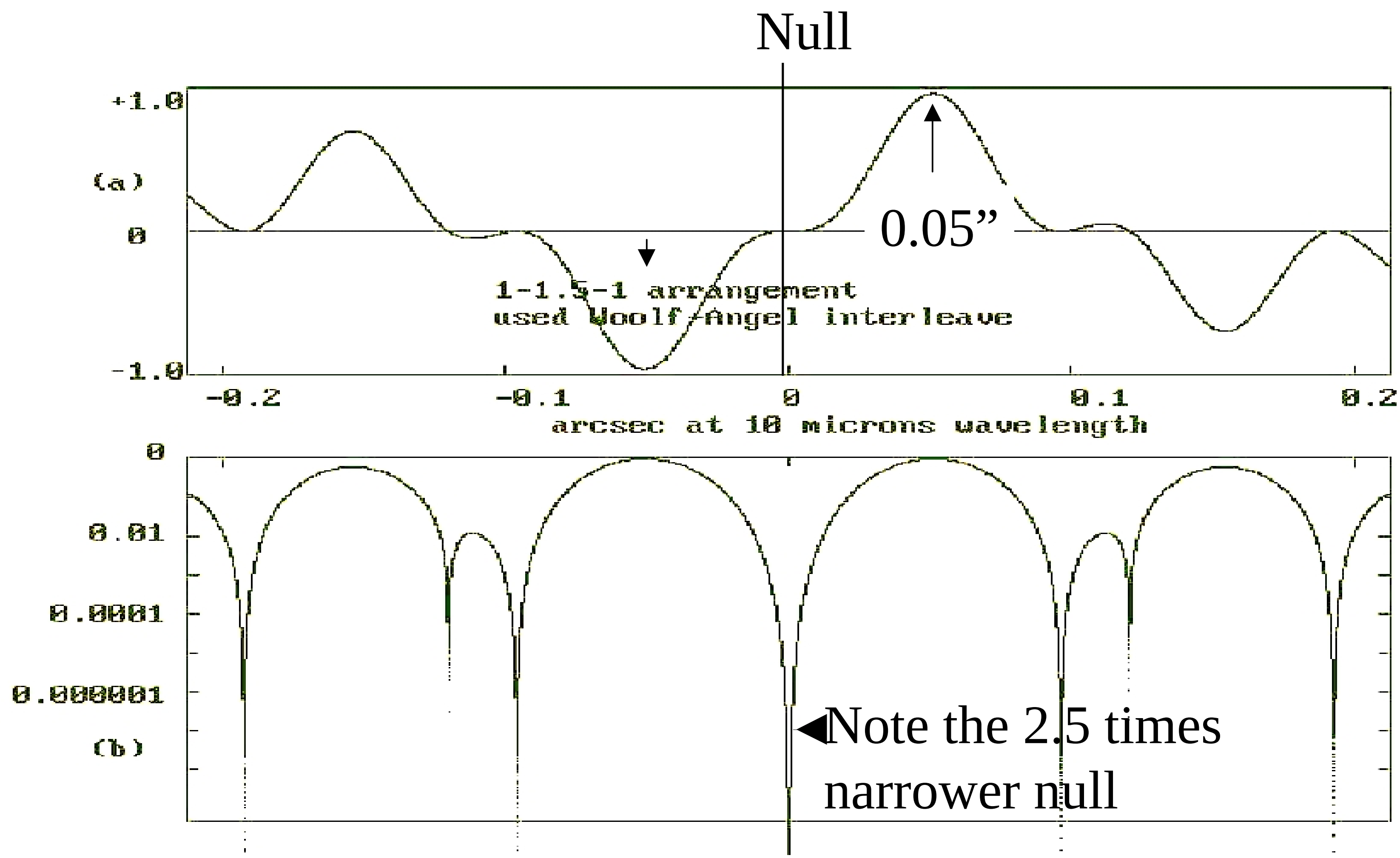
- A 6th magnitude star near 2microns in a 25% bandwidth gives $4x10^7$ photons /sec/square meter.
- From 5 square meters in 1/200 sec there will be 10^6 photons.
- Assume 10% optical efficiency, produces 10^5 events +/- 300
- So for Signal/noise 300, the phase is measured to~1/300 radian or 1nm. And for 1 second averages, the relative phase is measured to ~ 100 times better.
- For an error of 1/2 star diameter, the null changes by a factor 4. But 1nm corresponds to 1/50 star diameter, for which the intensity transmitted changes by ~5% of a terrestrial planet. (Depends on exact details)

Example using the 8m baselines of a 28m long nuller



Note there is also a closer null of lower transmission.

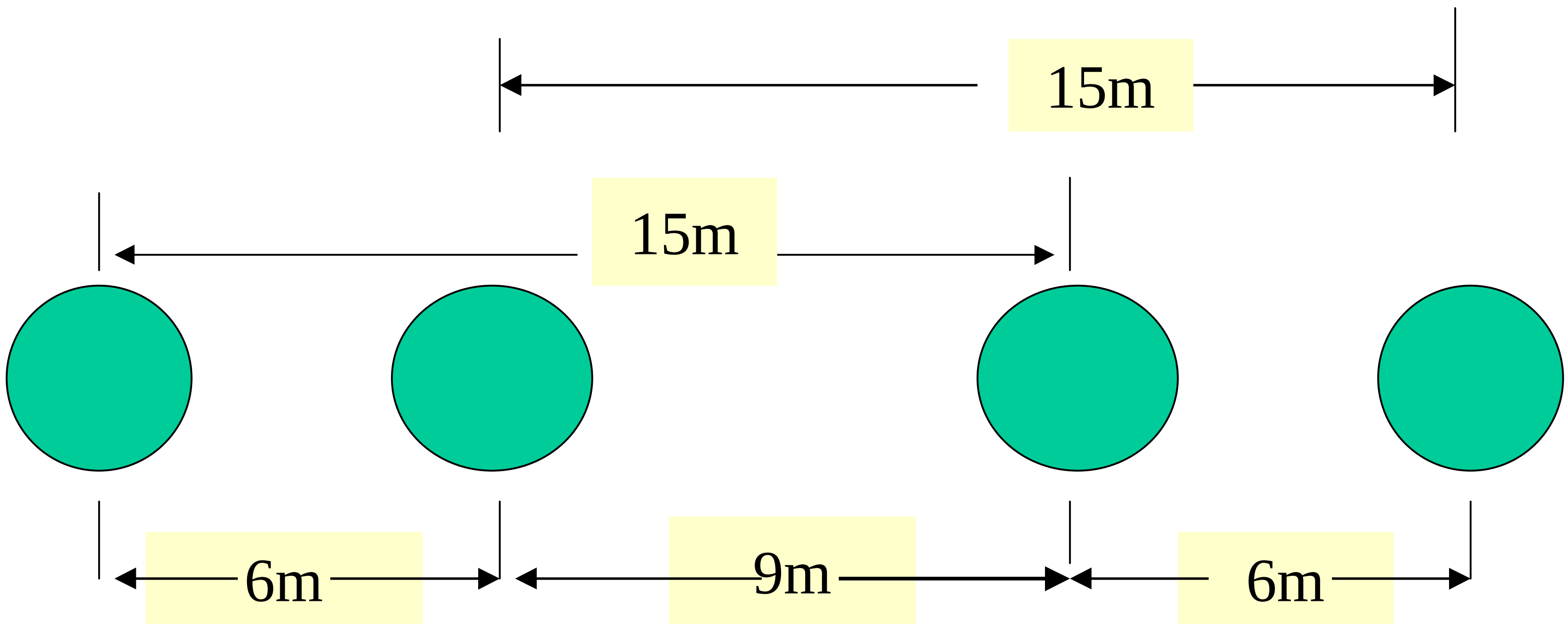
Using the 20m baselines of a 28m long nuller



Conclusions

- The 40m double Bracewell appears to be a potentially attractive alternative to the broader deeper null devices, because it is so much shorter.
- The 21m double Bracewell appear capable of a moderately reduced scope mission at a substantially lower cost.
- There is a need for free-flyers for the highest angular resolution.

Double Bracewell system
2 configurations



Living with 2 beam interference or having more complex interferometers?

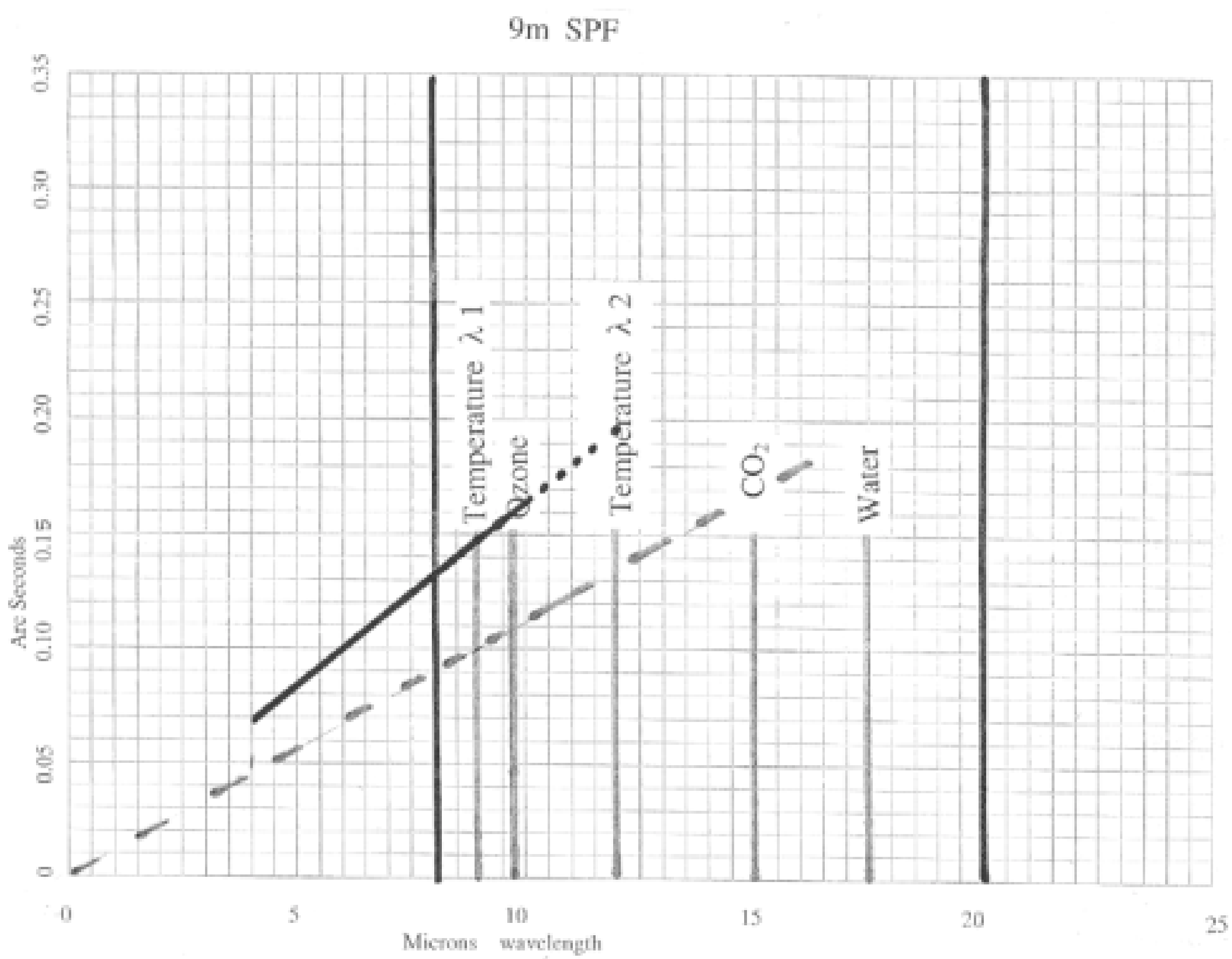
- Star leak = 0.154 $(\theta s/\theta p)^2$

Consider a 6m/15m nuller at 10 microns

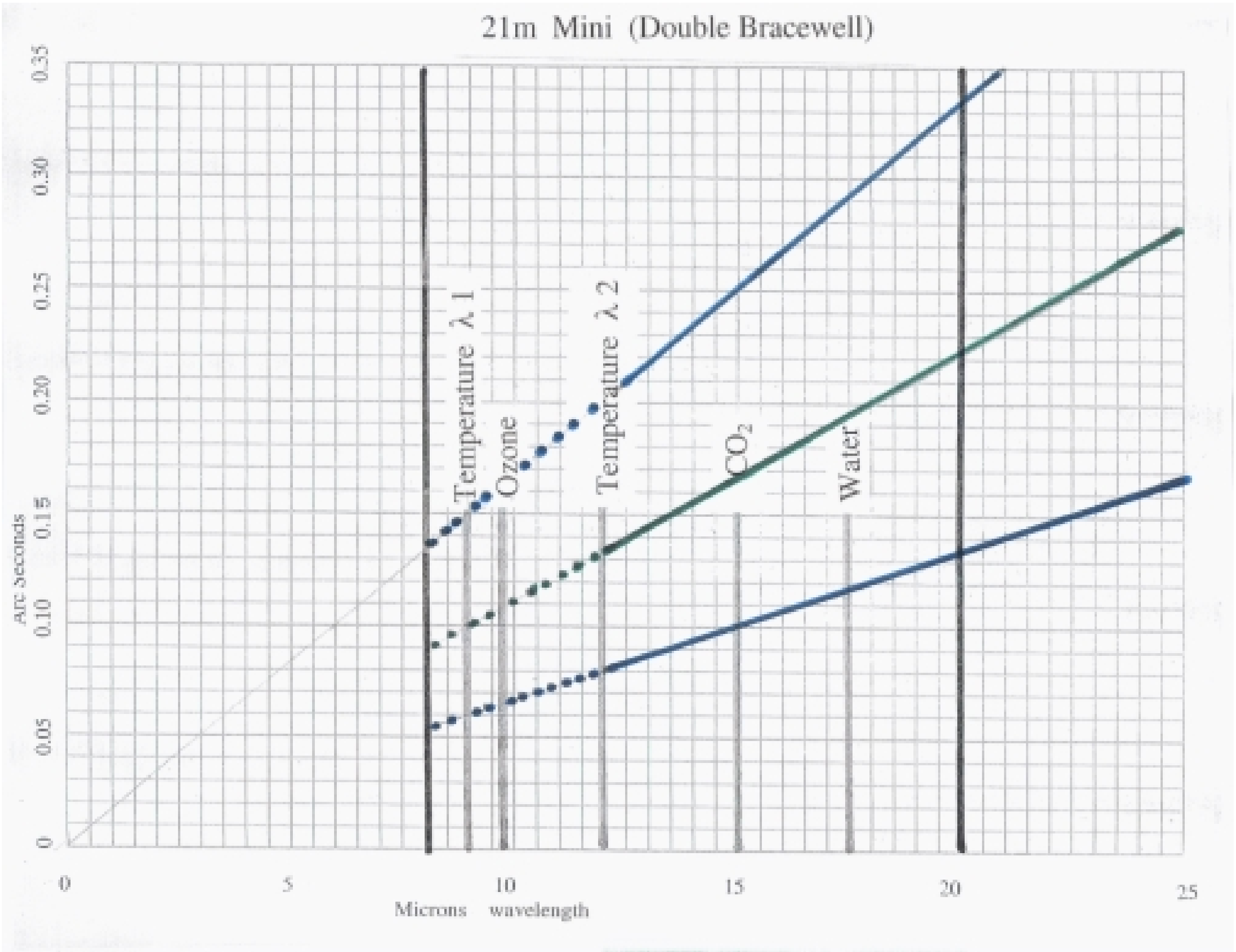
- stars at 4pc 6pc 8pc 10 pc
- 10pc = 1mas diameter
- 6pc = 1.67mas
- 4pc = 2.5mas

	4pc	6pc	10pc
• Leak at 6m	$3.4\ 10^{-5}$	$1.5\ 10^{-5}$	
• Leak at 15m		$9.6\ 10^{-5}$	$3.4\ 10^{-5}$
• Nulls	0.165"	0.011"	0.067"
	0.11"	0.067"	

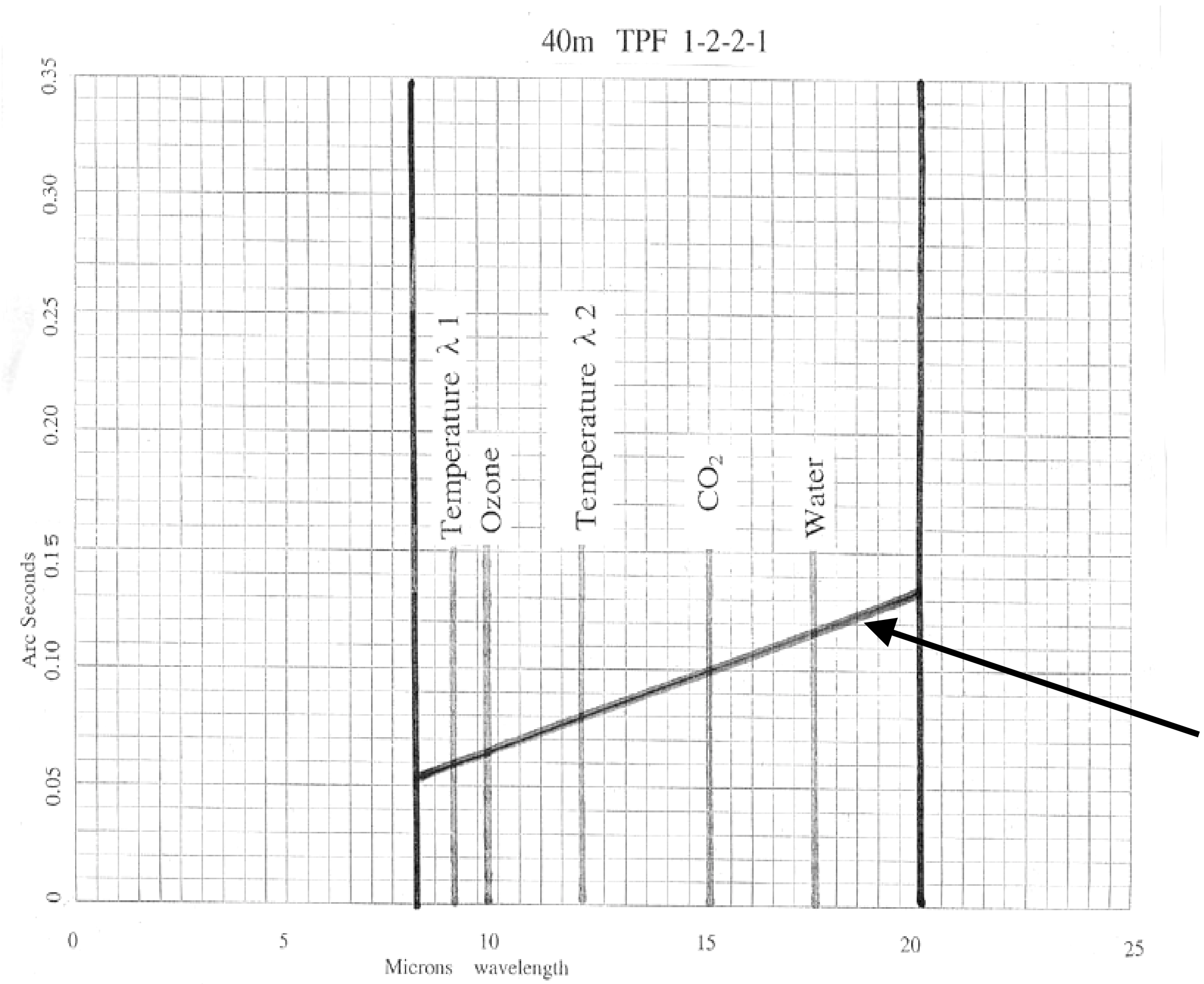
SPF 9m 2 element resolution



4x 1.7m. 21m Double Bracewell

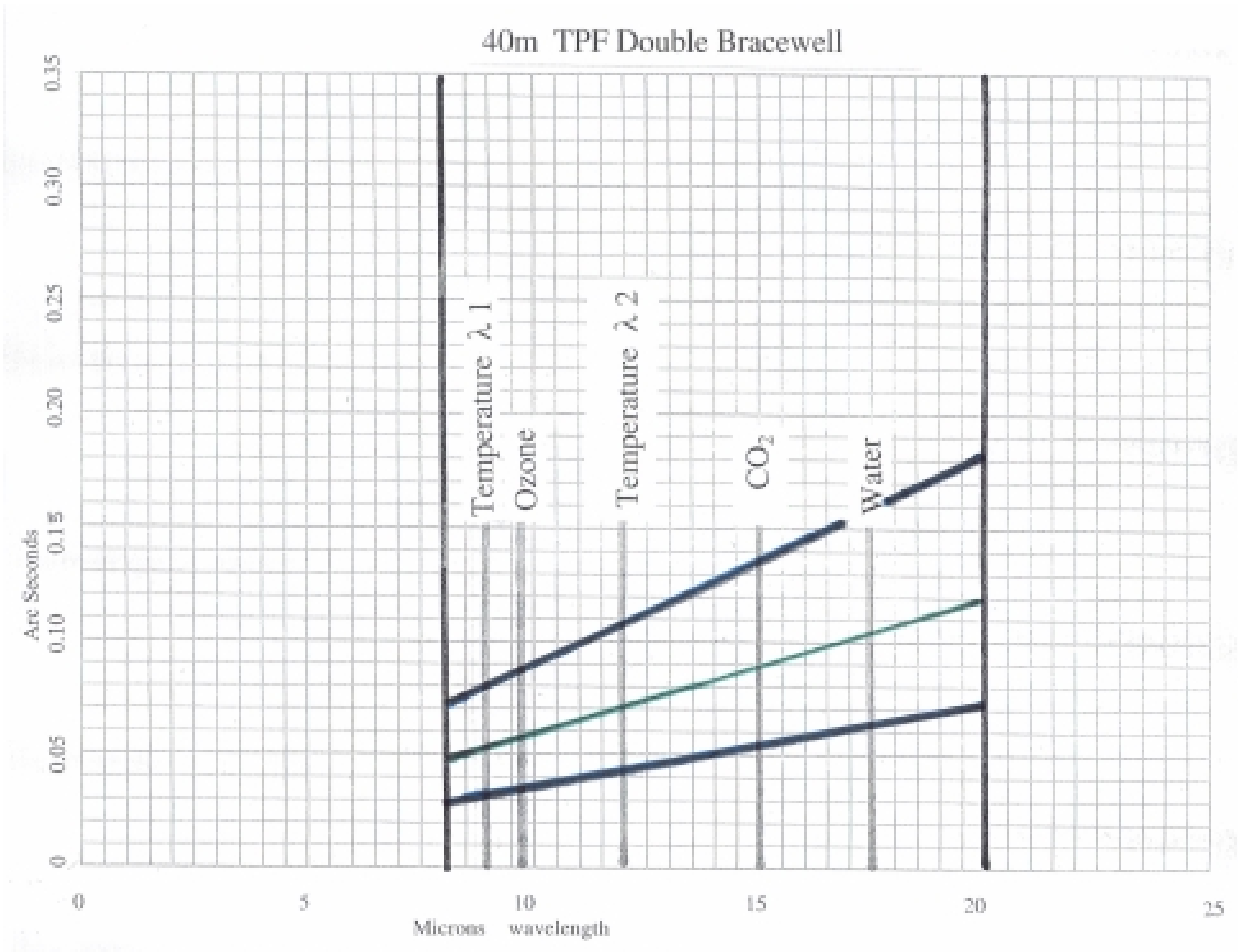


4x1.7m 40m 1-2-2-1 Resolution

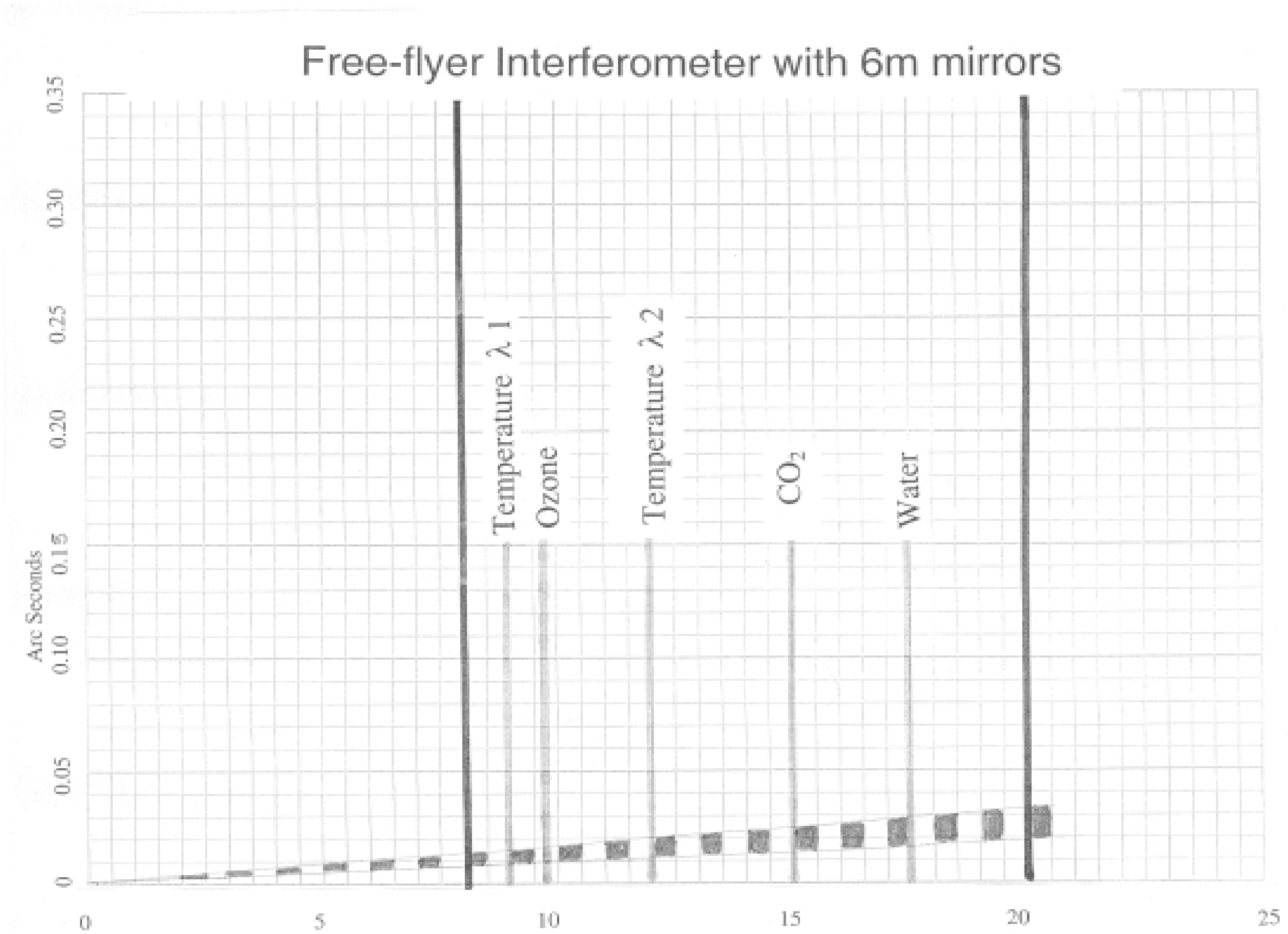


Note that resolution is the same as for the 21 meter truss!

4X3.5m 40m Double Bracewell



Free-Flyer with 6m mirrors



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Optics

John Miles
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Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

TPF Configurations

Baseline	Telescopes			Science Goals
	Number	Aperture	Temp	
9 m	2	60 cm	60 K	Young Jupiters
21 m	4	1.7 m	40 K-45 K	Earth to 12 pc, O_3, H_2O, CO_2 to 8 pc
40 m	4	3.5 m	40 K-45 K	Earth to 22 pc, O_3, H_2O, CO_2 to 15 pc
Free flyer	4	3.5/6 m	40 K-45 K	Planetary mission goals plus astrophysics

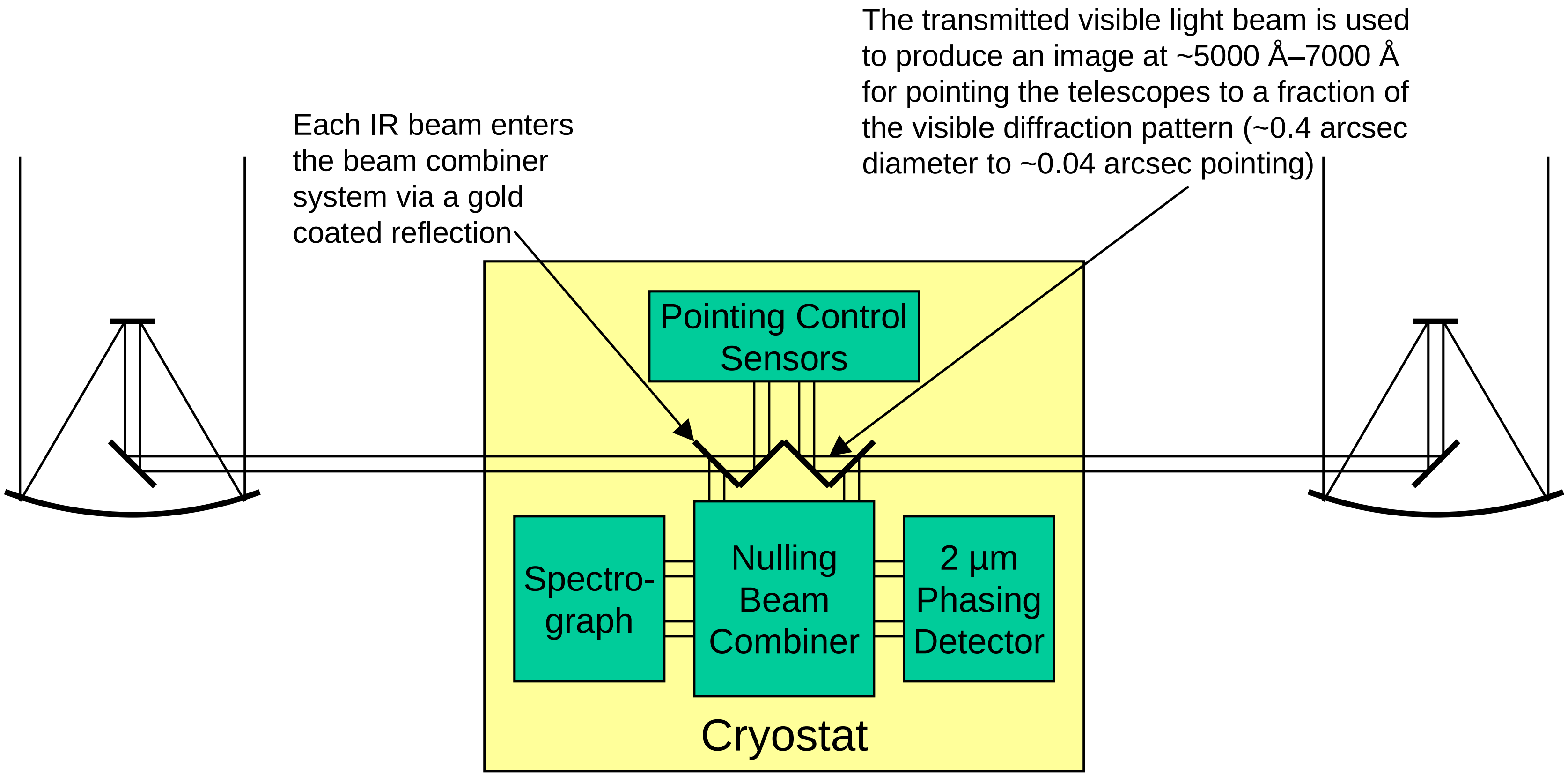
System Requirements

Baseline	9 m	21 m	40 m	Free flyer
Wavelength Band	4–12 µm (TBR)	7–17 µm	7–17 µm	3–23 µm (TBR)
Null depth	1.0E-04	3.7E-05	3.7E-05	3.7E-05
Telescope Diameter	0.6 m	1.7 m	3.5 m	6 m
f-ratio	*f*/ 1	*f*/ 1	*f*/ 1	*f*/ 1
Telescope Temperature	60 K	40–45 K	40–45 K	40–45 K
Optical Path Errors	7.2 nm	10.6 nm	10.6 nm	10.6 nm
Transmission Asymmetries	0.7 %	0.4 %	0.4 %	0.4 %
Pointing Jitter	82 milli-arcsec	54 milli-arcsec	26 milli-arcsec	15 milli-arcsec
Diff'l Pol'n Rotation	0.4 °	0.2 °	0.2 °	0.2 °
Diff'l Pol'n Delay	0.8 °	0.5 °	0.5 °	0.5 °

Optics Design Elements

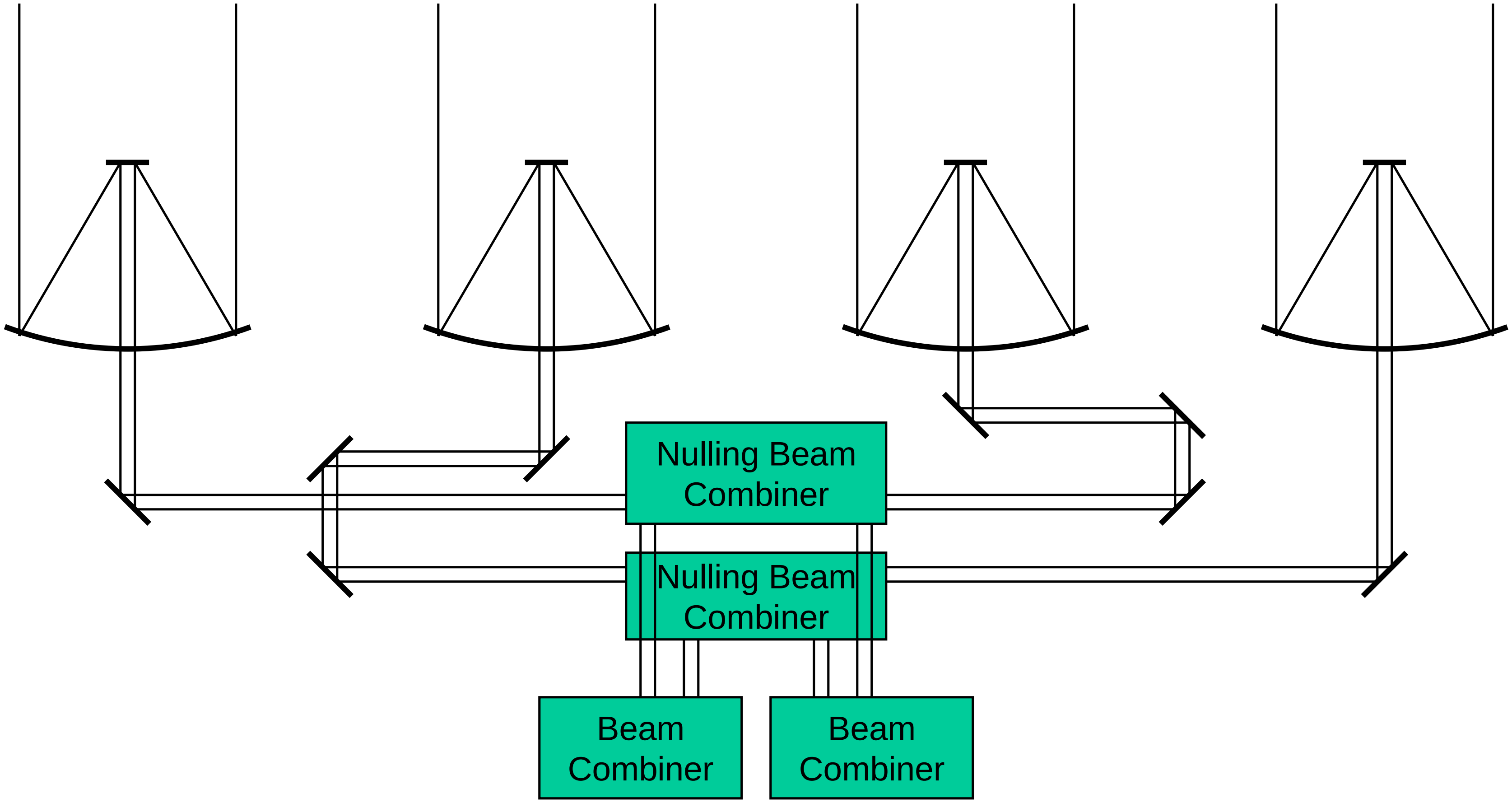
- Telescopes
  - Cassegrain f/1 with tertiary on 2-axis flex pivots
  - Diffraction limited at ~2 µm for phasing
  - Baffled tubes link to beam combiner
- Nulling beam combiner
  - Amplitude balanced, imaging interferometer, modified Mach-Zender design
  - Dielectric phase plates
  - Triple beam combiners for 4-mirror systems
  - Dichroic at beam combiner entrance sends visible light to pointing control sensor to control tertiary mirrors
- Spectrograph
  - Prism spectrograph, R ~ 20
  - Temperature of spectrograph can be up to 17 K
- Detectors
  - Cooling to 12 K for 9 m system
  - Cooling to 8 K for other systems
- Cryostat
  - Solid hydrogen, WIRE/NGSS-like
  - Beam combiner, spectrograph, visible-light pointing sensor all in cryostat

Optics Schematic, 2 Telescopes



Optics Schematic, 4 Telescopes

- Basic optics configuration uses four telescopes and two stages of beam combination

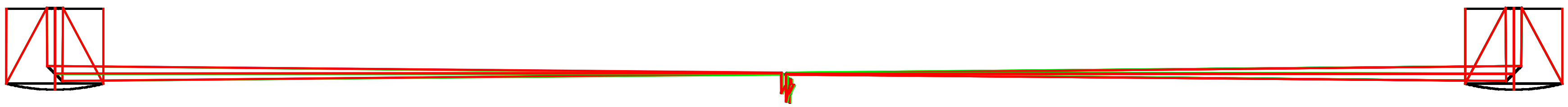


Primary Optics

- **Mirrors 1.7 m and smaller**
  - **Cryo-null figured beryllium (IRAS, SIRTF)**
  - **Glass**
- **3.5 m mirror**
  - **NGST technology**
    - **AMSD**
    - **NMSD**

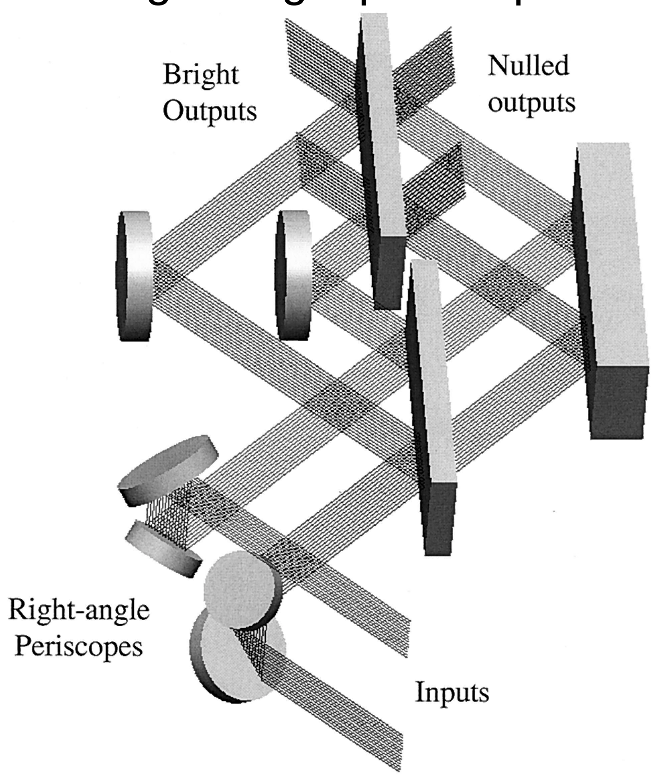
Two-Telescope Optical Design

- 60 cm telescopes
- *f*/1 primary
- 10 cm secondary
- Cassegrain design, 0.5 m telescope length
- 9 m baseline
- *f*/52.5 beams



Two-Telescope Nulling Beam Combiner Design

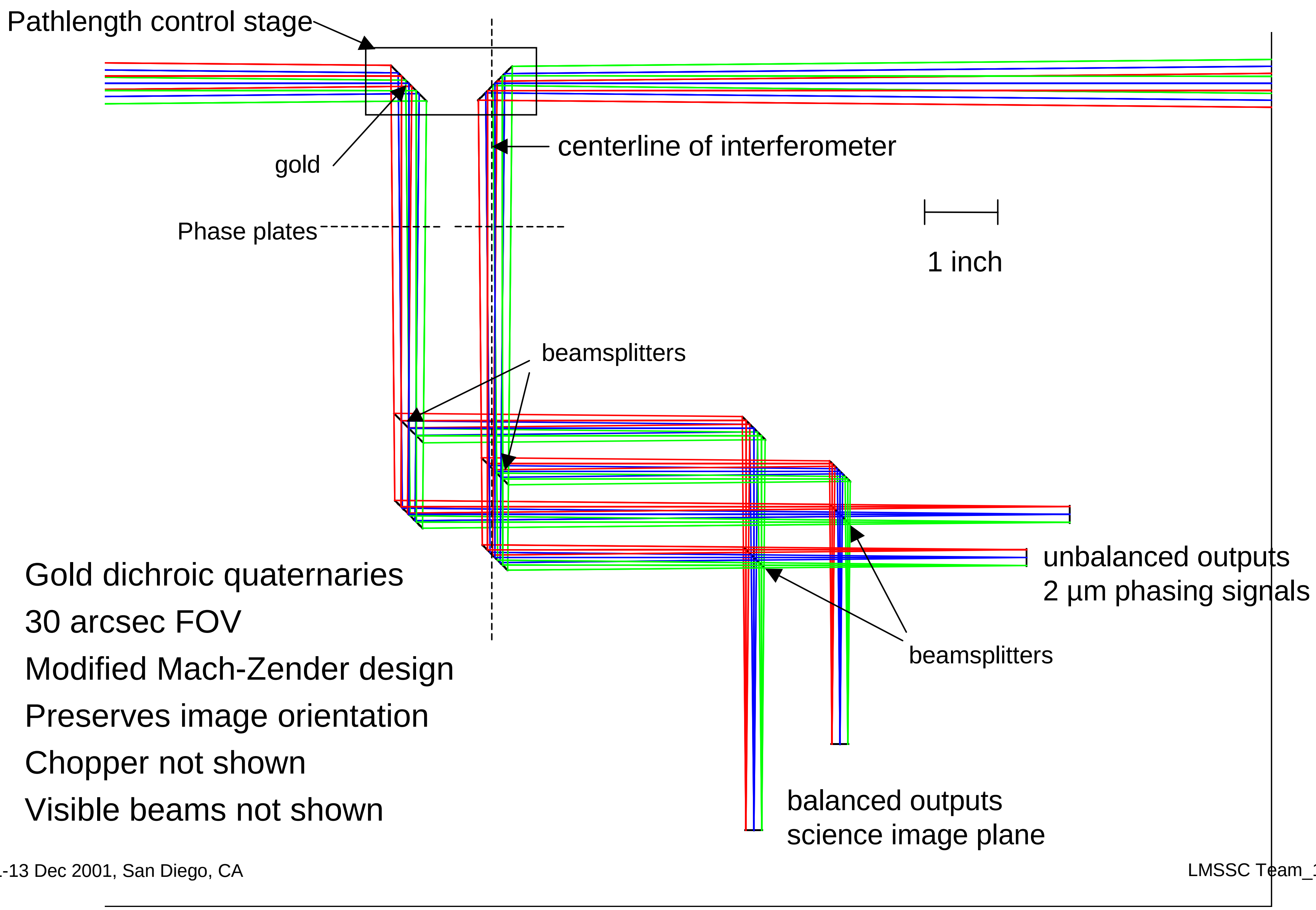
- The concept published by Serabyn & Colavita (Applied Optics, Vol. 40, 1 April 2001, pp. 1668-1671) provides a fully symmetric interferometer by introducing the field flip using a pair of periscope mirrors prior to beam combination.
  - We modify this design, using phase plates to introduce the π phase shift rather than the right-angle periscopes.



Phase Measurement

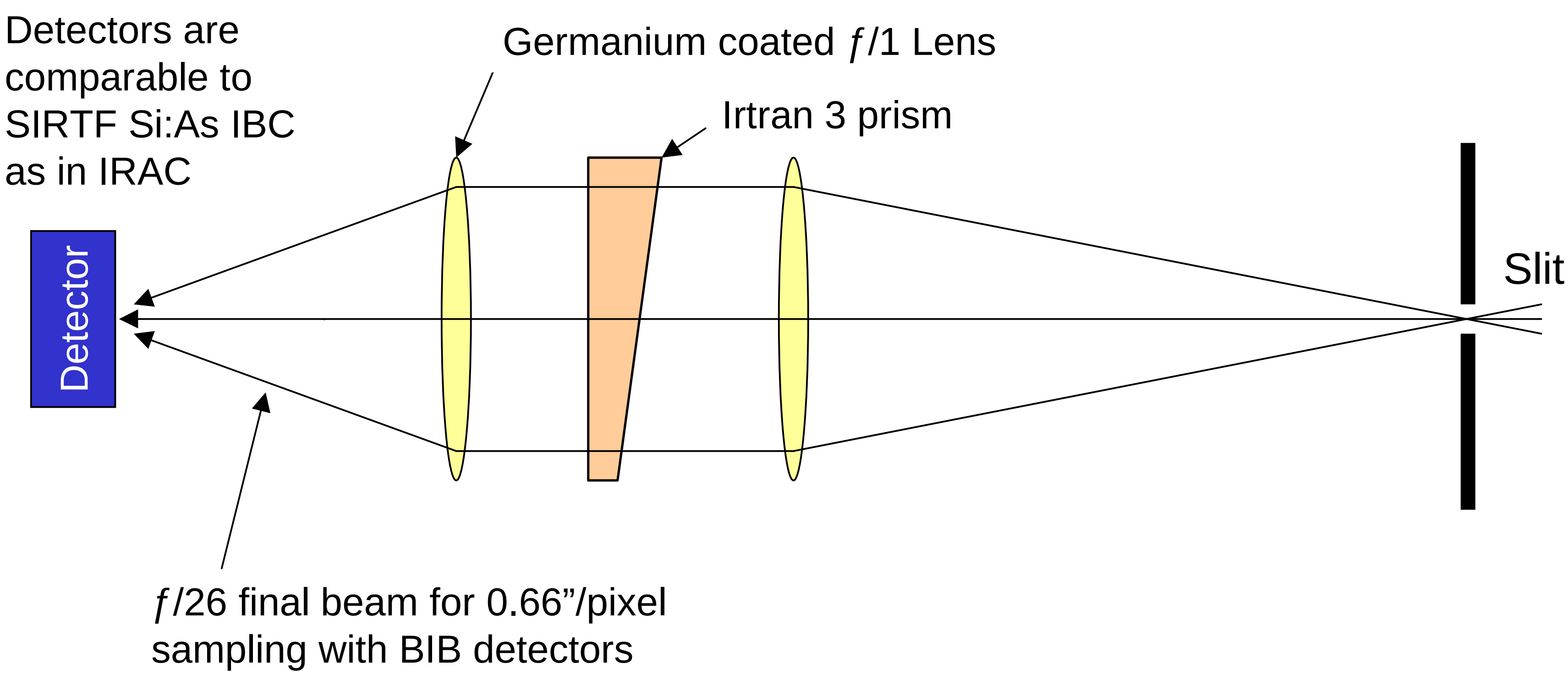
- **The use of phase plates breaks the symmetry of the Serabyn-Colavita nulling beam combiner, but it allows us to use the unbalanced outputs to provide phase control information at a shorter wavelength (~2 µm), where the phase plate produces ~3π/4 phase shift.**
  - **Phase is measured on the identical optical path as the science**
  - **Similar system 1st proposed by Shao & Serabyn**
  - **200 Hz readout**
  - **20 Hz authoritative control bandwidth**

MMZ Nulling Beam Combiner

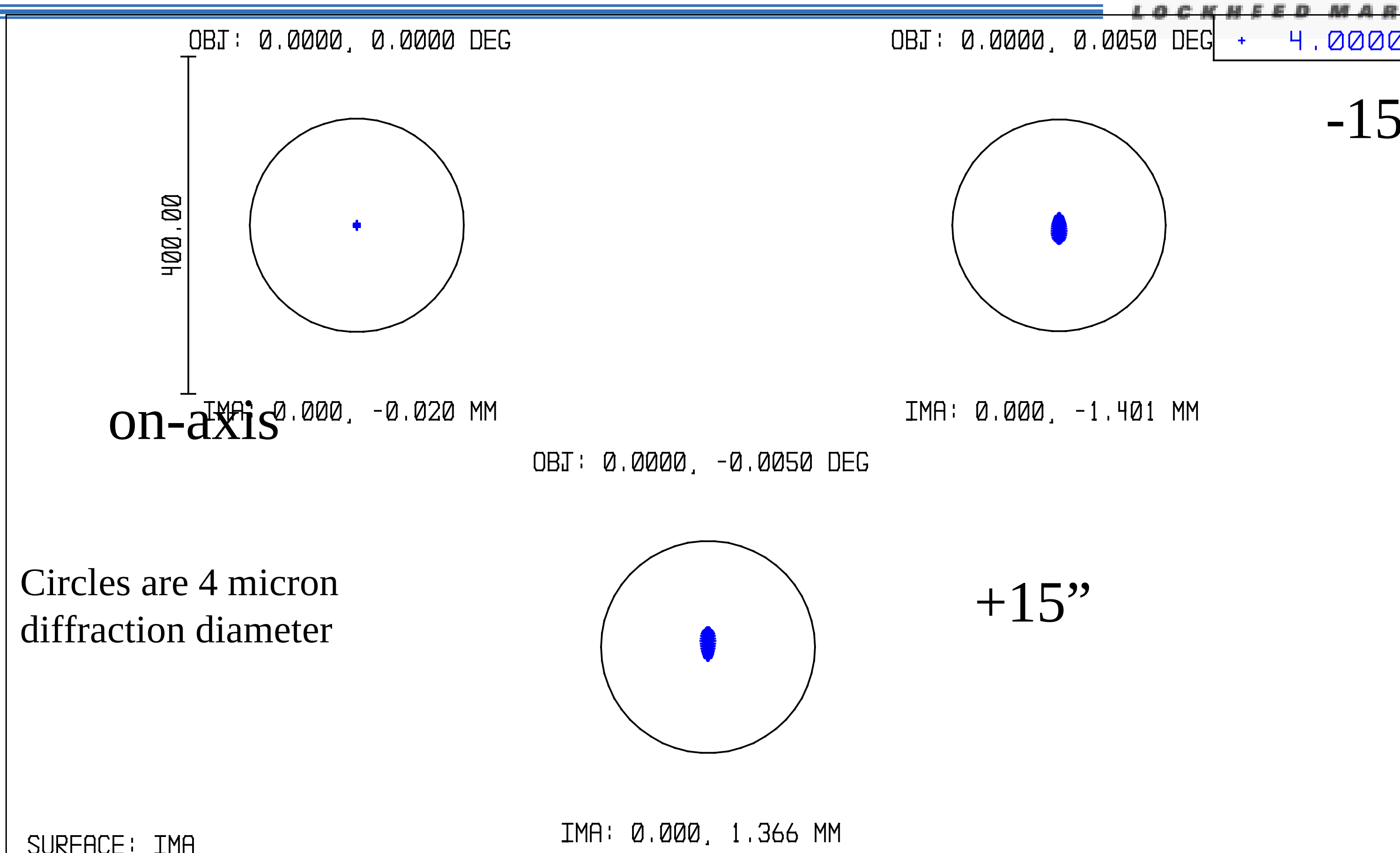


- Gold dichroic quaternaries
- 30 arcsec FOV
- Modified Mach-Zender design
- Preserves image orientation
- Chopper not shown
- Visible beams not shown

Spectrograph Cartoon



Spot Sizes at 4 μm



SPOT DIAGRAM

SPF RUN 3
THU OCT 18 2001 UNITS ARE MICRONS.

FIELD :	1	2	3
RMS RADIUS :	1.100	8.754	9.592
GEO RADIUS :	2.130	18.820	20.448

AIRY DIAM : 253.4 REFERENCE : CHIEF RAY

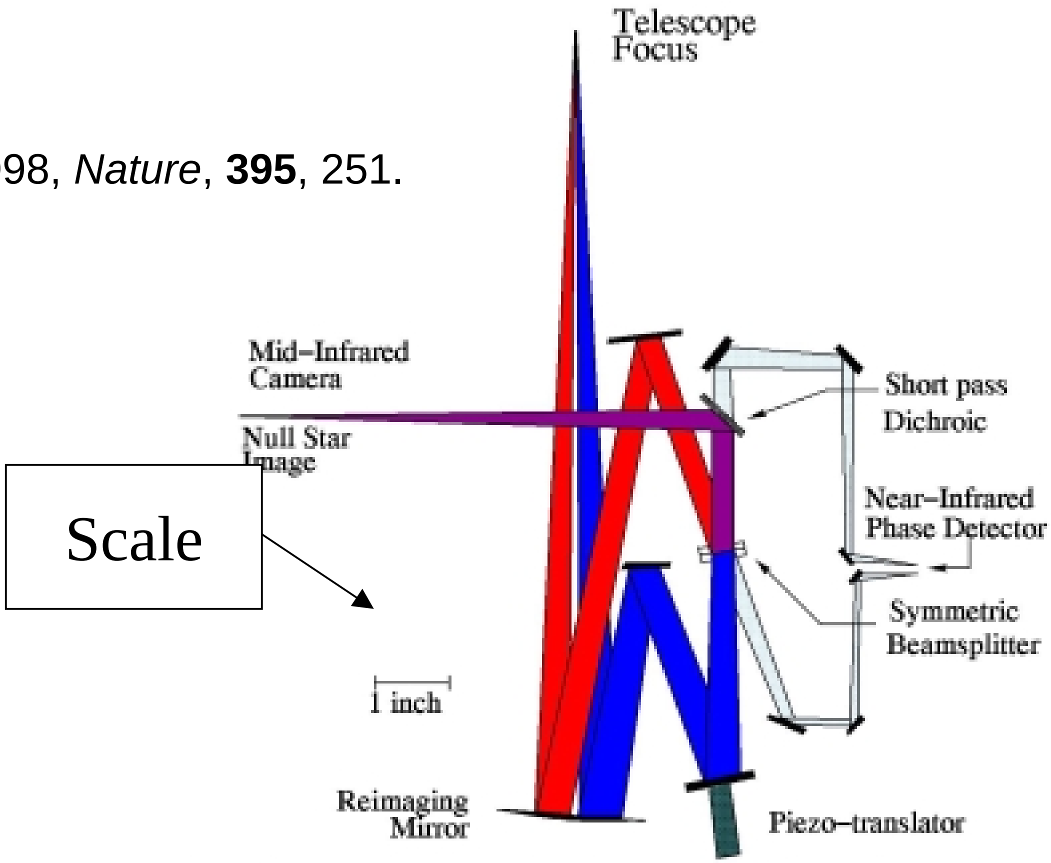
C:\DOCUMENTS AND SETTINGS\PHIL\DESKTOP\SPF\SPFCAMERA.ZMX
CONFIGURATION 1 OF 4

TPF
Terrestrial
Planet Finder

Phil Hinz' BLINC Instrument is Basis of Nulling Beam Combiner

6.5 m MMT used as a nulling interferometer

Reference:
Hinz, P. *et al*. 1998, *Nature*, **395**, 251.



Optical layout of the Bracewell Infrared Nulling Cryostat (BLINC)

Pointing Measurement

- **The entrance mirrors to the nulling beam combiner are gold film, so that IR light is reflected and visible light is transmitted.**
- **The visible light from each telescope is directed onto a quad cell, which tracks pointing displacements and corrects for them by controlling the tertiary steering mirror on the telescope.**
  - **200 Hz readout**
  - **20 Hz authoritative control bandwidth**

Moving Parts

- **Focus mechanisms**
  - **1 for each telescope**
  - **"Set and forget"**
- **Coarse "Trombone" path length adjustment**
  - **outside of cryostat**
  - **set and forget**
- **Fine path length adjustment**
  - **gold entrance mirrors mounted on a moving stage adjusted by PZT and controlled by 2 µm phase detector**
- **Chopper**
  - **Shifts location of spectrum on array to allow accurate subtraction of background drifts**

Integration and Test

- The nulling beam combiner, visible light pointing sensor, phase detector, and spectrograph are all mounted on a single optical bench inside the cryostat.
  - "Bolt and Go" design
  - Optics are mounted and aligned on the warm optical bench
  - Assembled optical bench is tested at flight temperature
    - Alignment is verified
    - Check out on LBT
  - Verified optical bench is integrated into the cryostat
    - Alignment is re-verified with cryostat in flight configuration
    - Integrated cryostat is never warmed up again
      - The only environmental change the optics see is the launch environment
  - This method is being used on SIRTF

Infrared Nulling Testbeds

- Keck Nulling Interferometer Testbed
  - Exo-zodiacal emission
- BLINC
  - Demonstration of nulling interferometry in the infrared
  - Ground-based observing
    - Adaptable for operation on MMT, Magellan, LBT, etc.
    - Exo-zodiacal emission
- 2 Beam Brassboard Testbed
  - Two beam modified Mach-Zender
    - Brassboard optics & cryostat design
  - Cryogenic laboratory system
    - Laser and broadband sources
    - Component and System testing w/ flight-like temperatures
  - Flight traceable system
    - Closed loop phase and pointing Cntl
    - Flight-like disturbances
  - Ground-based observing
    - Adaptable for operation on MMT, Palomar, Magellan, LBT, etc.
- TPF Brassboard Testbed
  - Four beam optics design
    - Brassboard optics & cryostat design
  - Cryogenic laboratory system
    - Laser and broadband sources
    - Component and System testing w/ flight-like temperatures
  - Flight traceable system
    - Closed loop phase and pointing control
    - Flight-like disturbances
  - Ground-based observing
    - Adaptable for operation on MMT, Palomar, Magellan, LMT, etc.

IR Nulling Technology Development and Validation

1999	2000	2001	2002	2003	2004	2005	2006	2007

Keck
- Demonstration of infrared nulling interferometry
- Ground-based observing

BLINC
- Demonstration of infrared nulling interferometry
- Ground-based observing

2 Beam Brassboard Testbed
- Two beam modified Mach-Zender
- Flight traceable system
- Ground-based observing

TPF Brassboard Testbed
- Four beam modified Mach-Zender
- Flight traceable system
- Ground-based observing

Detectors and Test Sources

Modeling
- Components
- System performance

Beamsplitter and phase plate validation
- Theory
- Design and Development
- Test

Beam attenuation technology
- Cryogenic actuation
- May not be needed??

Cryogenic control technology
- Cryogenic actuation

Optical support truss validation
- Pathlength demonstration
- Hinges and latches

Cryogenic materials technology
- Dielectric substrates
- Structures
- Actuators
- Dichroics
- Fibers

Spatial filter technology
- Multiwavelength fiber optic
- Spectrum slicer
- May not be needed??

Question to assess suitability of an architecture in meeting TPF science goals

- **Do the signal to noise calculations include reasonable assumptions about the targets (stars and planets), important instrumental efficiency terms, and important noise sources with reasonable values (including astrophysical sources)?**
- **Assumptions from TPF monograph**:

Table A3. Interferometer Observing System	
Baseline	75 m
Telescope Apertures	1.8:3.5:3.5:1.8 m (1 AU) 1.1:2.2:2.2:1.1 (5 AU)
Telescope Temperature	40 K (1 AU) 35 K (5 AU)
Telescope Emissivity	0.1
Spectral Resolution	20
Net Efficiency (Optics*Detector*Beam)	0.04
Deepest Null	10^{-5} (1 AU) 10^{-6} (5 AU)
Phase Center Pointing Jitter	0.25 milli-arcsec
Detector Dark Current	5 e- /s
Detector Read Noise	1 e-
Flat Field Error	10^{-5} (1 AU) 10^{-4} (5 AU)

Table A4. Signal and Noise Sources at 1 and 5 AU		
Signal (Photo-Electrons) R =20, $\tau=10^5$ s at 12 μm	2 m (5 AU)	3.5 m (1 AU)
Planet @ 10 pc	8.00E+03	2.50E+04
Exo-Zodiacal Background	7.10E+05	2.15E+06
Local Zodiacal Background	1.00E+05	8.56E+06
Nulled Star Leakage	4.00E+04	1.16E+06
Dark Current	5.00E+05	5.00E+05
Total Counts	1.35E+06	1.24E+07
Sqrt(Counts)	1.16E+03	3.52E+03
Flat*Counts	1.40E+02	1.20E+02
Noise	1.17E+03	3.52E+03
SNR (Signal/Noise)	7.0	7.1

Possible Program Flights

- **Self-luminous Planet Finder - 9 m**
  - **Young planetary systems with Jupiters at > 0.08 arcsec.**
  - **E.g., 8 AU from star @ 100 pc.**
- **Close Terrestrial Planet Finder - 21 m**
  - **Earths as close as 0.08 arcsec for T and O_3.**
  - **As close as 0.11 arcsec for CO_2 and H_2O.**
  - **Core program to 8 pc. Extended program to 11 pc.**
- **Intermediate Terrestrial Planet Finder - 40 m**
  - **Earths as close as 0.045 arcsec for T and O_3.**
  - **As close as 0.062 arcsec for CO_2 and H_2O.**
  - **Core program to 16 pc. Extended program to 22 pc.**

- ***Extended program only measures temperature and size.***

TPF Candidate Orbits

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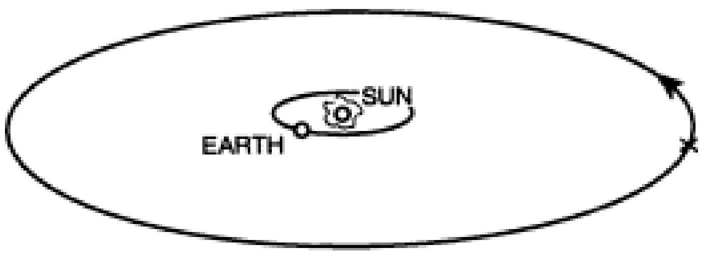
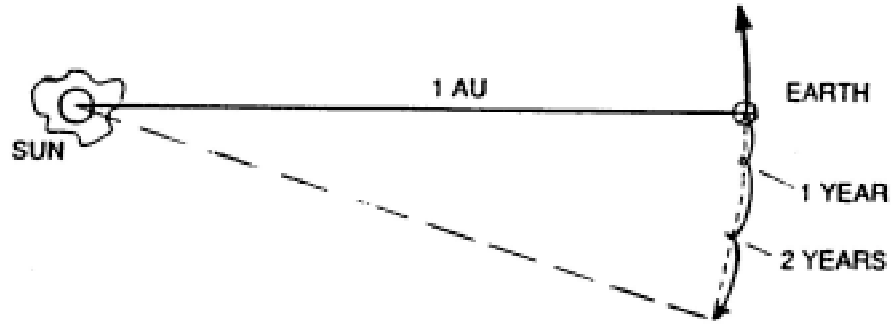
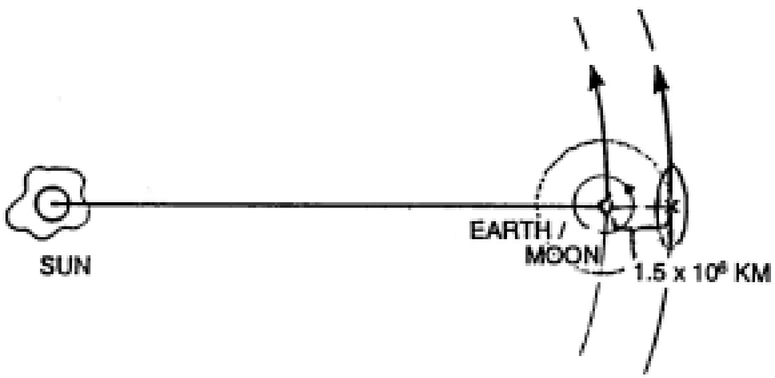
Candidate TPF Orbits



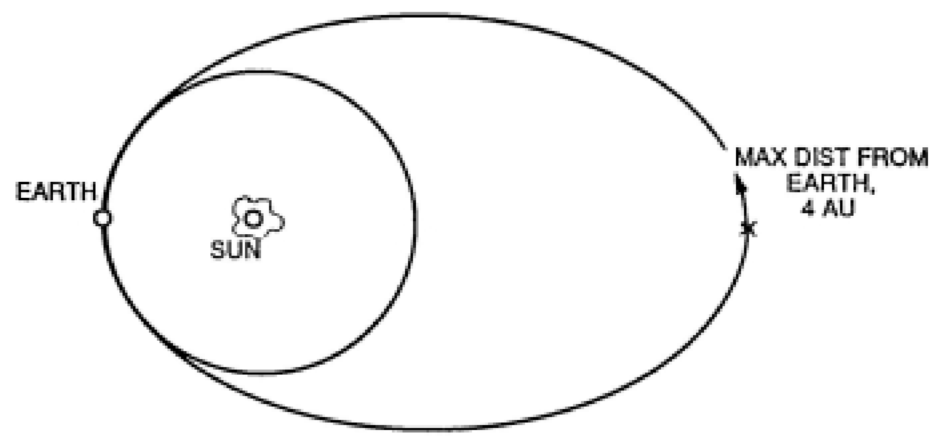
5-AU SOLAR ORBIT
(11.2 - YEAR PERIOD)



1-AU EARTH-TRAILING ORBIT
(~0.55 AU FROM EARTH AT 5 YEARS)



L2 LAGRANGIAN POINT HALO ORBIT
(~1 AU FROM SUN)



1 AU X 3 AU SOLAR ORBIT
(2.83- YEAR PERIOD)

High-Level TPF Orbit Comparison

	L2 HALO	EARTH TRAILING	1 x 3 AU	5 AU
Launchable Mass	moderate	moderate	less	least
Postlaunch Propulsion Req'd?	station-keeping	no	no	aphelion burn
Time To Optimal Operation	106 days	end checkout	1.41 yrs	2.60 yrs
Size Of Collector Primary	large	large	smaller	smallest
Is Constellation Expandable?	yes	no	no	no
Sky Accessibility	uniform	uniform	nonuniform	uniform
Ease of Passive Cooling	harder	harder	easier at aphelion	easiest
Solar Power Availability	lots	lots	mostly less	much less
Zodiacal Dust Environment	dusty	dusty	good at aphelion	outside of dust cloud
Communications	easy	harder	harder at aphelion	hardest

Conclusions from Earlier Orbit Work

- **Because of the heftier launch requirements of the Beyond-1-AU orbits, the L2 halo orbit and the SIRTF-like drift-away orbit remain the most attractive candidates for near-term TPF missions**

Additional Candidate Orbit

- **Some interest has been shown on our team in operating at or near the L2 point itself**
  - using the Earth as a “big blocker” (sun up to 85% occulted at L2 distance, or 100% occulted 100,000 km closer to Earth)

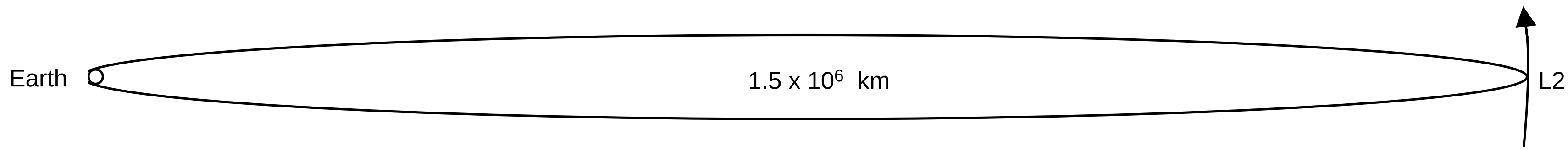
Advantages:

- Colder thermal environment (estimated temperature of optics 15° K, if in FULL shadow)
- Sunshield reduced in size, or eliminated
- Reduced stray light

Disadvantages:

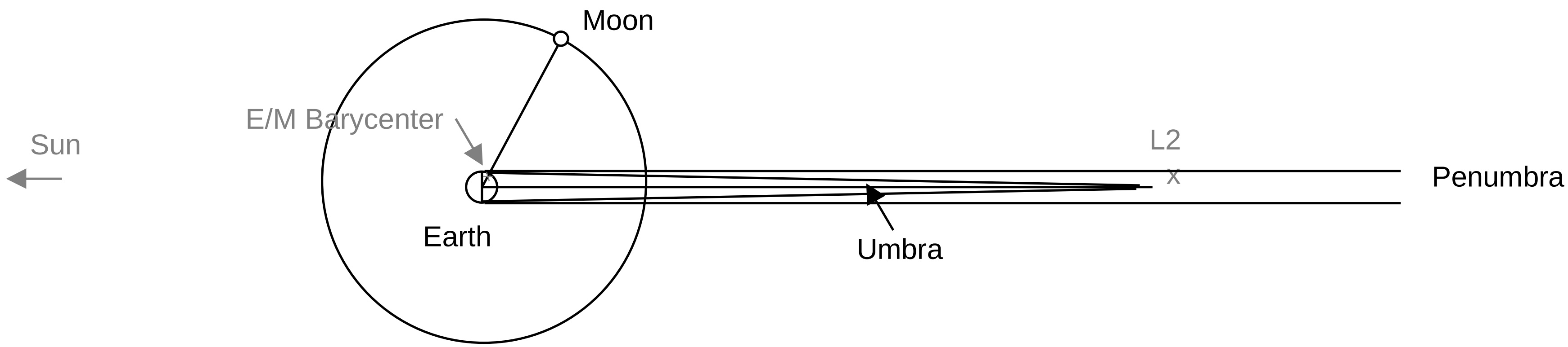
- Power generation
- Additional ΔV required to insert at L2 point
- More frequent stationkeeping required
- Communications uplink

Direct Transfer to L2: Hohmann 2-Body Approximation



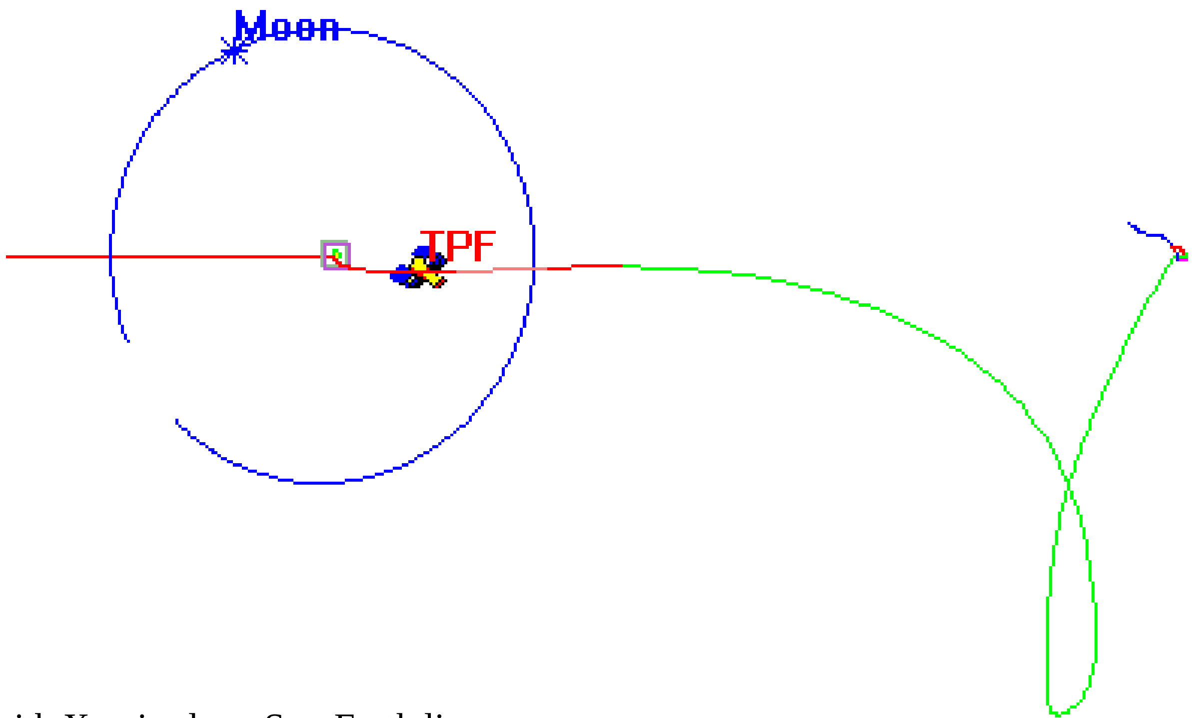
- **As a zeroth approximation, consider a 2-body Hohmann transfer from a 200-km earth parking orbit out to L2 distance**
  - 3200 m/sec burn to enter transfer orbit (~same as entering L2 halo trajectory)
  - Apogee velocity at L2 distance is ~50 m/sec
  - 37.4 days to L2
- **(For comparison, Hohmann transfer estimate for flight to lunar distance is 4.98 days**
  - Compare to Apollo “fast trajectory” of ~3 days)
- **Really need to work the 3-body problem for more accurate estimate**
  - We have modified an NGST smaller-halo L2 trajectory to approximate injection at L2

L2 and Earth Shadow Motions



- **Earth orbital eccentricity is ~.0167**
  - Causes position of L2 to shift along earth-sun line by thousands of km over year
    - Percentage of sun blockage goes up and down
  - Earth speeds up near perihelion, slows down near aphelion
    - No appreciable effect
- **Secondary body in 3-body problem is not earth but earth-moon barycenter**
  - 4670 km from earth center (toward moon)
  - L2 point is properly defined as being on line connecting sun and E/M barycenter
  - Thus center of earth penumbral cone is offset laterally from L2 by up to ±4670 km, varying over 29.5 days (earth radius = 6378 km)

TPF Sample Trajectory to L2

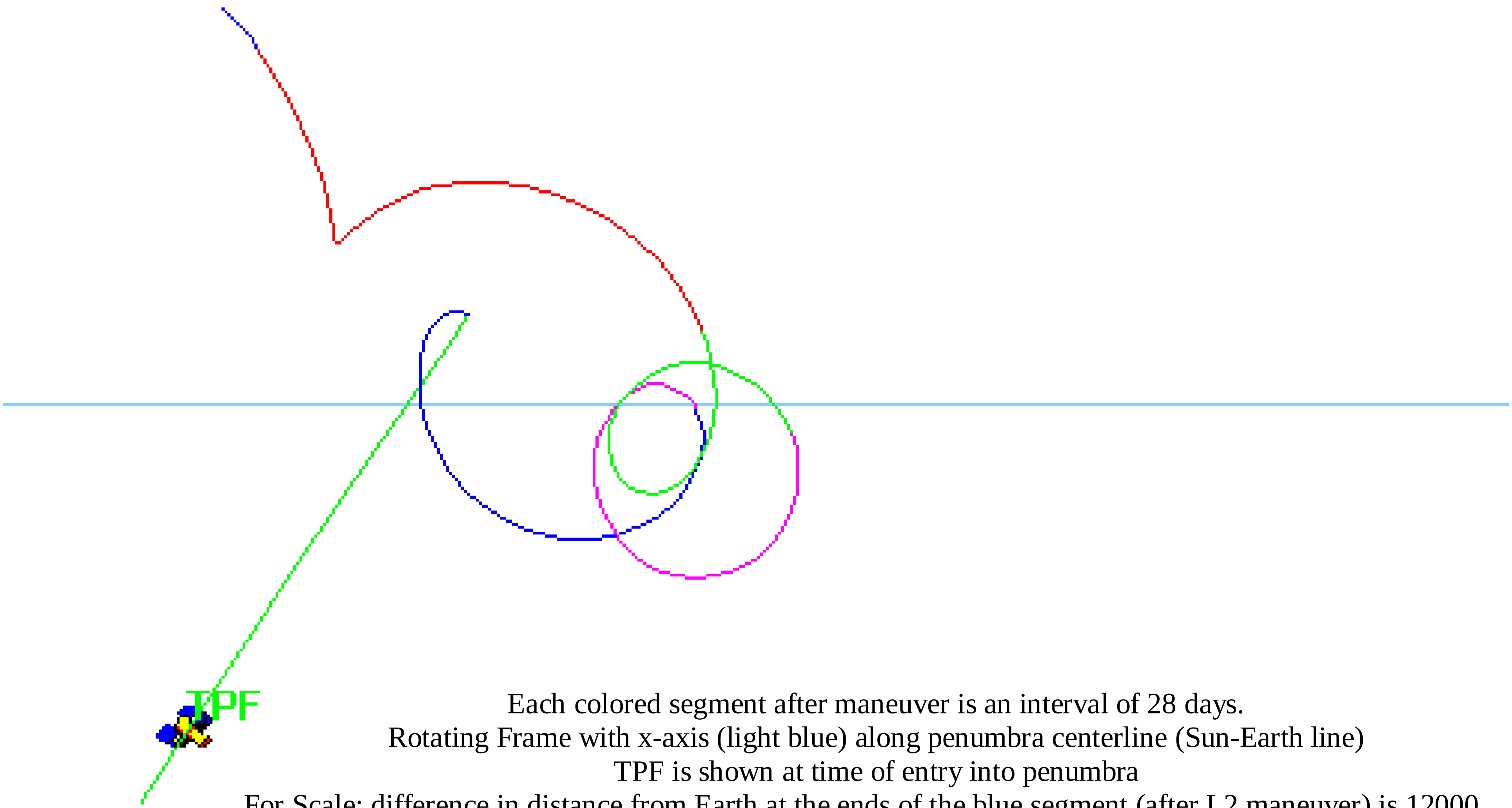


Rotating Frame with X-axis along Sun-Earth line

	X	Y	Z	Magnitude
Delta-V to Null Relative Motion at L2 Crossing	-168.3	-214.6	-15.6	273.2
With adjustment for L2+28 day Target	-167.6	-216.1	-15.5	273.9

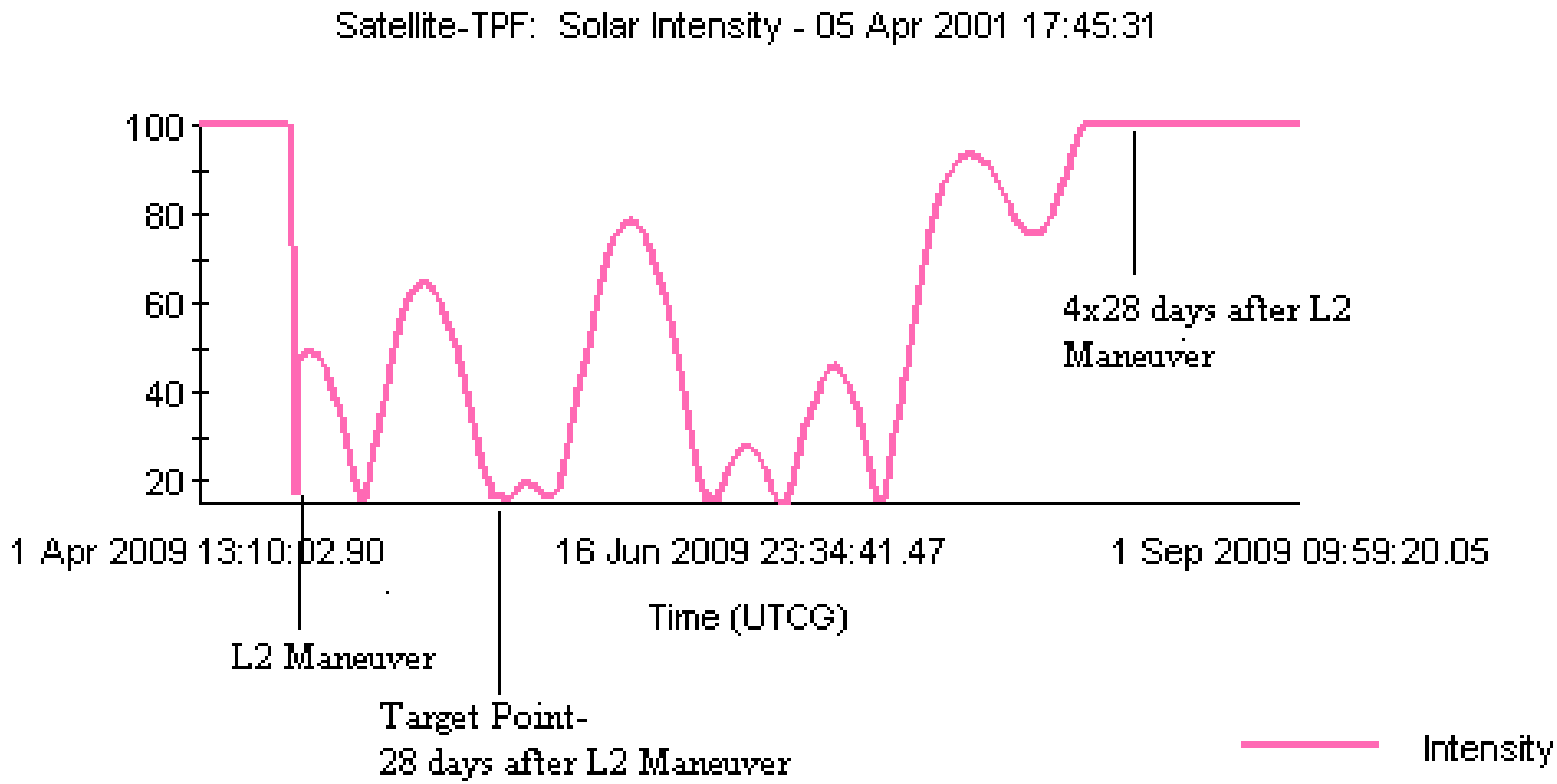
Table 1 Delta-Velocity Applied at L2 Crossing (meters/sec)
Expressed in Rotating Frame with X-axis along Sun to Earth/Moon Barycenter line

TPF Sample Trajectory to L2 (Detail at Arrival)



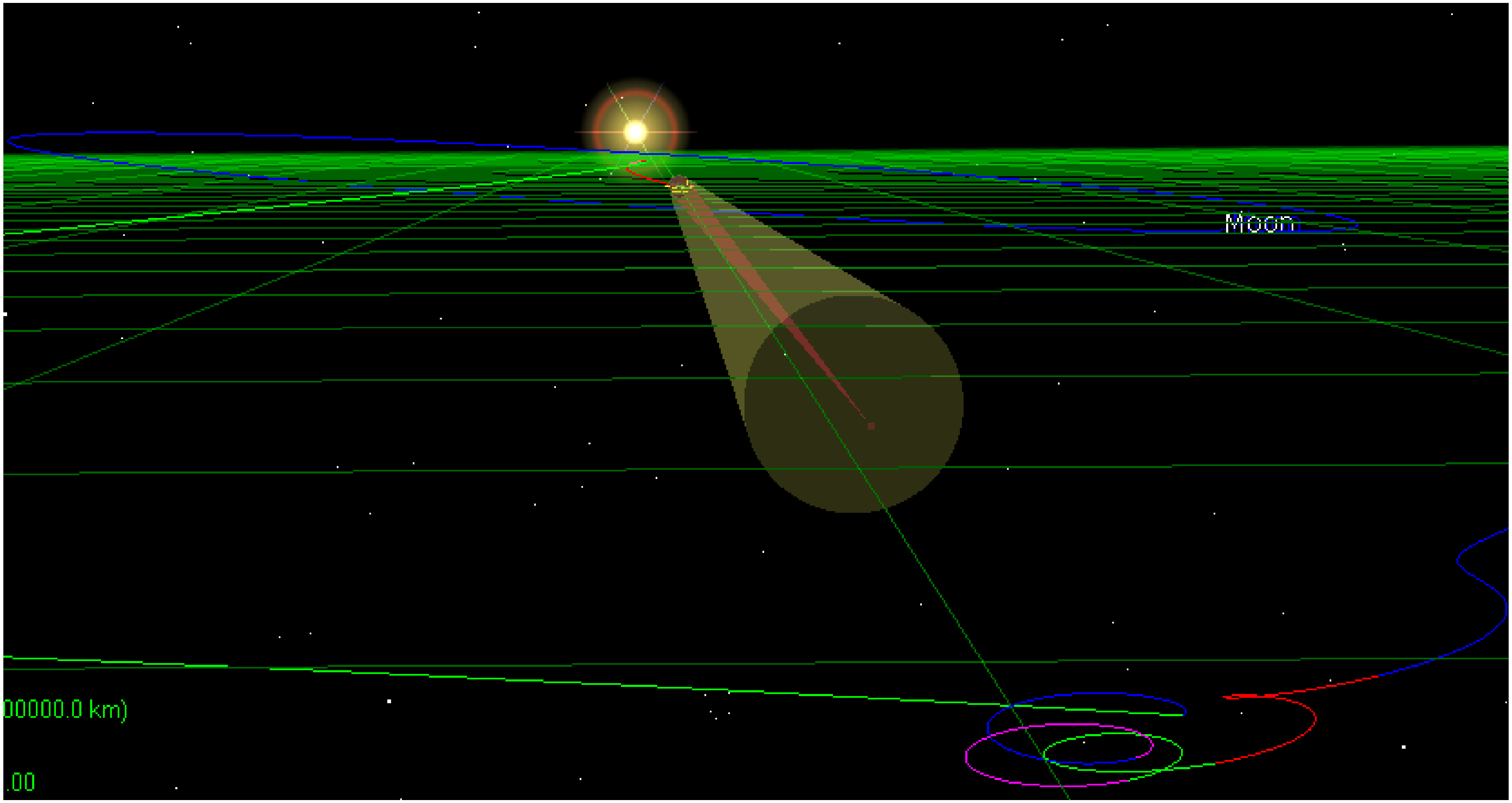
Each colored segment after maneuver is an interval of 28 days.
Rotating Frame with x-axis (light blue) along penumbra centerline (Sun-Earth line)
TPF is shown at time of entry into penumbra
For Scale: difference in distance from Earth at the ends of the blue segment (after L2 maneuver) is 12000 km

Sunlight Percentage Variation Without Stationkeeping



Solar Intensity at TPF During Passage Through Penumbra, as Percent of Non-Eclipsed Insolation

TPF Trajectory in Neighborhood of L2 Maneuver (3-D View)



TPF Trajectory in Neighborhood of L2 Maneuver, with Penumbra Cone Shown

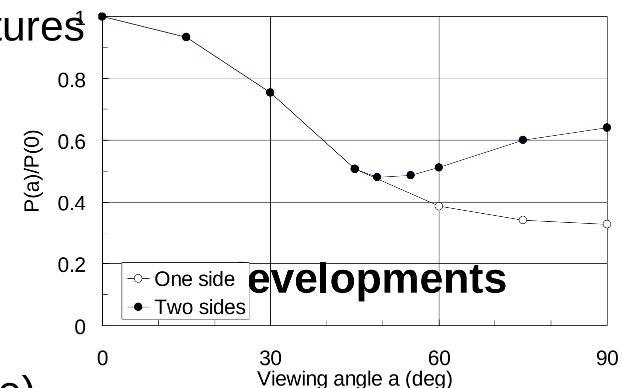
Each colored segment after maneuver is an interval of 28 days.

Comments

- **This example (nulling out velocity at L2 crossing for a halo-type transfer trajectory) is still not the “direct injection” (fast transfer) result**
- **It is possible that a lunar-assisted gravity-only trajectory could be found which would require much less ΔV to inject into L2 point**
  - In slightly longer than 115-day travel span of this case
- **Frequency of probable stationkeeping to stay in shadow at ~85% level is a drawback**
  - Weekly (or more often?) burns totaling ~16 m/sec per year compared to twice/year for halo orbits (8 m/sec per year)
  - Stationkeeping/formation flying burns for a free-flyer configuration would be more complex
- **Communications uplink is also a problem**
  - S/c trying to receive commands from earth with sun background interference

Preliminary Conclusions for TPF

- **The basic idea of achieving cold temperatures by operating in earth's shadow is intriguing**
- **However, it may not be appropriate for our conceptual 9-m precursor mission (spacecraft rotating with TPF truss)**
  - For an 85%-shadow case, need ~7 times larger solar array
    - Neglecting any gain from lower cell temperatures
    - When viewing about 45° from anti-sun, need ~14 times larger solar array (if single axis of array rotation) →



- **For later TPF missions, new technology developments may enable its use**
  - E.g., beaming power (via microwave or otherwise) from a companion spacecraft orbiting in sunlight
    - How hot would a microwave antenna/collector get?
  - Companion spacecraft could also relay uplink commands
  - Utilization of nuclear-powered spacecraft probably not an option for political reasons

Thermal Control

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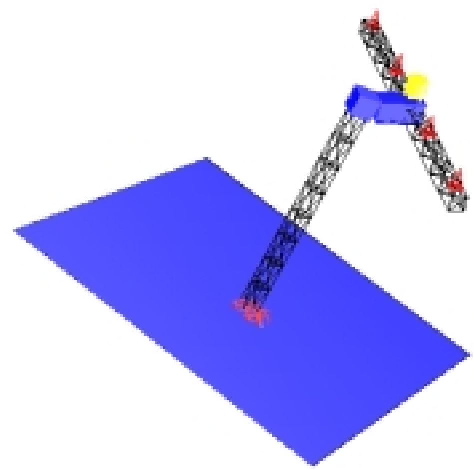
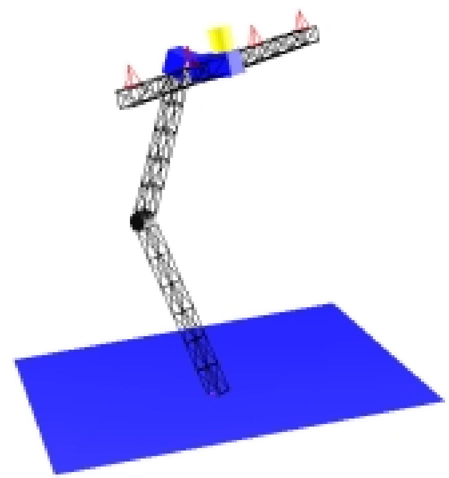
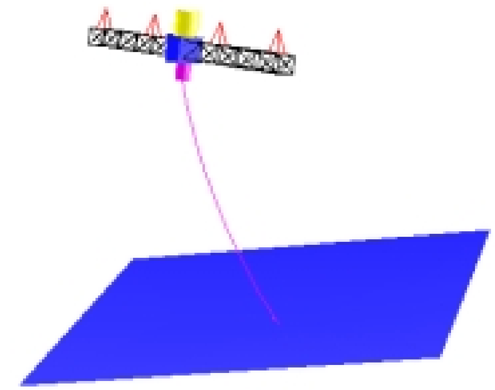
TPF Configuration Concepts



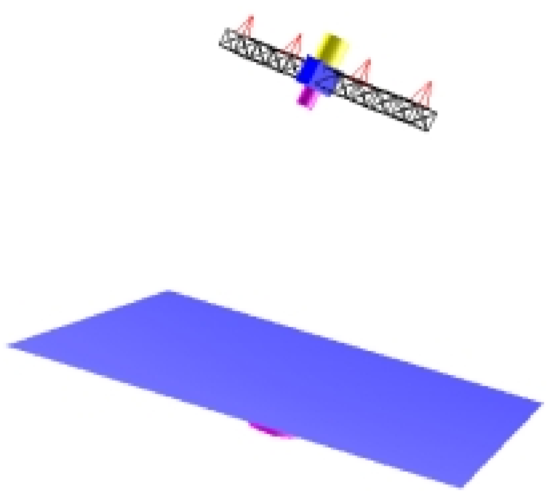
Connected/straight tower



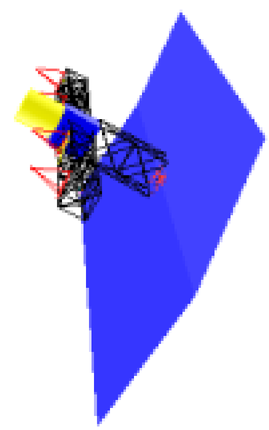
Connected/dog leg tower



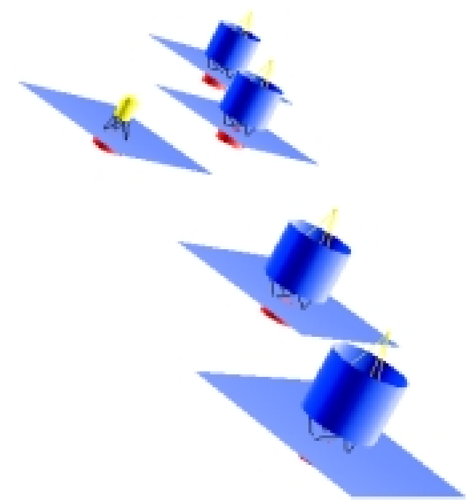
Connected/free flyer/umbilical



Connected/free flyer



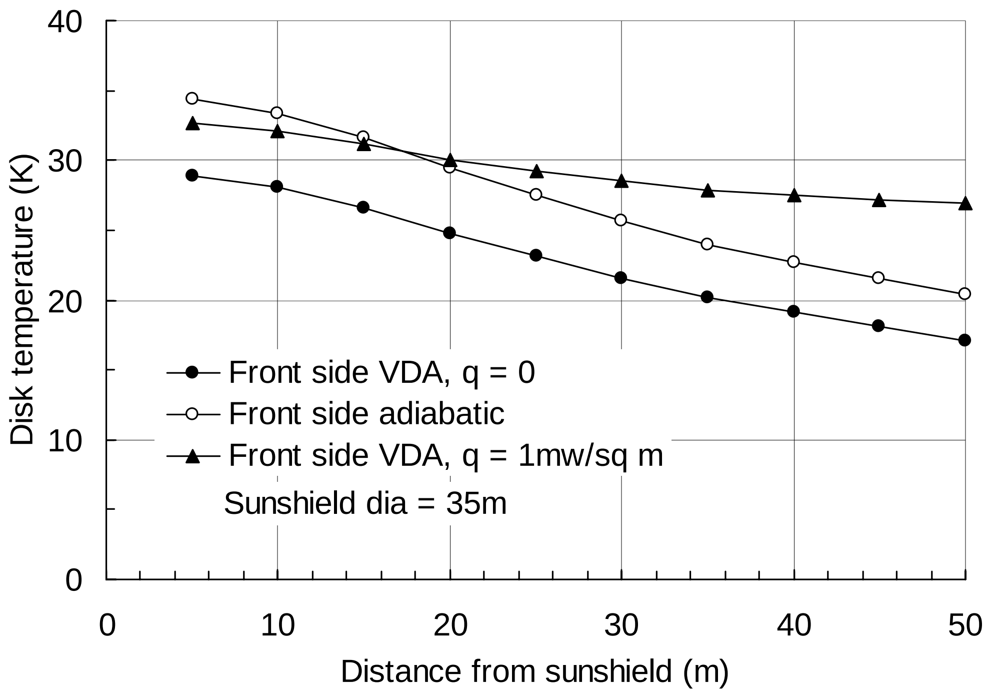
Connected/attached sunshield

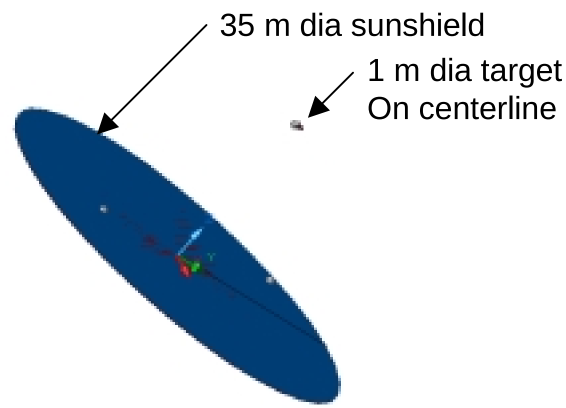


Individual free flyers

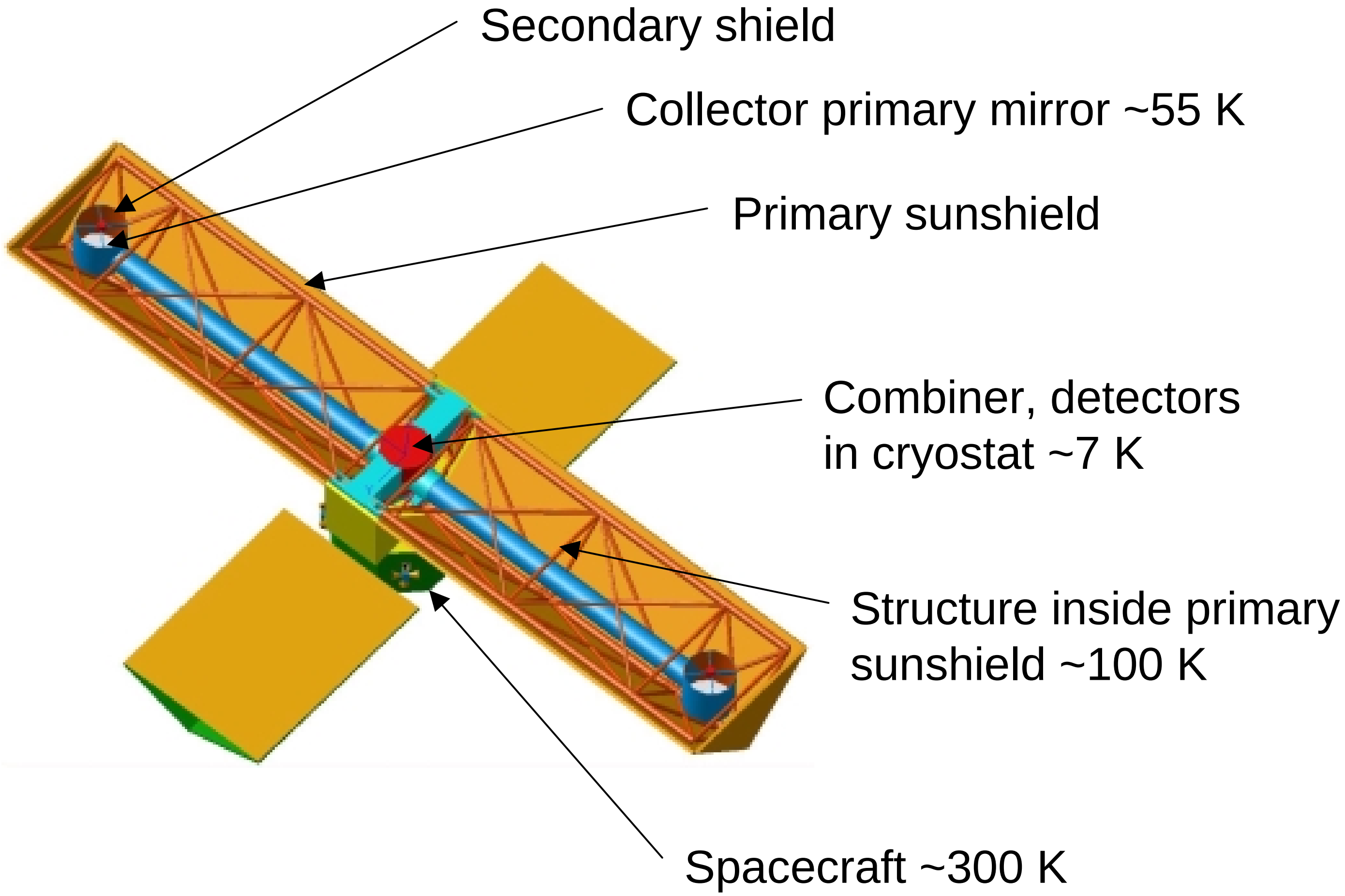
Temperature Variation Behind Circular Sunshield

- Sun side α/ε = .25/.80
- Cold side vacuum deposited aluminum (VDA)





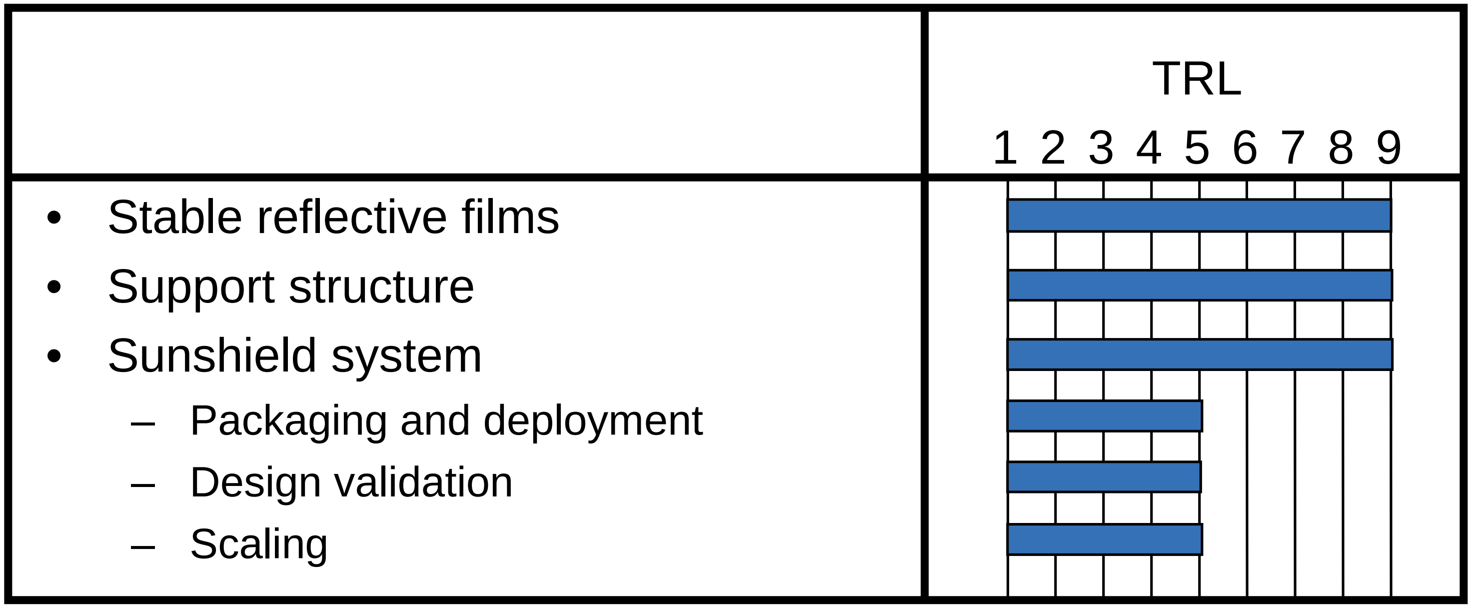
10 M Interferometer
Thermal Performance



Sunshield Technology Development

- **Subscale demonstration of sunshield system**
  - ***Test design***
    - **Performance requirements**
    - **Mechanical, thermal scaling requirements**
    - **Test facility constraints**
  - ***Packaging and deployment***
    - **Extended storage of tightly folded MLI, deployment after rapid evacuation**
    - **Repackaging and redeployment after verification test**
    - **Deployment in thermal vacuum environment**
    - **Deployment in 1-g environment**
  - ***Validation***
    - **Model correlation with subscale tests**
    - **Extrapolation to space environment**
    - **Extrapolation to full scale systems**
- **Options for deployment testing at 0-g**
- **On-orbit demonstration**

Sunshield Technology Status



Dewar Concept

Dean Read
Lockheed Martin Missiles and Space Company

Terrestrial Planet Finder (TPF)
Phase 2 Review
December 12, 2001

Cryogenic System Requirements

Item	9-m system	21-m, 40-m, or free flyer system
Number of Mirrors	2	4
Focal Plane Temperature (K)	< 12	< 7
Focal Plane Power Dissipation (mW)	1 to 5	1 to 5
Spectrometer Temperature (K)	< 17	< 17
Chopper Power Dissipation (mW)	1 to 5	1 to 5
Combiner Temperature (K)	< 60	< 40
Combiner Power Dissipation (mW)	1 to 5	1 to 5
Vacuum Shell Temperature (K)	< 60	< 40
Static Design Loads (g's)	10	10
Minimum First Frequency (Hz)	35	35
Instrument Envelope		
Length (cm)	70	88
Diameter (cm)	50	63
Instrument Mass (spectrometer + combiner) (Kg)	60	90

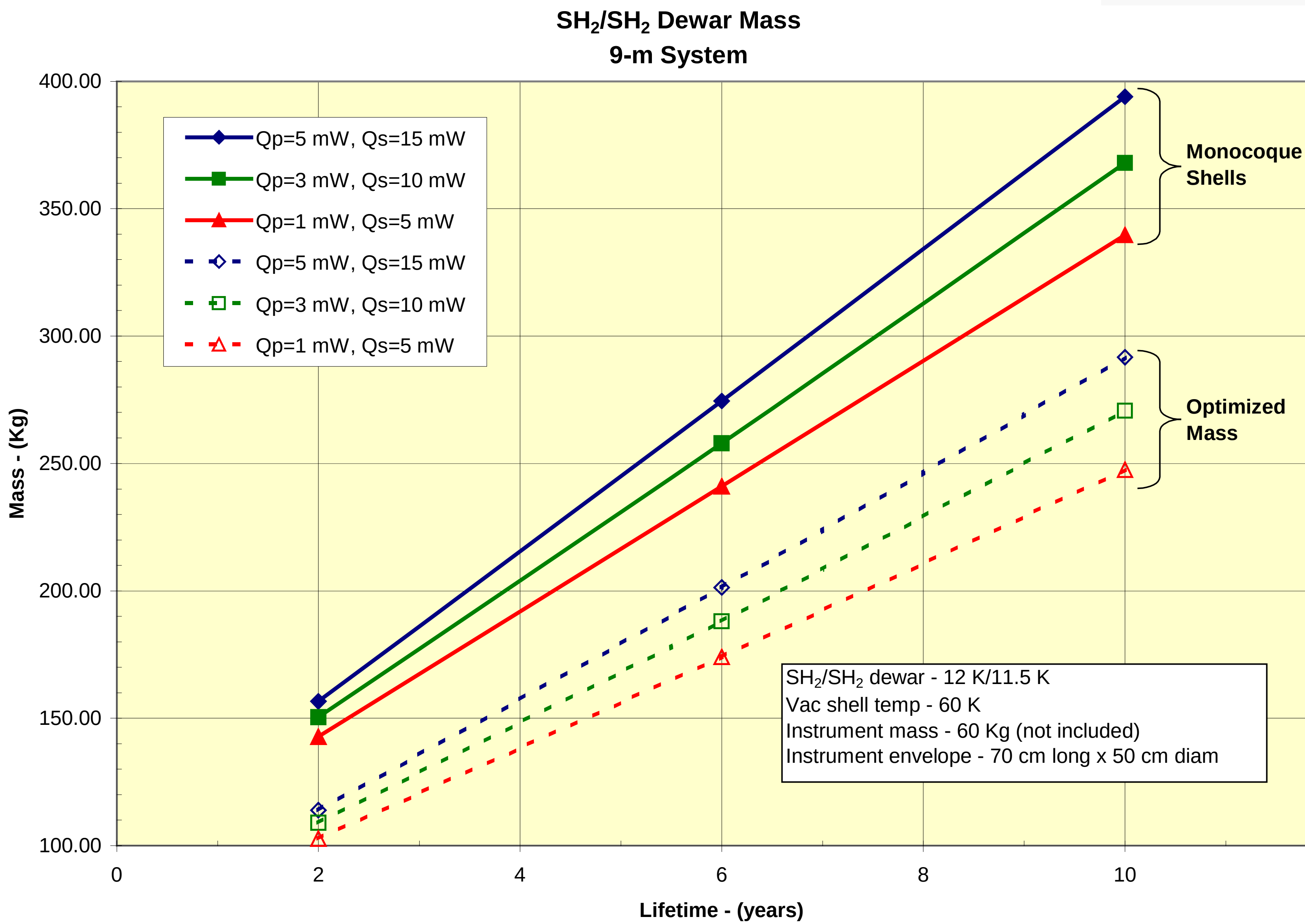
Cryogenic System Options
Advanced Cryocooler

- Cooling provided by active cryocooler and passive radiation - no stored cryogens
  - Long life and low mass
  - No ground hold issues
  - Power and radiator area needed to operate cryocooler
    - Mass, cost, risk of these items must be included in trade studies
- Instrument is launched warm and cooled on-orbit
  - Impacts verification testing
    - Requires specialized facilities to verify thermal and optical performance
- Candidate technologies include turbo-brayton, pulse tube, sorption, and stirling with J-T
  - Significant development required to achieve temperatures and heat loads required for TPF
    - JPL's Advanced Cryocooler Technology Development Program will deliver a EM cryocooler in Jan 2006

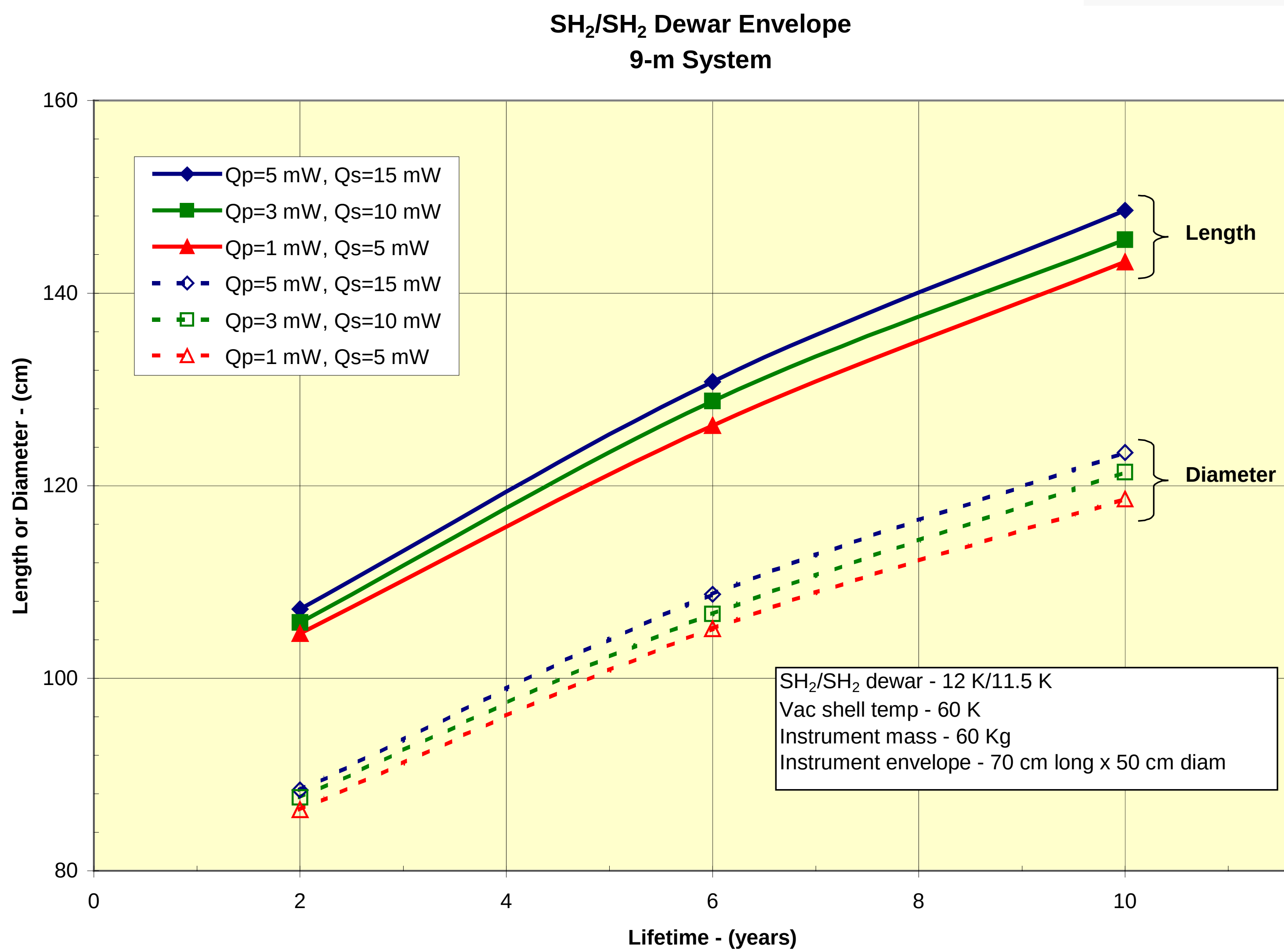
Cryogenic System Options
Stored Cryogens

- No development required - low risk technical solution
- Ground hold requirements can be a design driver
  - Can be mitigated with refrig-cooled shield (ground use only)
- Solid hydrogen or superfluid helium are required for focal plane cooling
  - Previous trade studies show that a superfluid helium system has much larger mass and envelope than a solid hydrogen system
    - Superfluid helium not studied
- Solid hydrogen or solid neon are candidate secondary cryogens for spectrometer cooling and to guard primary cryogen
  - Lower mass w/ SH2; smaller envelope w/ solid neon
- Combiner can be inside cryostat (cryogenically cooled) or launched warm and radiatively cooled on orbit
  - Combiner inside cryostat baselined for this study
    - Simplifies alignment and verification testing
    - Larger mass and volume than the radiatively cooled approach
      - Future work will quantify mass and volume penalty

9 Meter System Dewar Trade Study - Mass

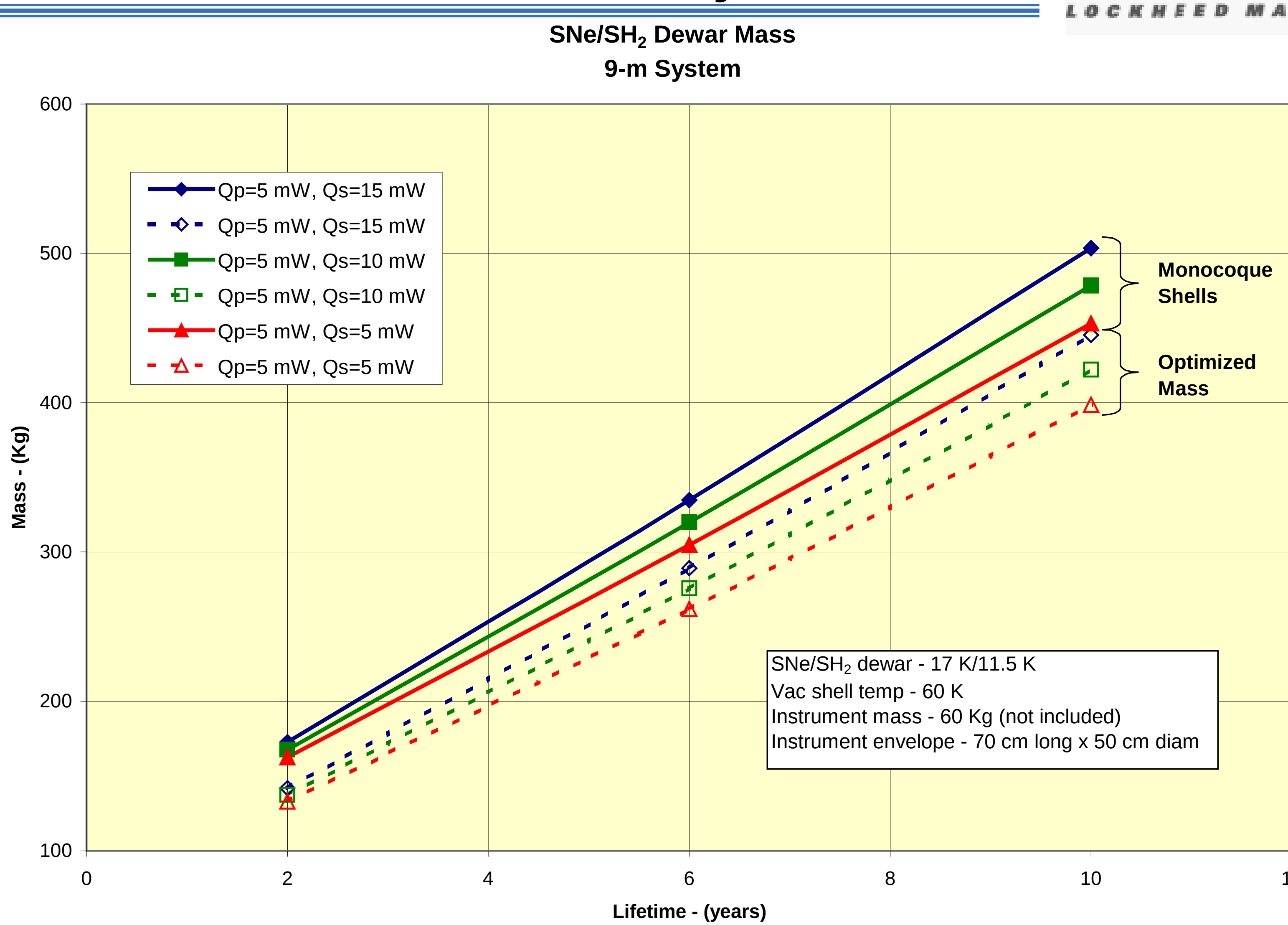


9 Meter System Dewar Trade Study - Envelope

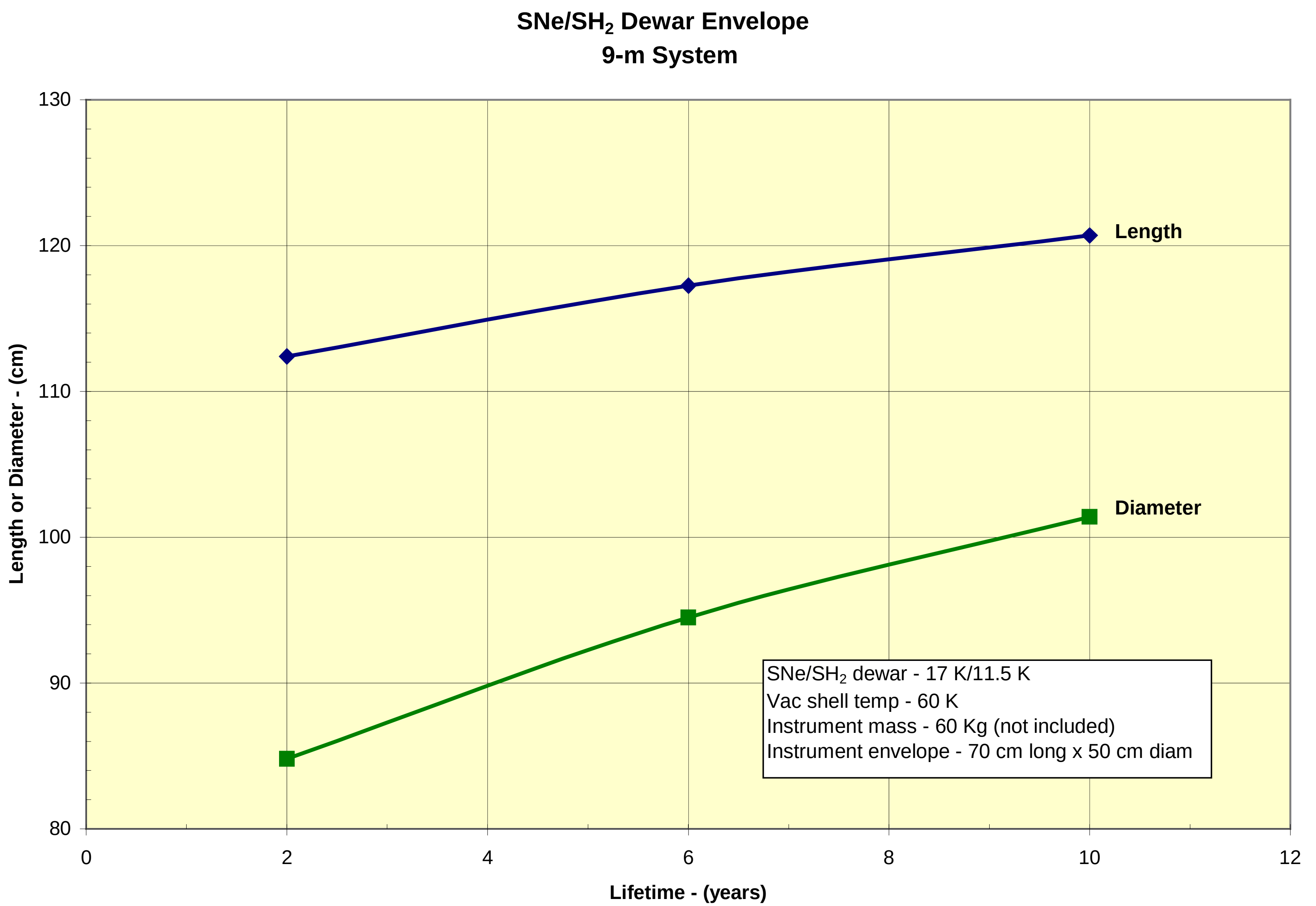


TPF *Terrestrial Planet Finder*

9 Meter System Dewar Trade Study - Mass

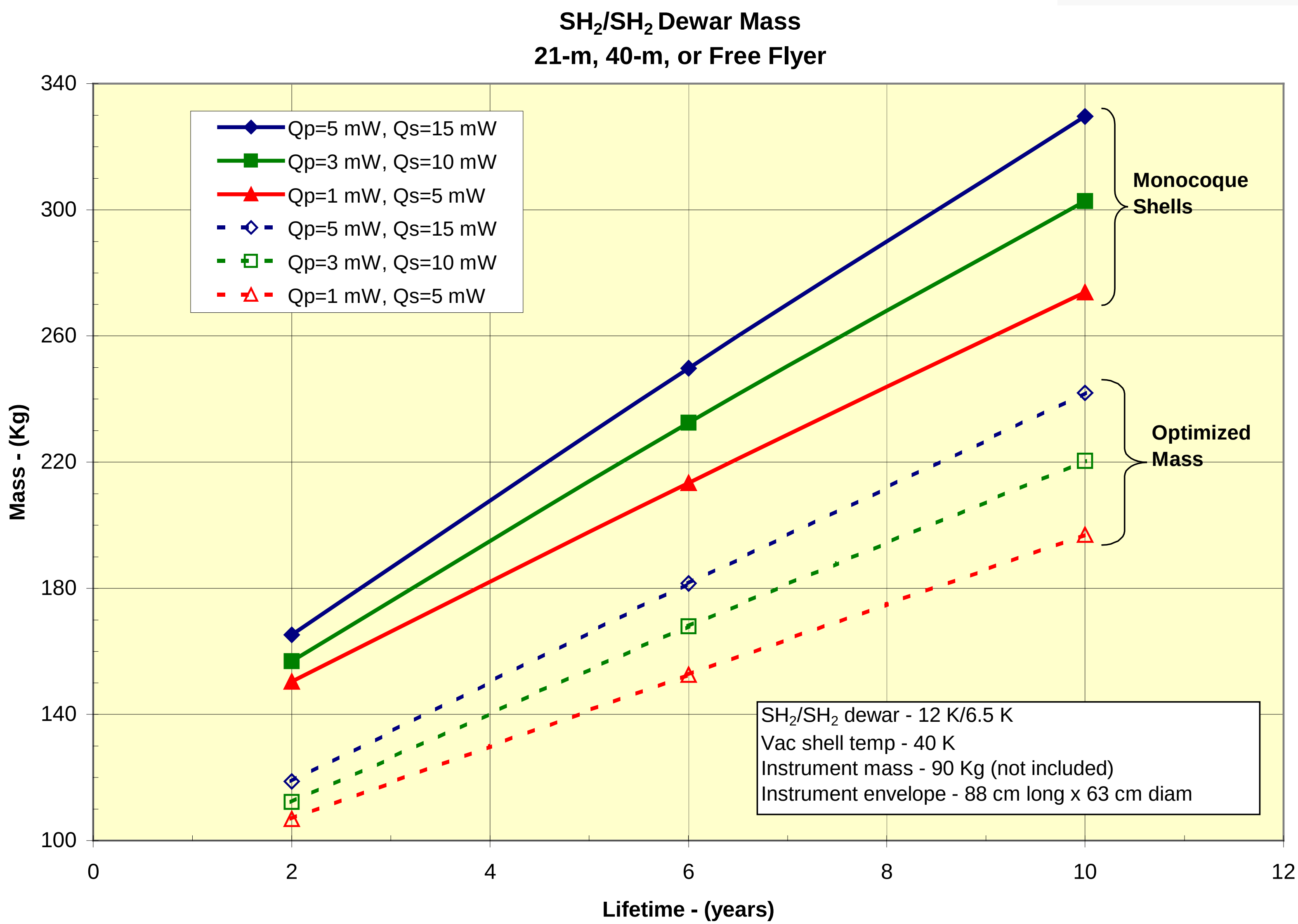


9 Meter System Dewar Trade Study - Envelope

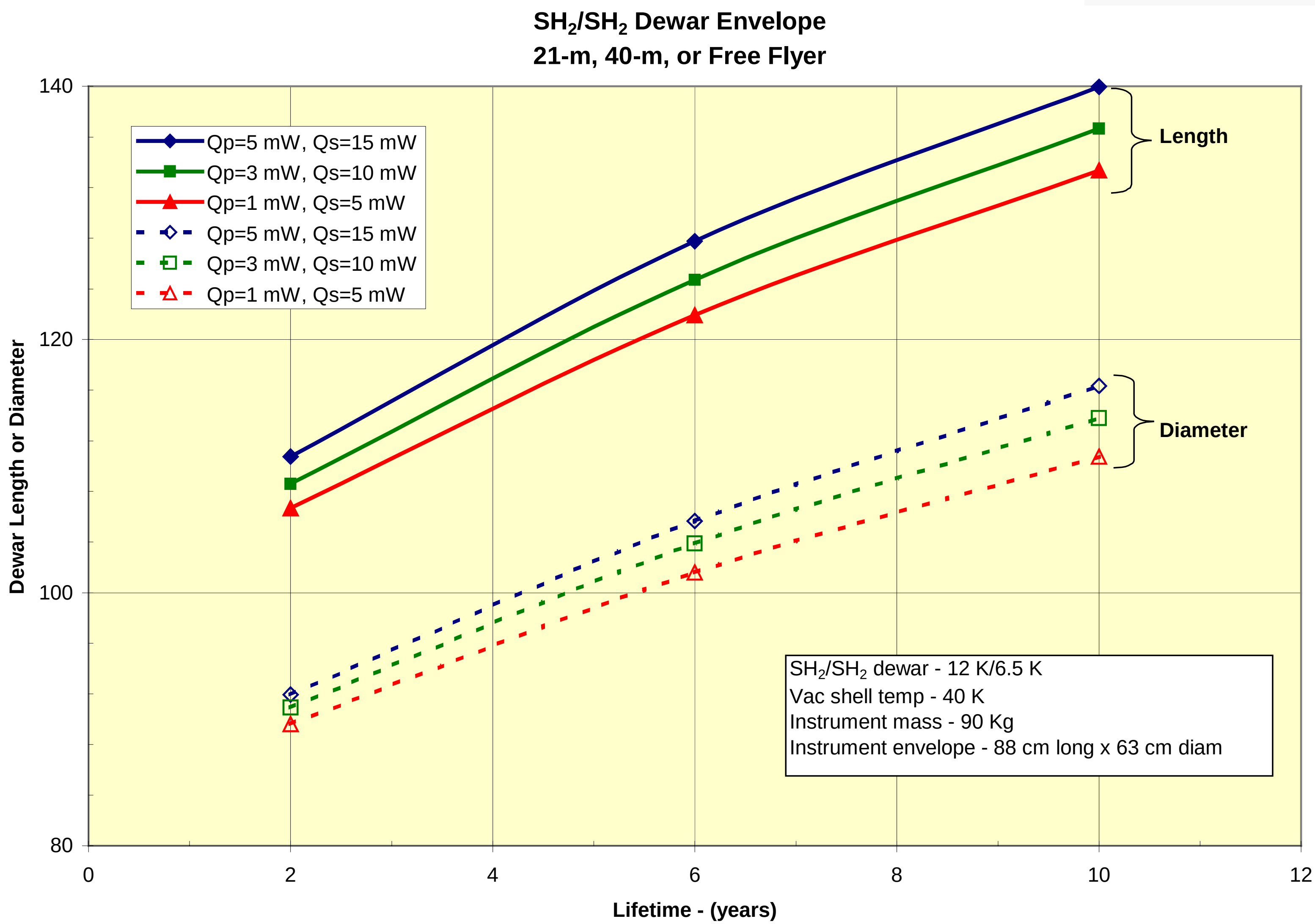


TPF *Terrestrial Planet Finder*

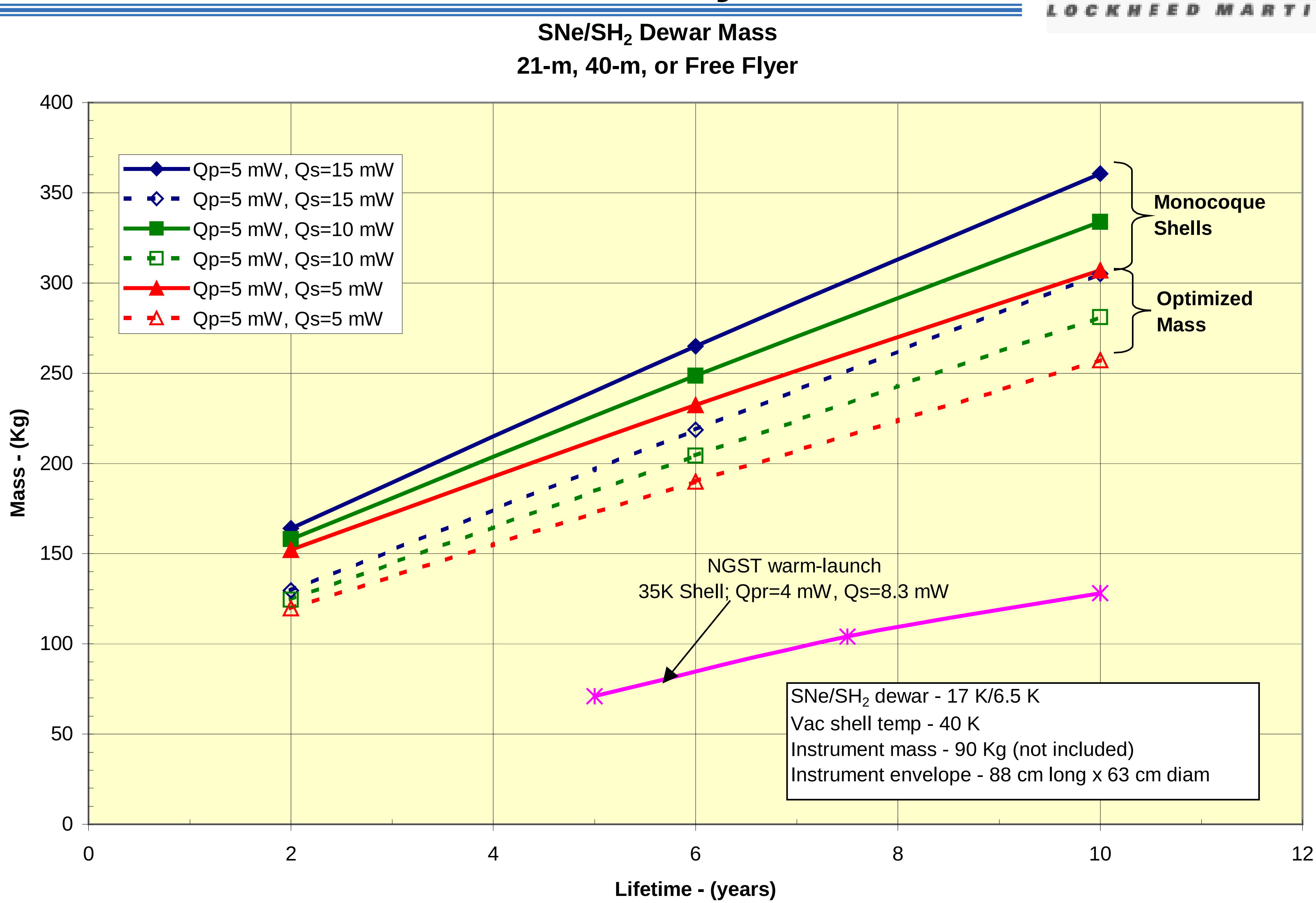
Large System Dewar Trade Study - Mass



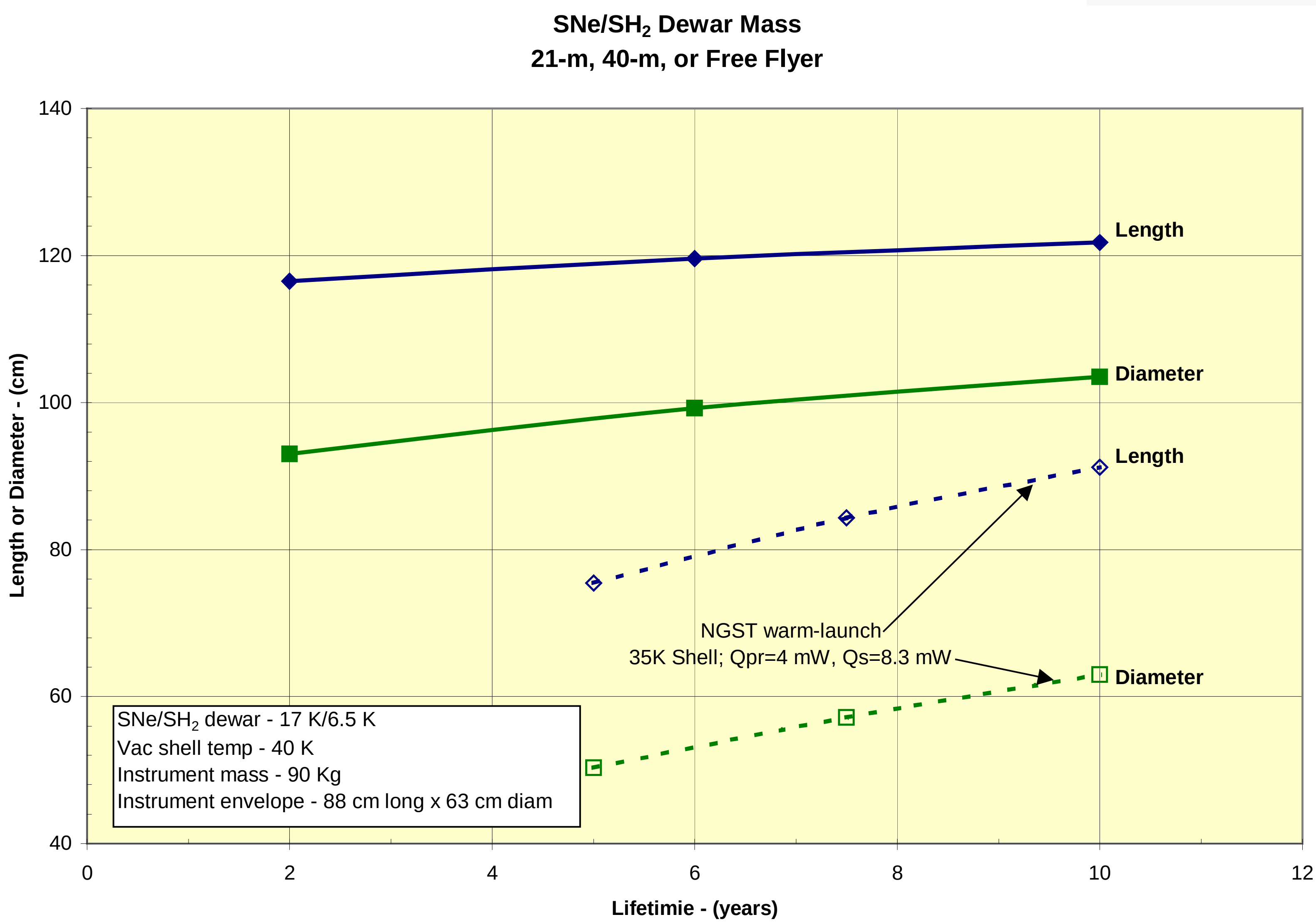
Large System Dewar Trade Study - Envelope



Large System Dewar Trade Study - Mass



Large System Dewar Trade Study - Envelope



Trade Study Summary SH_2/SH_2 system

- Significant mass savings using ring stiffened shells
  - Secondary tank and vacuum shell are large for the long life cases
- Mass and envelope driven by heat load to secondary tank
  - Larger systems are less mass than 9-m system because of lower vacuum shell temperature
- Lower mass and larger envelope than the equivalent SNe/SH_2 system

Trade Study Summary
SNe/SH_2 system

- Mass savings with ring stiffened shells not as dramatic as with the SH_2/SH_2 system
  - Secondary tank and vacuum shell size is driven by instrument volume, not cryogen volume
  - Secondary cryogen mass a significant contributor
- Mass is largely independent of primary instrument heat load
- Envelope is independent of instrument heat load
  - Tanks are relatively small so envelope is driven by instrument volume
- Mass driven by heat load to secondary tank
  - Larger systems are less mass than 9-m system because of lower vacuum shell temperature
- Larger mass and smaller envelope than the equivalent SH_2 /SH_2 system
- Warm launch architecture has potential to significantly reduce dewar mass

Cryogenic Test Concept

- Cryogenic test dewar needed for technology development testing of cold optics
- Commercial helium dewar is the most cost effective approach to achieve required temperatures
  - Use heaters and appropriately sized thermal links to simulate TPF temperatures
  - Size the dewar to accommodate 2-beam and 4-beam instruments
- Hydrogen test dewar is unnecessary
  - Hydrogen dewar technology has been demonstrated for WIRE and SPIRIT III
  - Hazardous test facility required
  - Increased cost to use hydrogen or neon for testing
- Hydrogen testing of flight system required for cryostat only
  - Perform fill, top-off, & heat rates at hazardous operations facility
  - All subsequent testing until pre-launch performed with helium
  - Load hydrogen at launch site just prior to launch

Optical Telescope Assembly
Truss Concept

Tom Connors
Steward Observatory, University of Arizona

Terrestrial Planet Finder (TPF)

Phase 2 Review

December 12, 2001

Topics

1) Truss Concepts development

2) The 6 segment truss packaging and deployment

3) The 6 segment truss analysis

4) The 2 segment truss concept

5) The 2 segment thermal issues

6) The 2 segment truss packaging and deployment

1) Truss Concept Development

- **Parallel studies of truss concepts to investigate packaging and performance of the 9-meter TPF.**

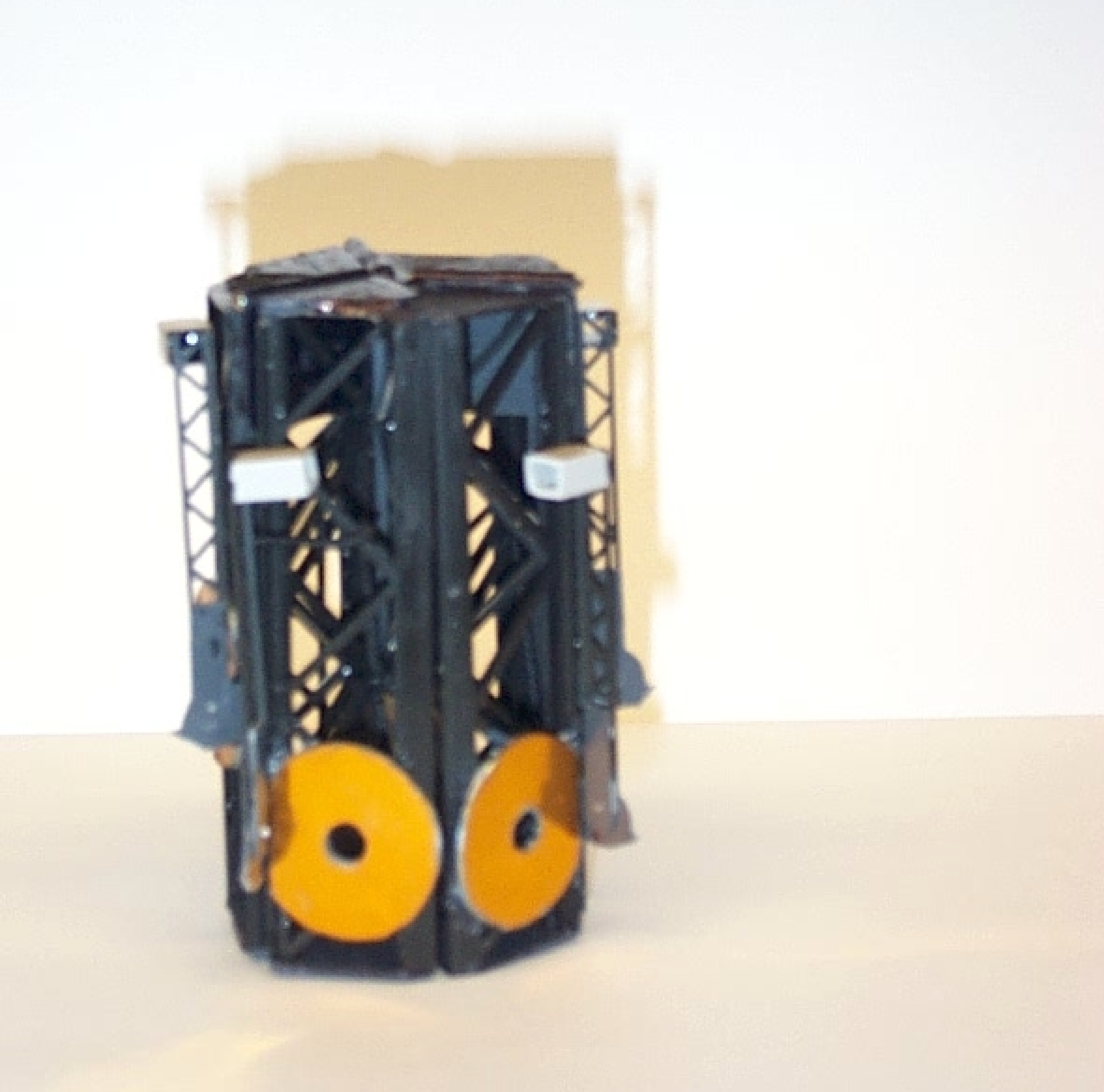
- **The U of AZ group investigated pre-assembled truss segments while the LMSSC group investigated the canister-type axially deployed truss concept.**

- **The LMSSC control model was applied to the more conservative truss concept and was therefore based on the more compliant canister-type truss.**

Truss Concept Development

- **Initial studies have followed the concept of a hinged truss which is unfolded and locked in position.**
- **During phase 1 the concept of a triangular section truss with 6 folds was explored.**
- **The big issue for this truss was that the telescopes were above the triangular section. Therefore the truss required a separate sunshield in order to have an appreciable solid angle of operation.**
- **Separate sunshields have appeared large and floppy, and therefore present potential dynamical problems to a truss-TPF.**
- **Therefore we have explored a variant of the truss in which the telescope is inside the structure, and so allows a 2π steradian field of view.**

2) 6 segment Truss concept (stowed)

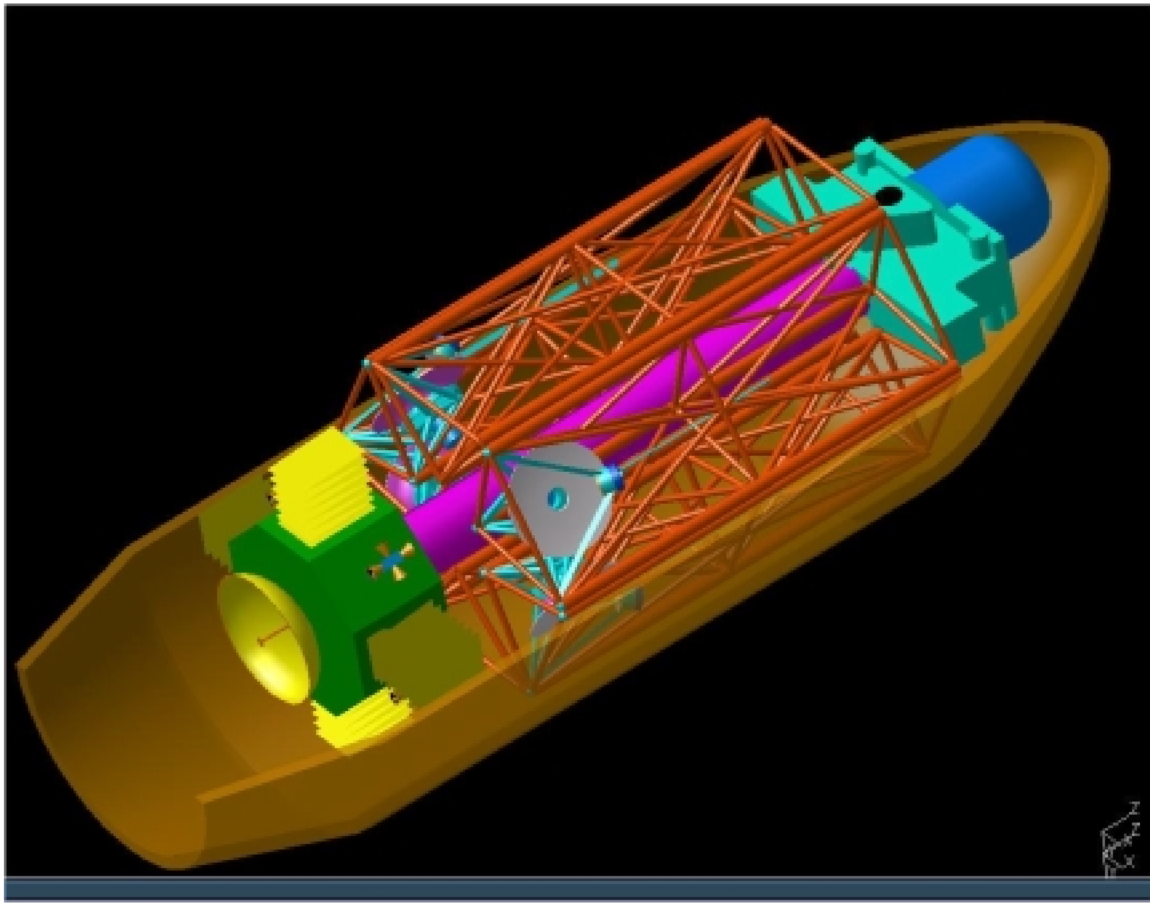


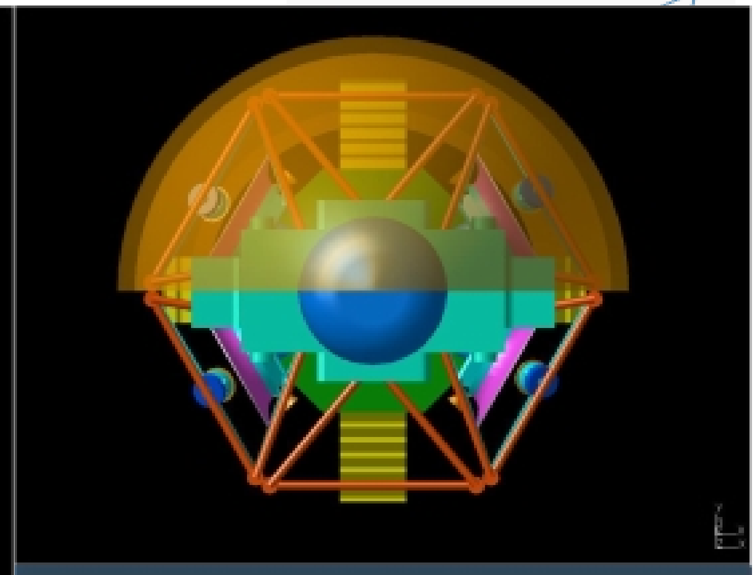
Truss unfolding

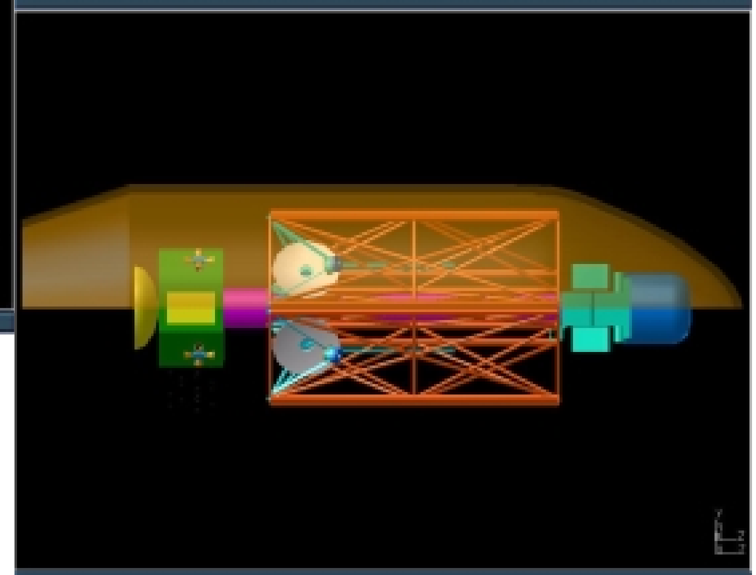
Truss Unfolded

Note the secondary mirror mounts sticking above the truss and therefore presenting sun-shielding problems.

6 Segment Truss concept

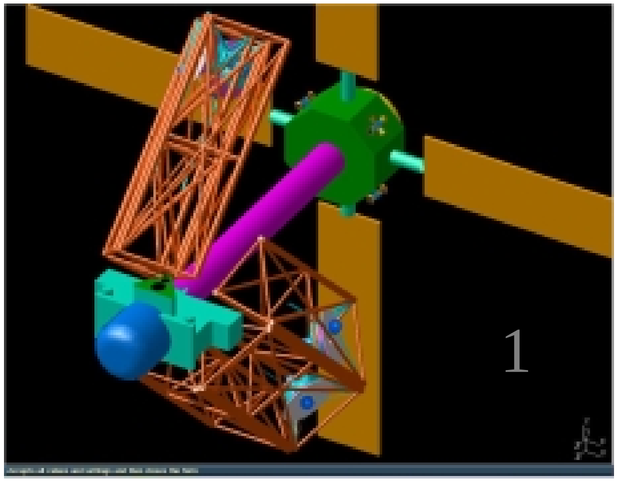


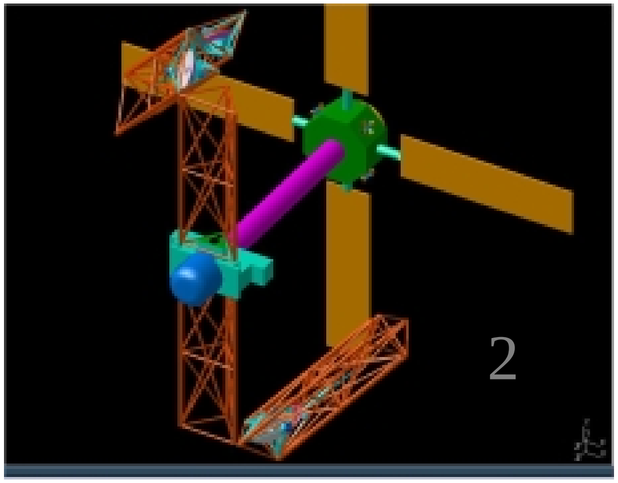


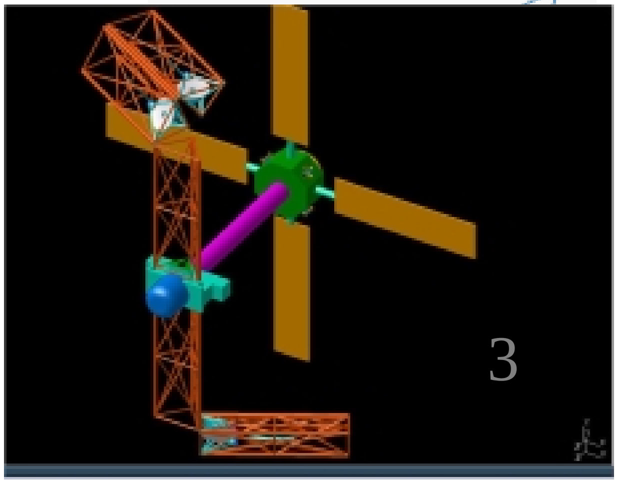


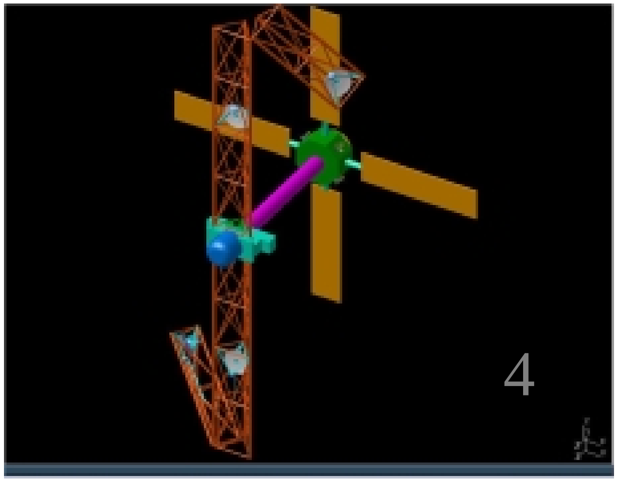
Packaging of 21-meter in Delta II-3 shroud

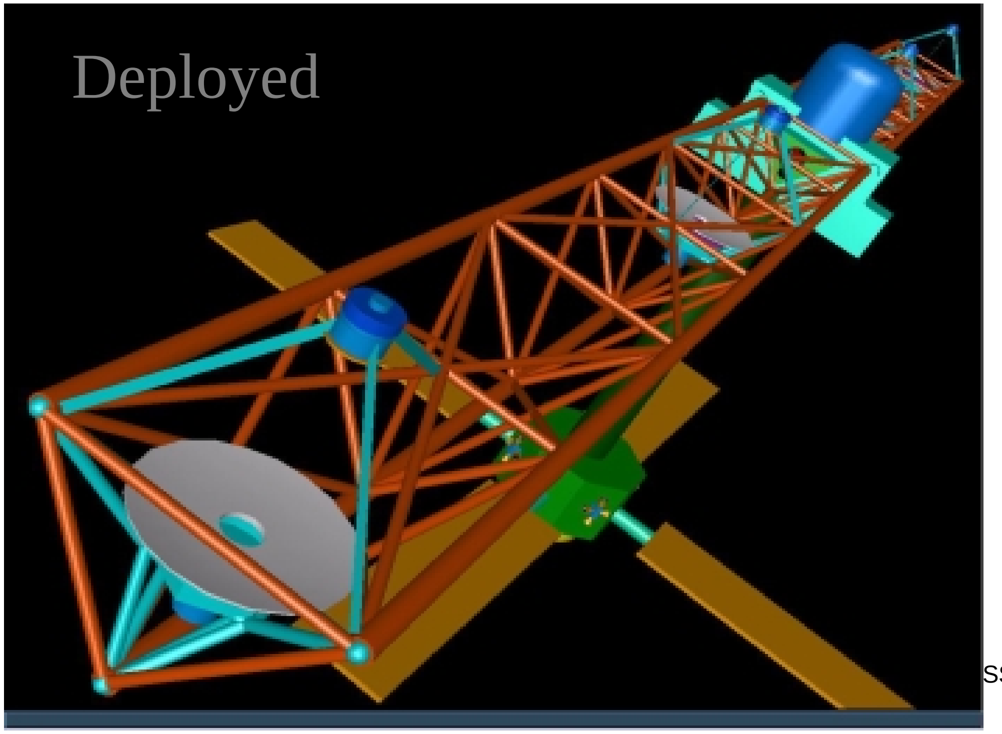
6 Segment Truss Deployment











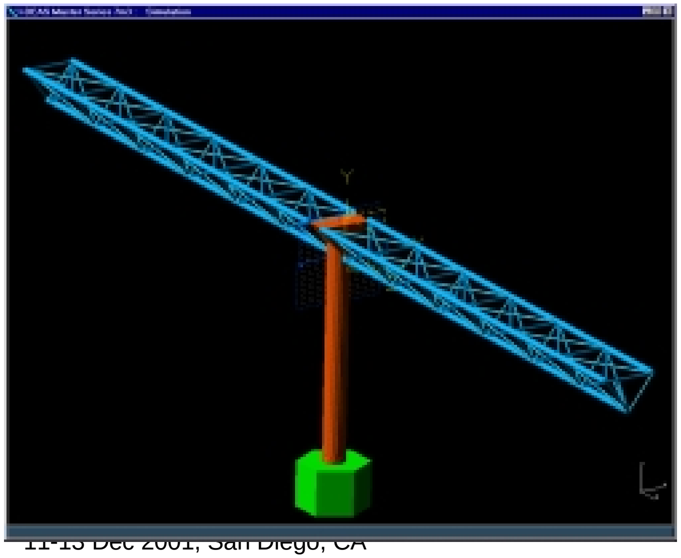
3) The 21 m 6 segment truss analysis

21-Meter TPF Optical Telescope Assembly – Modal Analysis

- 21-meter baseline packaged for Delta II-3 shroud
- Material: Aerospace Composite (see appendix for properties)
- High Order Beam Element model
- Mass Density for Beam Combiner, Bus Mast, and LM900 Buss modified such that these assemblies have a uniform density and a solid element mesh that yields a total weight of these components of approx. 630 kg. (520 LM900 bus, 10 kg mast, 100 beam combiner)
- Telescope lumped mass = 55 kg each (4 total)
- Bus solar panels and solar thermal shields excluded.

6 inch OD .04 thk wall longerons with 2 inch OD .01 thk wall diagonals and battons.
Weight of truss (excludes telescopes, beam combiner, truss hinges, latching and deployment devices and light pipes) = 114 kg (253lbs).

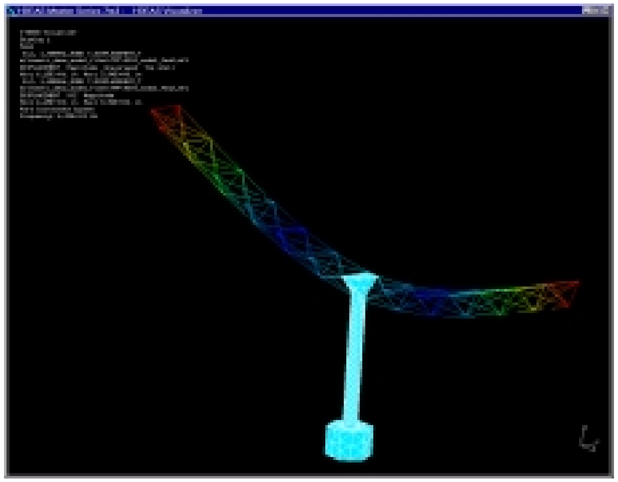
FEA Model



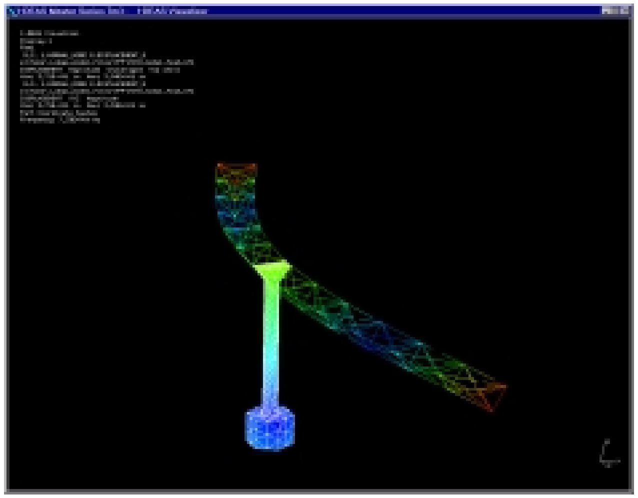
The 21 m truss analysis

Mode 1
f_1=4.5 hz

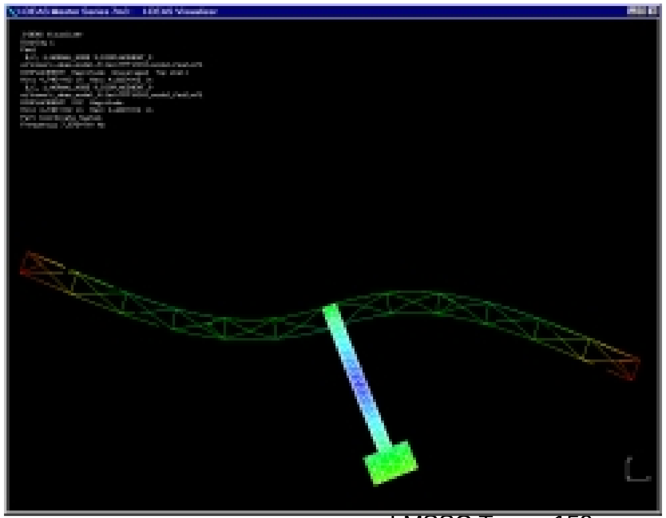
First OTA non-rigid body mode @ 4.5 hz.
Individual elements begin to ring at 47 hz, mode 16.



Mode 2
f_2=7.3 hz



Mode 3
f_3=7.6 hz



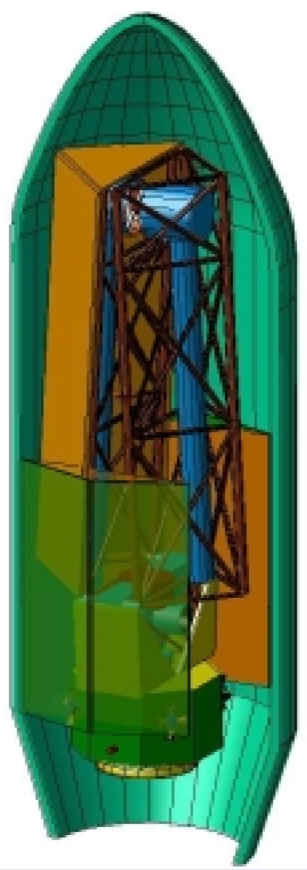
4) The 2 segment truss concept 9 meter

- **Following the analysis by Sherrill (Lockheed-Martin) it is apparent that 2π steradians needs to be accessible to the truss is it is to be able to observe all planetary systems for 6months at a stretch.**
- **This implies that the sunshield must be capable of shielding the device when it is 90 degrees to the sun-satellite line.**
- **When the truss rotates, the edge of the shield sweeps out a plane.**
- **If the telescopes are appreciably below the plane, there is a danger of the shield radiating into the telescopes.**
- **But if the telescopes stick above the truss, they will encounter direct sunlight.**
- **So there is a plane which should neither be violated by telescopes or sunshield. That is, the shield should wrap around the telescopes.**
- **The natural way to do this is to put the sunshield onto the truss.**

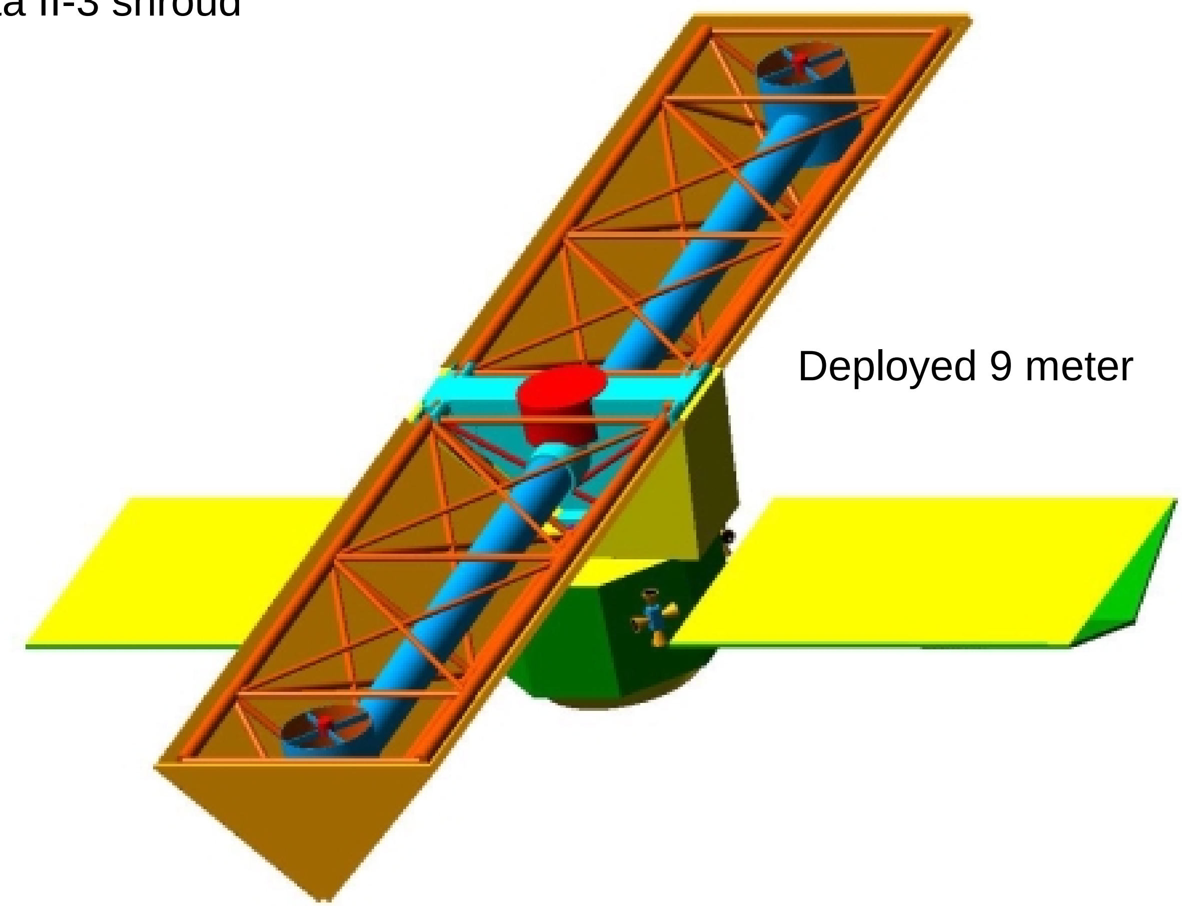
5) 9 meter truss thermal issues

- **In the new concept, the sunshield will change temperature as the truss rotates. Therefore it is necessary to add additional thermal shielding so as to keep the temperature of the telescopes and beam combiner sufficiently cool.**
- **The preferred cross section of telescopes and trusses is as triangles or cones with the wide end pointing towards the astronomical source. The upper end can in principal be open or black. The down-pointing end should be gold coated.**
- **There is an option of adding thermal blankets to make the thermal time constant long compared with the rotation period (2-8 hours).**
- **There is a possibility of adding additional thermal shields to bring down the temperature of the telescopes and beam combiner into the 20-30K range.**

9 meter 2 segment truss



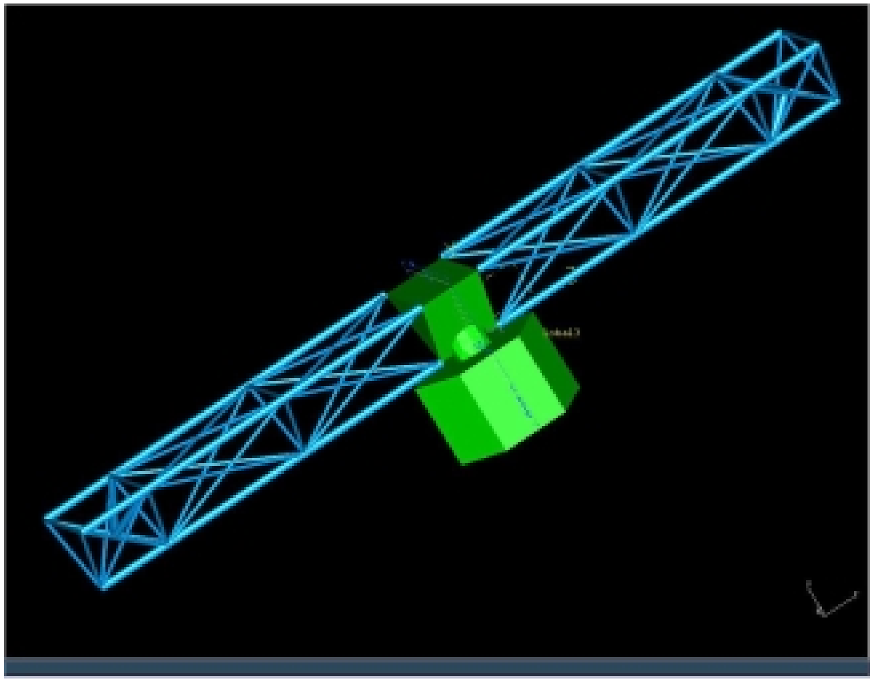
Packaging of 9 meter
in Delta II-3 shroud



Deployed 9 meter

6) 9 meter Truss

FEA Model



Beam element model with modified mass density solid elements for Beam Combiner and LM900 Space Buss

- 30 kg telescopes (2 total)
- 90 kg beam combiner
- 520 kg space buss
- 10 meter length
- truss weight 66 kg (aluminum)
- telescope spacing: 9 meter

Mode 1	Mode 2	Mode 3
f_1=16.6 hz	f_2=28.8 hz	f_3=33.9 hz

Pointing Control System

Nelson Pedreiro
Tom Trankle
Carol Kowalsky

Lockheed Martin Space Systems Company (LMSSC)

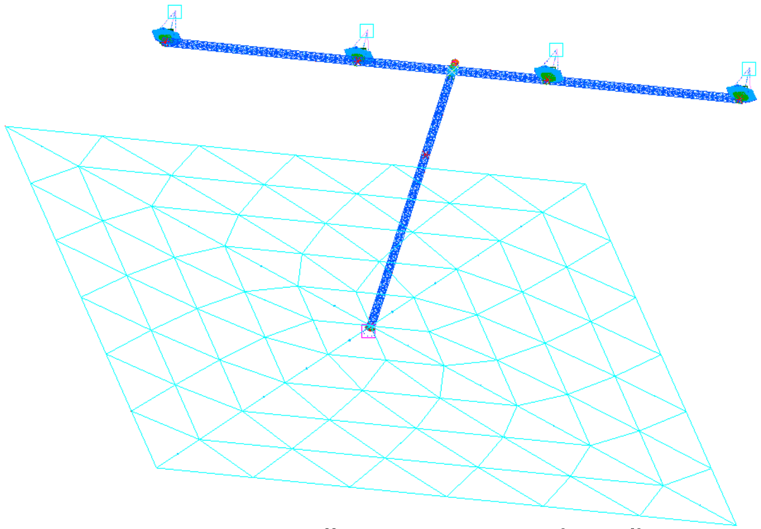
Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

Agenda

- System configurations and Control requirements
- Understanding the problem
- Vibration Mitigation Approach
- Control System Architecture
  - Attitude Control System
  - Pointing jitter and pathlength control
  - Basic operations (Slew, Spin, H-dump)
- Dynamic Model and Simulation Results
- Hardware
- Risk Assessment
- Technology Development

System Configurations & Control Requirements

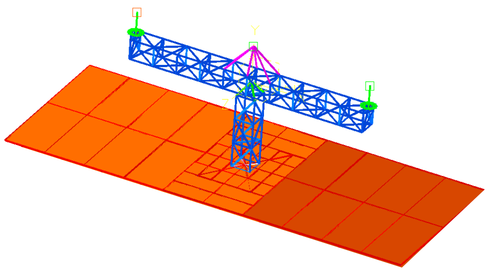
- Collectors, combiner and precision structure at cryogenic temperature connected through a truss/boom to spacecraft/sun-shield
- Four baselines considered
  - 80-m, 40-m, 21-m, 9-m
  - Trade: science, cost, schedule, risk
- Control requirements driven by required null-depth
- Analysis focused on limit configurations: 80-m and 9-m



TPF – 4 Collectors on 80-m baseline
Configuration 80A

Control Requirements for Various TPF Configurations

	CONFIGURATIONS			
	80-m	**40-m**	**21-m**	**9-m**
Null-Depth	**3.7E-5**	**3.7E-5**	**3.7E-5**	**1e-4**
Pointing Jitter	**15 mas**	**26 mas**	**54 mas**	**82 mas**
Optical Path-Length Error	**10.6 nm**	**10.6 nm**	**10.6 nm**	**7.2 nm**



2 Collectors on 9-m baseline
Configuration 9A

Understanding the Problem

- Large light-weight complex structure in cryogenic environment
  - Damping can be very low
  - Damping can not be reliably predicted
  - Direct effect on science
- Disturbance sources
  - Reaction wheels / CMGs / Thrusters
  - Cryostat venting
  - Mechanisms
  - Steering mirrors (small effect)
  - Fuel slosh
  - Slewing (transient effect)
  - Momentum dumping (transient effect)
  - Radiation pressure (quasi-steady)
  - Thermal gradient – Thermal snaps, micro-dynamics (transient-effect)
- Can not test the entire system in representative environment

Vibration Mitigation Approach

- Do not rely on structural damping

- Develop and demonstrate a system level solution
  - Mitigate vibration at the main sources
  - Provide system level damping (if required)
    - Passive (preferred – Tuned-Mass-Dampers)
    - Active (if required – broadband)
  - Active jitter compensation (fast-steering mirrors)
  - Active path-length-control (fringe tracking / delay lines)

- Continue development and validation of integrated modeling tool

RWA / CMG / Thruster Trade-off

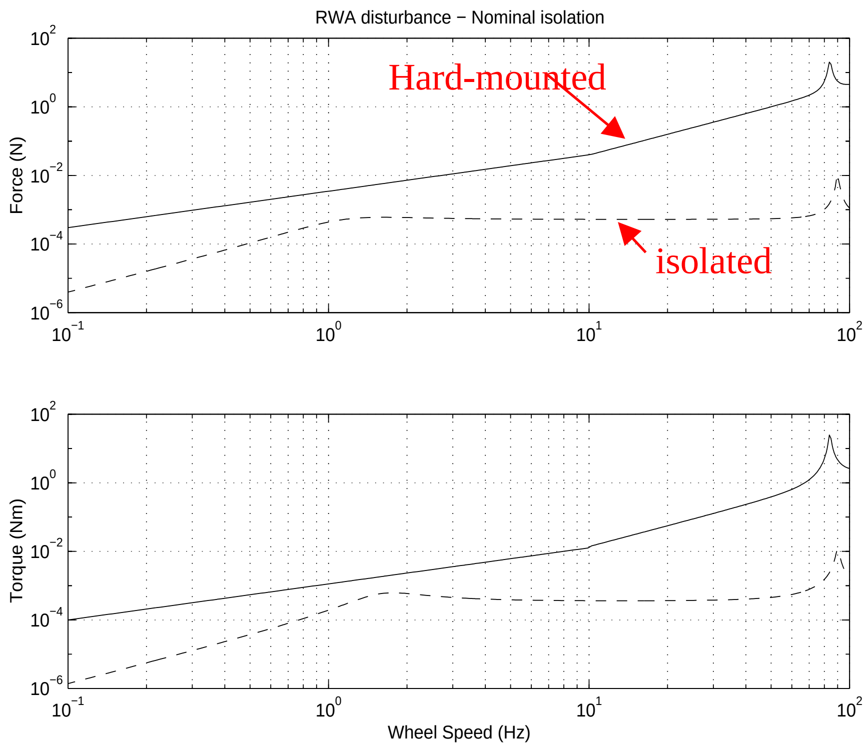
- Main source of disturbance
- Micro-N thrusters not as mature as reaction wheels and CMGs
  - RWA & CMG have been demonstrated in flight
  - Potential contamination issue with thrusters
- For TPF reaction wheels are favored over CMGs
  - Lower cost and complexity, higher reliability
- Baseline:
  - Reaction wheel assembly mounted on passive isolation system

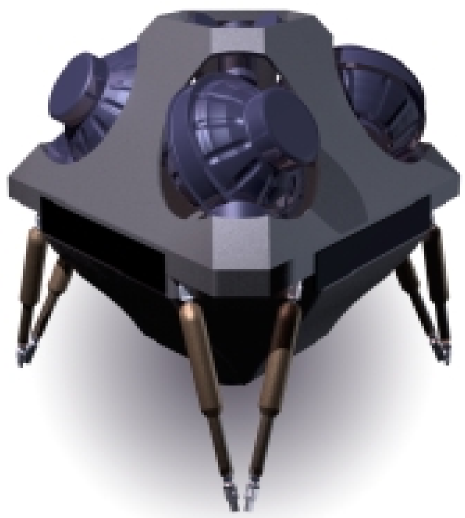
Control System Architecture

- Spacecraft bus ACS based on SIRTF/IKONOS
- Honeywell Paragon RWA (HR4820 - 65 N-m-s at 6000 rpm, 0.14 N-m)
  - standard balance
  - 4 wheels arranged in a pyramid configuration
- Honeywell D-strut™ ~2-Hz passive isolation system (hexapod configuration)
  - Optional active isolation can be used to reduce the break frequency to 1 Hz
    - Hybrid system (VISS) uses Sundstrand QA-3000 accelerometers, Kaman 5100 position sensors, custom designed voice-coil actuators
  - Active jitter compensation using detector signals and fast steering mirrors
- Active optical path-length control using fringe tracking and delay line

RWA & Isolation System

RWA Disturbance Envelope – Hard-Mounted and Isolated





Honeywell RWA & D-strut™ passive isolation system

Basic Operations - Slewing

- Slewing
  - RWA (Honeywell HR4820, 4-wheels in pyramid configuration)
  - Assume 80% of wheel torque used during slew

Configuration	Slew Angle	Slew Time	Max. Change in Wheel Speed
9-m	20-deg	5.3 min.	1,656 RPM
9-m	60-deg	9.2 min.	2,868 RPM
80-m	20-deg	2.1 hours	3,000 RPM (coasting required)
80-m	60-deg	6.3 hours	3,000 RPM (coasting required)

  - Slewing – Increased torque and momentum capacity
  - Example with 2 RWAs (Honeywell HR4820, 4-wheels in pyramid configuration)
  - Assume 80% of wheel torque used during slew

Configuration	Slew Angle	Slew Time	Max. Change in Wheel Speed
80-m	20-deg	1.1 hours	3,000 RPM (coasting required)
80-m	60-deg	3.2 hours	3,000 RPM (coasting required)

Basic Operations – Baseline Rotation

- **Spin-up**

Configuration	Period of Rotation	Time to Spin-up	Change in Wheel Speed	Notes
9-m	8 hours	8 s	83 RPM	- Single RWA - Spin-up of entire vehicle
9-m	2 hours	32 s	331 RPM	
80-m	8 hours	13.3 min.	8,272 RPM	
80-m	2 hours	53.3 min.	33,087 RPM	
80-m	8 hours	6.7 min.	4,136 RPM	- Two RWAs - Spin-up of entire vehicle
80-m	2-hours	26.7 min.	16,543 RPM	
80-m	8 hours	2.9 min.	1,787 RPM	- Single RWA - Spin up of truss with collectors and combiner only
80-m	2-hours	11.5 min.	7,148 RPM	

Basic Operations – Momentum Dumping

- **Angular momentum accumulation**
  - **Solar momentum rate = 4.4e-6 Kg/(m*sec^2)**
  - **Assume normal incidence and 100% reflectivity**

	Concept	
	9 meter	80 meter
Length (meters)	17	82
Width (meters)	7	82
Area (meters^2)	119	6724
Solar Radiation Force (Newtons)	0.00105	0.05917
Assumed Center of Pressure Offset (meters)	0.05	0.1
Torque (Newton*meters)	5.24E-05	0.00592
Daily angular momentum (Newton*Meter*Sec)	4.5239	511.24

- **RWA Momentum capability: ~150 N-m-s**
- **Momentum build-up represents an issue with 80-m configuration**
  - **Adjust relative position between CM and Center of Pressure**

Dynamic Model and Simulation

- Model description
  - Analysis conducted for early design configurations - unfavorable inertia properties and lower structural stiffness
  - Rigid and Flex body dynamics
    - Mass: ~1,200 Kg (9-m), ~1,800 Kg (80-m)
    - All modes included up to 100 Hz
    - 0.1% structural damping assumed for all modes
  - Detailed model of ACS and fine pointing sensors and actuators
    - Star-trackers, gyros
    - Quad-cell detectors
    - Reaction wheels (dynamic and static imbalance, higher harmonics included, drag)
  - Model of fringe-tracking sensor
    - Simplified model including noise and limited bandwidth
  - Control system
    - Dual mode Kalman filter (coarse and fine pointing)
    - PID attitude control loop

Models of Sensors & Actuators

- Star Trackers
  - Rate smearing, random noise, quantization
- Gyros
  - Bias, drift, random walk, band width, quantization
- Quad Cell Detectors
  - Random noise
- Reaction Wheels
  - Static, dynamic imbalance
  - Harmonics
  - Drag

Control Logic

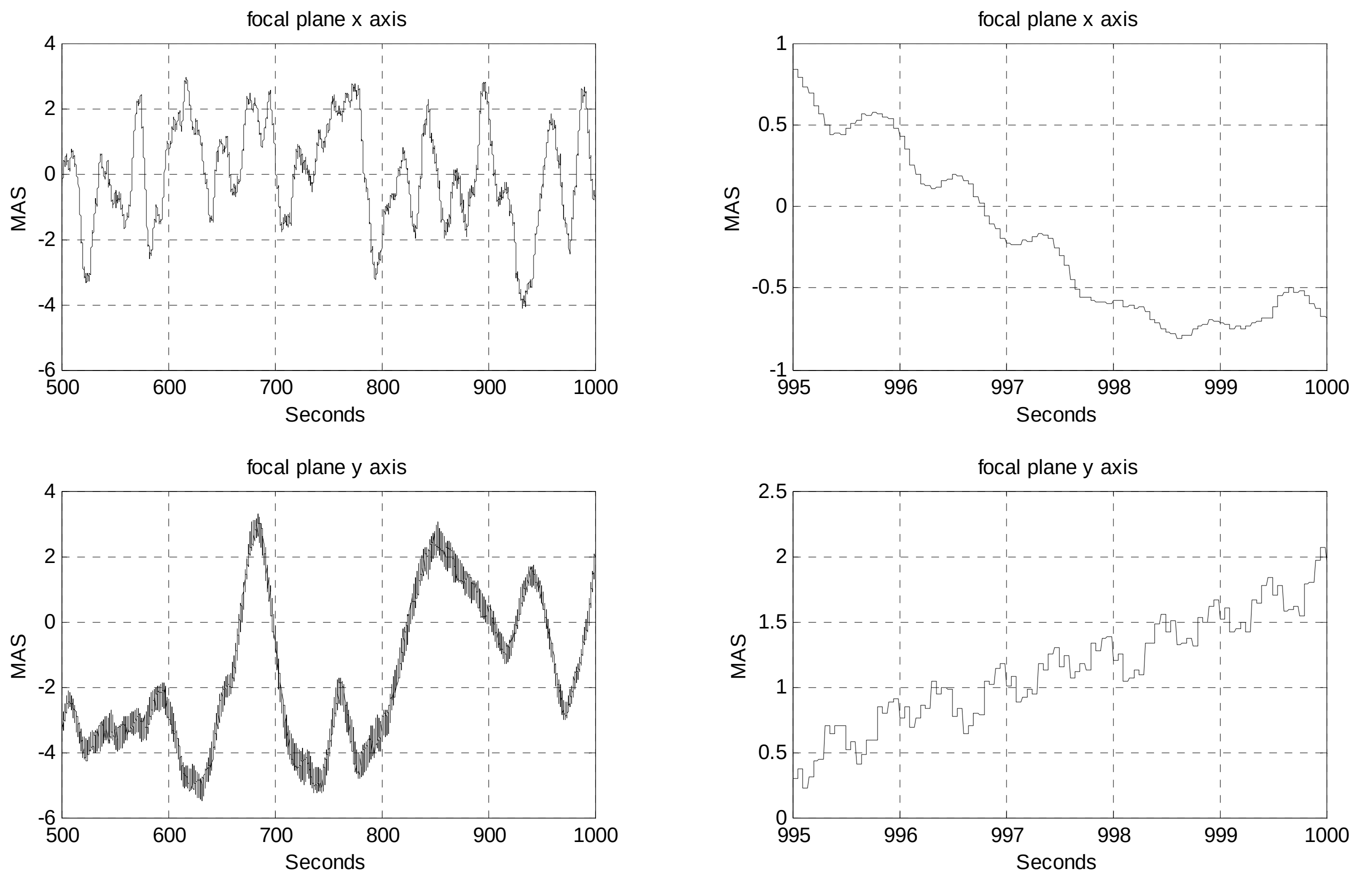
- **PID control w/ integrator anti wind-up**
- **Gain stabilized**
- **Feedforward used for slewing, spin-up & down, and H-dump**

Control-Loop Bandwidth (Hz)		
Configuration / Axis	9-meter	80-meter
X	0.04	0.01
Y	0.04	0.01
z	0.01	0.005

Simulation Results - 9-m Config.

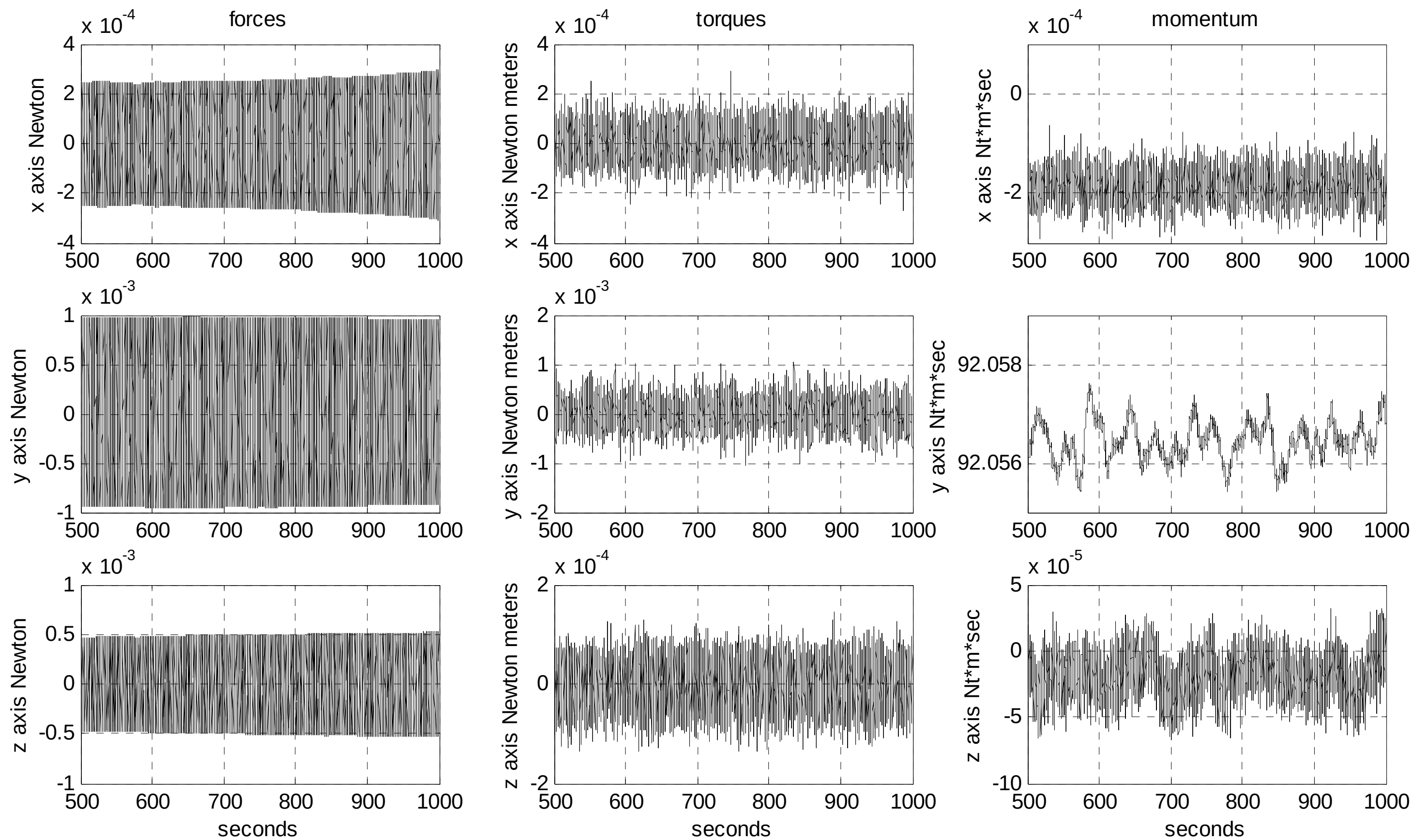
Centroid Image Motion on Quad-Cell Detector
Science Mode

2.7 mas-rms



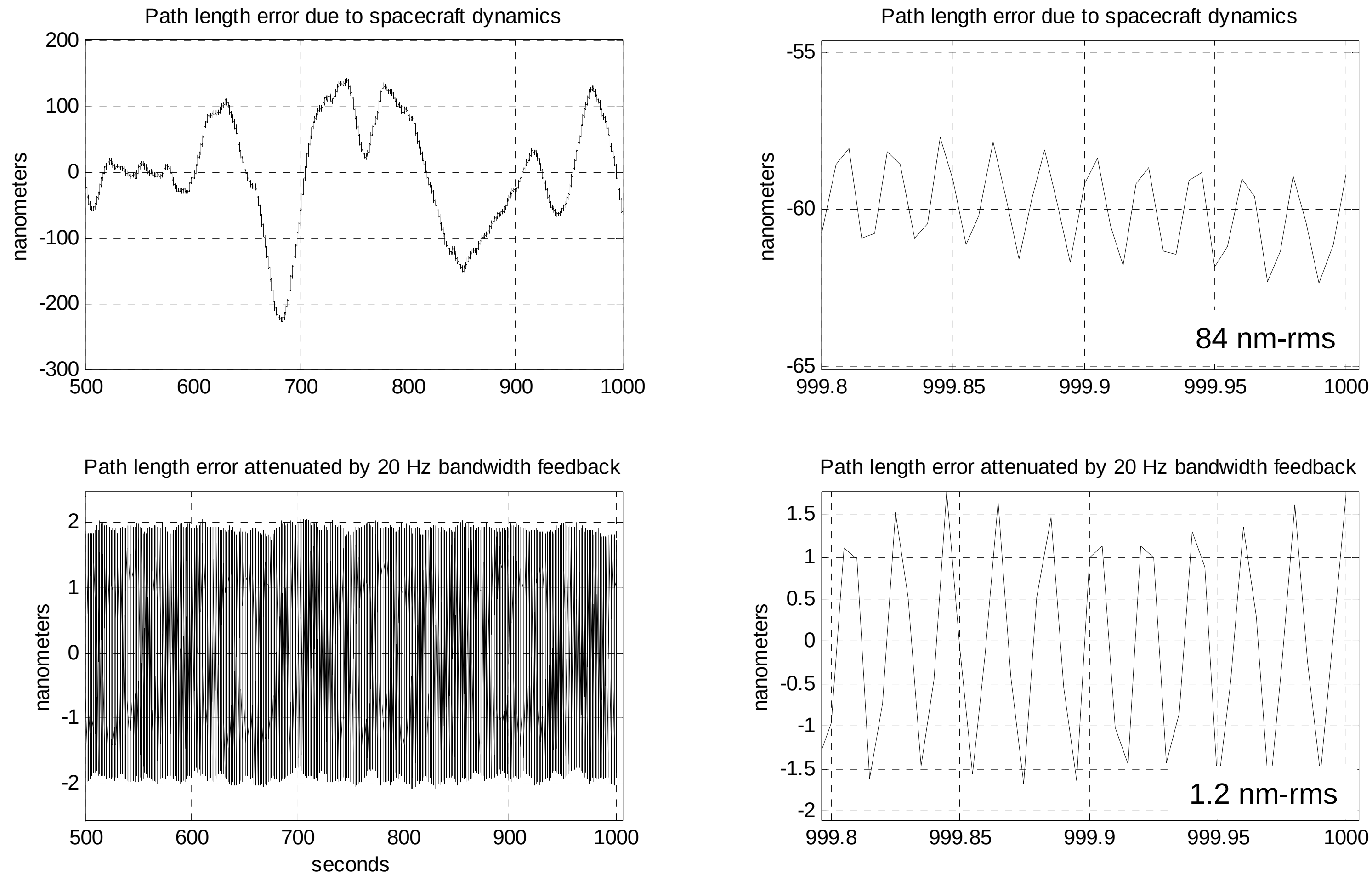
Simulation Results - 9-m Config.

Reaction Wheel Assembly - Science Mode



Simulation Results - 9-m Config.

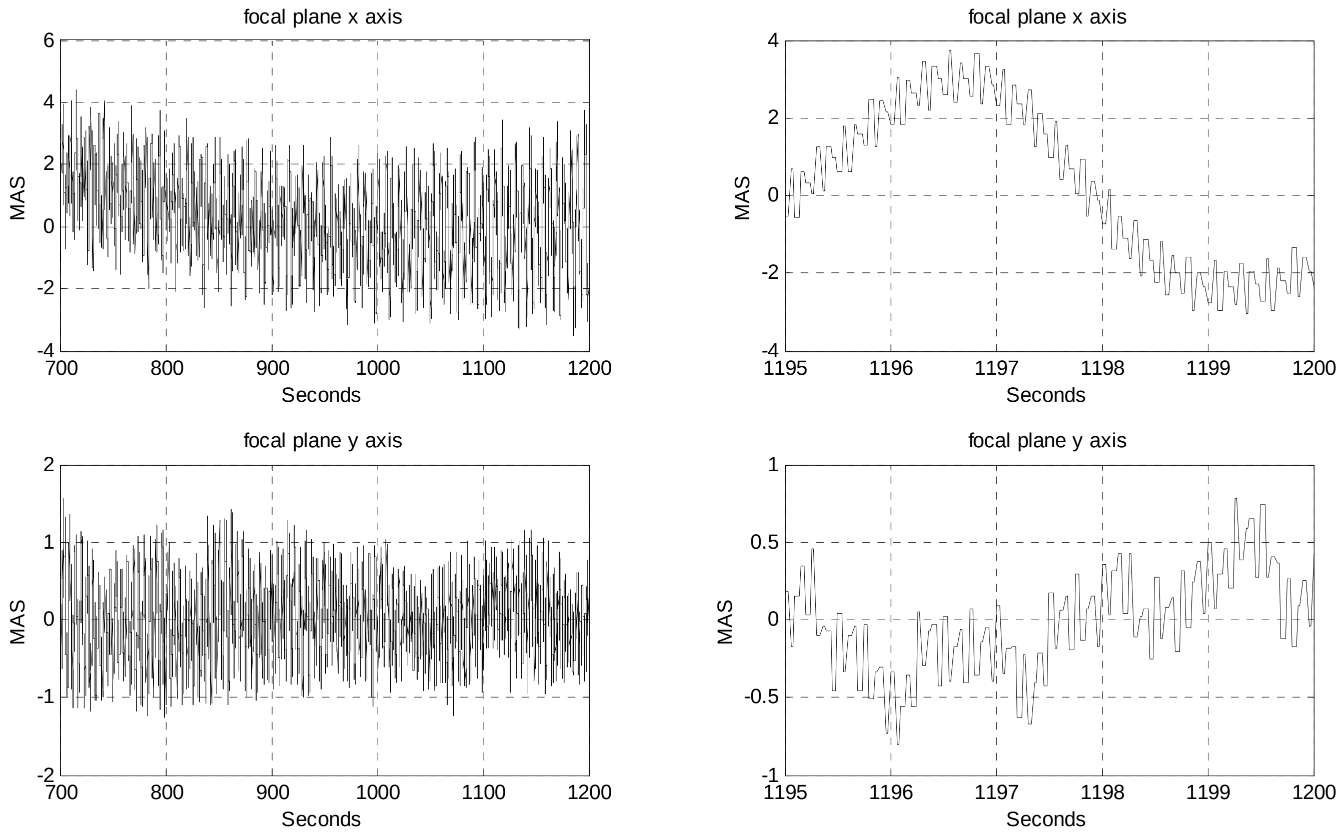
Raw and Attenuated Path Length - Science Mode



Simulation Results - 80-m Config.

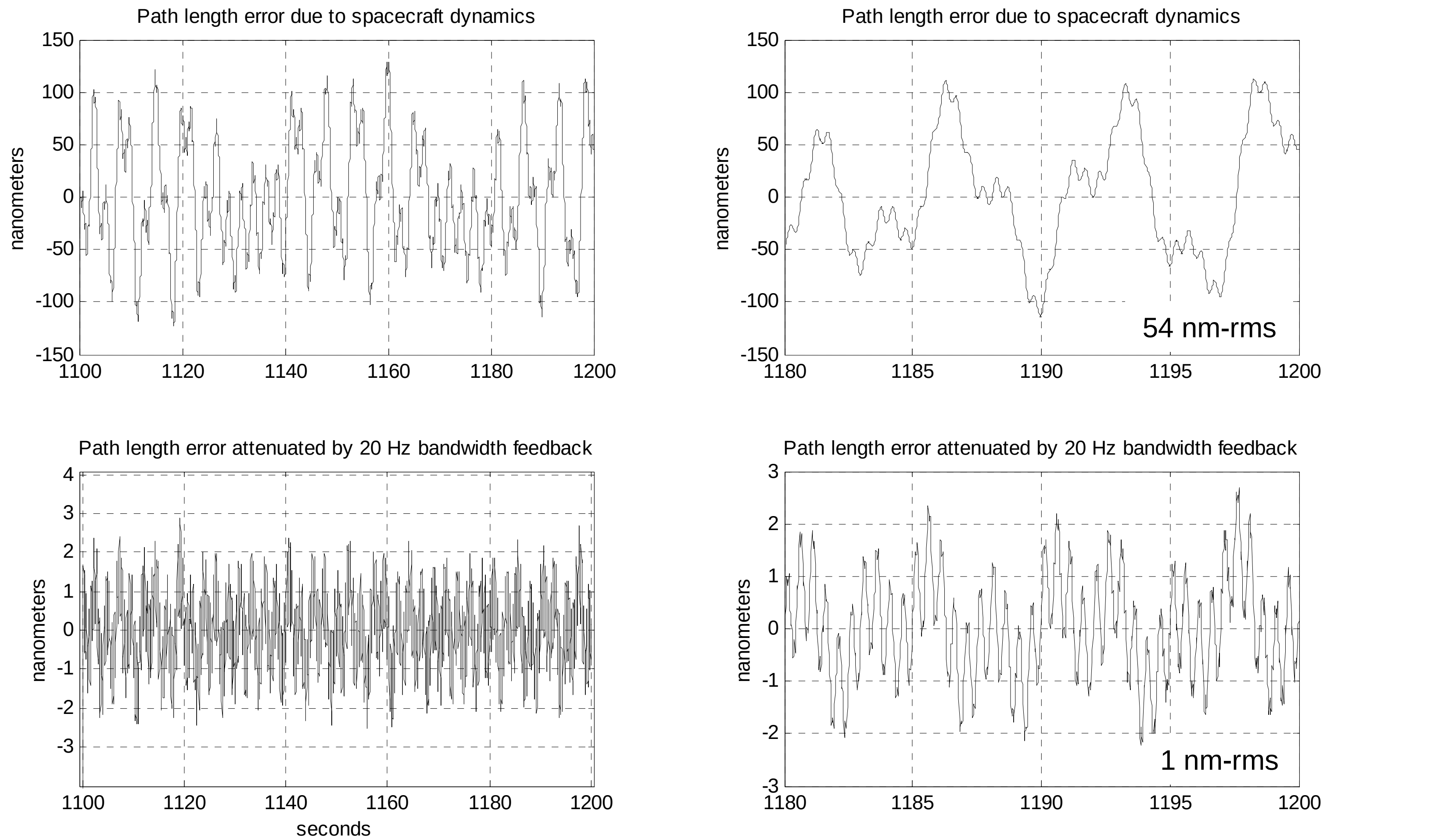
Centroid Image Motion on Quad-Cell Detector
Science Mode

1.4 mas-rms



Simulation Results - 80-m Config.

Raw and Attenuated Path Length - Science Mode



Performance Summary

	9-meter Configuration 9A	80-meter Configuration 80A
Requirements (rms)	82 mas & 7.2 nm	15 mas & 10.6 nm
Pointing Jitter (rms)	2.7 mas	1.4 mas
Raw Pathlength (rms)	84 nm	54 nm
Compensated Pathlength (rms)	1.2 nm	1 nm

GNC Hardware List
Ikonos Bus

Component	Vendor	Number	Unit Mass (kg)	Unit Power (W)	Features	Heritage
Star Tracker with Shade *	Ball CT-602	2	8.2	10.0	6 arc sec NEA 3.8 asec other errors	CT-601- Ikonos
Inertial Reference Unit	Litton Scalable SIRU	1	5.4	19.0	4-for-3 redundancy ARW =6.0E-3 a-s/$s^{1/2}$ RRW=5.0E-6 a-s/ $s^{3/2}$ NEA =2 arc sec	Single String SIRU- Ikonos
Reaction Wheel	Honeywell HR 4820	4	10.2	36 nominal, 165 peak	0.14 Nm Torque 65 Nms Momentum 4 units in 30 deg (to XY plane) pyramid	
Sun Sensor	LMSS	2	0.2	3.0	2 deg accuracy	Ikonos
Solar Array Drive Assembly	Schaeffer Magnetics	2	6.5	6.0	Includes solar array resolver	Iridium
Propulsion System	General Dynamics	12 thrusters	85 (system total)	40 W, 17 W for valves	12- 0.2 lbf hydrazine thrusters 10 kg hydrazine	A2100

* Payload will be used for fine attitude knowledge <= 0.02 asec

GNC Hardware List
SIRTF Bus

Subsystem Components	Quantity	Vendor	Unit Mass (kg)	Contingency (%)	Predicted Mass (kg)	Unit Power (W)	Features
Inertial Reference Unit**	2	Kearfott	13.7	2	14	17	3-axis (4 skewed axes)
							bias instability <0.003°/hr over 8 hrs
							ARW <53 μdeg $hr^{1/2}$
							0.005 asec resolution
Star Tracker with Shade*	2	Ball	8.2	25	10.3	10	6 asec NEA
							3.8 asec other errors
Reaction Wheels	4	Honeywell	10.2	25	12.8	36 nominal	0.14 Nm torque
						165 peak	65 Nms momentum
							4 units in 30° (to YZ plane) pyramid
Coarse Sun Sensors**	2	LMMS	0.6	2	0.61	2	2π sr FOV
							0.2° accuracy at boresight
Solar Array Drive Ass'y****	2	Schaeffer Magnetics	6.5	2	6.6	6	Includes Resolver
Propulsion system *****	12 thrusters	General Dynamics	85 (system total)	25	94	40 W total 17 W for valves	12- 0.2 lbf hydrazine thrusters
							10 kg hydrazine

* Payload will be used for fine attitude knowledge <= 0.02 asec
** Heritage SIRTF
*** Heritage IKONOS
**** Heritage Iridium
***** Heritage A2100

Risk Assessment

- **ACS / Vibration Mitigation (TRL 7)**
  - **Low/moderate risk**
    - **Basic ACS demonstrated in flight, mature hardware**
    - **Depending on configuration may require non-traditional approach**
      - **Second RWA**
      - **Rotating collectors/combiner truss**
- **Pointing jitter control (TRL 6)**
  - **Low risk, active jitter compensation using fast steering mirrors is mature technology**
  - **Technology is compatible with cryogenic application**
- **Optical path-length control (TRL 4)**
  - **Moderate technical risk**
  - **Concept for fringe tracking close to demonstration on Large Binocular Telescope**
  - **Need to demonstrate performance in expected on-orbit environment**
  - **Fall-back position for fringe tracking**
    - **Dithering based approach demonstrated at JPL**

Technology Development

- Configuration dependent
  - Sensors, TMDs and actuators compatible with cryogenic operation exist
  - Demonstrate reliability, end-of-life performance in relevant environment
    - Component level tests
  - For larger configurations demonstrate momentum management approach
    - Analysis
    - Laboratory demonstration
    - Relevant environment

- Fringe-tracking using phase plate is a key technology requiring development and demonstration
  - Close to demonstration on Large Binocular Telescope
  - Demonstration in relevant environment (~ 2 years)
    - Relevant vibration environment
    - Cryogenic operation
    - Vibration environment and cryogenic operation

TPF Systems Analysis

David W. Miller
Massachusetts Institute of Technology
Space Systems Laboratory

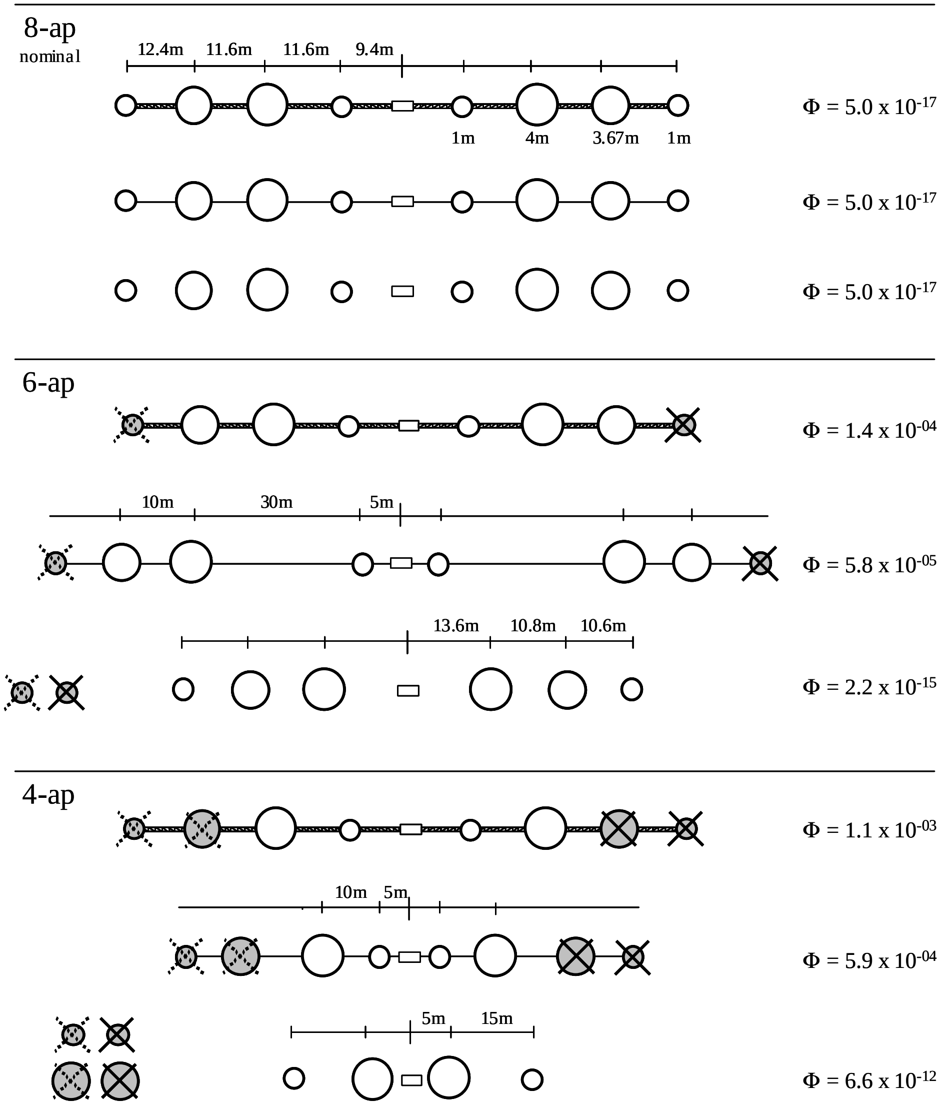
Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

GINA - Metrics Matrix

Trades \ Metrics	Isolation (Angular Resolution)	Rate (Images per unit time)	Integrity (SNR & **u-v coverage**)	Availability (Overhead time)
Orbit (**Earth Trailing, Halo, L_2**)	**N/A**	**Different noise environments & comm. delays influence rate**	**Different local zodical noise & solar thermal flux levels**	**Different comm. delays affect non-autonomous calibration**
Interferometer Type (SCI,SSI, **TSI**)	**SSI & TSI have flexibility of changing baselines**	**SSI prop. & TSI power sensitive to rate changes. Different imaging modes**	**SCI - dynamics noise, SSI - alignment noise, TSI - dyn. & alignment**	**Different safe mode complexity and unique calibration events**
Number of Apertures (4 to 10)	**More apertures help tuning of interferometer transmission**	**Increased collecting area improves rate**	**Tuning of transmission suppresses starlight and exo-zodi dust**	**Operational complexity & graceful degradation**
Size of Apertures (1 to 4 m in diameter; **4 to 8 m in length**)	**N/A**	**Increased collecting area improves rate**	**An increased size narrows FOV that will collect less local zodi**	**N/A**
Aperture Type (Circular or **Rectangular**)	**Interferometer transmission sensitive to aspect ratio**	**Longer dimension of rectangle enables quick u-v coverage**	**Rectangle has more mirror area on axis, better SCI - u-v coverage**	**N/A**
Interferometer Baseline **(30 - 120 m)**	**Baseline drives angular resolution & transmission tuning**	**N/A** Only as Isolation & Integrity drive rate	**Tuning of transmission suppresses starlight and exo-zodi dust**	**Calibration complexity increases w/ distance between elements**
Wavelength **(7,10,20 μm)**	**Transmission tuning less effective at longer wavelengths**	**N/A** Detections & spectroscopic images span 7-17 μm	**Longer wavelengths diminish null & increase instrument noise**	**N/A**

Legend
Aperture Physics
DOCS
Environment
GINA
Operations
Spacecraft Bus

Graceful Degradation



(illustration not to scale)

- ***Graceful Degradation***

  Architectures that can reconfigured without a substantial loss in performance are said to degrade gracefully

  -SCIs have fixed aperture position, severely limiting performance as components fail

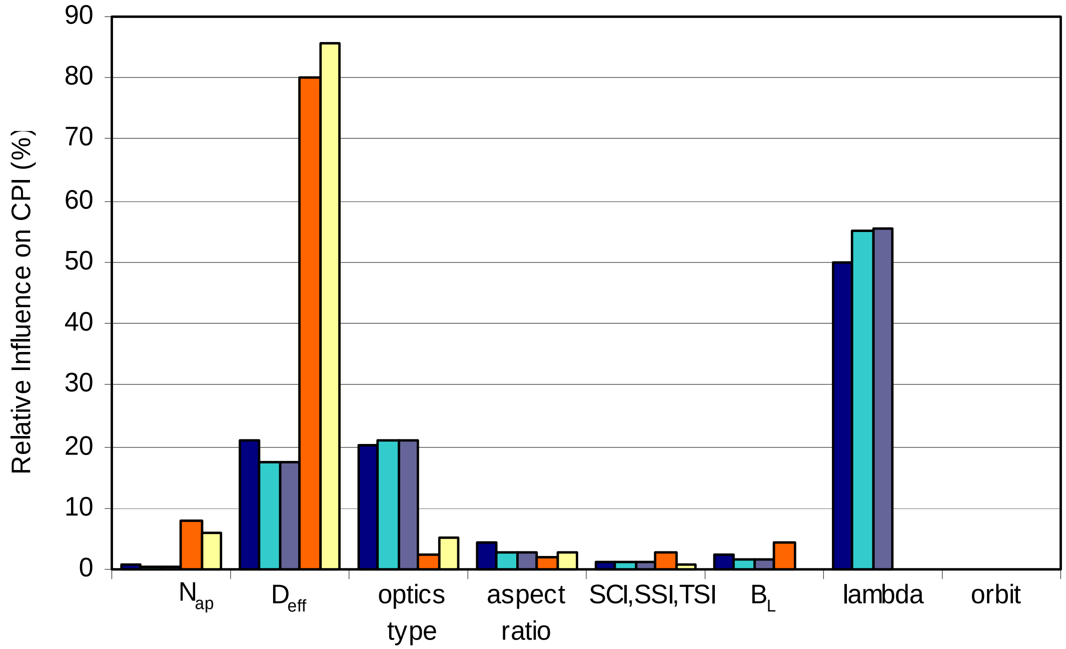
  -TSI apertures can be reconfigured in a line, improving performance in partially failed states

  -SSI apertures can maneuvered freely, giving it an even better performance during degradation

- ***Sub-optimization***

  If each collector pair has a unique size, there are (n/2)!/2! unique partially failed states. Each state corresponds to a potential aperture re-configuration, a sub-optimization, which differs depending on the interferometer type.

Performance - ANOVA



Less Influential Variables

- **Interferometer Baseline**

  Baseline drives local performance & cost effects. For a common set of variables, baseline changes can always improve CPI (but only by a relatively small amount)

- **Orbit (Halo, Earth Trailing, and L_2)**

  For the chosen orbits, there are only negligible changes in local-zodi & detection performance.

More Influential Variables

- **Architecture Area**

  Drives transmissivity function and imaging model. Most influential design variable.

- **Aperture Type**

  Circular optics out-perform strips in detection operations. Modest benefit in imaging (competing factors).

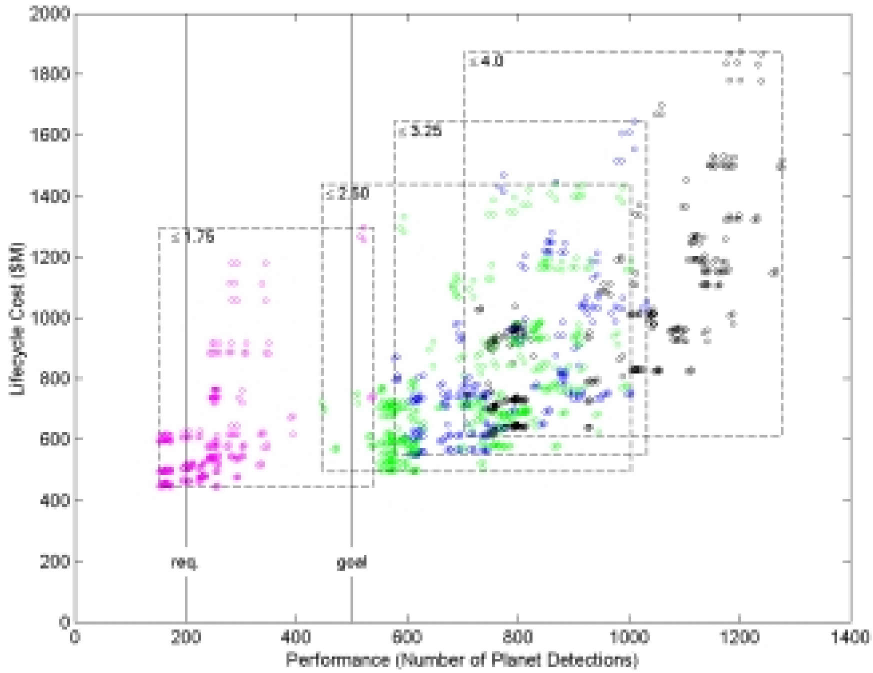
- **Interferometer Type**

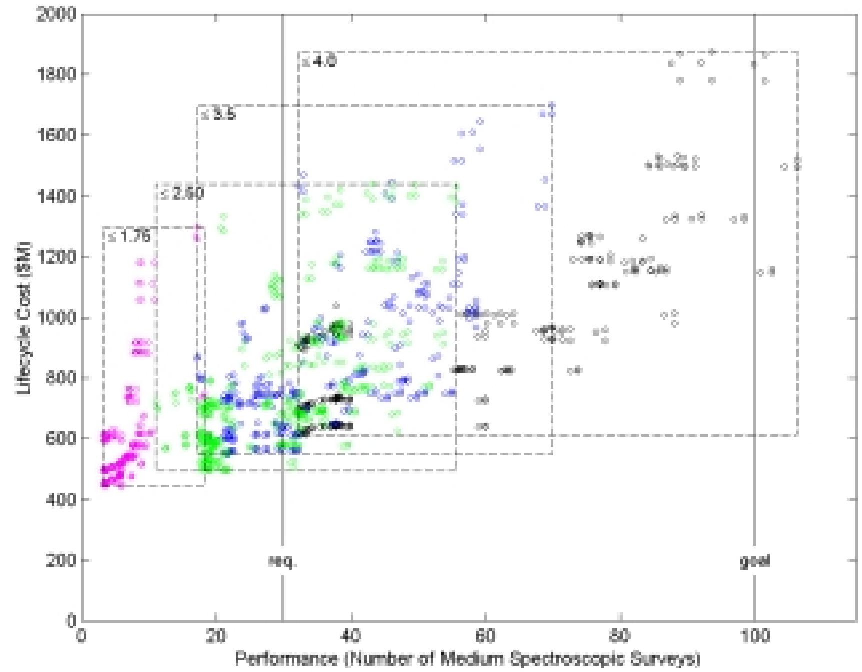
  Architecture a clear cost driver. Graceful degradation effect on performance – a function of failure rate.

- **Wavelength**

  Most influential in detection ops, yet observations must span λ range – unless the mission requirements are compromised.

Planet Detection - D_{eff}





Influence of D_{eff} on Detection Operations

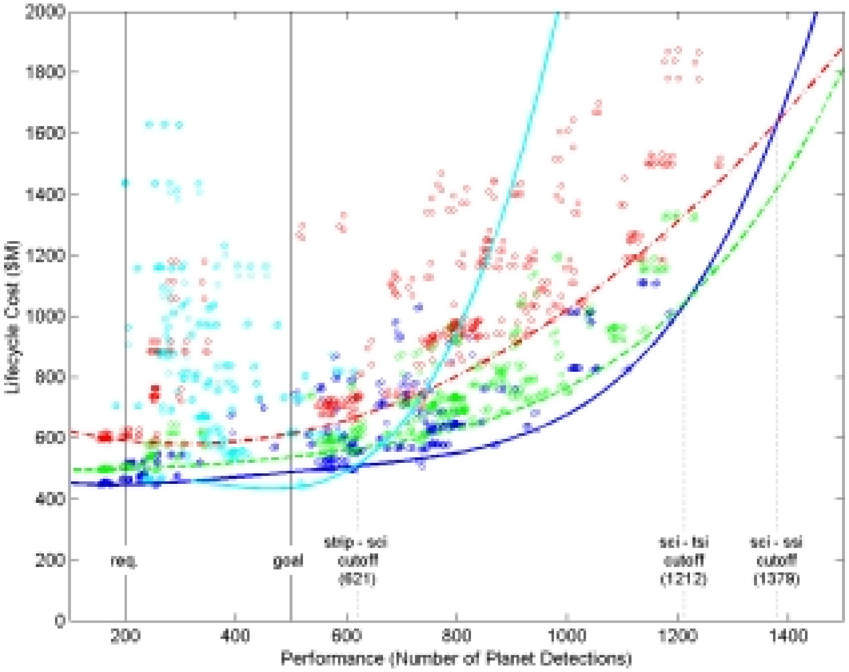
- *Effective diameter (D_{eff}) scales architecture area, driving the transmissivity function and cost (because it is an indication of payload size and complexity).*
- *D_{eff} influences cost, performance, and CPI.*
- *According to ANOVA, increasing D_{eff} is the **most cost effective** way to increase performance. The other option is to add apertures which is an expensive endeavor*

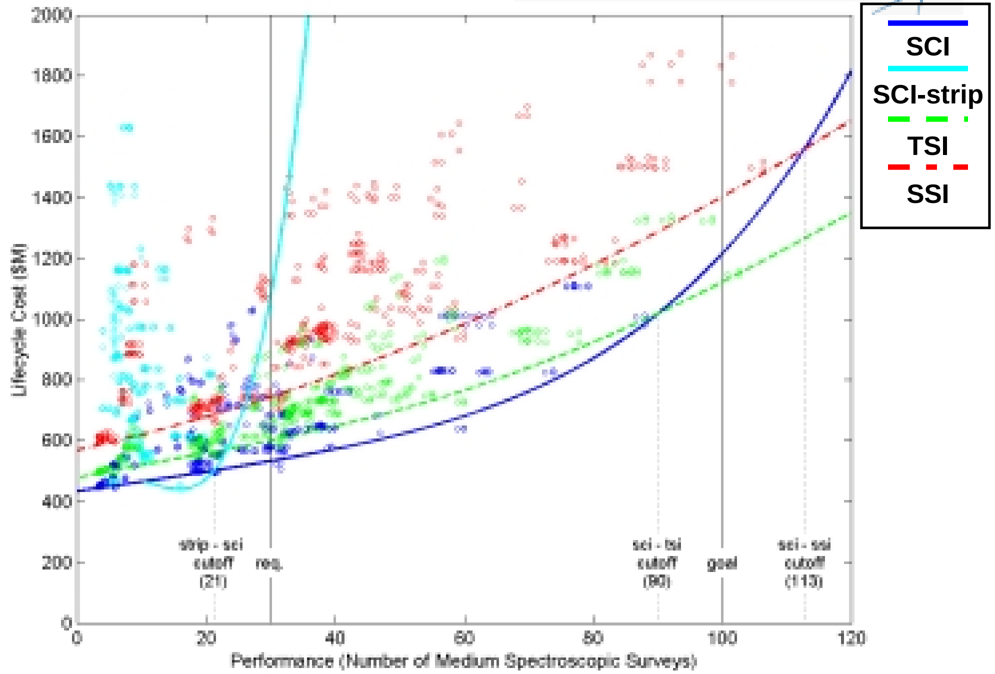
Requirements per Operational Mode

- *Planet detection requirements can be met with the smallest aperture size (D_{eff} = 1).*
- *Medium and Deep spectroscopy requirements demand much larger apertures due to the distortional time spent in each mode.*
- *Medium Spectroscopy requires D_{eff} > 2.0m and Deep Spectroscopy (not shown) requires D_{eff} >3.5m*
- *This mismatch motivates **timeline optimization***

TPF
Terrestrial Planet Finder

Planet Detection - SSI,TSI,SCI





Influence of Interferometer type

– *Interferometer type is influential in cost but not in performance. Hence the vertical (and not horizontal) separation of the pareto fronts.*

Interferometer type Evaluation

– ***SCI** is preferred for detection operations. In some cases, SCI-strips offer a cost benefit because its assumed that two strips are cut from a single circle aperture.*

Graceful Degradation of SCI, TSI, & SSI

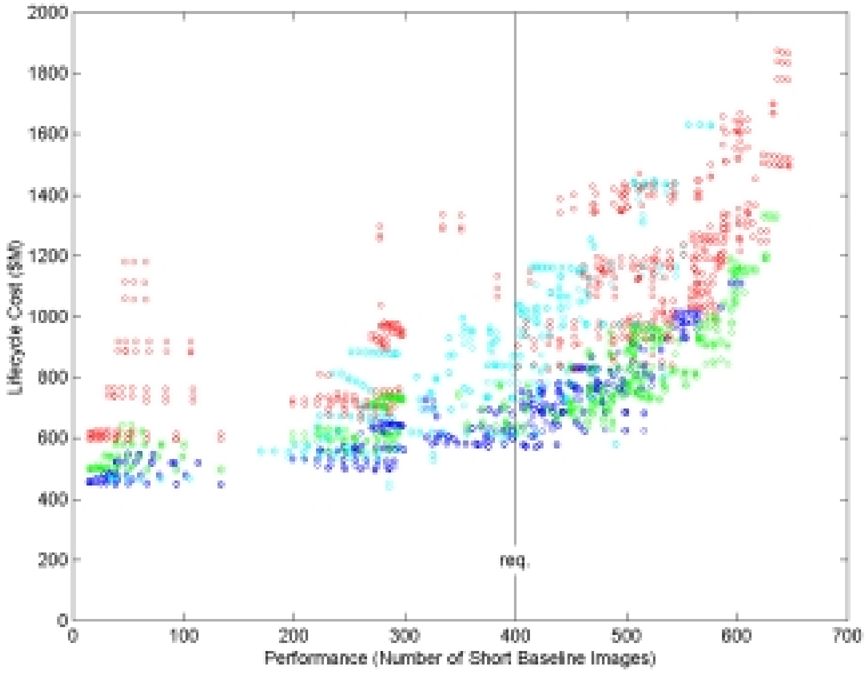
– *Nominally, each interferometer type will have the same performance. It is in the presence of failures that it influences performance*

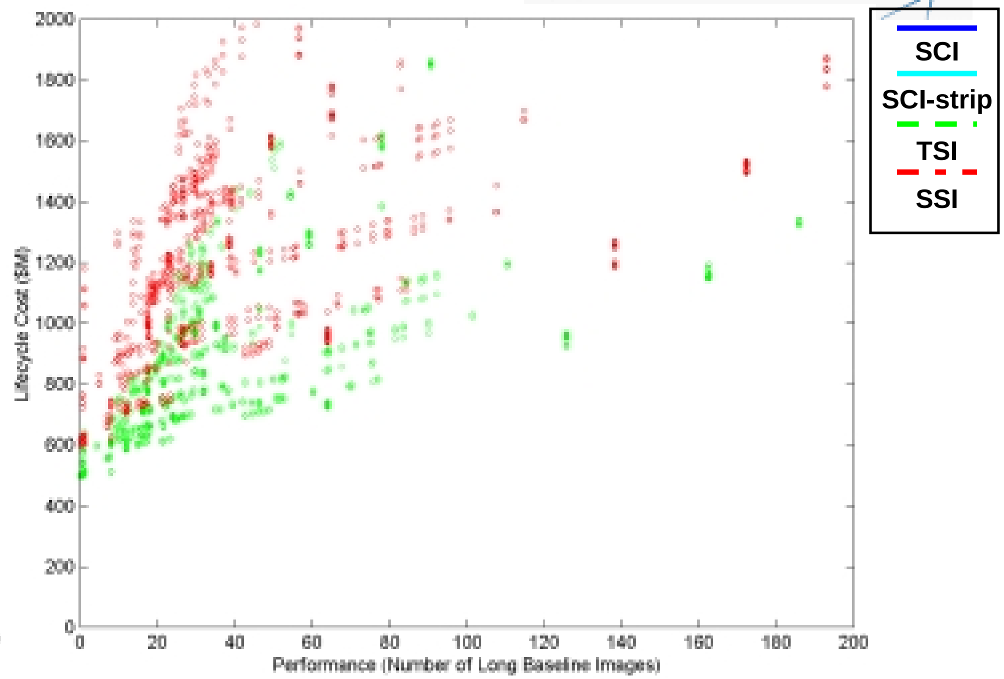
– *SCIs are fixed, severely limiting performance as soon as one collector fails.*

– *TSIs can be reconfigured in a line, improving performance in partially failed states.*

– *SSIs have an additional degree of freedom (dof) giving it an even better performance during degradation.*

Astrophysical Img. - SSI,TSI,SCI





Interferometer Type Evaluation

- ***SCIs*** *are preferred for short b/l images but with reservations concerning image quality.*
- ***TSIs*** *are preferred for long b/l images.*

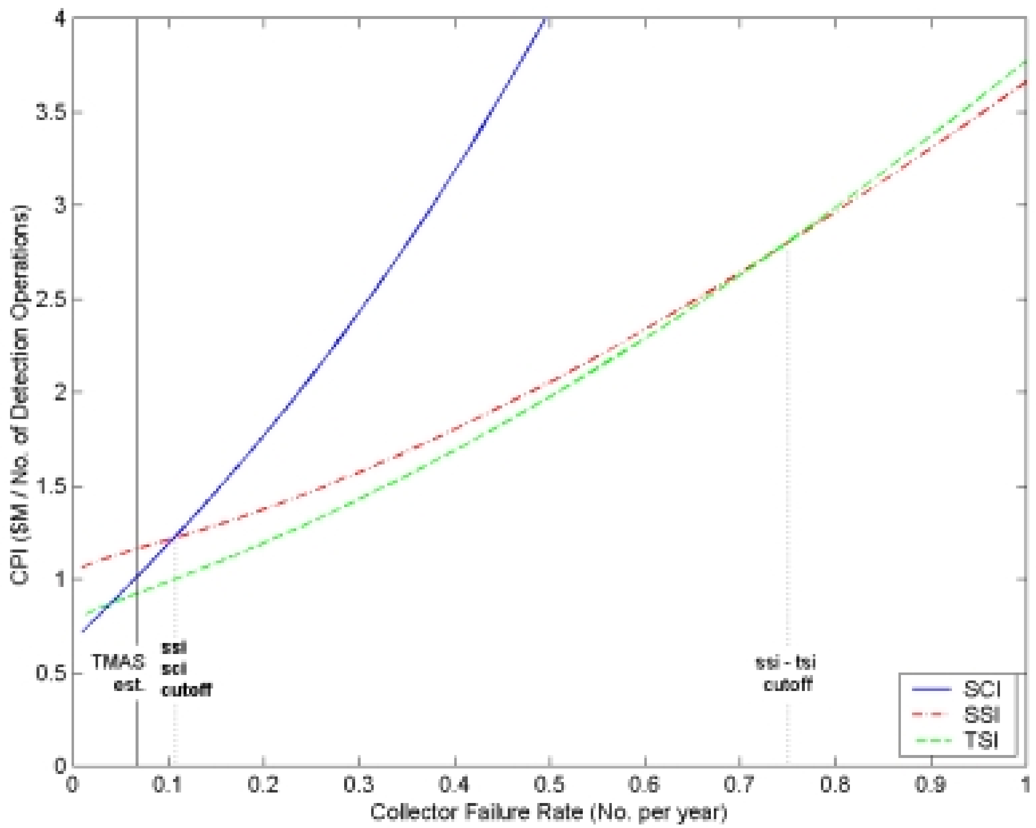
Interferometer Type & u-v coverage

- *The quality of a SCI image is limited by the amount mirror area on its axis.*
- *SSI and TSI arrays sidestep this limitation because they can be reconfigured and completely fill the u-v plane.*

Graceful Degradation Modeling

- *If a collector fails, the integration time model simply recalculates the number of orientations it would take to fill the u-v plane, assuming the array can complete the necessary maneuvers.*
- *Array geometry, failure order, potential baseline reduction (for SCIs) and drop in image quality not modeled.*
- *Some u-v coverage calculations archived in Makins et al, 2001 but only for architectures that performed well in CPI.*

Regimes Favoring SSI



This plot shows the adaptability of CPI to changes in the collector failure rate for a specific architecture: 8-apertures, 110m baseline, variable-sized optics. Care should be taken when extrapolating this trend to other architectures in other regions of the trade space.

- **Long Baselines**

  As baseline increases, truss and/or tether mass becomes prohibitive.

  Longer baselines also increase collector centripetal acceleration and propellant - but a lower rate.

- **Slow Rotation Rates**

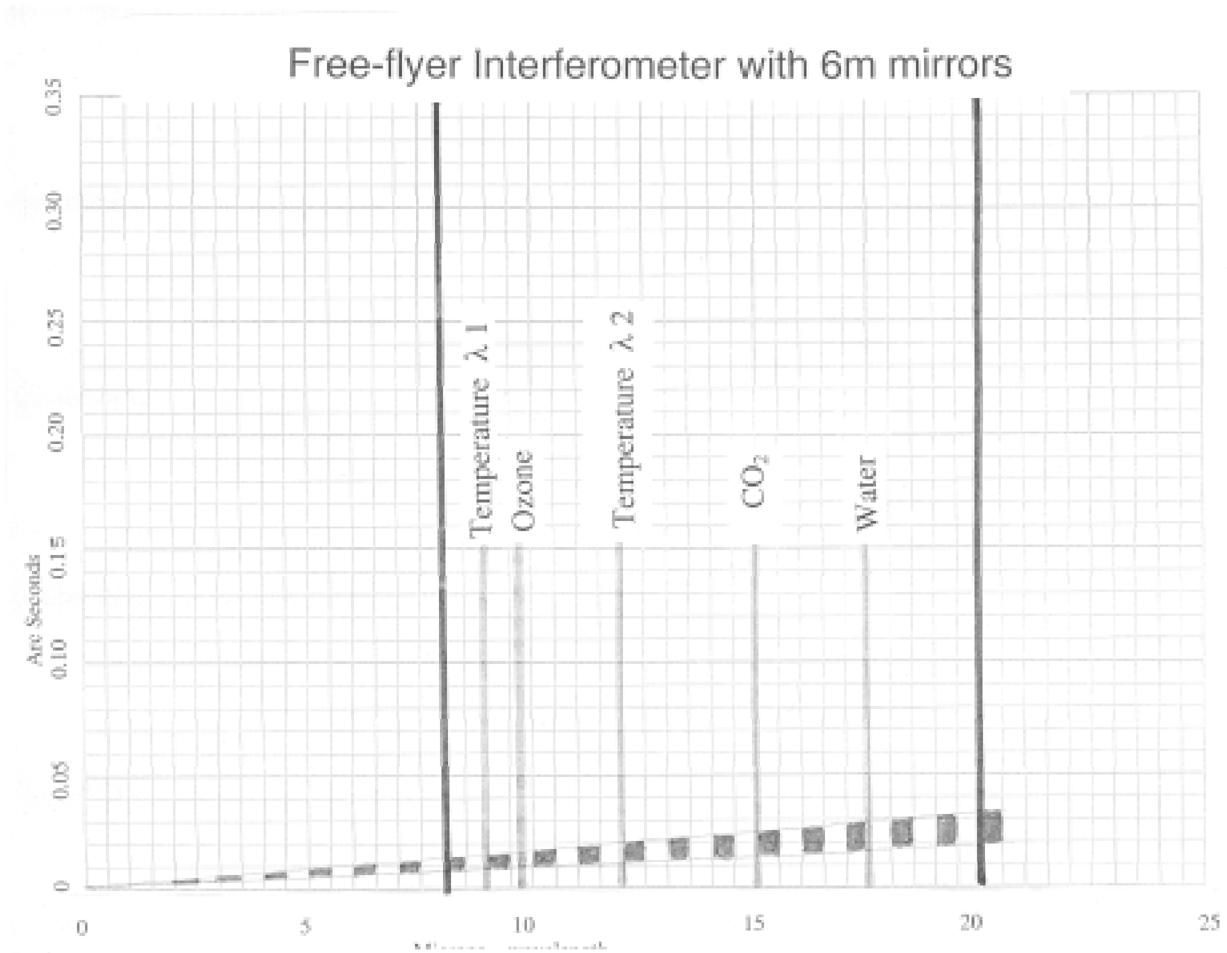
  As rotation rate decreases, centripetal acceleration for SSIs decreases. This drives down propellant and cost.

- **Risk prone Missions**

  As failure rate increases, SSI shows its graceful degradation capability, especially for arrays with variable-sized optics

  SSI architectures are preferred over SCI when failure rate is greater than 1/10 year $^{-1}$

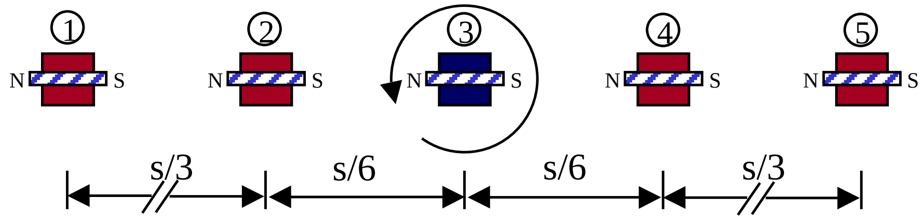
Free-Flyer with 6m mirrors



Conclusions

- A 4-element structurally connected interferometer with D>2m **could meet a majority of the requirements** – planet detection, medium spectroscopy and short baseline imaging.
- The remaining requirements – deep spectroscopy and long baseline imaging may be met **if the operations timeline is optimized.**
- Tethered spacecraft interferometers appear to be a viable compromise between SCI and SSI although the dynamics and control complexity has not been modeled.
- While the technology for SSI is tractable, the aggressive maneuver (rotation) severely limits science throughput limiting SSI to longer baseline science. Key technologies are
  - micro-spacecraft technology
  - electromagnetic formation flight
  - propellant replenishment
  - autonomous fleet control

EMFF Case Study Parameters



$$F_{cent} = \frac{m_o s \omega^2}{2}$$

$$F_{M_{12}} = \frac{3}{2}\mu_o \pi \frac{n_1 n_2 i_1 i_2 \chi^2 R^4}{s^4}$$

- Array is to rotate at a fixed rotation rate (ω = 1rev/2 hours)
- All collector spacecraft have same EM core and coil design
- Force balancing equations:

$$F_{cent_1} = F_{M_{12}} + F_{M_{13}} + F_{M_{14}} + F_{M_{15}}$$

$$F_{cent_2} = -F_{M_{21}} + F_{M_{23}} + F_{M_{24}} + F_{M_{25}}$$

EM mass components

$$m_{sc} = m_{dry} + m_{sa} + m_{core} + m_{coil}$$

TPF spacecraft* (*m*$_{dry}$)

Collector Spacecraft	
Dry	600 kg, 268 W
Propulsion	96 kg, 300 W
Propellant	35 kg
Combiner Spacecraft	
Dry	568 kg, 687 W
Propulsion	96 kg, 300 W
Propellant	23 kg

Solar Array (*m*$_{sa}$)

Power to mass conv	25 W kg^{-1}

Steel core (*m*$_{core}$)

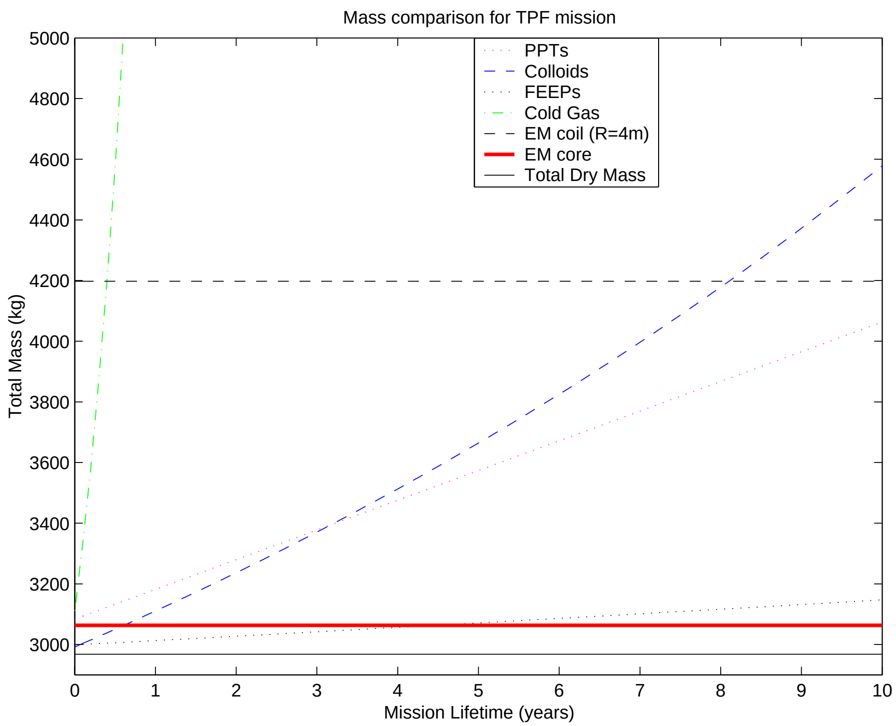
Density (ρ_{St})	7750 kg m^{-3}
Relative permeability (♍)	3000
Core aspect ratio (α)	0.1

Copper coil (*m*$_{coil}$)

Density (ρ_{Cu})	8950 kg m^{-3}
Resistivity (ρ)	1.7×10^{-8} Ωm

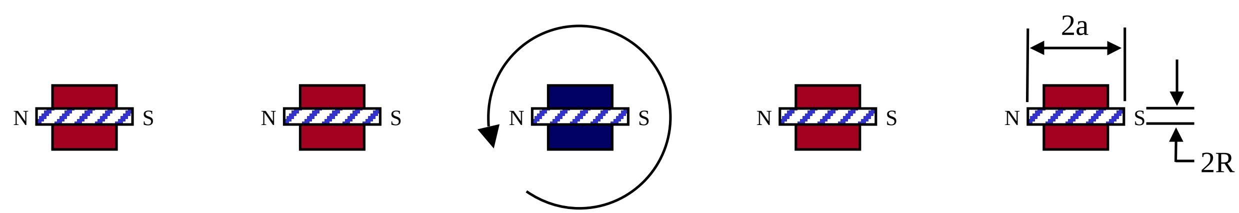
*Source: TPF Book (JPL 99-3)

Current Design with Paramagnetic Core

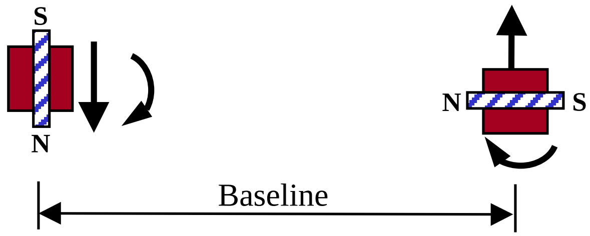


- Minimum system mass design can be determined
- Increasing core radius increases magnetic force (~ R^4) while reducing power required
- A balance between
  - reducing solar array and coil mass
  - increasing core mass

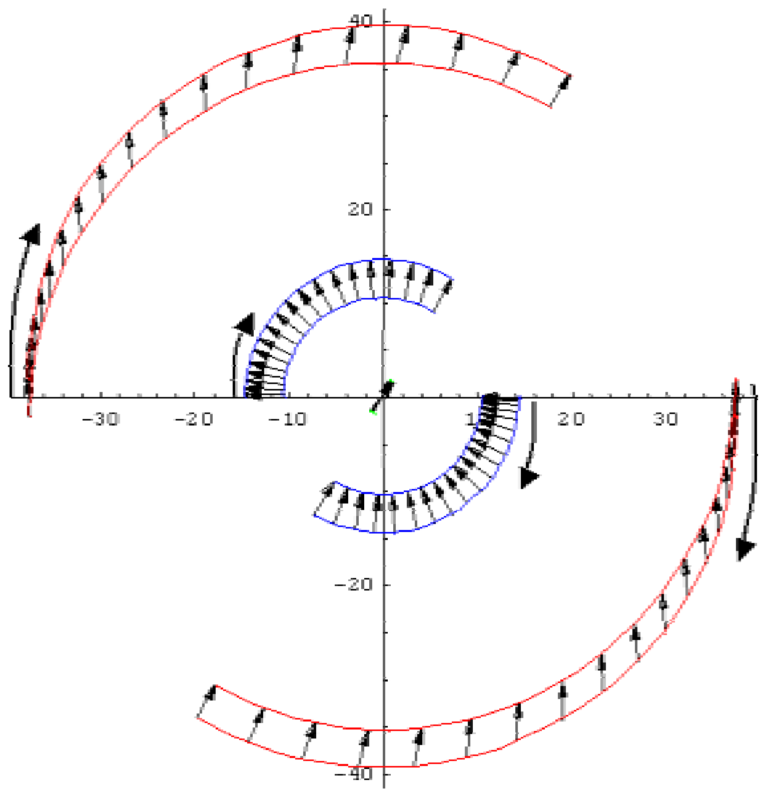
		3	218	197	**Power (W)**
		40	2000	2000	**N (turns)**
		9.6	13.4	12.7	**Current (A)**
		20.5	20.5	20.5	**R (mm)**
		41	41	41	**2a (cm)**
		0.9	1.1	1.1	**r (mm)**
$F_{cent} = -17.72$	$F_{12} = 16.45$	$F_{13} = 0.05$	$F_{14} = 1.03$	$F_{15} = 0.19$	**$F_{on\ 1}$ (mN)**
$F_{21} = -16.45$	$F_{cent} = -5.91$	$F_{23} = 3.96$	$F_{24} = 17.37$	$F_{25} = 1.03$	**$F_{on\ 2}$ (mN)**

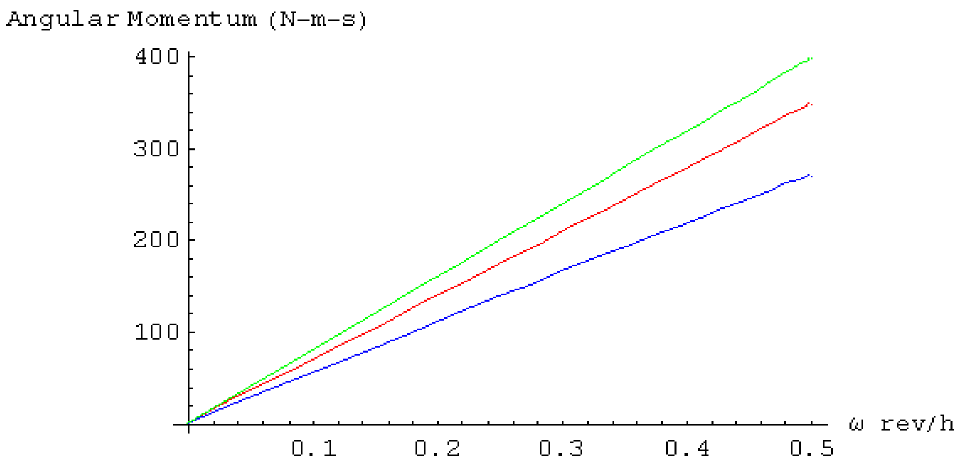


Using Electromagnetics for Spin-Up



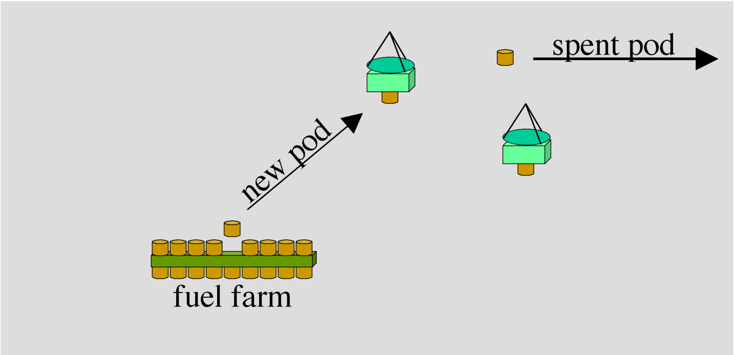
- By properly orientating the poles of each electromagnet, the cluster can be spun to a specified angular velocity without the need for propellant.
- Reaction wheels must be used to capture the change in angular momentum.
- The results are shown for a five S/C config., 600kg per S/C, 75m baseline, accel to 0.5 rev/hr in one hour.

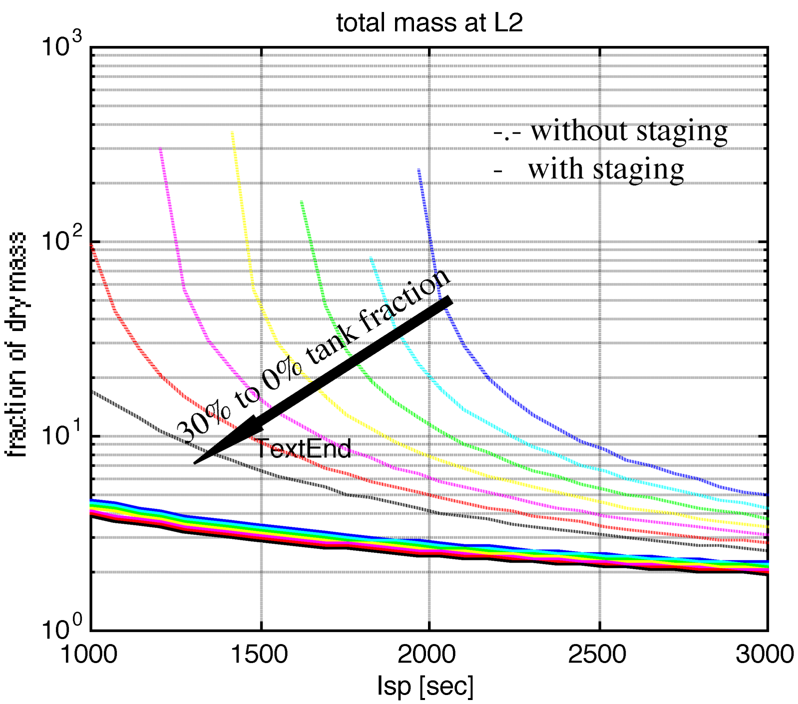




Fuel Replenishment: Imaging

- 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





Formation Flight Requirements

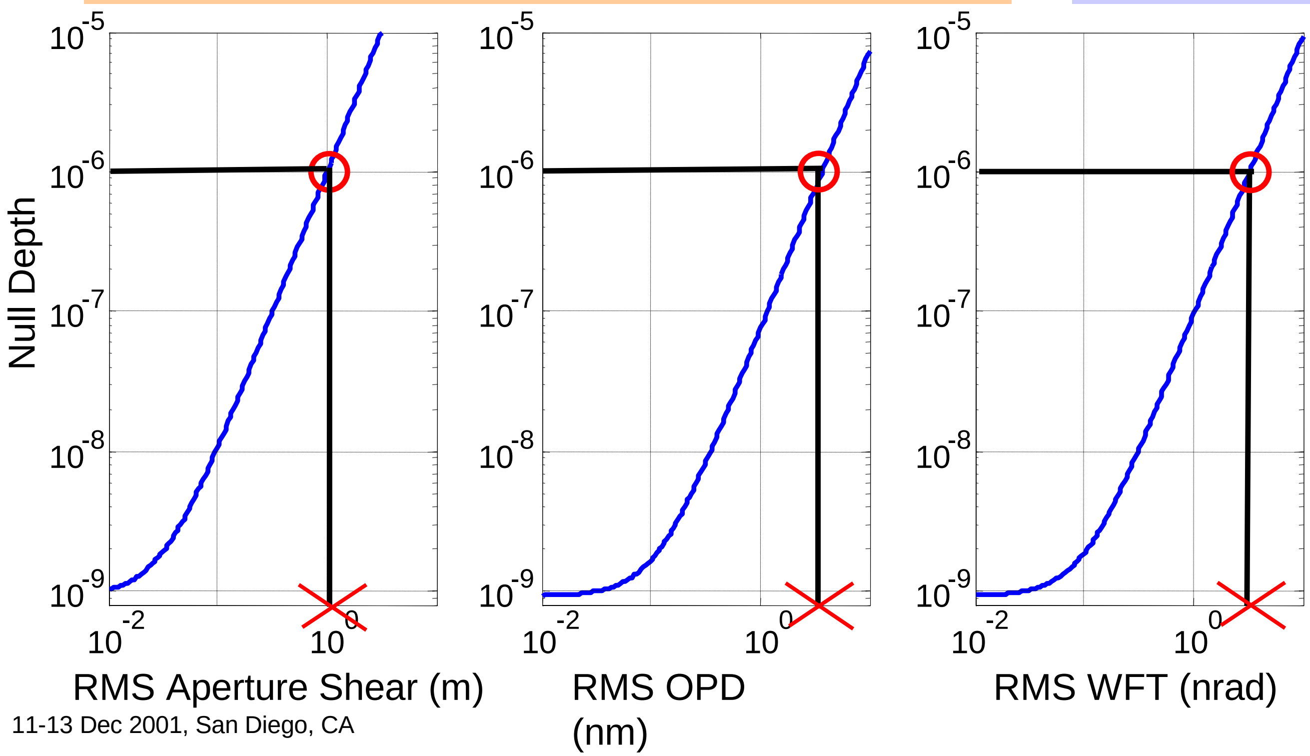
- Describe transmissivity function of a two-dimensional aperture array as [Mennesson, 1997]

$$\Theta = \left| \sum_{k=1}^{N} G_k(\theta_k)\exp\left(j\left[\frac{2\pi r}{\lambda} x_k \cos(\theta) + \frac{2\pi r}{\lambda} y_k \sin(\theta) + \phi_k \right] \right) \right|^2$$

- Time-averaged, perturbation analysis:

$$\Theta \approx \Theta_o + \sum_{\substack{m= \\ \text{all } \delta q}} \frac{\partial \Theta}{\partial \delta q_m}\delta q_m + \frac{1}{2}\sum_{\substack{m= \\ \text{all } \delta q}} \sum_{\substack{n= \\ \text{all } \delta q}} \frac{\partial^2 \Theta}{\partial \delta q_m \partial \delta q_n}\delta q_m \delta q_n$$

$$\langle \Theta \rangle \approx \Theta_o + \frac{1}{2}\sum_{\substack{m= \\ \forall \delta q}} \sum_{\substack{n= \\ \forall \delta q}} \frac{\partial^2 \Theta}{\partial \delta q_m \partial \delta q_n}\sigma^2_{q_m q_n}$$



- Sample Case:
  - 75 m baseline
  - 4 aperture 1-2—2-1
  - λ=12 µm
- RMS performance to achieve 10^{-6} ND:

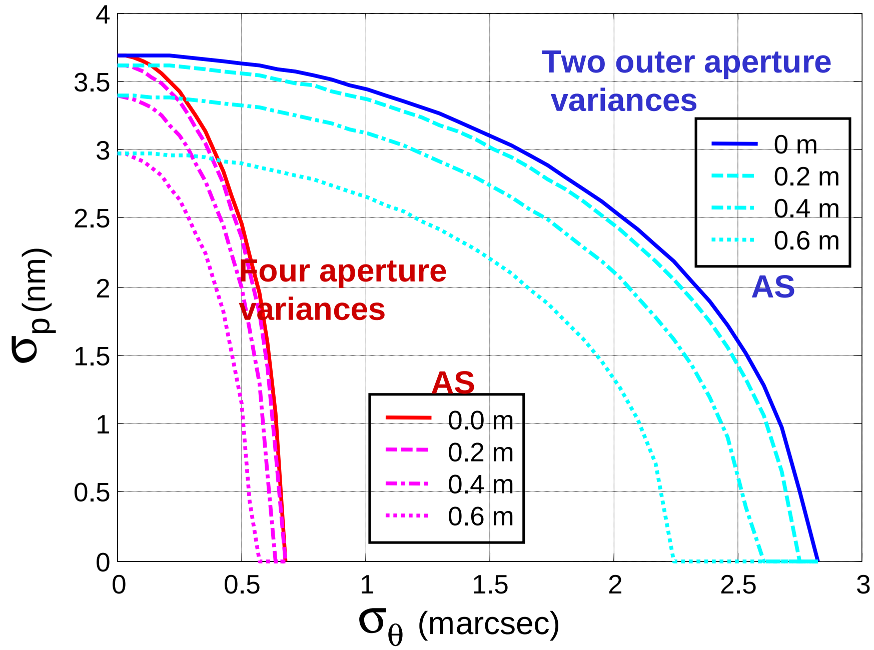
$$\sigma_{AS} = 1.0\ \text{m}$$

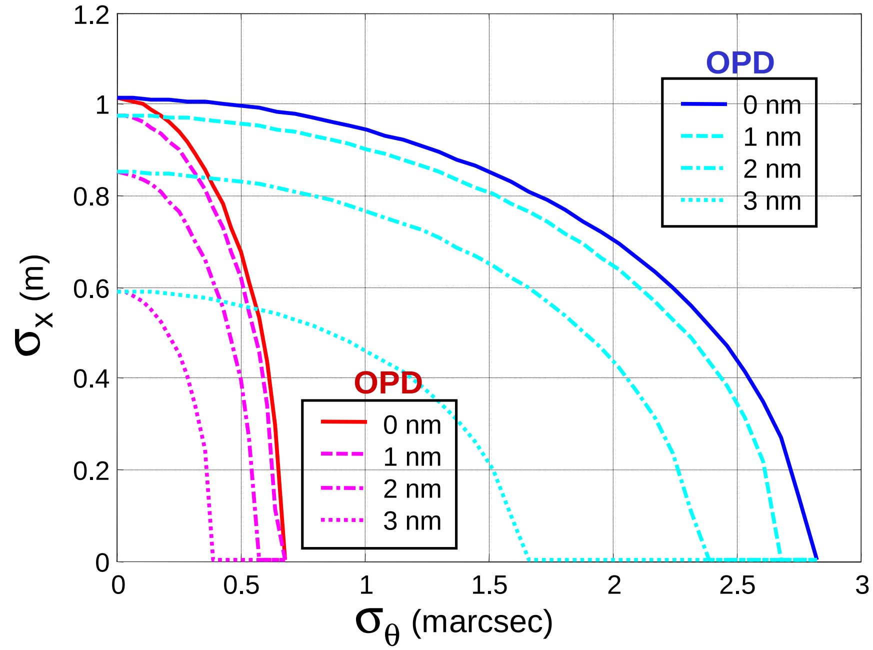
$$\sigma_{OPD} = 3.7\ \text{nm}$$

$$\sigma_{WFT} = 3.3\ \text{nrad}$$

Stability Requirement Trades

- Allows careful requirements allocation holding ND constant (10^{-6})
  - Red: all four apertures have equal, uncorrelated rotations
  - Blue: only outer two apertures have rotations
- Allowable AS (B=75m) for 1 amin FSM stroke is 1 cm. Otherwise, could relax station-keeping requirement.





Formation Flying Technology

Bob Dougherty

Lockheed Martin Missiles & Space Company

Advanced Concepts Group, Palo Alto

Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

Technology Areas for Formation Flyers

Mission Operations

- (A.1) Guidance / Operations
- (A.2) Navigation (Formation Control Algorithms)
- (A.3) Control (Algorithms)
- (A.4) Fault Detection Isolation and Recovery (FDIR)

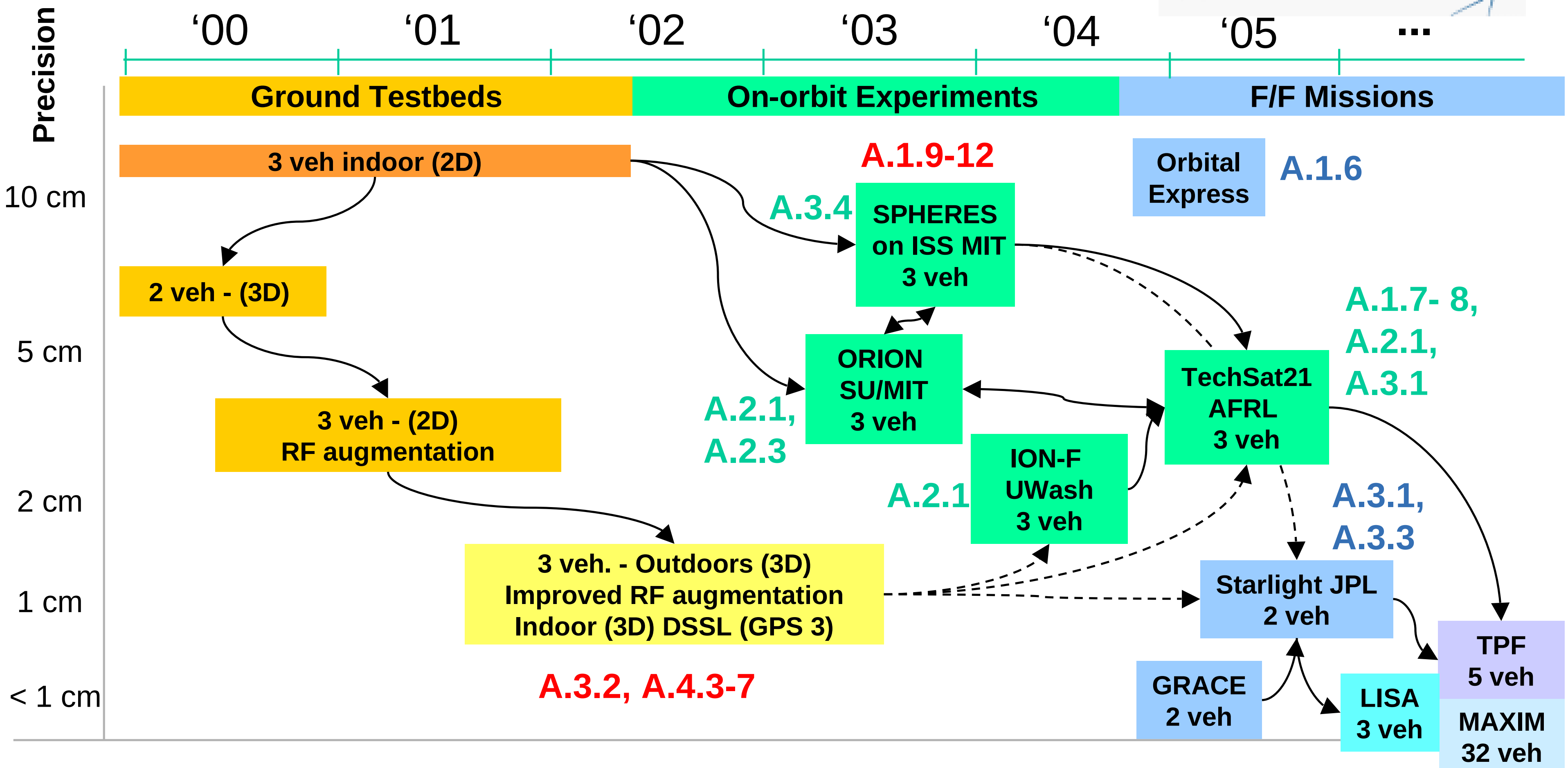
Intra-Cluster Communications

- (B.1) Navigation
- (B.2) Science

Spacecraft Infrastructure

- (C.1) Data Bus
- (C.2) Distributed Computing
- (C.3) Data Storage

Formation Flying Roadmap



(A.1) Guidance / Operations

(A.2) Navigation (Formation Control Algorithms)

(A.3) Control (Algorithms)

(A.4) Fault Detection Isolation and Recovery (FDIR)

(B.2) Science Intra-Cluster Communications

Summary - FF Technology Assessment

		TRL Assessment			
Technology Areas		Available (7-9)	Qualifable (4-6)	Develop (1-3)	Critical Technologies
A	Mission Operations				
	Guidance/Operations	X	X	*	Autonomous Operations {Calibration, Planning}
	Navigation	X	X	*	Distributed Control Algorithms
	Control	X	X	*	Drift Through Fringe Tracking & Electromagnetic Control
	FDIR	X	X	*	Autonomous Reconfiguration; Coordinated Safing
B	Intra-Cluster Communications				
	Navigation	X	X	X	RF-Base Transceivers, Ultra Wide Band & Optical
	Science	X	X	*	Node Control and Configuration
C	Spacecraft Infrastructure				
	DataBus	X	X	X	StrongARM, Mongoose V, 750 PowerPC
	Distributed Computing	X	X	X	Distributed Process Architecture
	Data Storage	X	X	X	RAM Disks (100GB)

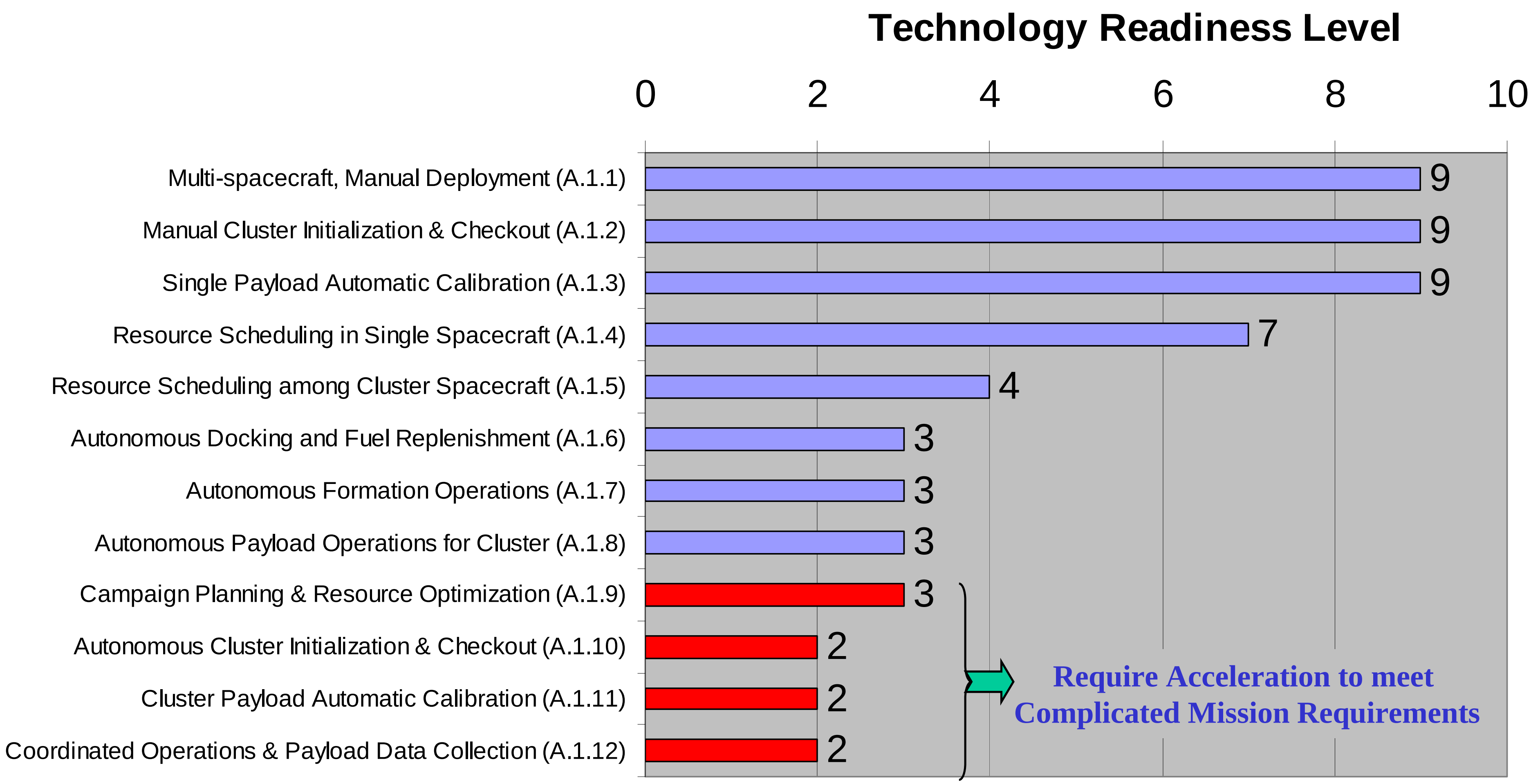
Key:
X - Being Developed
* - Requires Acceleration

Development of These Key Technologies Will Enable TPF

Technology Readiness Levels

TRL 1	Basic principles observed and reported	Basic Research
TRL 2	Technology concept and/or application formulated	
TRL 3	Analytical and experimental critical function and/or characteristic proof-of-concept	
TRL 4	Component and/or breadboard validation in laboratory environment	Applied Research
TRL 5	Component and/or breadboard validation in relevant environment	
TRL 6	System/subsystem model or prototype demonstration in a relevant environment (ground or space)	
TRL 7	System prototype demonstration in a space environment	Advanced Dev.
TRL 8	Actual system completed and “flight qualified” through test and demonstration (ground or space)	
TRL 9	Actual system “flight proven” through successful mission operations	

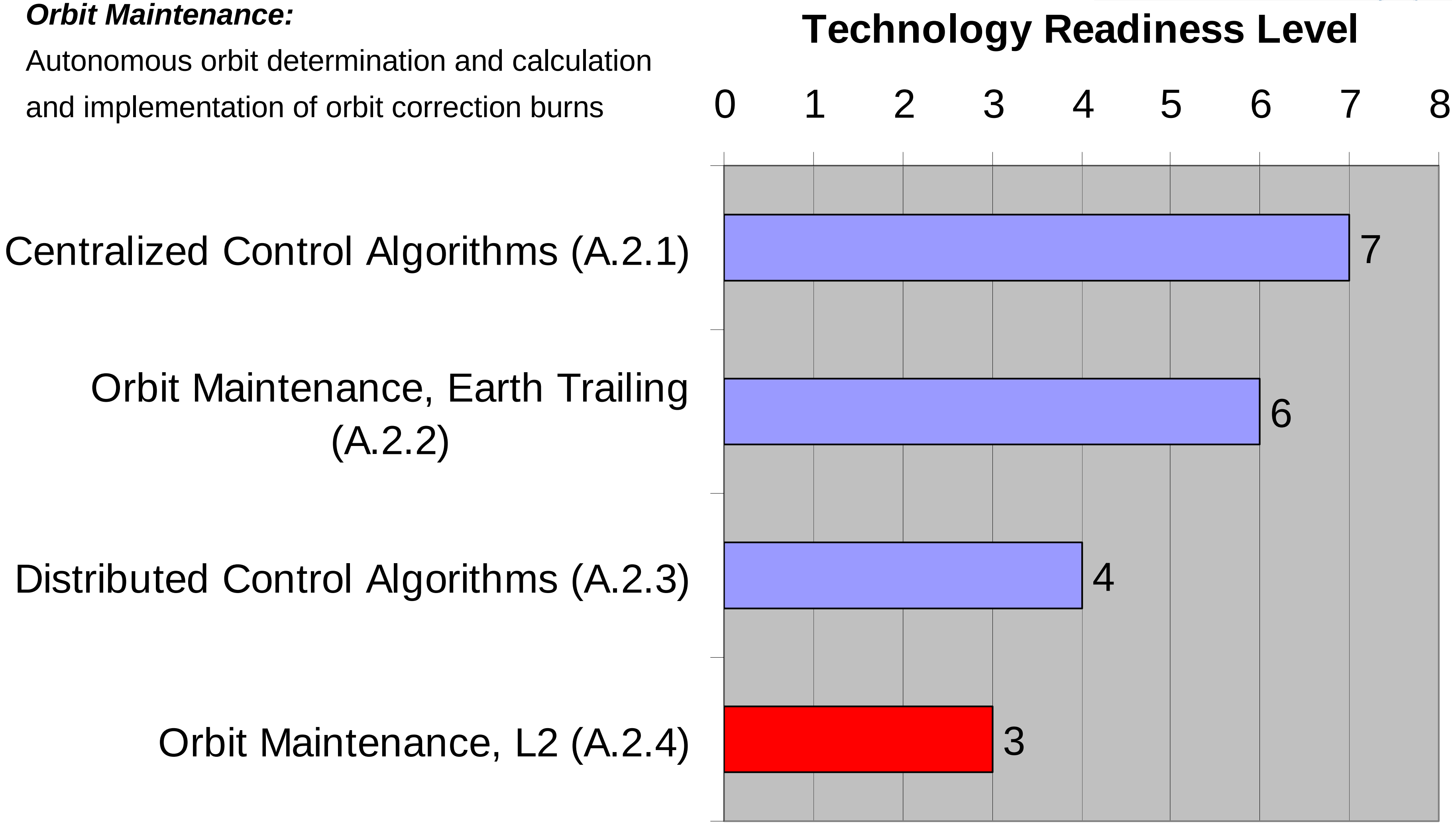
(A.1) Guidance / Operations



(A.2) Navigation (Formation Control)

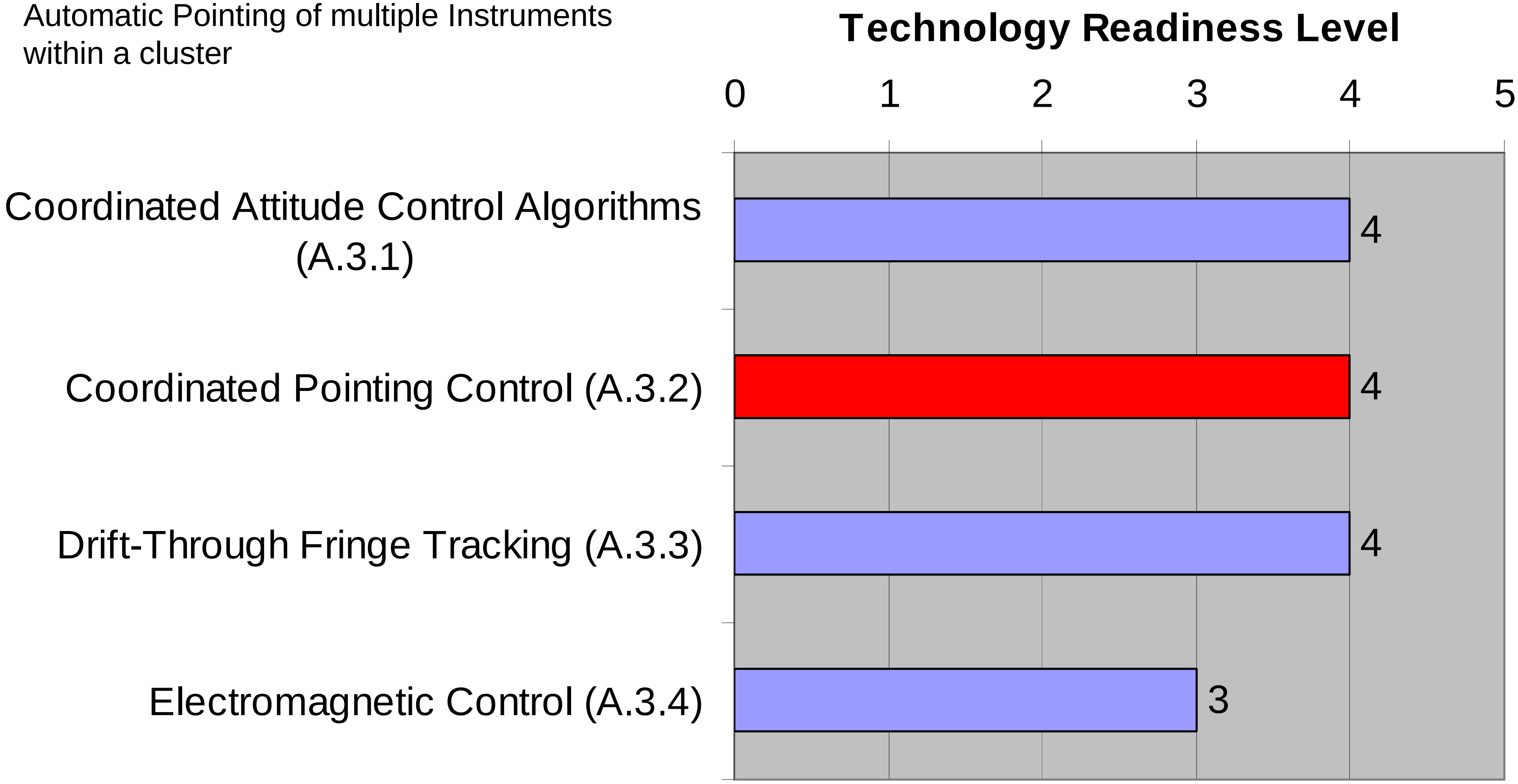
Orbit Maintenance:

Autonomous orbit determination and calculation and implementation of orbit correction burns

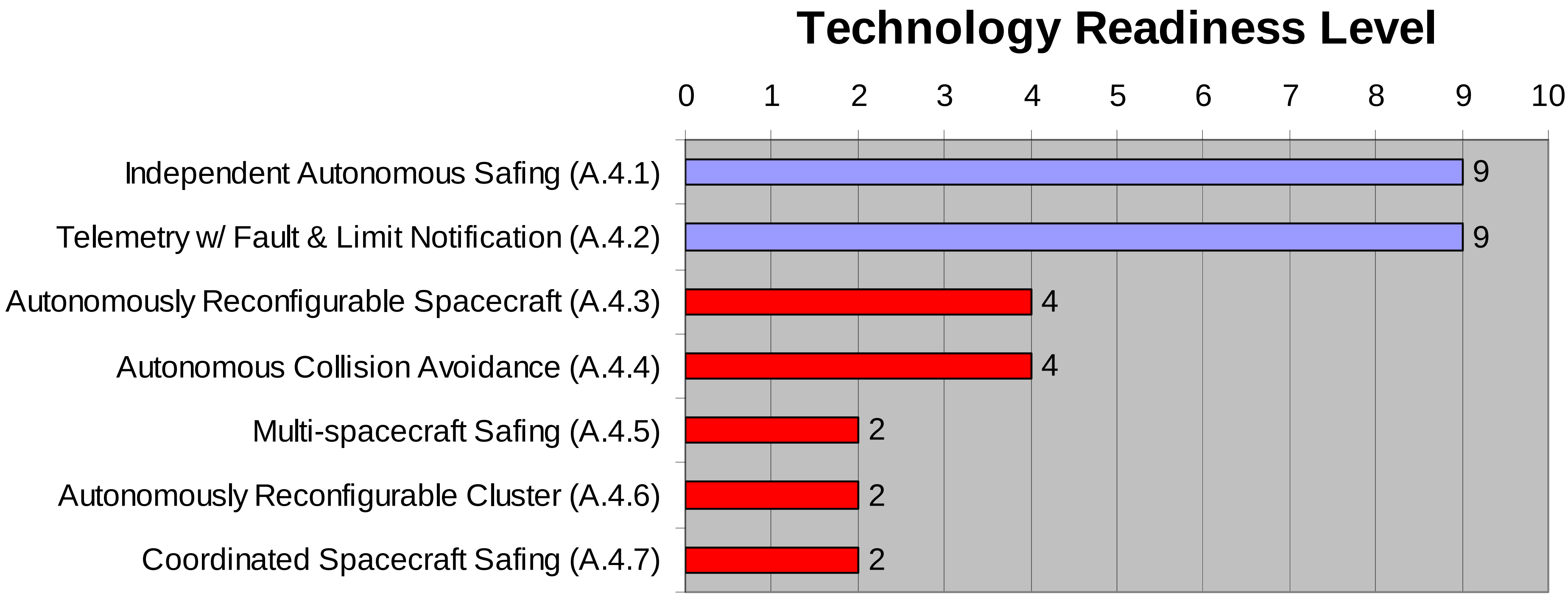


(A.3) Control

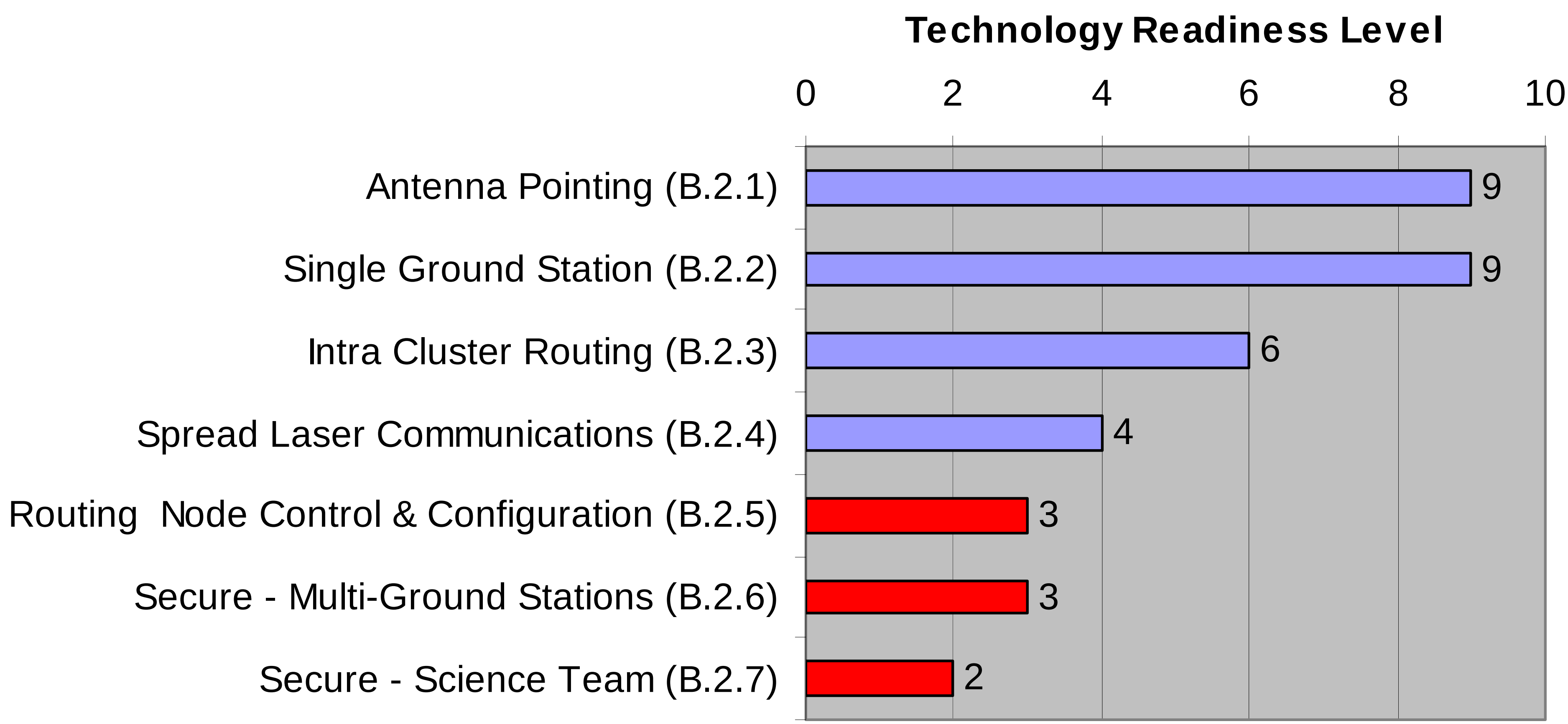
Coordinated Pointing Control:
Automatic Pointing of multiple Instruments within a cluster



(A.4) Fault Detection Isolation & Recovery



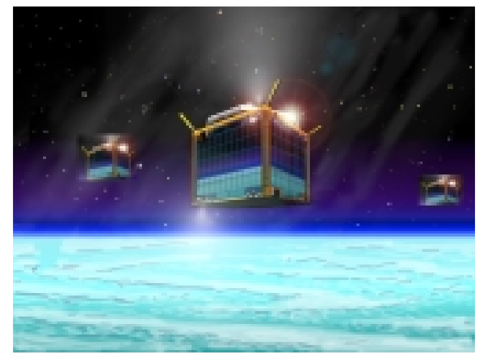
(B.2) Science Intra-Cluster Communications



Planned Formation Flying Experiments

- SPHERES (MIT) - risk tolerant investigation of formation flying control, metrology, autonomy
  - SPHERES manifested on ISS-12a.1, Oct. 2002 for 1 year
  - Standardized ports allow peripherals to be launched/attached thereby upgrading the capabilities of the facility - different sensors and cameras

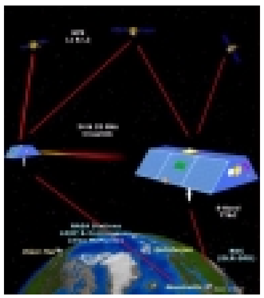
- Orion/Emerald (SU/MIT) - validation of precise carrier differential GPS (CDGPS) as a formation flying sensor
  - Demonstrate formation flying control algorithms and autonomous operations in actual on-orbit environment (Shuttle launch early 03)
  - **ION-F** similar, but includes APL's cross-link transceiver (CLT) and a micro-PPT by Primex



- TechSat21 - formation flying vehicles used to form a distributed SAR
  - Plan to use CDGPS with a local RF augmentation
  - Mission focus is on precise position knowledge not real-time control
  - Validate various formation flying control and autonomy algorithms

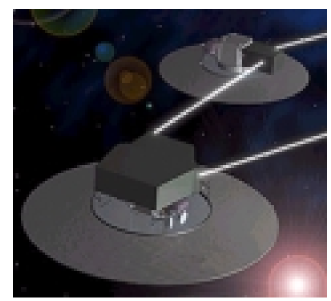
Planned Formation Flying Science Missions

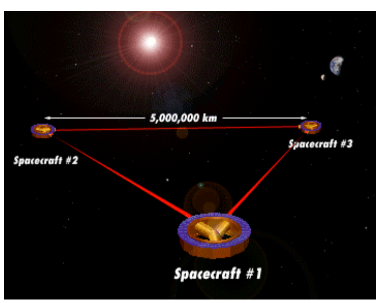
- ST-5 - relatively coarse formation flying of 3 satellites
  - Verification of basic RF ranging sensor



- GRACE – 2 vehicles used to measure gravity variations
  - *Verification of precise RF augmentation to GPS*

- Starlight - 2 vehicle formation flying interferometer
  - Validation of the AFF sensor (stand-alone RF) and demonstration of combined RF and optical metrology
  - Miniaturized nitrogen cold gas thrusters

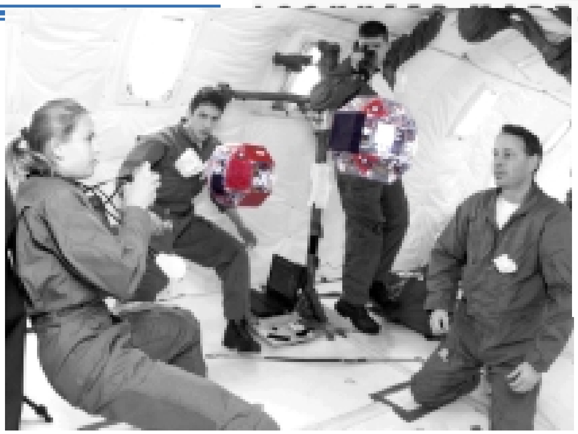


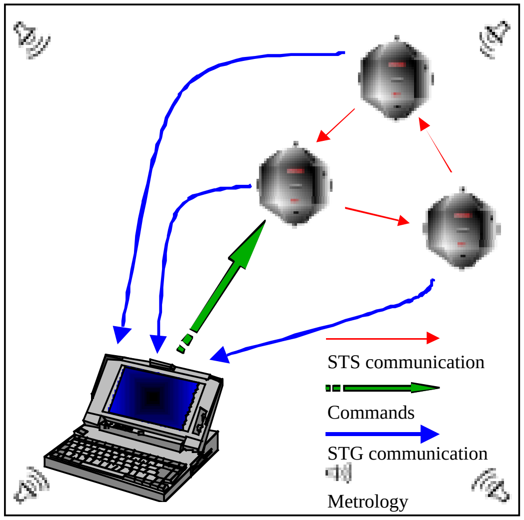


- LISA – 3 vehicles to measure gravity waves
  - *Very precise measurements using laser metrology*
  - *Micro-Newton thruster under development*

SPHERES Formation Flight Laboratory

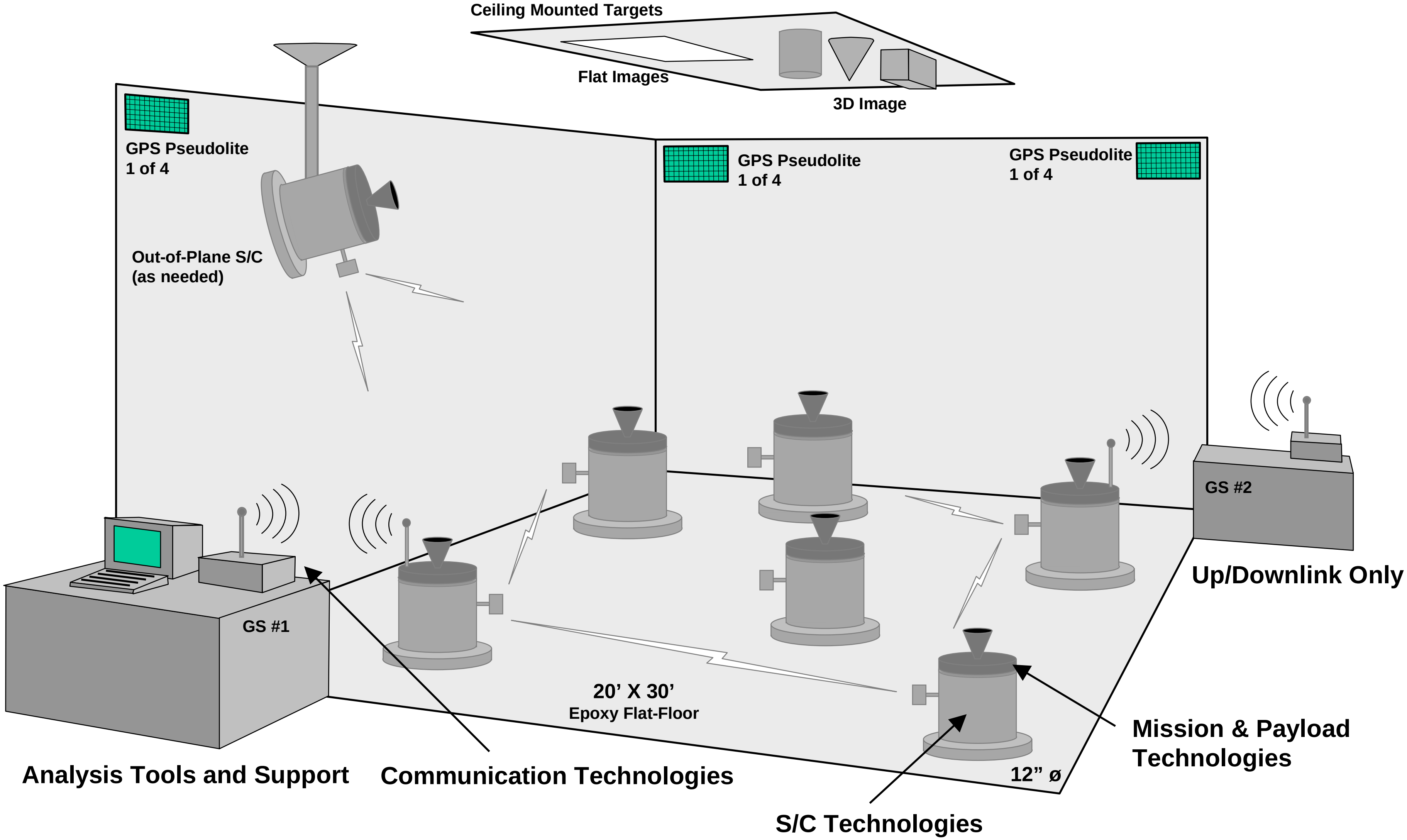
- Formation flight (control, metrology, autonomy) needs a space-representative, risk tolerant environment for maturation
  - SPHERES is manifest on ISS-12a.1 in Oct. 2002 for one year+ on ISS
  - Provides multi-vehicle communication and control as well as rapid algorithm uplink and data downlink and video
  - Risk tolerance comes from replacability of propellant, batteries, and some components as well as crew intervention





- Standardized ports allow peripherals to be built, launched and attached thereby upgrading the capabilities of the facility
  - Different sensors and cameras
  - Optical elements (e.g., FSMs & ODLs)
  - Docking ports
- For several $100k rather than several $100M, SPHERES will mature many crucial formation flight technologies
  - In particular, high risk yet potentially high payoff algorithms would be allowed to undergo maturation on SPHERES

Distributed Space Systems Laboratory



Summary - FF Technology Assessment

		TRL Assessment				
Technology Areas		Available (7-9)	Qualifable (4-6)	Develop (1-3)	Critical Technologies	Min. Cost ($M) to Raise TRL to 8
A	Mission Operations					
	Guidance/Operations	X	X	*	Autonomous Operations {Calibration, Planning}	150 - 230
	Navigation	X	X	*	Distributed Control Algorithms	15 - 50
	Control	X	X	*	Drift Through Fringe Tracking & Electromagnetic Control	5 - 40
	FDIR	X	X	*	Autonomous Reconfiguration; Coordinated Safing	60 - 100
B	Intra-Cluster Communications					
	Navigation	X	X	X	RF-Base Transceivers, Ultra Wide Band & Optical	0
	Science	X	X	*	Node Control and Configuration	20 - 40
C	Spacecraft Infrastructure					
	DataBus	X	X	X	StrongARM, Mongoose V, 750 PowerPC	0
	Distributed Computing	X	X	X	Distributed Process Architecture	0
	Data Storage	X	X	X	RAM Disks (100GB)	0

Key:
X - Being Developed
* - Requires Acceleration

Development of These Key Technologies Will Enable TPF

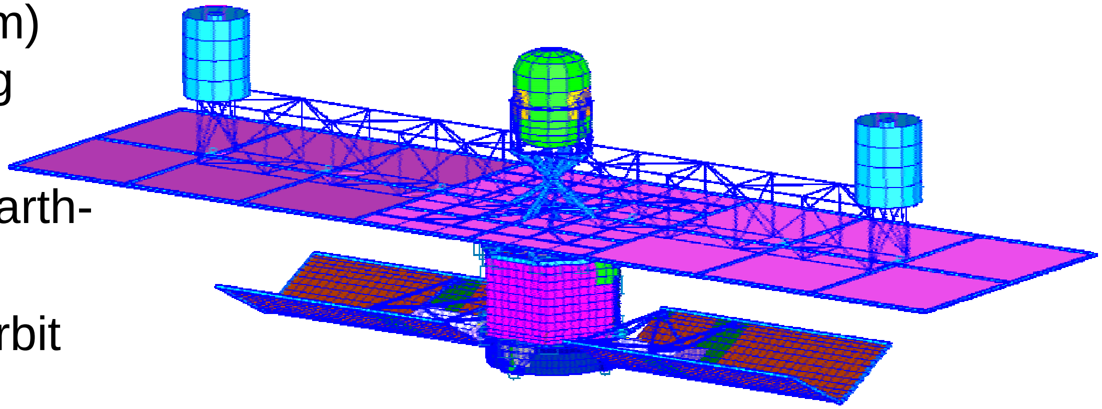
Spacecraft Bus

Ken Hooper
Lockheed Martin Space Systems Company

Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

Studies Performed

- Accommodation of SPF (9 m) interferometer using existing technology
  - SIRTF-derived bus in Earth-trailing orbit
  - LM900 bus in L2 halo orbit



- Readiness for 21 / 40 / 80 m interferometer
  - Effects of evolution

Partition between Instrument and Spacecraft

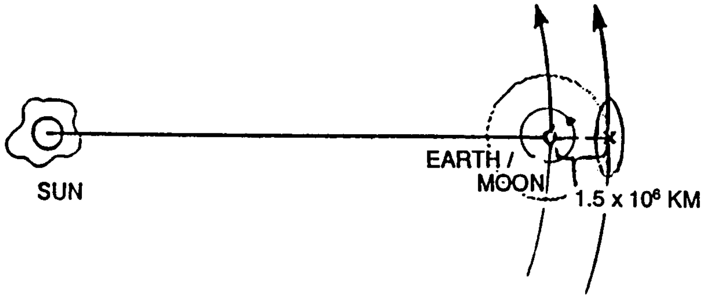
- Instrument module includes:
  - Truss & tower structures
    - Sunshield
    - Truss to tower joint (except SPF)
  - Collector telescopes
    - Steering mirrors
  - Beam combiner
    - Pointing sensors
    - Phase sensor
    - Phase / path length mechanisms
    - Science detector and readout
  - Cryostat
    - Venting mechanism
  - Payload electronics (located in spacecraft and operated warm)
    - Path length / phase control
    - Steering control
    - Readout control and processing
- Spacecraft subsystems include:
  - Bus structure
    - Launcher interface
  - Mechanisms
    - Deployment
    - Solar array tracking
  - Thermal Control
    - Electronics operating temps.
  - Power subsystem
    - Solar arrays
    - Battery
  - Attitude Determination & Control
  - Communications
  - Command & Data Handling
    - Solid state recorder
    - Software to control all above

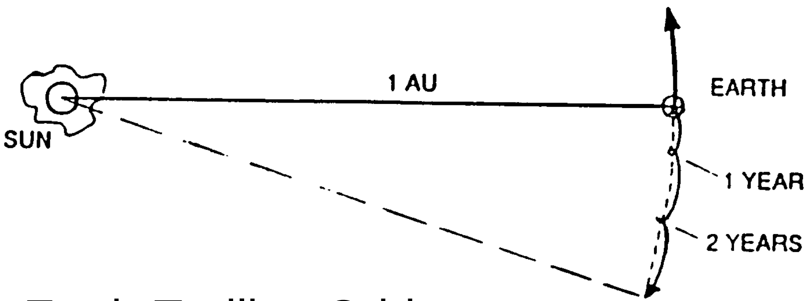
Spacecraft Requirements

	Qualitative Requirement	SPF (9m)	CTPF / ITPF / TPF (21 / 40 / 80 m)
Instrument Power	Sufficient for instrument electronics to observe continuously	~64 W	~80 W
Instrument Mass	Support instrument during launch, slew instruments to targets	~400 kg	1000 to 4000 kg (TBR)
Pointing Knowledge	Sufficient for instrument fine steering system to unambiguously acquire target	~10 arcsec	
Pointing Control	Within range of steering mirrors (in turn bounded by off-axis aberration)	15 arcsec*	
Pointing Stability	Within science stability allocation over steering mirror sample time	10 milli-arcsec over 200 Hz*	
Repointing Time	Short compared to average observation	<6 hrs*	
Orbit Maintenance	Keep in mission orbit for mission life	Earth-trailing $\Delta V = 0$ L2 Halo ΔV = TBD	
Science Data Rate	Exceed average output rate of instrument	24 kbps average*	
Data Storage	7 days at average rate*	14 Gbits	
Science Downlink Capacity	Adequate to downlink data collected daily within ~1.5 hours	400 kbps*	
Mission Design Life	Adequate for required number of planet detection observations	>2.5 years (4 year goal)	>5 years* (10 year goal)
Environment	Design for Earth Trailing or L2*		

* from TPF book

Candidate Orbits





L2 Lagrangian Halo Orbit

- ~1.01 AU from Sun
- Short Lunar eclipses only
- Unstable along Sun-Earth line
  - Requires propulsion to maintain
- C3 Energy = -0.69 km^2/s^2
  - ~108 day direct insertion
- C3 Energy = -2.24 km^2/s^2
  - Lunar swing-by

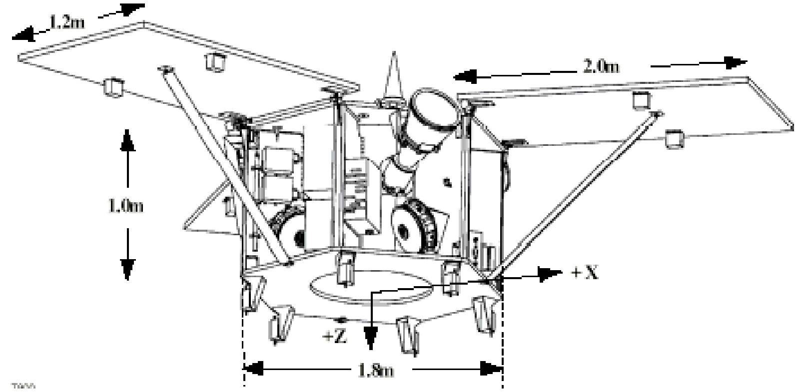
- LM-900 bus used in study

Earth-Trailing Orbit

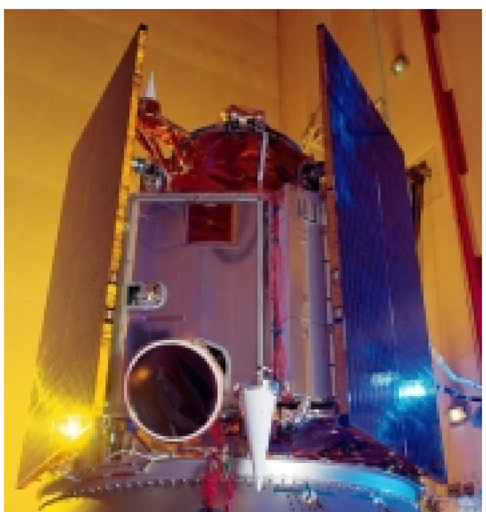
- ~1 AU from Sun
- No eclipses
- Drifts away from Earth ~0.12 AU/year
  - Communication range gradually increases / data rate drops
- Propulsion system needed only for momentum management
- C3 Energy = 0.4 km^2/s^2

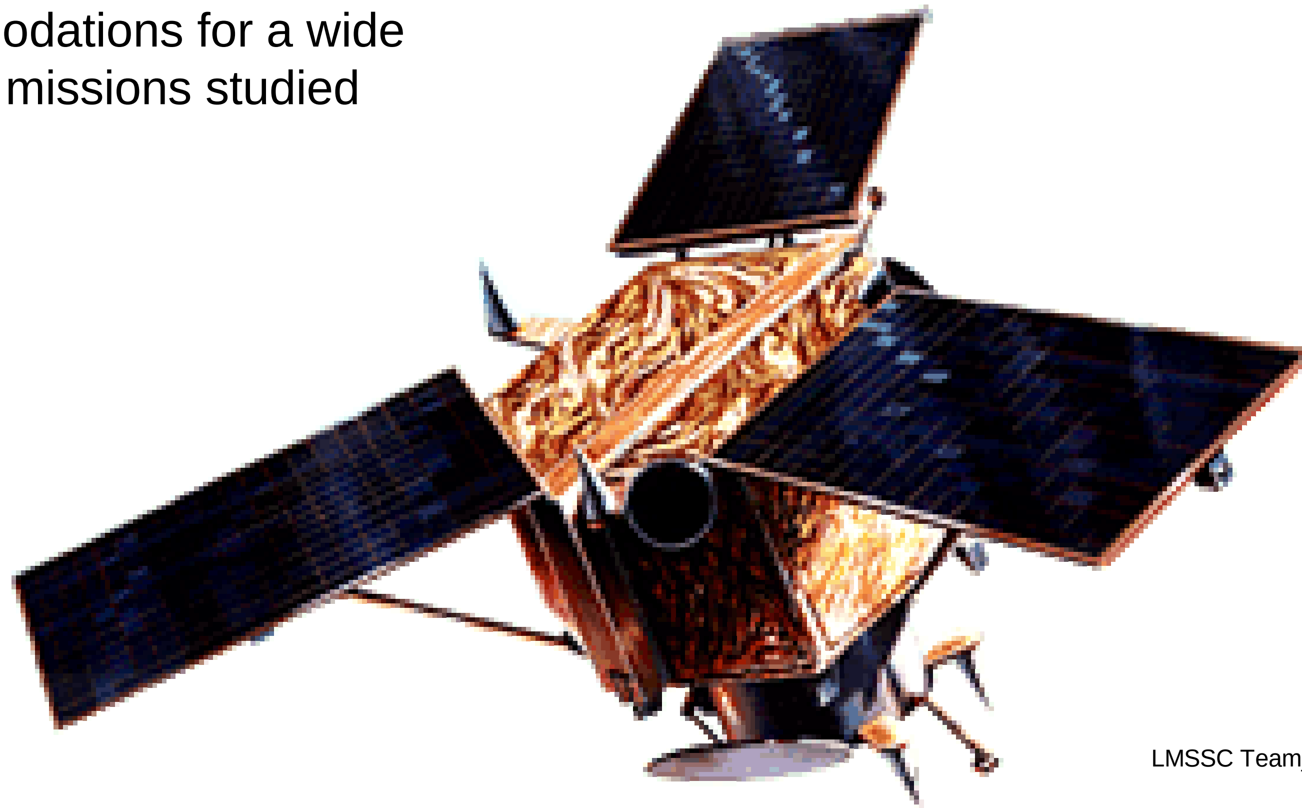
- SIRTF-derived bus used in study

LM900 Bus

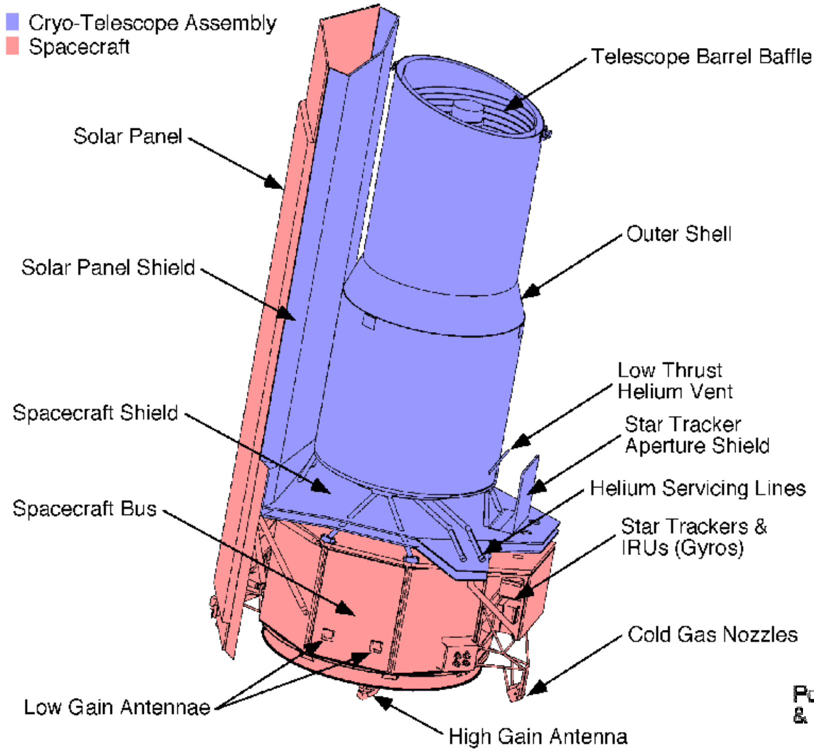


- Flying on Ikonos™ mission
- In RSDO catalog
- Enhanced block II version in development
- Derivatives proposed for several other missions
  - Accommodations for a wide range of missions studied

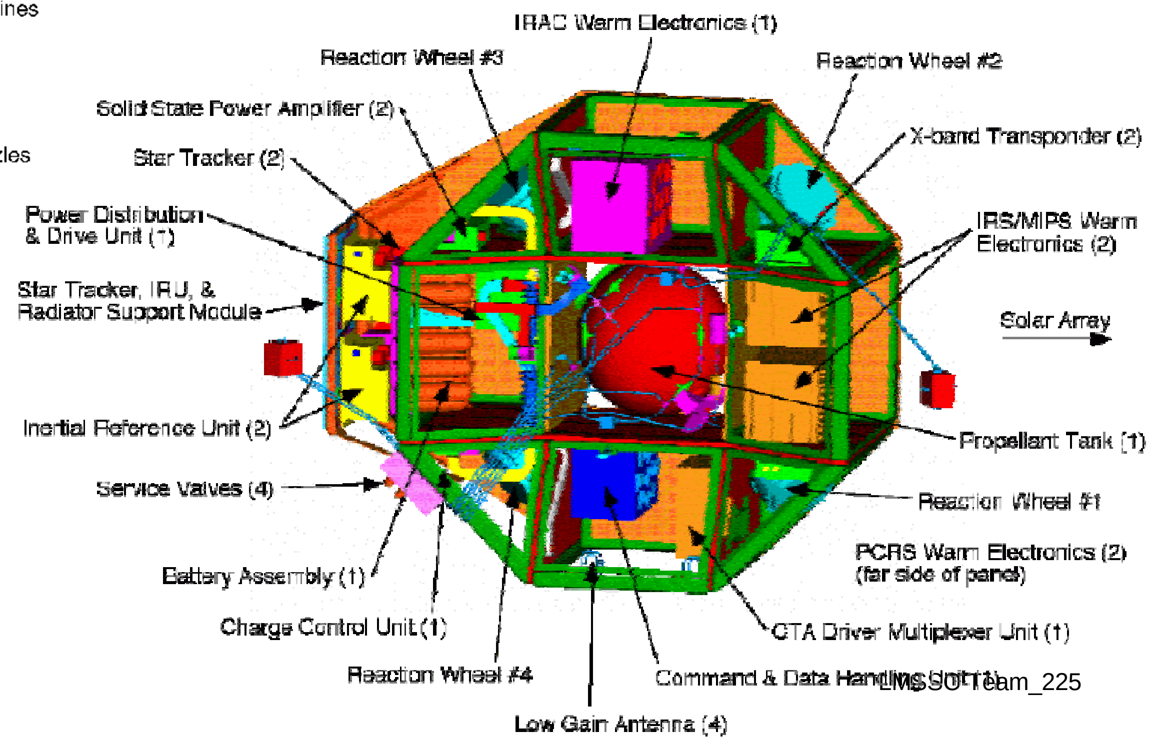




SIRTF Spacecraft
(Basis for S-Bus)



- Precision pointing control
  - High stability
- Passive Cooling
  - Earth-trailing orbit
  - Solar panel / shield (always faces Sun)
  - Thermal isolation



Bus Capabilities

	LM-900	S-Bus	SPF (9 m)	CTPF / ITPF / TPF (21 / 40 / 80 m)
Instrument Power	344 W, 28 V	~64 W	~64 W	~80 W
Instrument Mass	470 kg		~400 kg	~1000-4000 kg
Pointing Knowledge	10 arcsec	5 arcsec	~10 arcsec	
Pointing Control	12 arcsec	5 arcsec	15 arcsec*	
Pointing Stability	0.8 arcsec/sec	0.3 arcsec over 200 seconds	10 milli-arcsec over 200 Hz*	
Repointing Time	65 sec (2.2 x 1.27 m P/L)	1000 s (SIRTF P/L)	<6 hrs*	
Orbit Maintenance	66 m/s 3σ ΔV, 38.4 kg N_2H_4	None	Earth-trailing $\Delta V = 0$ L2 Halo ΔV = TBD	
Instrument Data	Mission specific	1 Mbps peak	24 kbps average*	
Data Storage	Mission specific	16 Gbits BOL	14 Gbits*	
Science Downlink Capacity	Mission specific	2.2 Mbps	400 kbps*	
Mission Design Life	6 years	5 years	>2.5 years (4 year goal)	>5 years* (10 year goal)
Environment	LEO	Earth-trailing	Design for L2 halo or Earth-trailing*	

Capabilities listed are drawn from public literature
Designs to accommodate greater requirements (e.g. GLAST LAT) have been studied
* from TPF book

Other Spacecraft Features

	LM-900	S-Bus
Spacecraft Mass	492 kg dry	
Spacecraft Power		
Power Generation	1200 W BOL	
Battery	50 Ah NiH2 CPV	
Structure	Aluminum honeycomb hexagon	Graphite/cyanate-ester octagon
Size	102 cm high, 157 cm across	
Launch Vehicles	Athena, Taurus, Delta II	Delta II
Processor	12.5 MHz R3000	20 MHz RAD-6000
Data Bus	Mil-Std-1553 or RS-422	1 Mbps, 19.2 kbps RS-422
Ground System	DSN or STDN	
Space-link protocol	STDN	

SPF (9 m) Accommodations using LM900 Spacecraft

- **Replace standard solar arrays with smaller Sun-tracking array**
- **Add Iridium™ axis solar array gimbal mechanisms**
  - **Drive provided by Iridium™ Intergrated Bus Electronics already included**
- **Include solid state recorder and wideband downlink hardware**
  - **Ikonos™ units far exceed TPF requirements - substitute to save cost**
    - **40 Gbit SSR available off-the-shelf**
    - **Wideband components available off-the-shelf**
- Modify attitude control system to use instrument steering sensor input
  - Similar to HST Fine Guidance Sensor
- Revise thermal control radiator/insulation pattern per revised equipment set and mission attitude profile
- Add payload/mission support software
- Add solar array deployment & tracking software
- Omit GPS receivers, magnetometers and torque rods

SPF (9 m) Accommodations using S-Bus Spacecraft

- **Derivative of SIRTF spacecraft**
- **Make solar array Sun-tracking**
  - **Add deployment mechanisms**
  - **Add solar array pointing mechanism**
    - **Mars mission heritage**
- **Enlarge or replace propulsion system**
  - **Manage larger solar torque imbalance**
- Modify attitude control system to use instrument steering sensor input
  - Similar to HST Fine Guidance Sensor
- Revise thermal control radiator/insulation pattern per revised equipment set and mission attitude profile
- Add payload/mission support software
- Add solar array deployment & tracking software

Mass Summary (kg)

Configuration Bus used	SPF (9 m) LM900	 S-Bus	ITPF (40 m) LM900	 S-Bus
Telescopes	79	79	600	600
Cryostat	150	150	270	270
Combiner	60	60	90	90
Instrument Electronics	29	29	29	29
Truss	49	49	456	456
Tower	10	10	40	40
Sun Shade	15	15	188	188
Instrument Total	**392**	**392**	**1673**	**1673**
Structures and Mechanisms	171	121	205	145
Thermal Control	38	44	38	44
Attitude Control	86	54	86	81
Communications	22	26	22	26
Command & Data Handling	55	23	55	23
Electrical Power	87	111	87	120
Propulsion	12	12	22	22
Spacecraft Total (dry)	**470**	**390**	**515**	**462**
Observatory Total (dry)	**862**	**782**	**2189**	**2135**
Propellant	38	38	96	96
Observatory Total (wet)	**900**	**820**	**2285**	**2232**
Atlas V 401 Capability (w/ adapter)	3306	3291	3306	3291
Margin	267%	301%	45%	47%

Power Summary

(Average Watts)

Configuration	**SPF (9 m)**		**ITPF (40 m)**	
Bus used	**LM900**	**S-Bus**	**LM900**	**S-Bus**
Telescopes	0	0	0	0
Cryostat *				
Combiner	0	0	0	0
Instrument Electronics **	64	64	80	80
Truss				
Tower				
Sun Shade				
Instrument Total	**64**	**64**	**80**	**80**
Structures and Mechanisms	12	12	12	12
Thermal Control	24	24	24	24
Attitude Control	103	69	103	193
Communications	43	33	43	33
Command & Data Handling	105	66	105	66
Electrical Power	***	26	***	26
Battery Charging	18	18	18	18
Cable Loss	6	6	6	9
Propulsion	1	1	2	2
Spacecraft Total	**312**	**256**	**314**	**383**
Observatory Total	**376**	**320**	**394**	**463**
Power Capability EOL	681	396	681	574
Margin	81%	24%	73%	24%

* Cryostat monitoring electronics included in spacecraft bus

** Instrument Electronics includes controls for combiner, phase/path length, and fine steering

*** LM900 Electrical Power system boxes are included in C&DH

Technological Readiness Summary

Subsystem	SPF (9 m)	CPF / ITPF / TPF (21 / 40 / 80 m)
Electrical Power	**9**	**9**
Command & Data Handling		
Integrate next generation processor / architecture	7	4
Flight Software (exc, GN&C algorithms)		
Integrate interferometer-unique algorithms		
Fine steering	6	6
Phase / path-length control	4	4
Guidance, Navigation & Control		
Hardware	9	9
Algorithms		
Integrate pointing with instrument steering	7	7
Isolate sunshield dynamics		5
Communications	**9**	**9**
Propulsion	**9**	**9**
Thermal Control		
Passive cooling, fixed sunshield, thermal isolation	8	8
Deployable Sunshield		
Materials & Structures		9
Deployment & dynamics		5
Structures & Mechanisms	**9**	**9**

Propulsion system
Micro-Thruster

Vadim Khayms
Lockheed Martin Space Systems Company

Vlad Hruby
BUSEK

Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

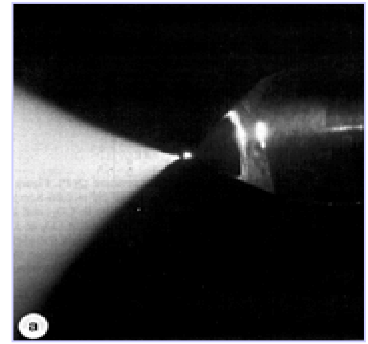
Propulsion System Requirements

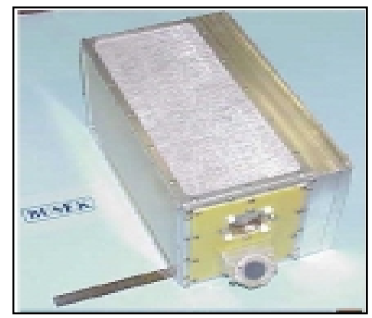
- **Propulsion system choice is dictated by specific mission objectives and performance requirements**
- **Possible applications**
  - orbit maintenance (high thrust ~10 mN; to compensate for disturbances caused by solar radiation, etc)
  - momentum dumping (intermediate thrust levels; to de-saturate reaction wheels)
  - precision attitude control (thrust range 10 μN -10 mN; to completely replace reaction wheel system)
- **Performance drivers**
  - thrust level range (need wide range if multiple applications are envisioned)
  - minimum impulse bit (control loop bandwidth)
  - power efficiency (inefficiency causes excessive power dissipation)
  - propellant efficiency (specific impulse, not a major driver due to low ΔV requirements)

Technology Selection and Status

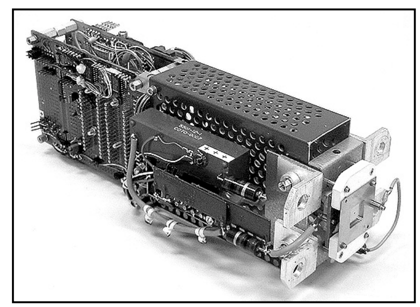
- **Typical requirements**
  - maximum required thrust level: 10 mN
  - controllability: to within 0.1 μN
  - minimum impulse bit: TBD
  - specific impulse: 200 - 500 sec

- **Existing colloidal micro-thrusters can meet these requirements with minimal additional development**
  - Busek Co. demonstrated thrust levels of 20 -189 μN, max. I_{sp} of 389 sec, and max. efficiency of 85% using an array of 57 emitters
  - Stanford U. design: thrust levels of 440 μN, max I_{sp} of 200 sec using an array of 100 emitters
  - Both systems have a flow controller and a power processing unit. Busek's thruster has a field-emission cathode to prevent charge buildup





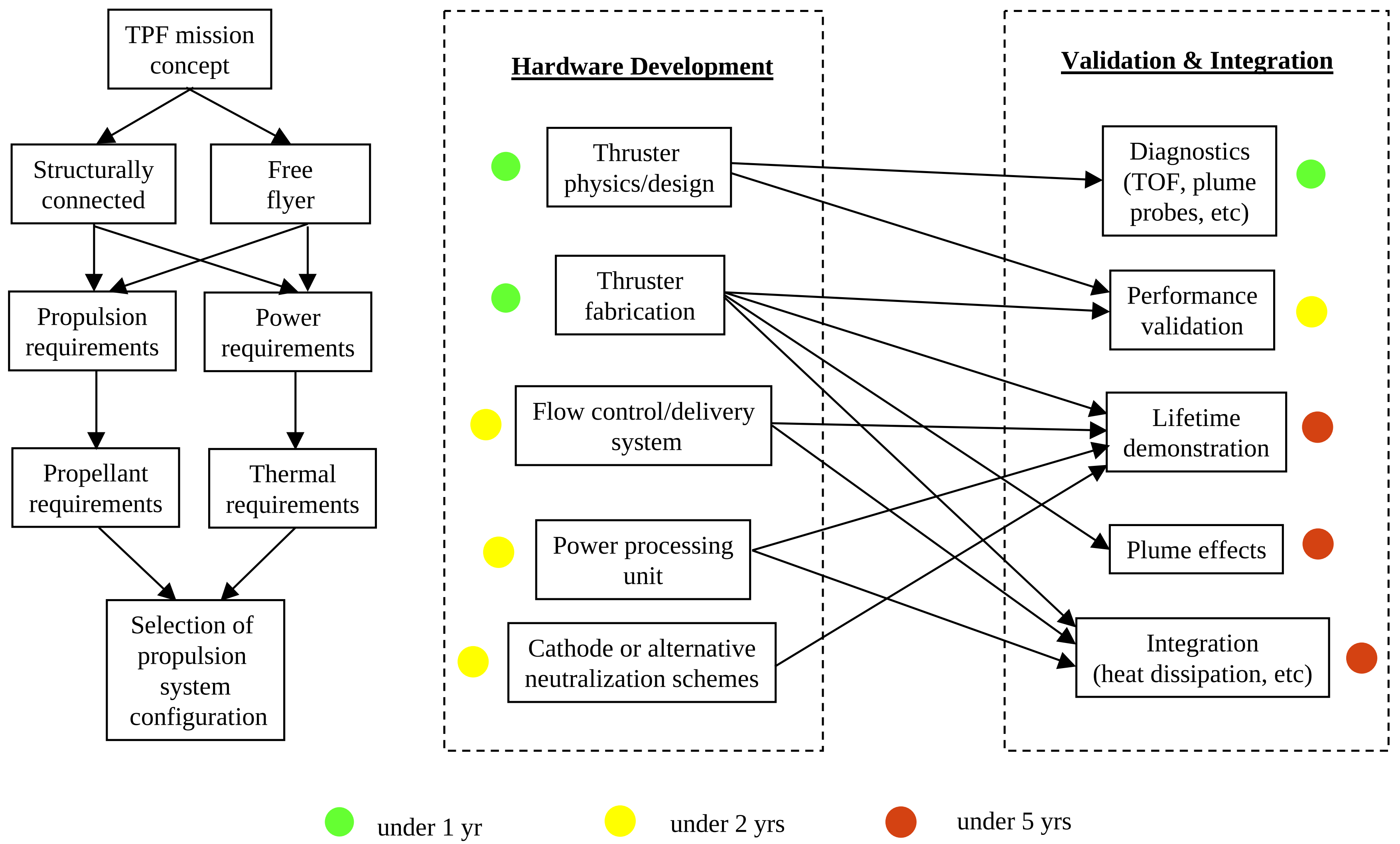
Busek's design



Stanford U. design

TPF
Terrestrial Planet Finder

Propulsion System Development Roadmap



Development Needs & Challenges

- **Thruster assembly/performance**
  - select thruster assembly configuration (e.g. single two-dimensional array; multiple arrays with separate feed systems, arrays with different thrust capabilities, etc)
  - identify thrust control mode (flow rate vs. voltage modulation)
  - verify thrust modulation time constant against position/orientation requirements
- **Flow system/PPU**
  - choice of propellant (need to be chemically inert, have high conductivity, low vapor pressure, and desirable optical properties)
  - depending on design, flow delivery system and PPU may dissipate large amounts of heat
- **Plume effects**
  - impinging liquid droplets or frozen particles may damage optical equipment or cause degradation of thermal properties
  - plume impingement may induce mechanical vibrations
- **Operating life**
  - erosion/chemical corrosion of thruster components
  - propellant decomposition, capillary clogging, neutralizer contamination

Flight Operations

John Day
Lockheed Martin Space Systems Company
(Inspace Systems)

Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

Agenda

- Mission Overview Comparison
- Operability Comparison
- Data System Comparison
  - SIRTF Data System
  - Envisioned SPF Data System
- Mission Operations Staffing

Mission Overview (vs. SIRTF)

Feature	SIRTF	SPF (9 m)	40 m
Telescope	One 85-cm cryogenic (5.5K), 3.5 µm - 160 µm	Two 60-cm cryogenic (60K), 4 µm - 12 µm	Four 75-cm cryogenic (40K), 7 µm - 17 µm
Cryogen	super-fluid Helium	solid Hydrogen	solid Hydrogen
Instruments	3	1	1
Arrays	$4x256^2$, $5x128^2$, 32x32, 2x20, for imaging and spectroscopy	$1x128^2$, for imaging and spectroscopy $1x256^2$, for phase detection	$1x256^2$, for imaging and spectroscopy
Orbit	solar orbit, trailing Earth and receding at 0.12 AU/year	solar orbit, trailing Earth and receding at 0.12 AU/year	solar orbit, trailing Earth and receding at 0.12 AU/year
Lifetime	2.5 years, goal of 5 years	2.5 years, goal of 4 years	5 years, goal of 10 years
Ground Station	DSN	DSN	DSN
On-board Storage	Up to 4 Gbits per 12 hours	Up to 4 Gbits per 12 hours	Up to 4 Gbits per 12 hours
Max. Downlink Rate	2.2 Mbps	2.2 Mbps	2.2 Mbps

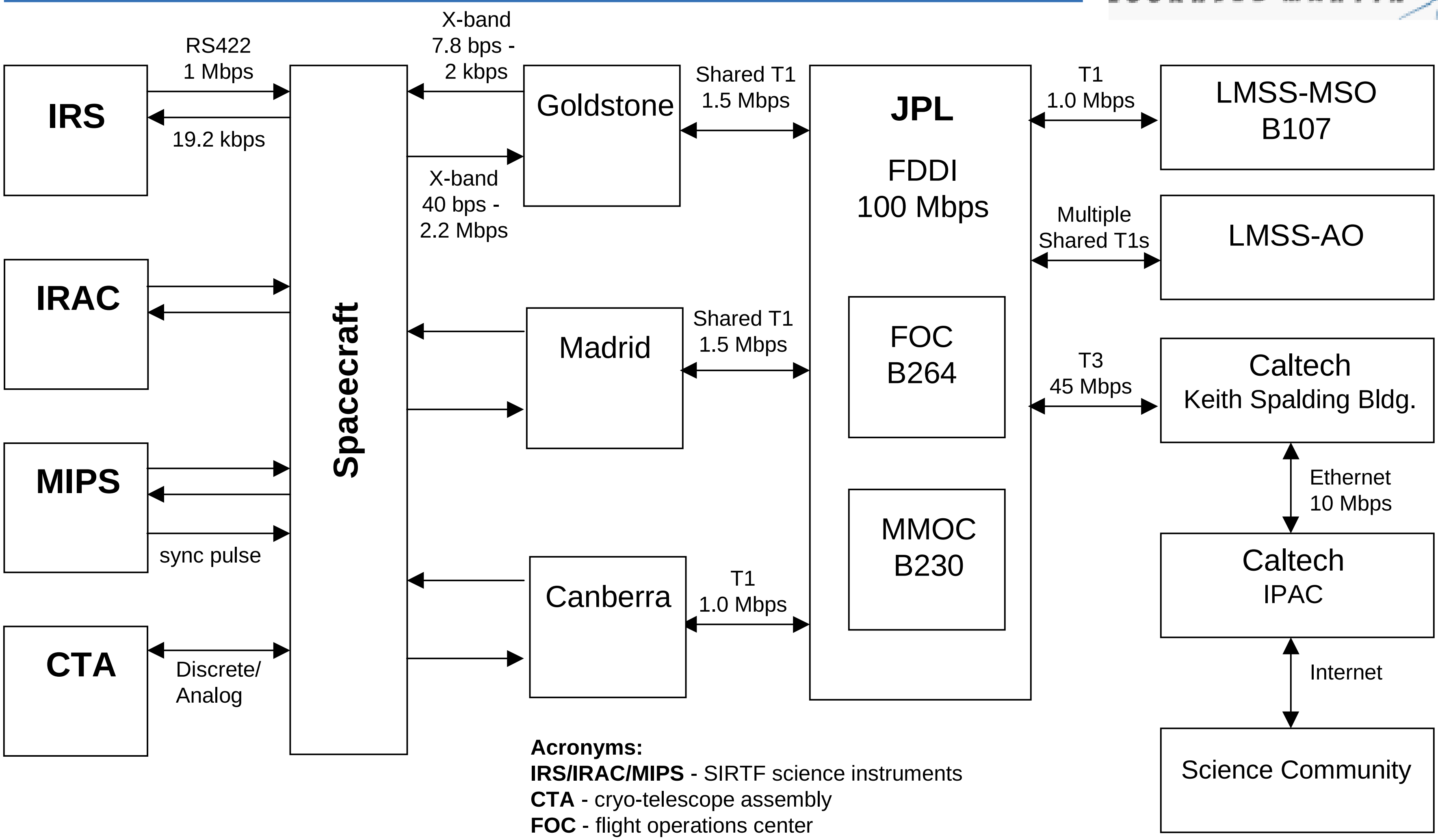
SPF mission is similar to SIRTF, with simpler instrument

Operability Characteristics (vs. SIRTF)

SPF/40m Characteristic	vs. SIRTF
Solar orbit provides simple pointing constraints and stable environment	same
One instrument	three instruments
One observing mode	multiple observing modes
16 Gbit on-board storage	same
Nominal downlink once a day using DSN 34m	twice daily downlinks
On-board lossless compression	same
No observation during downlink	same
Planned uplink once per week, opportunity w/ each downlink	same
On-board autonomy - momenum management - memory management	same

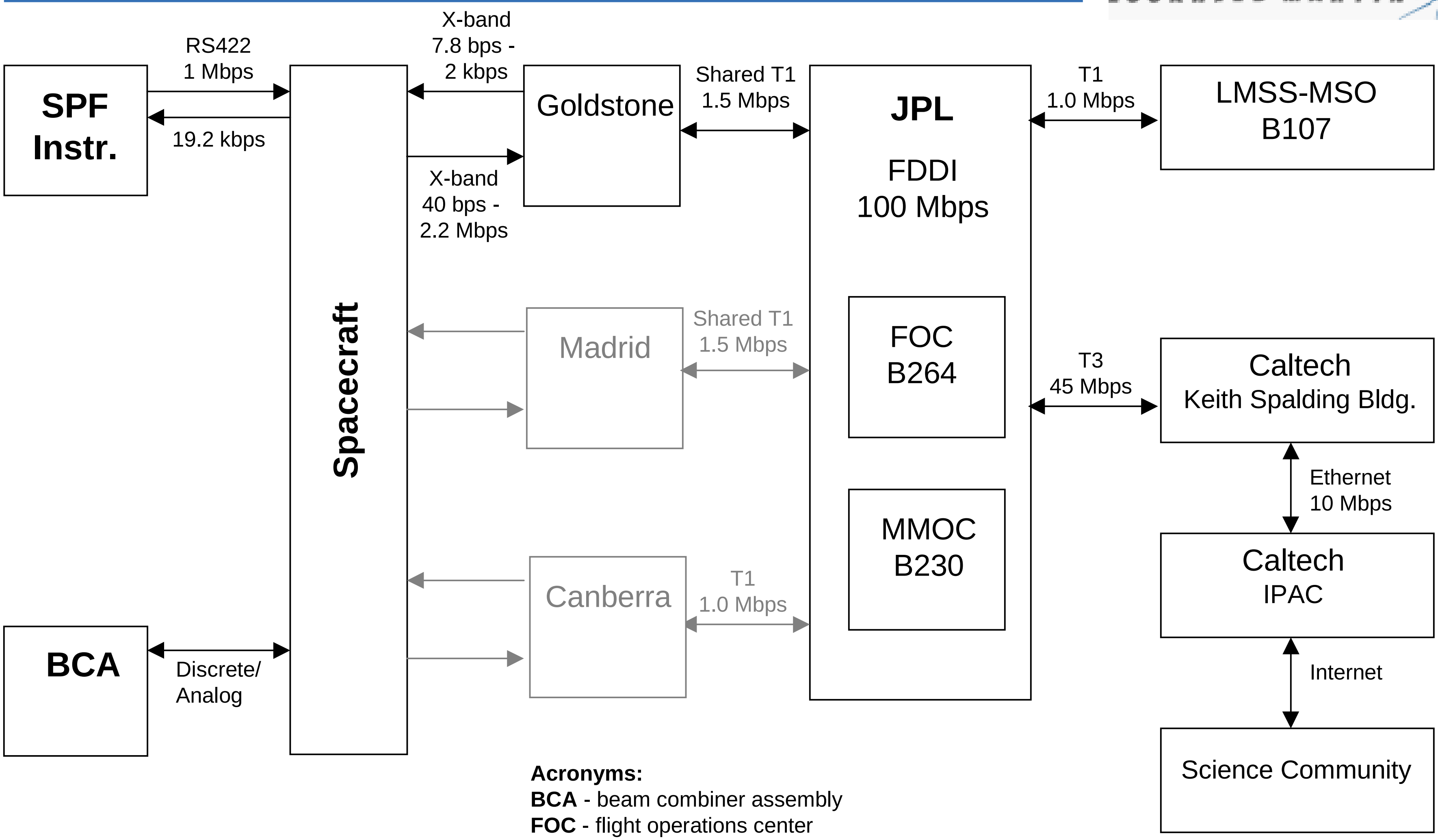
SPF/40m key operability characteristics are the same as, or simpler than, SIRTF

SIRTF Data System



Acronyms:
IRS/IRAC/MIPS - SIRTF science instruments
CTA - cryo-telescope assembly
FOC - flight operations center
MMOC - multi-mission operations center
MSO - LM Missiles and Space Operations (Sunnyvale)
AO - LM Astronautics Operations (Denver)
IPAC - infrared processing and analysis center

Envisioned SPF/40m Data System



Acronyms:
BCA - beam combiner assembly
FOC - flight operations center
MSO - LM Missiles and Space Operations (Sunnyvale)
MMOC - multi-mission operations center
IPAC - infrared processing and analysis center

Mission Operations Staffing

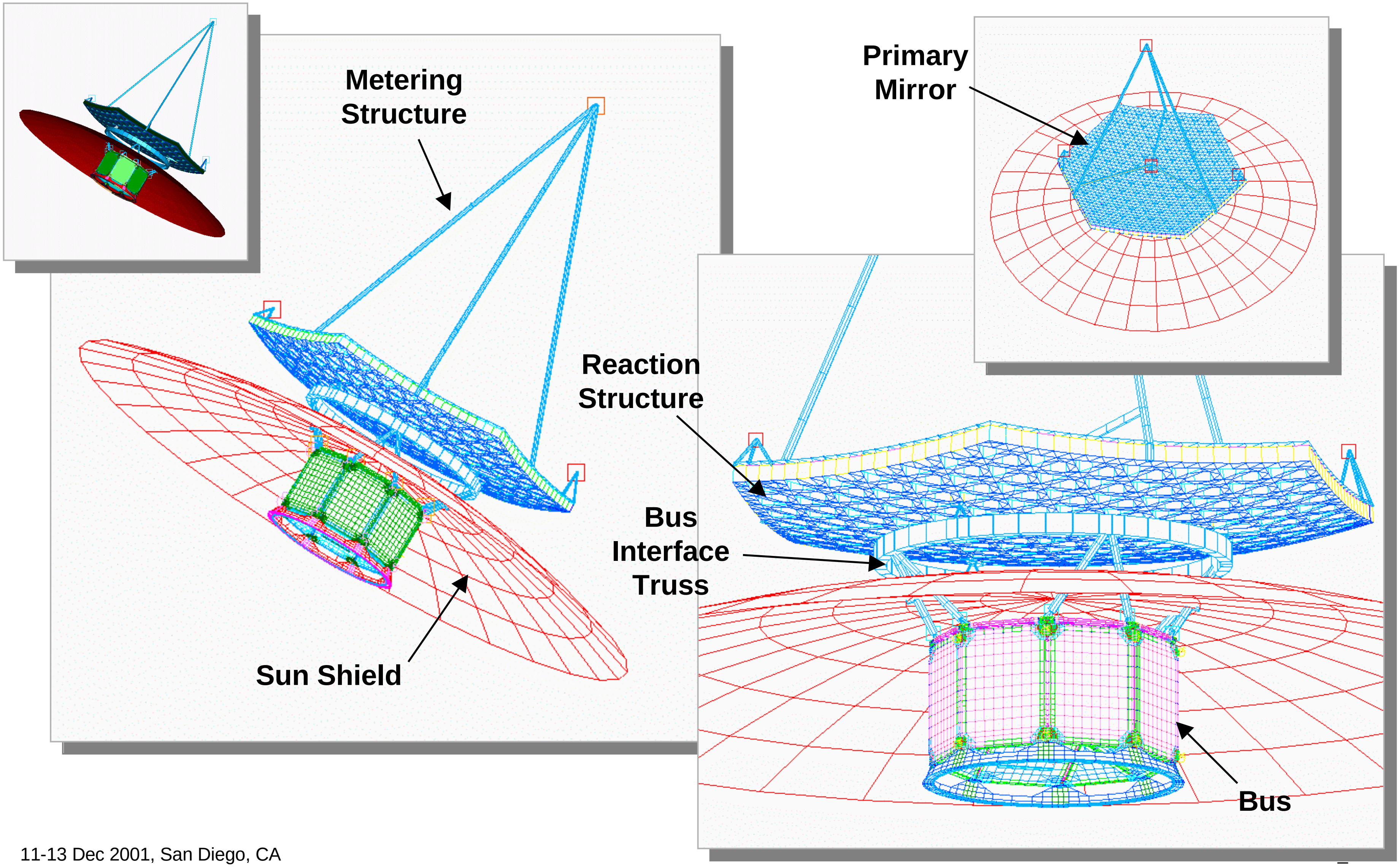
SCIENCE	
Director's Office/Financial/Adm	1.5
Systems Engineering	1
Science/SI/Observer Supports	2
Uplink/Downlink SW Maintenance	1
Sub-total	*5.5*
ENGINEERING	
Engineering Manager's Office	0.5
Observatory Analysis	2
Flight Control	1
Uplink Planning/Sequencing	1
Sub-total	*4.5*
Total	**10**

Integrated Modeling

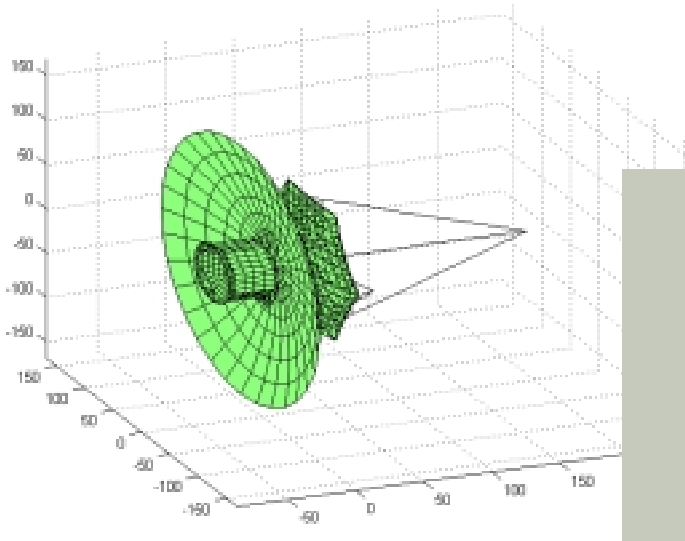
YC Yiu
Lockheed Martin Space Systems Company

Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

3.5-Meter TPF FEM

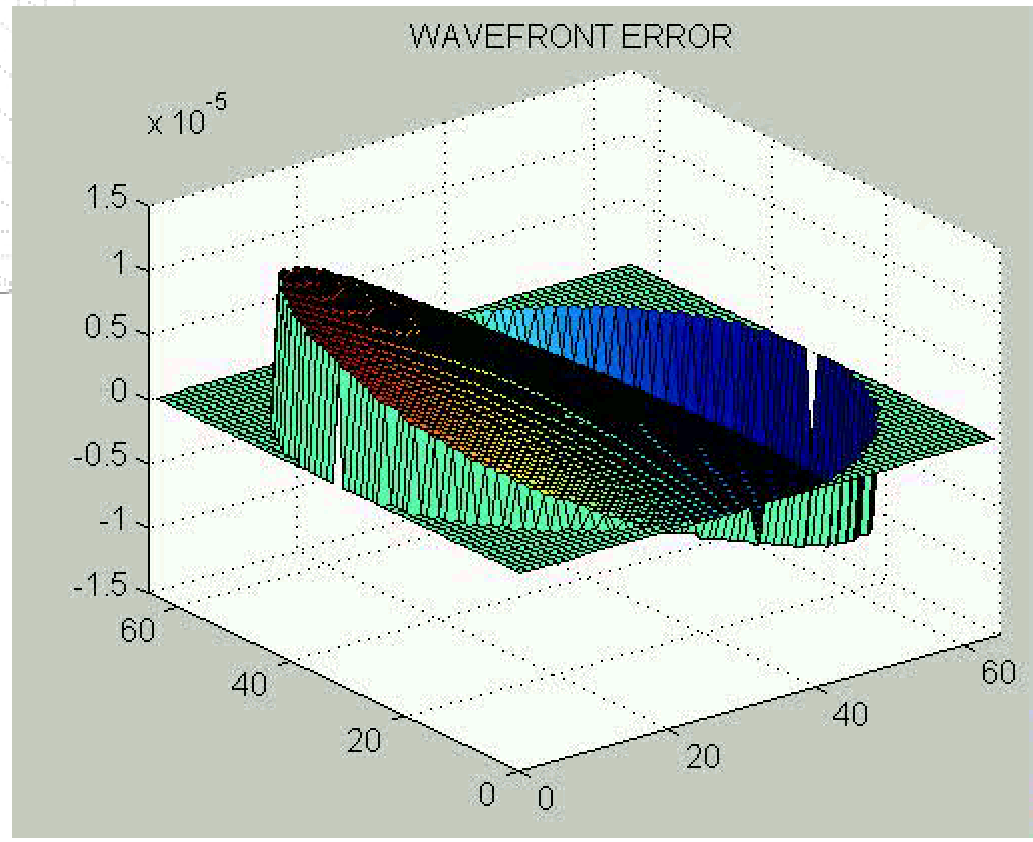


OPD due to RWA Disturbance



FEM

OPD Animation



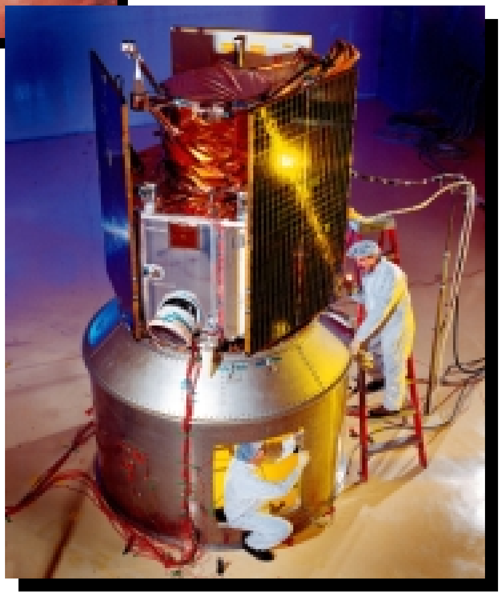
Lockheed Martin LM-900 Spacecraft Bus Overview

Glenn Butcher
Lockheed Martin Space Systems Company

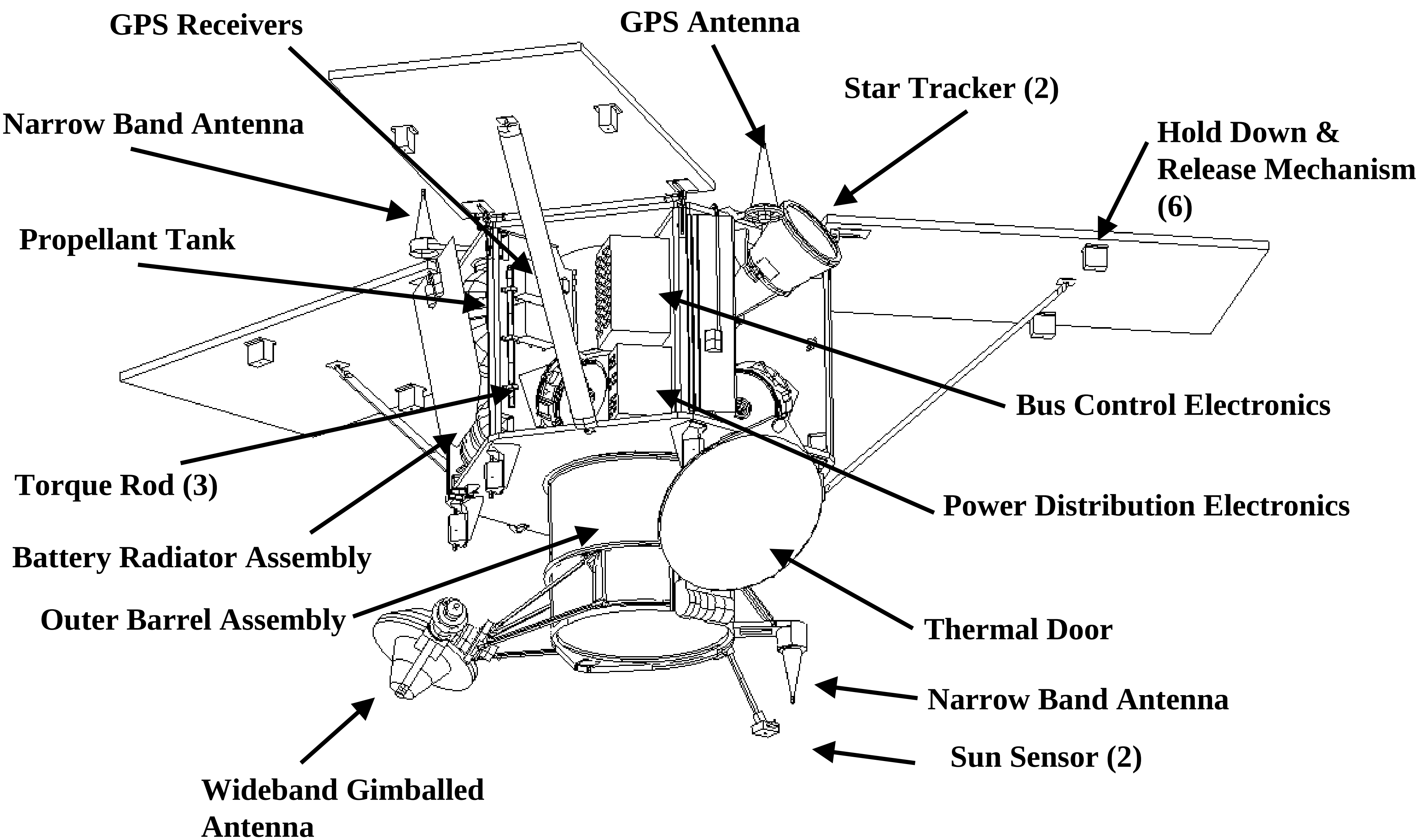
Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

IKONOS® Heritage of LM900™

- Customer:
  - Space Imaging
- Operation:
  - Agile spacecraft to image arbitrary earth locations
  - Images collected by precision scan of linear array
- Lockheed Martin Role:
  - Prime contractor and system integrator
  - Space, ground and launch segment
- Launch:
  - September 1999



IKONOS® Spacecraft Deployed Configuration



Images from IKONOS

Lingshui, China

Imagery courtesy of Space Imaging

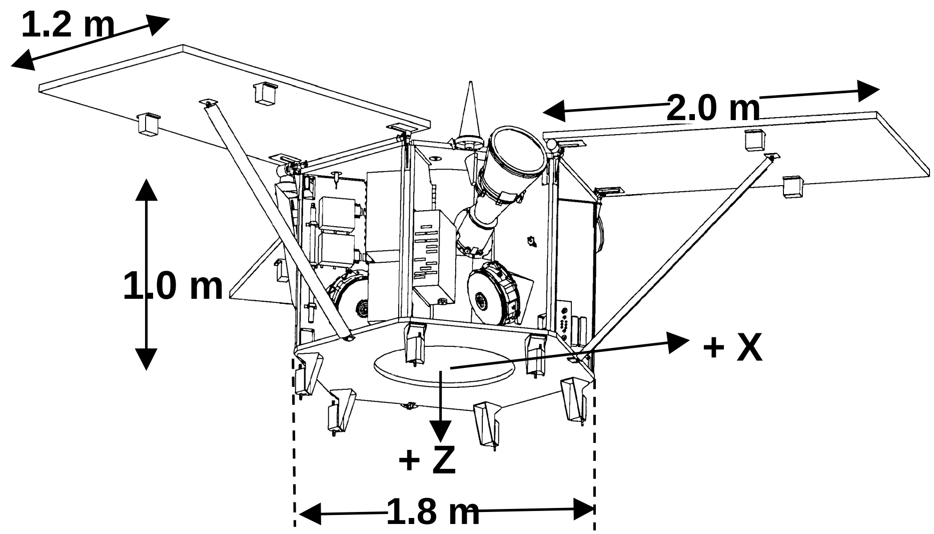
Images from IKONOS

JPL campus at Pasadena, CA

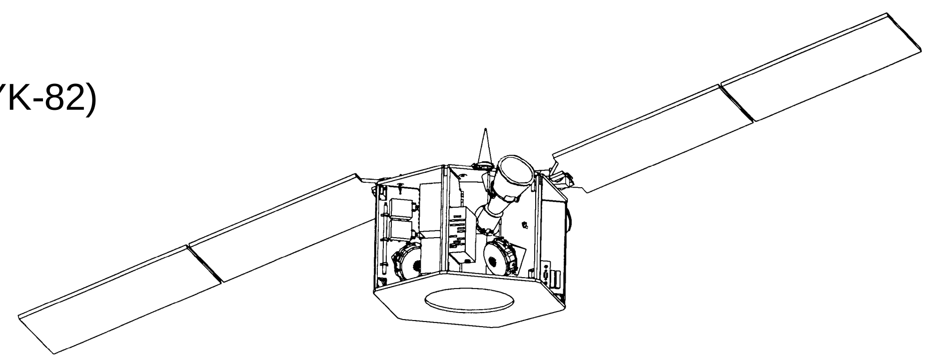
Imagery courtesy of Space Imaging

Payload Support Capabilities

- Payload Mass
  - Up to 500 kg
- Payload Volume
  - Internal Cylinder Vol: 78 cm dia x 101 cm
  - External Volume: 220 cm dia x 127 cm
  - Electronics Bay: 94cm x 84cm x 38cm
- Power
  - Solar Arrays: 3 Fixed
    1200W BOL/ 1022W EOL peak
    power to payload orbit dependent
  - Enhancement: 2 tracking solar arrays
    nominal 300 W orbit average
- Communications (Tailored options available)
  - X-Band @ 32 Kbps (optional:2-3 Mbps)
  - telemetry downlink (encrypted MYK-41)
  - S-Band @ 2 Kbps cmd uplink (encrypted MYK-82)
  - X-Band @ 150 (up to 600) Mbps downlink
  - Two Axis Gimballed Antenna,
- Solid State Recorder
  - 80 GBit up to 700 Gbit (BOL) EDAC
  - protected high-speed memory
- Thermal Control
  - Precision Thermal Control Available

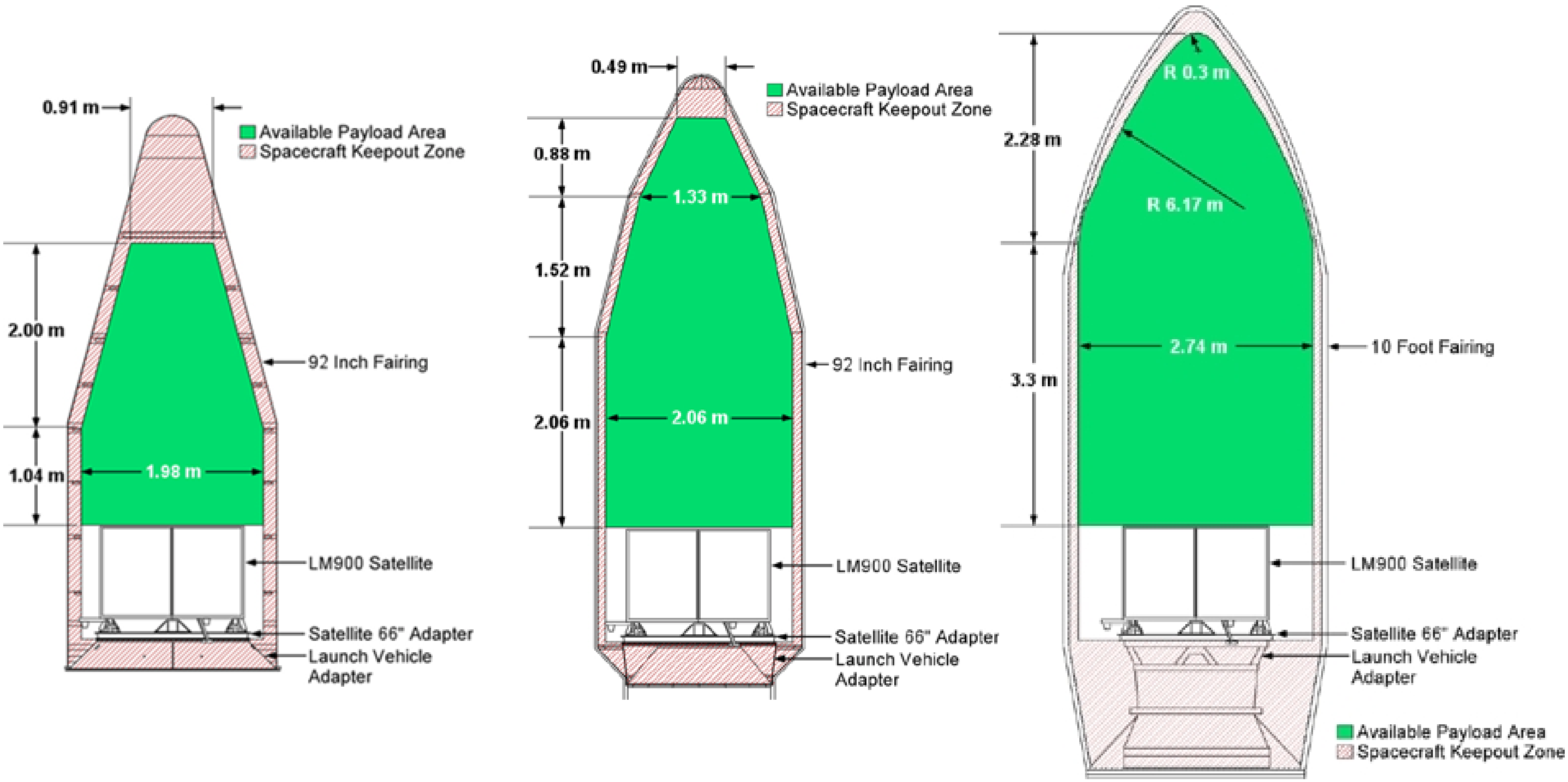


LM900™ Baseline



LM900™ with Tracking SA

Payload External Envelopes



Athena II Taurus Delta II

LM900 solar arrays are not shown. Solar array configuration may reduce the available payload envelope.

ACS Capabilities Overview

The LM900™ Attitude Control Subsystem is designed for

✓ *Tight pointing control*

Accurate attitude estimates and high-bandwidth control support excellent pointing performance.

✓ *Precise pointing knowledge*

Star trackers provide accurate real-time attitude estimate.

✓ *Low jitter*

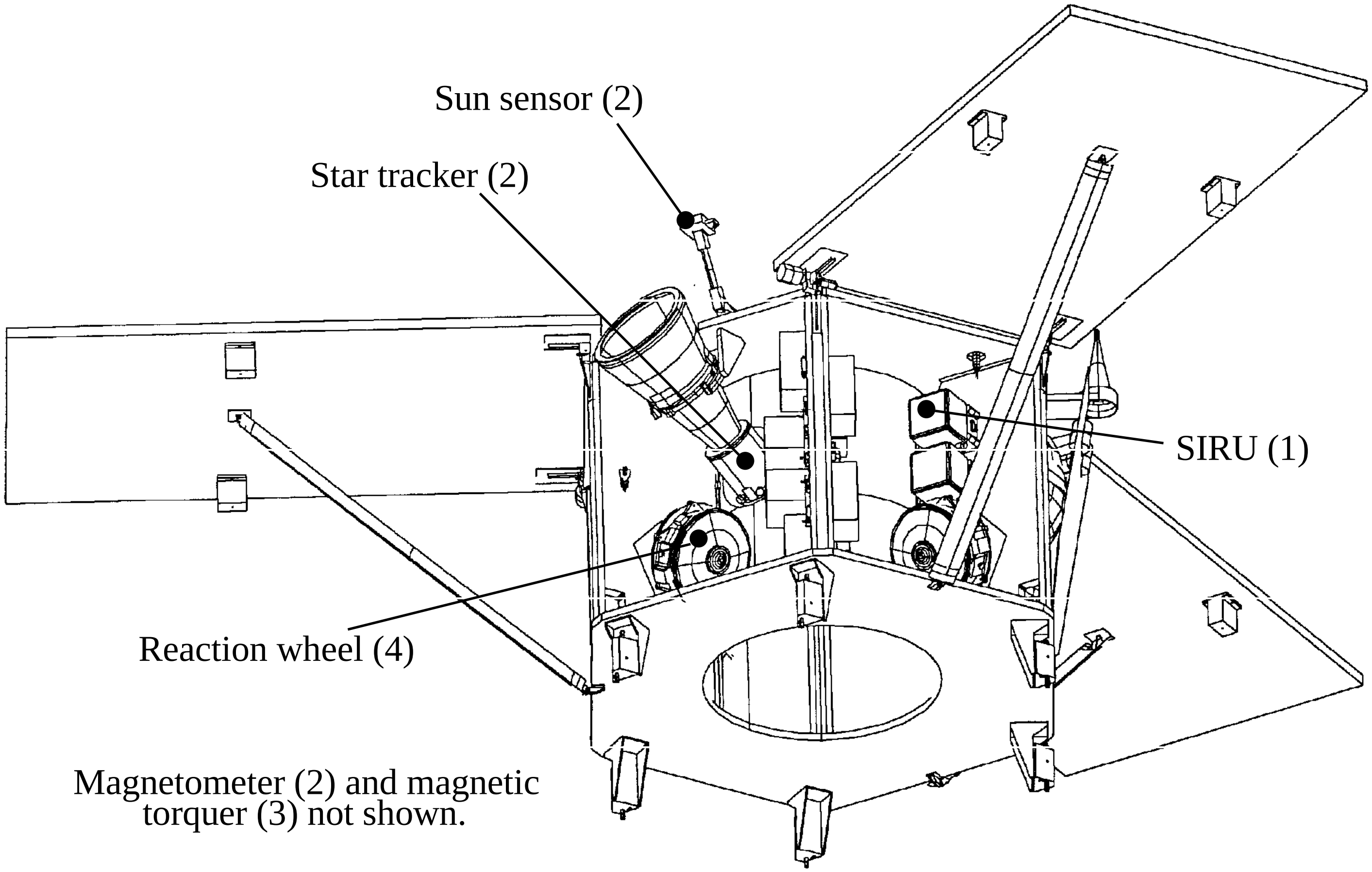
Design utilizes expertise from Corona and Hubble Space Telescope to attain low disturbance levels required for imaging.

✓ *High agility*

Reaction wheels provide 1.7 N-m of torque and 50 N-m-s of momentum to allow rapid repointing of the spacecraft boresight.

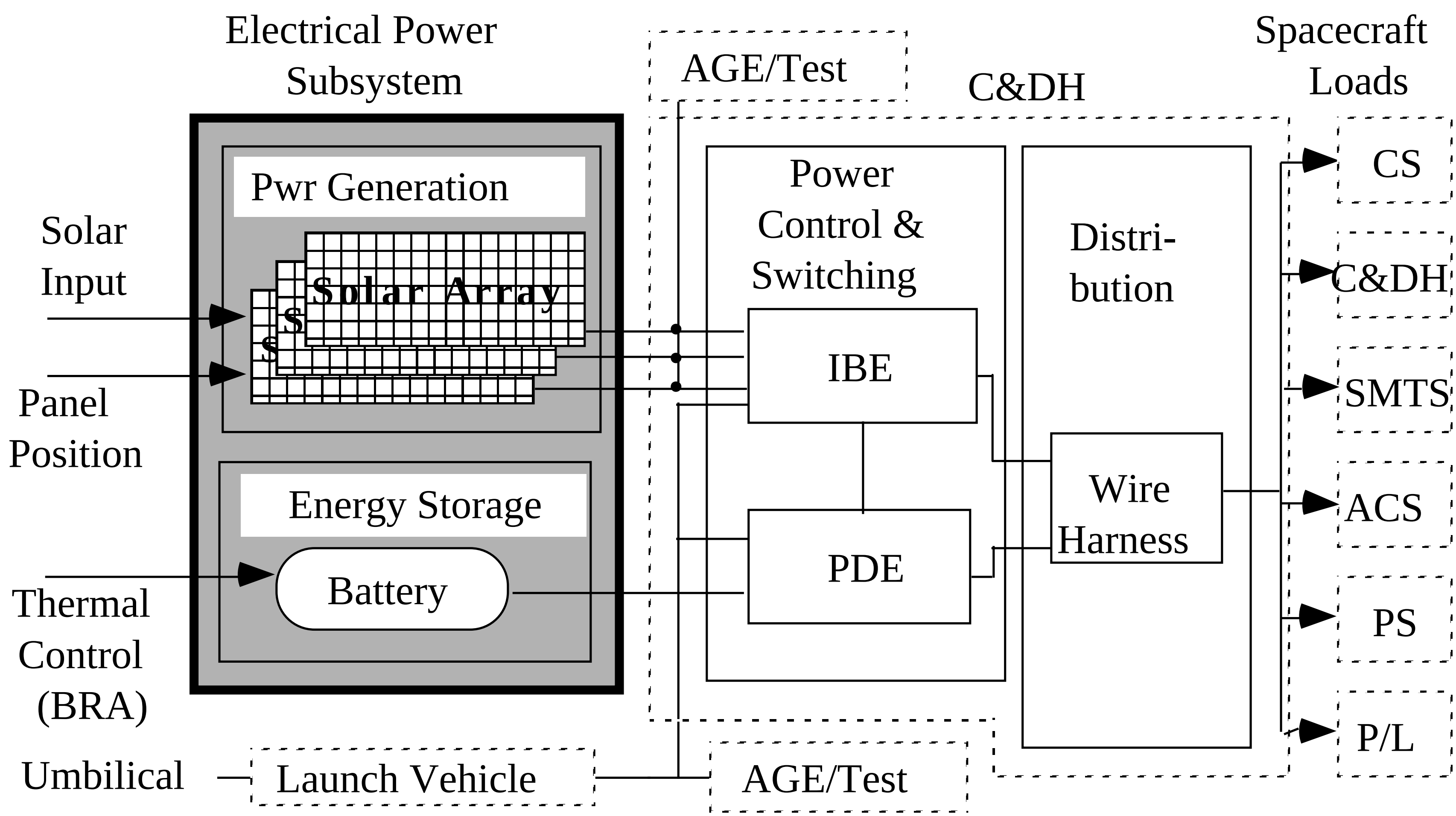
Designed for a 1-sigma line of sight (LOS) pointing stability of 12 arcsec but must also meet peak-to-peak jitter and rate requirements of the IKONOS mission

ACS Overview



Magnetometer (2) and magnetic torquer (3) not shown.

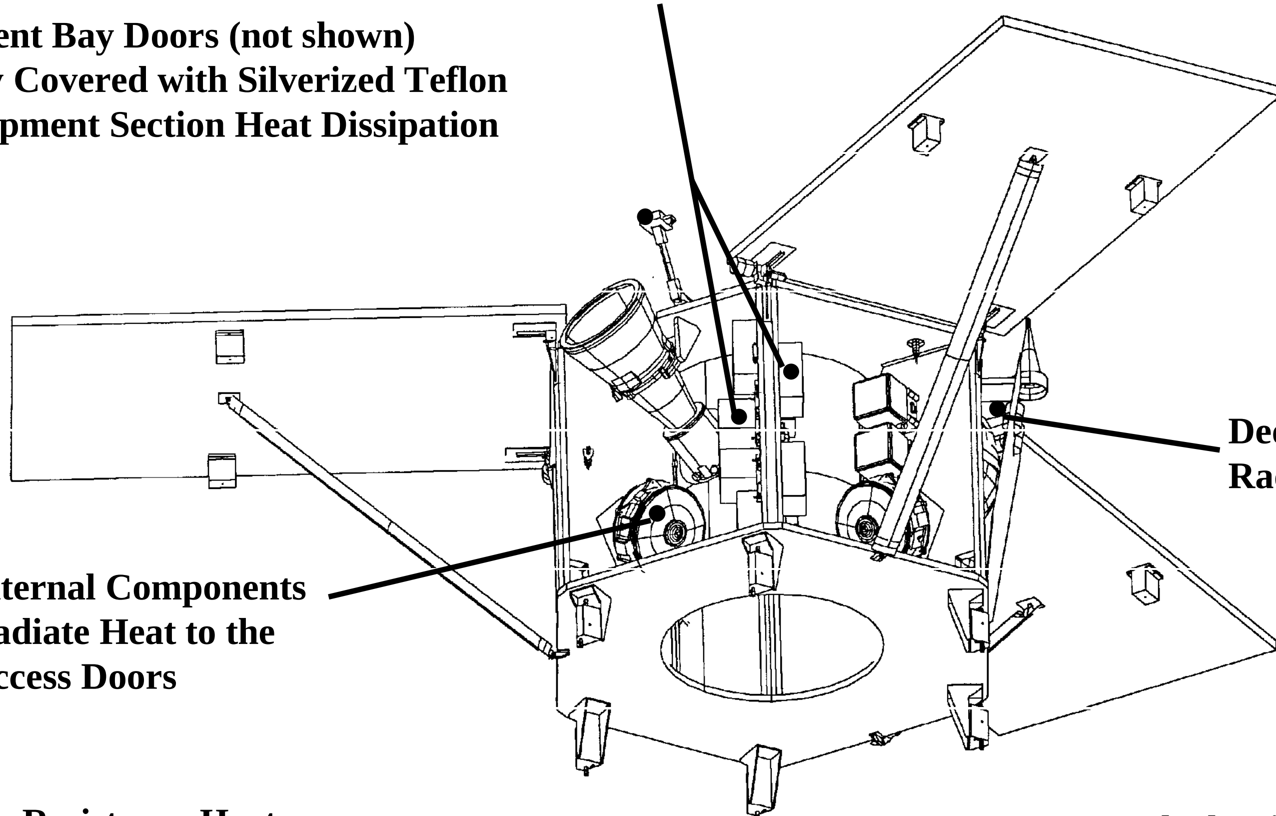
Power Subsystem Overview



Thermal Control Subsystem Overview

Communications Subsystem Components Conduct Heat to Structure

Equipment Bay Doors (not shown) Partially Covered with Silverized Teflon for Equipment Section Heat Dissipation



Dedicated Heat Pipe Radiator for Battery

Internal Components Radiate Heat to the Access Doors

Electric Resistance Heaters on Structure and Components Prevent Over-Cooling

MLI and Aluminum Tape on Non-radiator surfaces Minimizes Undesired Heat Loss

Thermal Control Subsystem Description

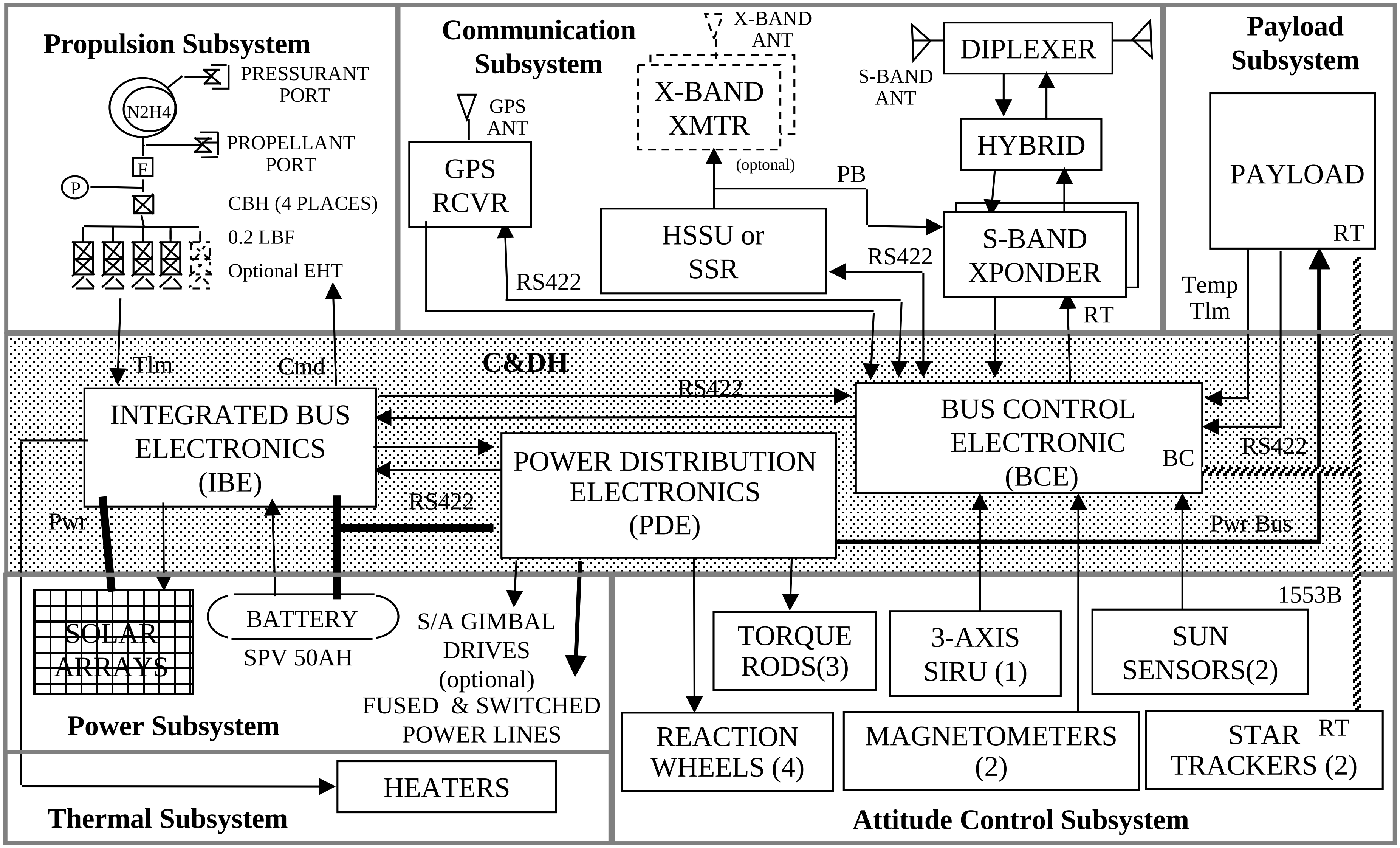
- **Most Equipment Section components cooled by radiation to structure**
  - **Communications Subsystem components cooled by conduction to their mounting surfaces**
  - **Most LM900™ bus components radiate waste heat to the bus access doors. The doors are partially covered with Silverized Teflon Flexible Optical Solar Reflector (FOSR) to efficiently radiate the waste heat to space**
- **Battery cooled by conduction to a heat pipe**
- **Externally mounted components provide their own thermal control**
- **Electric resistance heaters maintain components above minimum acceptable temperatures**
- **Multi-Layer Insulation minimizes undesirable heat transfer**
- **Variable-Conductance Heat Pipe Radiator System available for precision thermal control of payload equipment**

C&DH Subsystem Description

- The C&DH Subsystem provides command and control and collects telemetry to and from all Spacecraft Subsystems and consists of three major components.
  - the BCE (Bus Controller Electronics) provides 1553 Bus interface and optional high data rate RS422 interface to the payload, and as well as the HSSU (or optional Solid State Recorder) and Communication Subsystem.
  - the IBE (Integrated Bus Electronics) provides solar array cell switching and optional solar array gimbal drives for tracking solar array
  - the PDE (Power Distribution Electronics) accepts both switched solar array and battery power and provides conditioning, switching, and distribution of regulated and unregulated power to the satellite electrical loads

- Interface to the C&DH Subsystem is provided either through the RS422 interface or the 1553 Bus.
- The optional Solid State Recorder is a unit sized to meet the payload requirement. An optional high rate data downlink playback is provided directly to the X-Band transmitter.
- Two real time outputs: 1. housekeeping telemetry and payload engineering telemetry for direct X-Band transmission to ground stations and 2. real time data but includes payload Science data for storage into the SSR for later downlink playback during ground contacts

Command & Data Handling Subsystem Overview



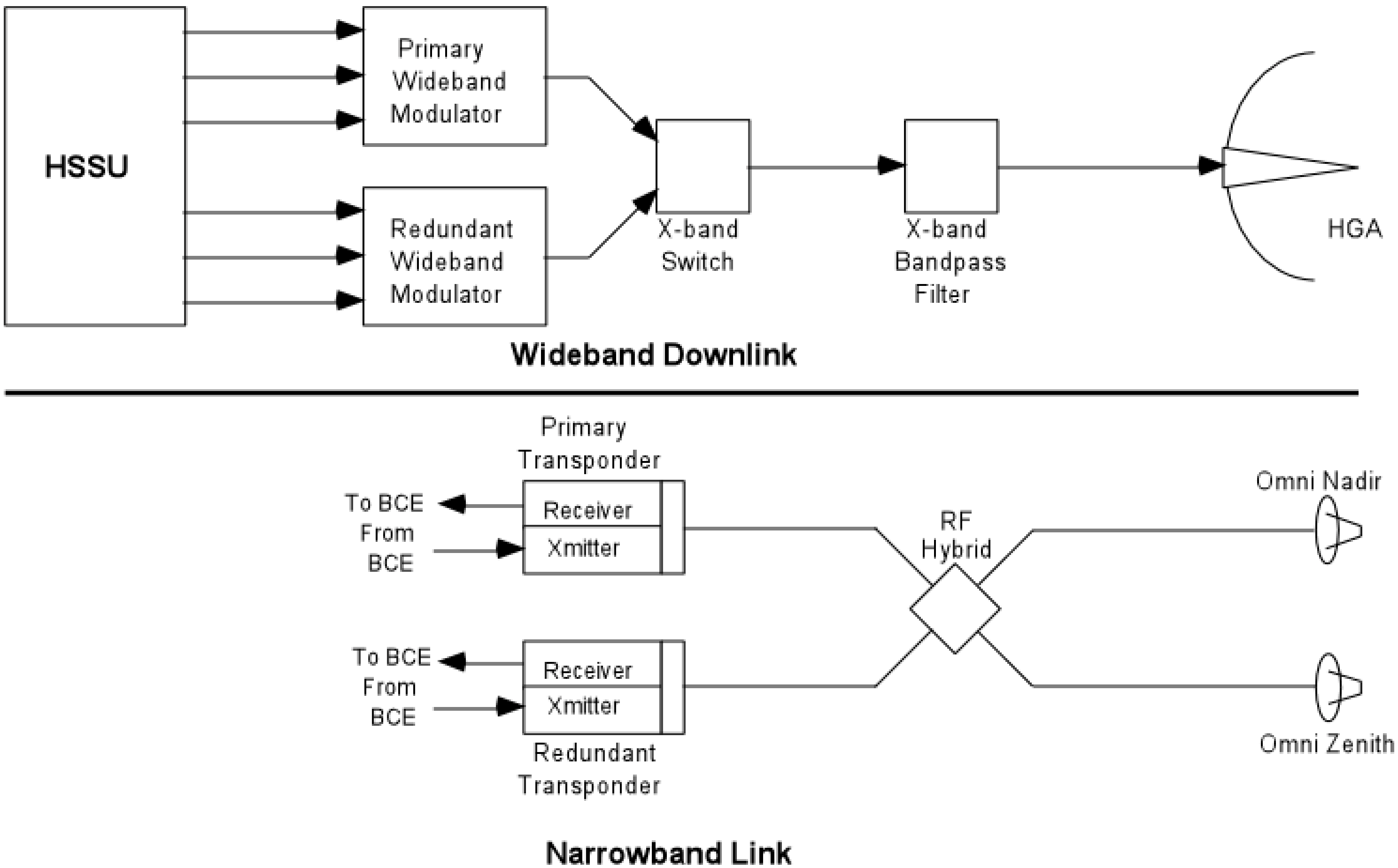
Optional Spacecraft Ground & Payload Interface

- **Uplink Command (S-Band) 2K-10K Bps**
  - **Format:** **CCSDS COP-1**
  - **Command Verification:** **CLCW**
  - **Uplink Command/Data Rate:** **1 Kbps (Configurable)**
- **Downlink Telemetry : up to 32K Bps Tlm, 320 M Bps Science**
  - **Telemetry Data Format:** **CCSDS AOS Grade Service 2**
  - **Fault Tolerance:** **Reed Solomon/CRC/Convolution Encoding**
  - **Real Time Hskp (S-Band):** **16 Kbps (Configurable)**
  - **Playback (X-Band):** **5 Mbps (Configurable)**
  - **High Rate Playback (X-Band):** **Up to 320 Mbps (Optional&Configurable)**
- **Instrument Interface:**
  - **Science Cmd/Data Format:** **CCSDS 203.0-B-1**
  - **Science Data Format:** **CCSDS Source Packet version 1**
  - **Time Code:** **CCSDS 301.0-B-2**
  - **High Rate Data Link** **RS422 (Configurable Data Rate)**

CCSDS = Consultative Committee Space Data Systems
COP = Command Operations Procedure
CLCW = Command Link Control Word
AOS = Advanced Orbiting Systems

Communications Overview

Communication Subsystem Block Diagram



Communications Description

- **Wideband downlink to transmit data to ground stations worldwide at a rate up to 600 Mbps, (wideband downlink provides 600 Mbps data at X-band. The system contains redundant wideband modulators and S- to X-band upconverters, feeding a gimbal nadir pointing antenna.)**
- **Narrowband uplinks for reception of satellite commands and tasking requests at a 2 kbps rate, and (narrowband uplink and downlink provides a 32 kbps telemetry stream and a 2 kbps ground command stream. The system has component redundancies for the S-band transponder and the S- to X-band upconvertors)**
- **Narrowband downlink to transmit satellite telemetry**
- **Global Positioning System (GPS) link to provide the satellite with GPS time and position data. The GPS link, with redundant receivers, provides initialization data, position, velocity, time, pseudo range, and carrier phase**
- **The narrowband uplink uses the NASA standard Spaceflight Tracking Data and Network (STDN) modulation scheme to transmit satellite command and tasking requests at 2 kbps**

Flight Software Functions

Flight Software (FSW)

Flight Control (FC) CSCI

Data Management
- Real time commands
- Stored program commands
- Memory block loads
- Crypto key mgmt
- Programmable format tlm
- H&S data collection
- Metadata collection
- Out-of-contact storage
- Memory dump
- I/O Drivers
- Automated Actions

Attitude Determination
- SIRU
- Magnetometer
- Star tracker

Command Generator
- Nadir pointing
- Inertial hold
- Imaging Maneuvers

Attitude Control
- Attitude control law
- RWA commands

Momentum Management
- Magnetic control law
- Magnetic torquer

Position Determination
- Reference ephemeris
- GPS processing

Antenna Pointing
- Open loop positioning
- Gimbal torque commands

Payload Support
- Tasking control
- Restricted areas

Bus Support
- Battery charge control
- Heater control
- Thermal door control

Protective Measures
- Fault detection
- Self checks
- Backup modes
- Save status/history

Operating System (OS) CSCI

Executive
- Initialization
- Scheduling
- Timekeeping
- Interrupts
- Memory management

Interface Services
- InterProcess comm.

Startup & Safing Firmware (SF) CSCI

Startup diagnostics
- Initialization
- Hardware diagnostics

Firmware Executive
- Resource management
- I/O drivers
- Memory scrub

Safe Mode Control
- Attitude control
- SIRU/sun sensor/RWA/thrusters
- Electrical power monitor
- Thermal control
- Boost & deployment backup

Command Backup
- Real time commands
- Crypto key change
- Memory block load

Telemetry Backup
- Real time H&S telemetry
- Memory dump
- Inactive processor memory dump

CSCI = Computer Software Configuration Items

LM-900 Leverages Significant Lockheed Martin Investment in IKONOS

- System engineering, analyses and models
- Requirements, drawings, supply chain databases
- Proven flight software
- Subsystem designs
- Space / ground interfaces
- System control and Tasking
- Proven commercial practices
- Satellite and system Integration & Test
- Payload and vehicle calibrations
- End-to-end image chain analysis and validation
- Extensive on-orbit certification of performance and validation of all models
- Satellite bus implementation in 24-36 months for first unit
- Satellite integration with payload and test 6-12 months for first unit
- Cycle times for additional units would be significantly reduced
- Specific schedules are dependent on requirements and quantities

Lockheed Martin has invested in excess of $300M in the design, development and test of the IKONOS satellite. LM-900 is based on this proven system capability

Command and Data Handling System

Glenn Butcher
Lockheed Martin Space Systems Company

Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

Command and Data Handling System

TPF C&DH Baseline derived from Ikonos:

- **BCE Bus Controller Electronics, including flight processor and hardware safemode electronics.**
    - ***Honeywell 603e Flight Processor.***
- **IBE Iridium Bus Electronics, including solar array switching, solar array motor drive electronics and battery charging.**
- **PDE Power Distribution Electronics, includes 42 circuits, fusing, Antenna gimbal motor drive and reslovers, torque rod drives.**
- **SSR, Seakr Solid State Recorder, 40 Gbit end of life, high speed interfaces, and Reed-Soloman encoding.**
- **Spacecraft Harness, includes all interconnects and propulsion plumbing.**

Key C&DH Interfaces

- **Flight Software Interfaces and the Flight Processor, includes vehicle time.**
- **Communications Interfaces, U/L D/L encryption (N/A), TDRSS protocol.**
- **Power System Interfaces, Solar Arrays switching, Battery charging controls.**
- **Telemetry System Interface, Health & Status data collection and formatting.**
- **Safe Mode Interfacing, Enables & Monitors, Redundancy, Protective measures.**
- **Thermal Control System Interfaces, thermistors, heater and cryogenic controls.**
- **Mechanical Interfaces, Gimbal motors, deployment, separation systems.**
- **Payload Telescope & Combiner Interfaces, High Rate Data, Modes, Power switching.**
- **Science Data System Interface, Control, Storage, & Formatting, ancillary data.**
- **Propulsion Interface, Orbit insertion & adjust interface controls.**
- **Attitude Control System (ACS), 5 sensors and 3 actuator types.**

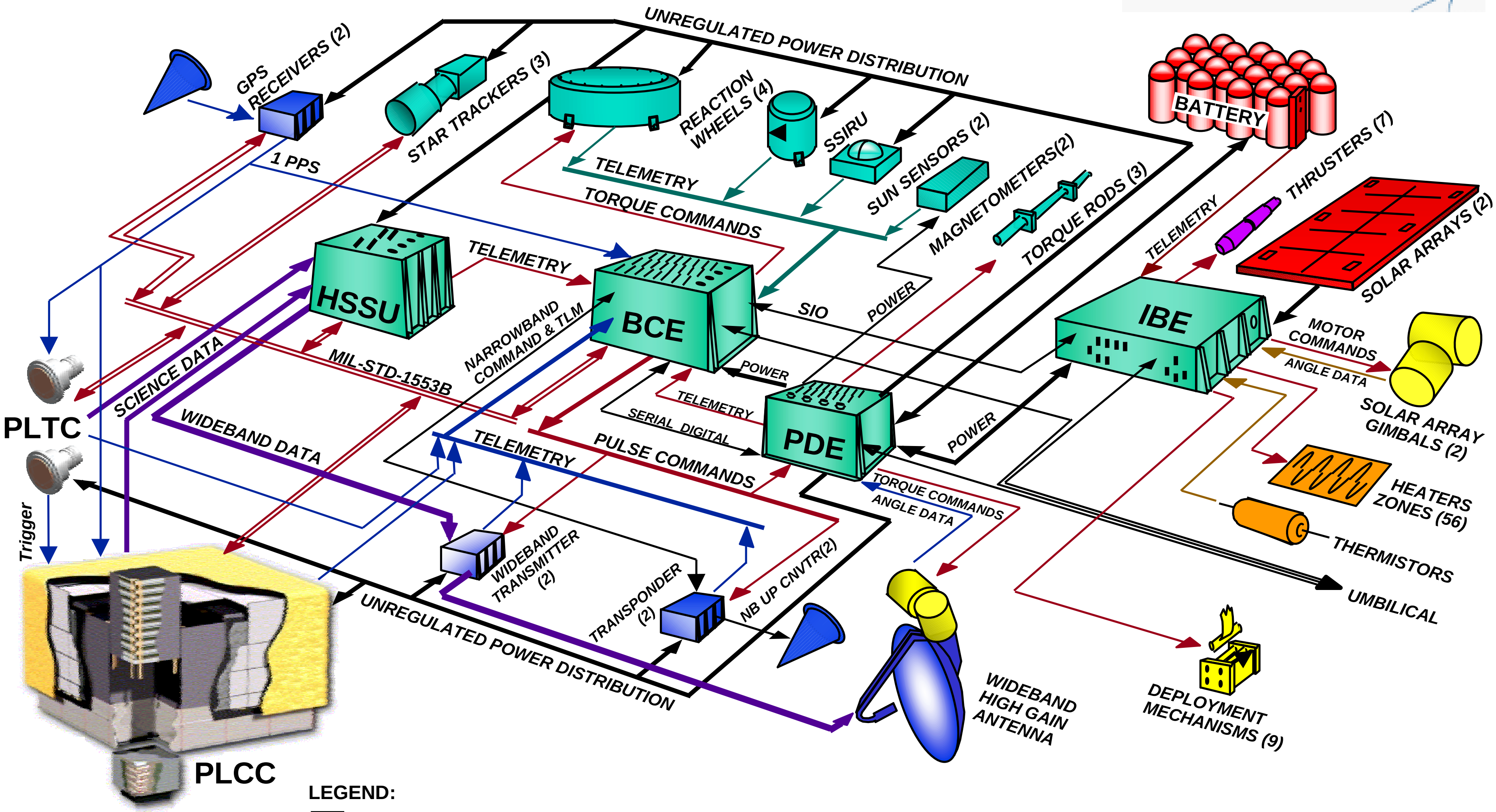
ACS I/Fs: Sensors:

- **Gyros = SIRU not RLGs**
- **Star Trackers**
- **Sun Sensors**
- **Range & Rate Tracking**

ACS I/Fs: Actuators:

- **Reaction Wheels**
- **Thrusters**
- **Propulsion & Orbit Adjustment**
- **Antenna Gimbals & Solar Array drives**

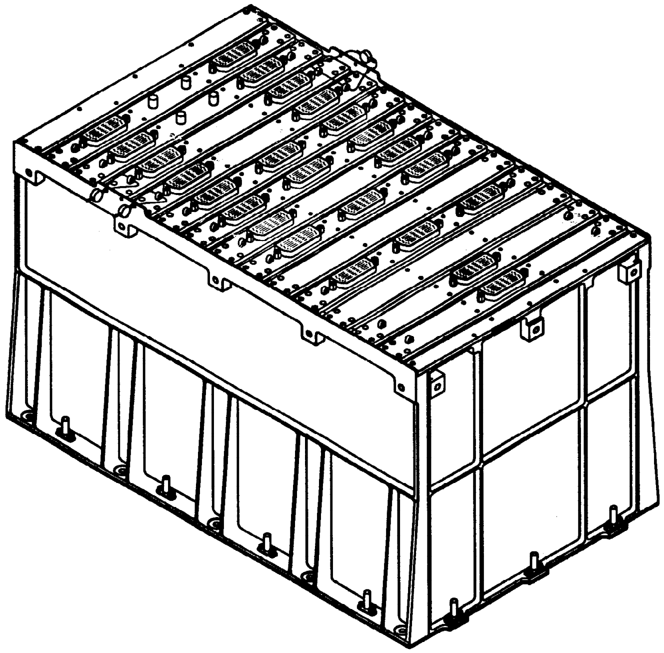
Spacecraft Block Diagram



LEGEND:

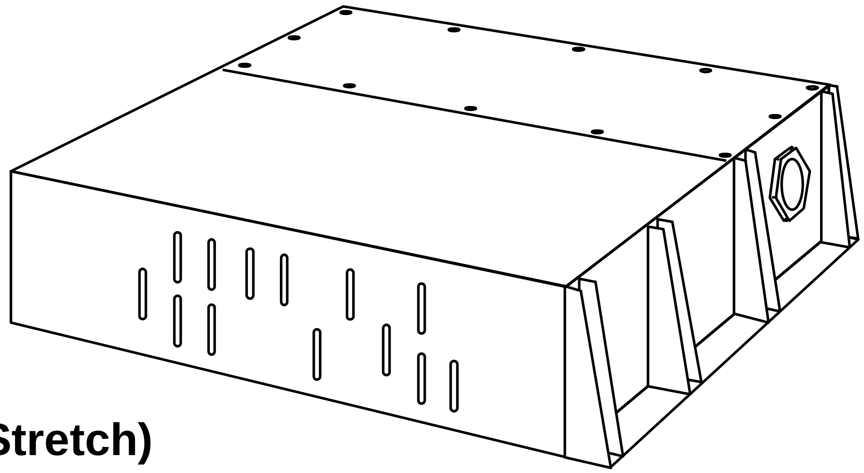
- COMMAND & DATA HANDLING SUBSYSTEM
- COMMUNICATIONS SUBSYSTEM
- ELECTRICAL POWER SUBSYSTEM
- ATTITUDE AND ORBIT CONTROL SUBSYSTEM
- MECHANISMS
- THERMAL CONTROL
- PROPULSION

BCE Product Description



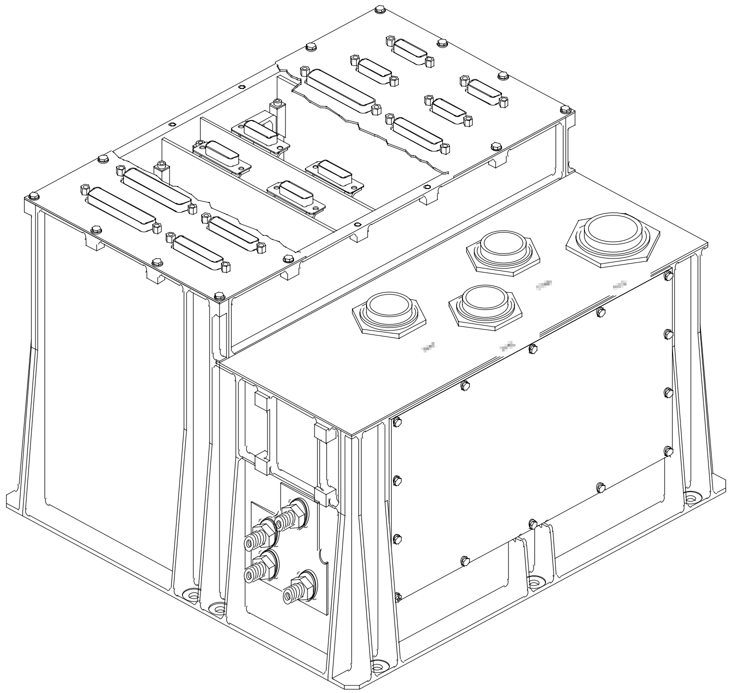
- **Weight = 36.2 lbs.**
- **Power = 42.5 Watts Average**
  50 Watts Max
- **Dimensions = 17.5" x 10.9" x 10.5"**
- **Reliability = 0.98 @ 5 Years**
- **Product Design:**
  - **Dipped Brazed Al Enclosure**
  - **12 CCA's Including Backplane**
  - **9.187" x 8.661" Multilayer Card Size**
  - **Mixed SMT & PTH Technology**
- **Thermal Environment:**
  - **-20°F to 129°F (ProtoFlight)**
  - **Radiation Cooling > 80%; Conduction Cooling < 20%**
- **Dynamic Loading:**
  - **0.2 G^2/Hz @ 50 Hz - 600 Hz Random Vibration**
  - **9.1 Gs @ 30 Hz - 70 Hz Sinusoidal Vibration**
  - **3,000 Gs @ 3 KHz - 8 KHz Pyrotechnic Shock**
- **Radiation > 13 K Rads Total Dose (Component Capability)**

IBE Product Description



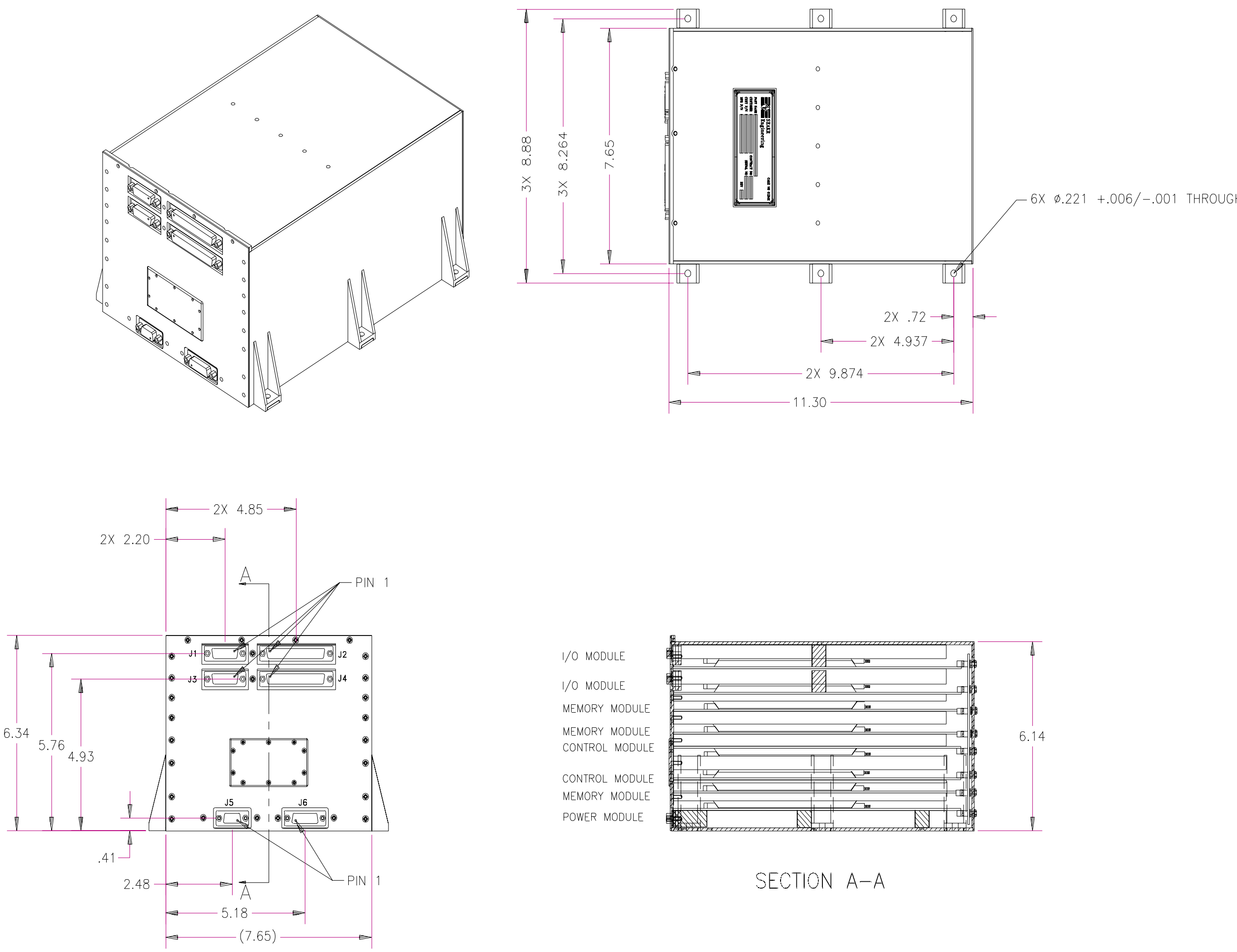
- **Weight = 28.2 lbs.**
- **Power = 16.4 Watts Eclipse**
  23.7 Watts Sunlight
- **Dimensions = 17.5” x 14” x 6.1”**
- **Reliability = 0.994 @ 5 Years**
- **Product Design:**
  - **Dipped Brazed Al Enclosure**
  - **12 CCA’S Including Backplane**
  - **5.88” X 8.25” Board Size (SEM-E Stretch)**
  - **Mixed SMT & PTH Technology**
- **Thermal Environment:**
  - **- 4°F to 122°F (Qualification)**
  - **Radiation Cooling > 80%; Conduction Cooling < 20%**
- **Dynamic Loading:**
  - **0.5 G^2/Hz @ 50 Hz - 300 Hz Random Vibration**
  - **9.1 Gs @ 30 Hz - 70 Hz Sinusoidal Vibration**
  - **3,000 Gs @ 3 KHz - 8 KHz Pyrotechnic Shock**
- **Radiation > 32 K Rads Total Dose (Component Capability)**

PDE Product Description



- **Weight = 26 lbs.**
- **Power = 16 Watts CRSS Standby**
  35 Watts CRSS Imaging
  45 Watts Maximum
- **Dimensions = 13" X 11.5" X 9.5"**
- **Reliability = 0.99 @ 5 Years**
- **Product Design:**
  - **Dipped Brazed Al Enclosure**
  - **9 CCA'S Including Backplane & Spare**
  - **5.88" X 8.25" Board Size (SEM-E Stretch)**
  - **Mixed SMT & PTH Technology**
- **Thermal Environment:**
  - **-20°F to 129°F (ProtoFlight)**
  - **Radiation Cooling > 80%; Conduction Cooling < 20%**
- **Dynamic Loading:**
  - **0.2 G^2/Hz @ 50 Hz - 600 Hz Random Vibration**
  - **9.1 Gs @ 30 Hz - 70 Hz Sinusoidal Vibration**
  - **3,000 Gs @ 3 KHz - 8 KHz Pyrotechnic Shock**
- **Radiation > 11.4 K Rads Total Dose (Component Capability)**

SSR Estimated Enclosure Dimensioning



BASIC CONFIGURATION

Hardware List

- **One Flight Bus Controller Electronics (BCE).**
  - ***includes two Honeywell 603e flight computers.***
  - ***includes hardware safe-mode protection logic and commanding.***
  - ***provides uplink and downlink controller interface.***
- **One Flight Iridium Bus Electronics (IBE).**
  - ***includes solar array switching, and battery charging interface.***
  - ***includes solar array motor drive electronics.***
  - ***provides propulsion and heater interfaces.***
- **One Flight Power Distribution Electronics (PDE).**
  - ***Payload power interface and distribution, 4 primary and 4 redundant.***
  - ***Antenna gimbal motor drive and resolver interface.***
- **Seakr Solid State Recorder Unit (SSR).**
  - ***40 Gbit end of life, dynamically configurable circular buffer.***
  - ***4 high speed ports in, one comm port out.***
- **TPF Payload and Spacecraft interconnection Harness.**

C&DH Integration Facilities

Lockheed has developed the C&DH H/W & S/W integration facility

- **Lockheed Commercial Remote Sensing Satellite developed a Hardware Software Integration Facility. Now called Flight Software Test System (FSTS).**
- **Outgrowth of BCE/PDE development, test and integration.**
- **BCE EU Special Test Equipment used for environmental testing was modified to build a software qualification and simulation facility.**
- **Engineering models of BCE, PDE, IBE, HSSU I/F, gimbals, RWA, GPS receivers, and associated cabling were all integrated here.**
- **Two separate development platforms.**
- **High Speed telephone link to support ground station testing.**
- **All levels of Flight Software were written, tested and qualified on the two BCE engineering unit platforms.**
- **One platform is fully redundant. The other independent platform is fully redundant except for redundant power supply and redundant flight processor.**
- **Extremely useful for orbital simulations and on-orbit anomaly investigations.**

C&DH Integration & Development Hardware

- **One Bus Controller Electronics Engineering Unit (BCEeu), fully populated.**
- **One BCE Special Test Equipment for development and proto-qualification.**
- **One Iridium Bus Electronics Engineering Unit (IBEeu), fully populated.**
- **Borrow the IBE Special Test Equipment for development and proto-qualification.**
- **One Power Distribution Electronics Engineering Unit (PDEeu) fully populated.**
- **One PDE Special Test Equipment for development and proto-qualification.**
- **Engineering Cabling to support development and proto-qualification.**
- **Lockheed Thermal Vacuum and Vibration Testing Facilities.**
- **Lockheed Flight Software Test System integration Facilities.**

Payload Control Electronics System

Glenn Butcher
Lockheed Martin Space Systems Company

Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

Telescope and Interferometer Interfaces

- **TELESCOPE CONTROLS.**
- **LIGHT PATH CONTROLS.**
- **COMBINER CONTROLS (inside cryogenic assembly).**
- **DETECTOR CONTROLS (inside cryogenic assembly).**
- **CRYROGENIC CONTROLS.**
- **DEPLOYMENT CONTROLS.**
- **INTERFACES NOT CURRENTLY REQUIRED.**

Telescope and Interferometer Interfaces

- **TELESCOPE CONTROLS: Two 60-85 cm telescopes for 9 meter precursor mission, adapt to Four telescopes for TPF missions:**
  - **Telescope Secondary Mirror Focus Mechanism.**

    Linear adjustment with position measurements, non-dynamic (set and forget). (Discussed SIRTF Space Infra-Red Telescope Facility's, CDMU Cryo-Telescope Drive Multiplexer Unit, focus drive warm electronics as possible design candidate).
  - **Tertiary Mirror Fast Steering Motor, two axis piezo-electric drive.**

    Used to align collected beam onto quad-cell detectors. Fast rates and constant adjustments with feedback control from quad-cell detectors. Range 30-60 arcsec (TBR). Control drive rate, 20Hz. (Discussed SIRTF, MIPS Multi-Band Imaging Photometer Sensor, scan mirror and drive electronics as possible design candidate).
  - **Telescope temperature monitors, ambient baseline.**
- **LIGHT PATH CONTROLS:**
  - **"Trombone" or Light Path Length Adjustment Mirrors. Paired 90 degree mirrors on single Linear actuator with position measurement, periodically adjustments ~10 mm (TBR) control range.**

Telescope and Interferometer Interfaces

- **COMBINER CONTROLS (Located inside cryogenic dewar assembly):**
  - **Fine Phase Adjustment Mechanism, opposing light paths adjusted with single linear actuator. Very fast dynamics, used to adjust light wave phasing relationship with feedback control from the Near-InfraRed (NIR) Phasing detectors. Processing logic and latency estimates, phase detection approx 200 HZ, Drive rate >20 Hz.**
  - **Alternating Chopper Mirror Motors. Dual or coupled chopper motors driven from single mechanism, with position feedback, dynamic actuation at approximately 4.0 to 0.25 Hz. (The SIRTF MIPS scan mirror and driving warm electronics as possible design candidate).**
- **DETECTOR CONTROLS (Located inside cryogenic dewar assembly):**
  - **Infrared Detector Arrays for Spectroscopy Analysis. Single Large Detector Array sufficient for both images. Primary Science data.**
  - **Near-Infrared Detector Arrays for Fine Phase Measurements. Single Detector Array for both images. 2 μm wavelength, read at 200 Hz.**
  - **Two Quad Cell Detector Arrays for Telescope Fine Pointing. Detector array read at approx 200 Hz. (Closed loop controls with telescope tertiary fast steering mirrors, drive rate approx 20 Hz.)**

Telescope and Interferometer Interfaces

- **CRYROGENIC CONTROLS:**
  - **Single Pyro-actuation type for Venting Valve.**
  - **Cryro Low Temperature monitors, approximately 12.**
- **DEPLOYMENT CONTROLS: (baseline was passive deployment with springs and latches)**
  - **Hold Down and Release Mechanisms, 8 to 10 drive and sense.**
  - **Option to provide a two axis truss gimbal for telescopes.**
  - **Additional Motors, Actuator, and Mechanisms, not defined.**
  - **Measurement and Sensors Interfaces, none defined.**
- **INTERFACES NOT CURRENTLY REQUIRED (TBR):**
  - **Telescope Dust Covers, motors and sensors.**
  - **Light Path Aperture Doors, actuators and sensors.**
  - **Additional Cryo Control Logic and Mechanisms.**
  - **Cryo Pressure or flow rate measurements.**
  - **Laser Alignment System for Truss.**
  - **Additional Spectrometer controls.**
  - **No amplitude balancing systems needed.**

Payload Control System Electronics

Warm Electronics to Interface to TPF Payload (NEW):

- **PLTC Payload Telescope Controls Electronics**
  - **Secondary Focus Drive Electronics**
  - **Tertiary Fast Steering Mirror Drive Electronics**
  - **Trombone Path Length Adjust Drive Electronics**
  - **Quad Cell Detector Processing Electronics**
  - **Cryogenic Temperature Interface Electronics**
  - **Attitude Control System Interface to S/C**
- **PLCC Payload Combiner Controls Electronics**
  - **Chopper Motor Drive Electronics**
  - **Infrared Detector Data Handling Electronics**
  - **Near Infrared Phase Detector Electronics**
  - **Phase Adjustment Control and Processing**
  - **Fine Phase Adjust Drive Electronics**
  - **Science Data Handling Interface**

Cost & Summary

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Terrestrial Planet Finder (TPF)
Phase 2 Final Architecture Review
Dec 12, 2001

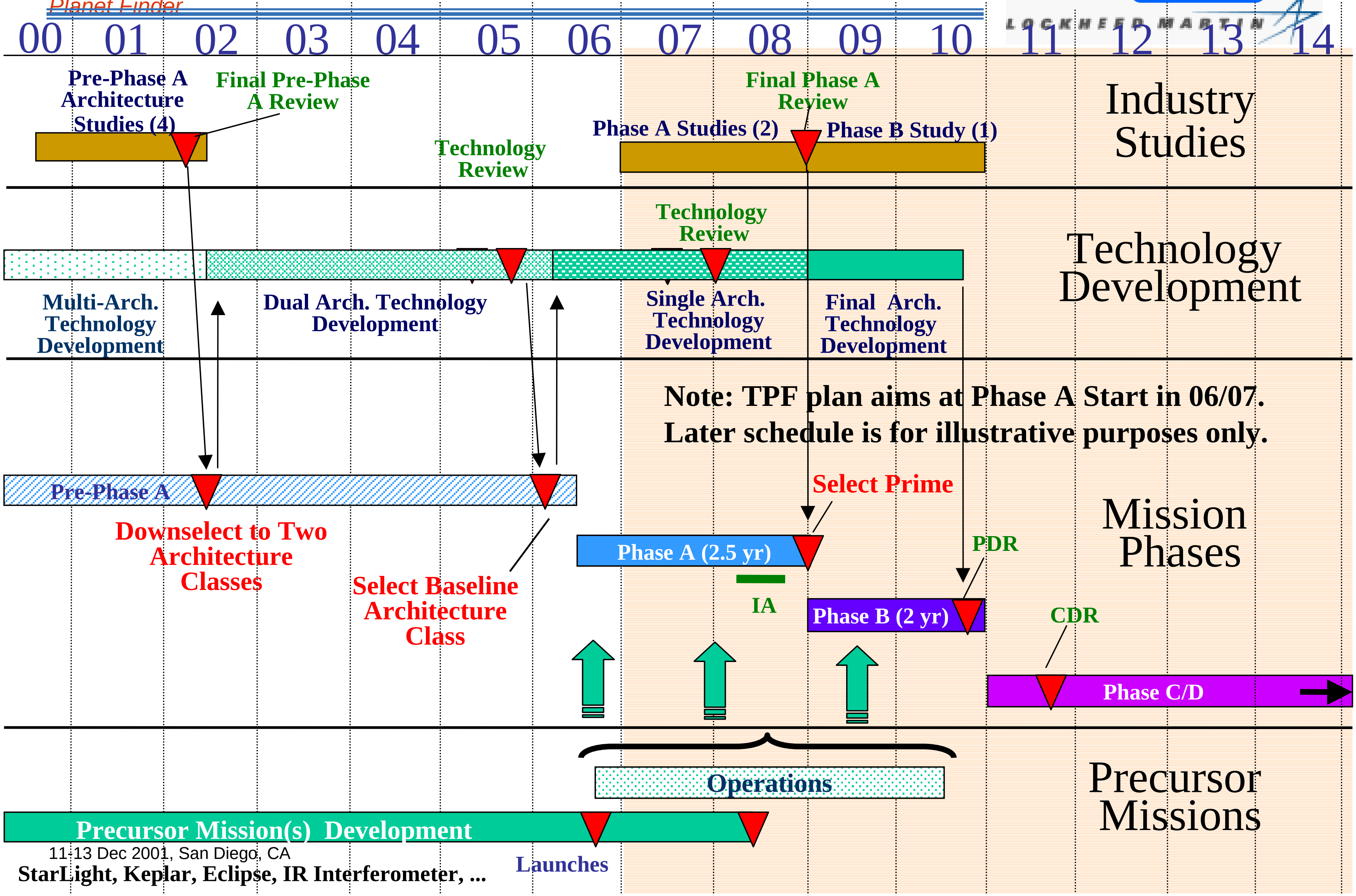
Exhibit II Science Requirements*
January 7, 1999

General Mission Assumptions	Rqmts	9 m	21 m	40 m	FF	Comment
1. Sky coverage	60%	>90%	>90%	>90%	90%	
2. Mission duration (years)	5	4	5	5	10	
3. Nominal planet is defined as a solid body with Earth radius at 1 AU, T=270 K.						9m mission:Jupiters
4. The planet detection and characterization program will be allocated ~50% of the design mission lifetime with the remainder of the lifetime allocated for general imaging and spectroscopy.						
5. Spacecraft use non-nuclear power sources.						
Planet Detection/Characterization						
1. # of stars (F5-K5) surveyed for planets (R=3, SNR=5)	150	30	44	348	500	
2. Number of scans for CO_2/H_20 (R=20, SNR=10)	30		18	>100	>100	
3. # of scans for Ozone/strong CH_4 (R=20, SNR=25)	5		5	>25	>25	
4. Spectral Band (μ m)	7-17	4-10	7-17	7-17	3-23	Zodiacal light limited
5. Spectral Resolution	20		20	20	100	
6. Maximum distance of ozone detection (pc)	10	10	13	>20	>20	
7. Minimum distance of planet detection (pc)	3		3	3-22	22	
8. Exo-zodiacal dust will be the same as in our own solar system for requirement, up to 10 times the solar system level.						
9. Follow-up (high spectral resolution) surveys are uniformly distributed throughout the volume of the initial survey.						
10. Point source sensitivity: 5 σ, 2 hr at 12 μm, R=3. (μ Jy)	0.3		0.53	0.13		
High Resolution Imaging (TBR)						
1. Imaged objects for 5 year mission	800				1600	(1 object/day)
2. Resolution at 3 μm (milliarcsecond)	0.75				0.75	
3. Band (μm)	3-17				2 to 40	
4. Spectral resolution	3-300				3 to 300	
5. Special purpose spectral resolution (FTS mode) in specified lines					120	
7. Effective minimum baseline for synthetic imaging (m)	100				<50 (interferometric only)	
8. Dynamic range in Reconstructed Image	50:1				100:1	

TPF Configurations

Baseline	Telescopes			Science Goals
	Number	Aperture	Temp	
9 m	2	60 cm	60 K	Young Jupiters
21 m	4	1.7 m	40 K-45 K	Earth to 12 pc, O_3, H_2O, CO_2 to 8 pc
40 m	4	3.5 m	40 K-45 K	Earth to 22 pc, O_3, H_2O, CO_2 to 15 pc
Free flyer	4	3.5/6 m	40 K-45 K	Planetary mission goals plus astrophysics

Revised TPF Schedule(JPL)

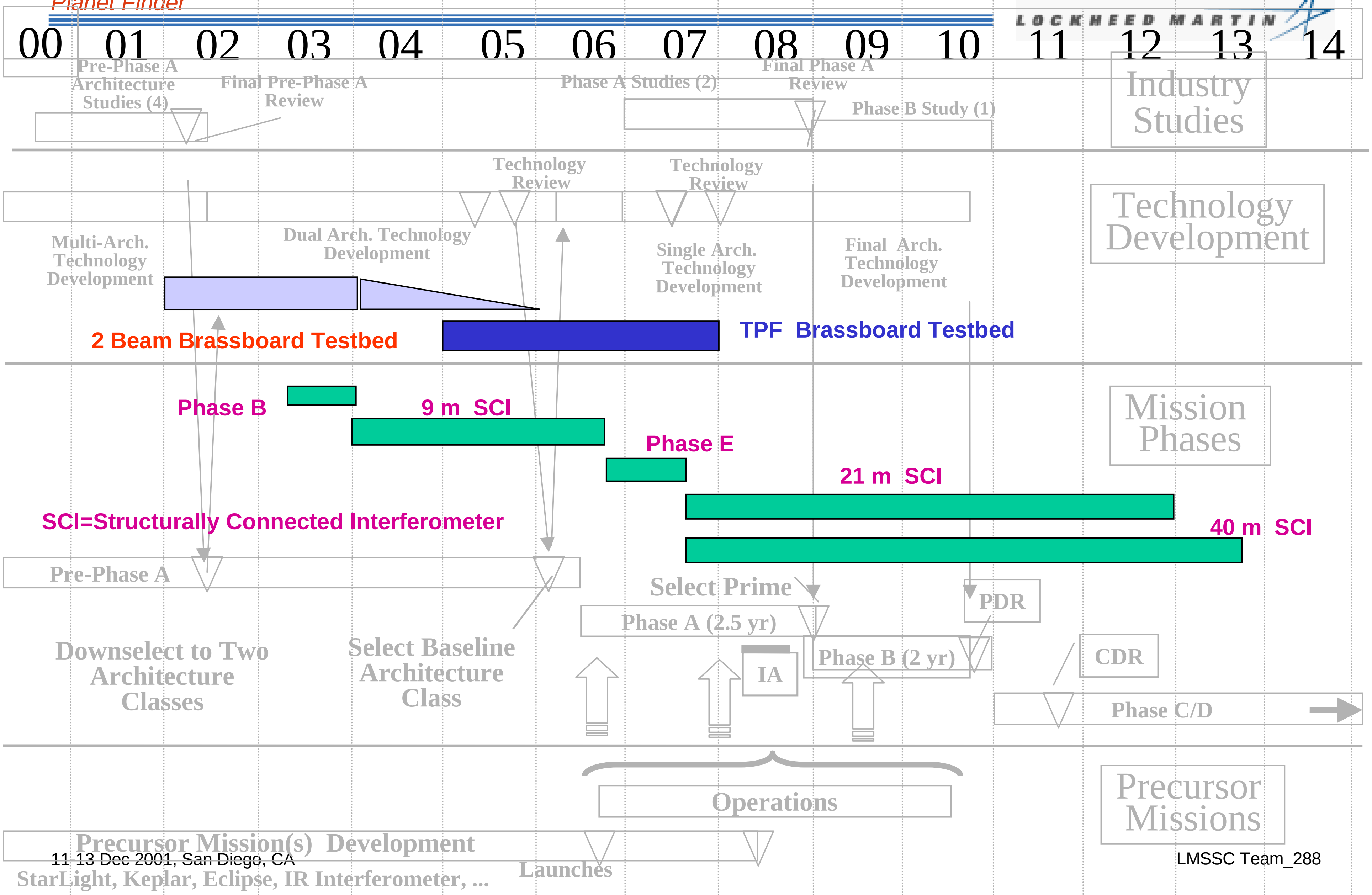


TPF
Terrestrial Planet Finder

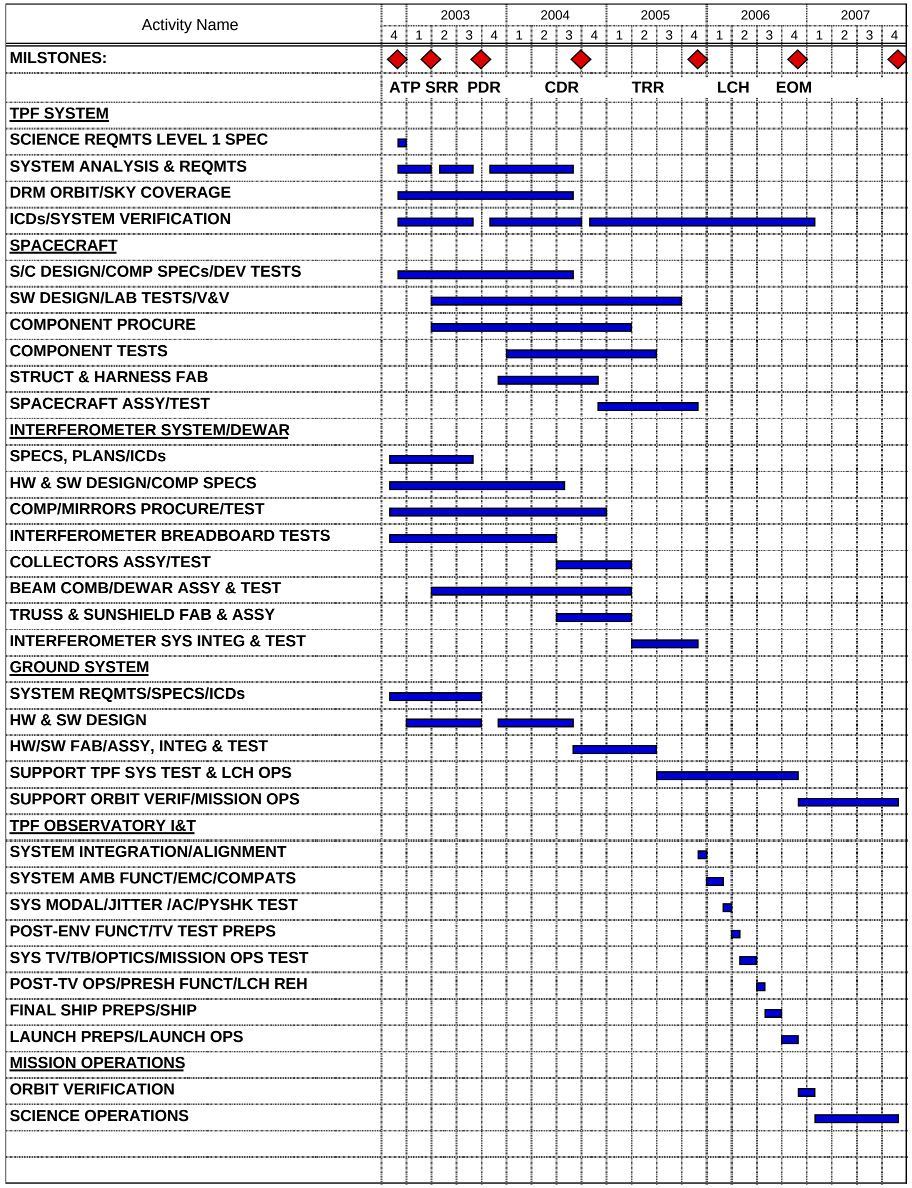
Pre-Formulation Phase Study -Final Architecture Review

LMSSC P556045

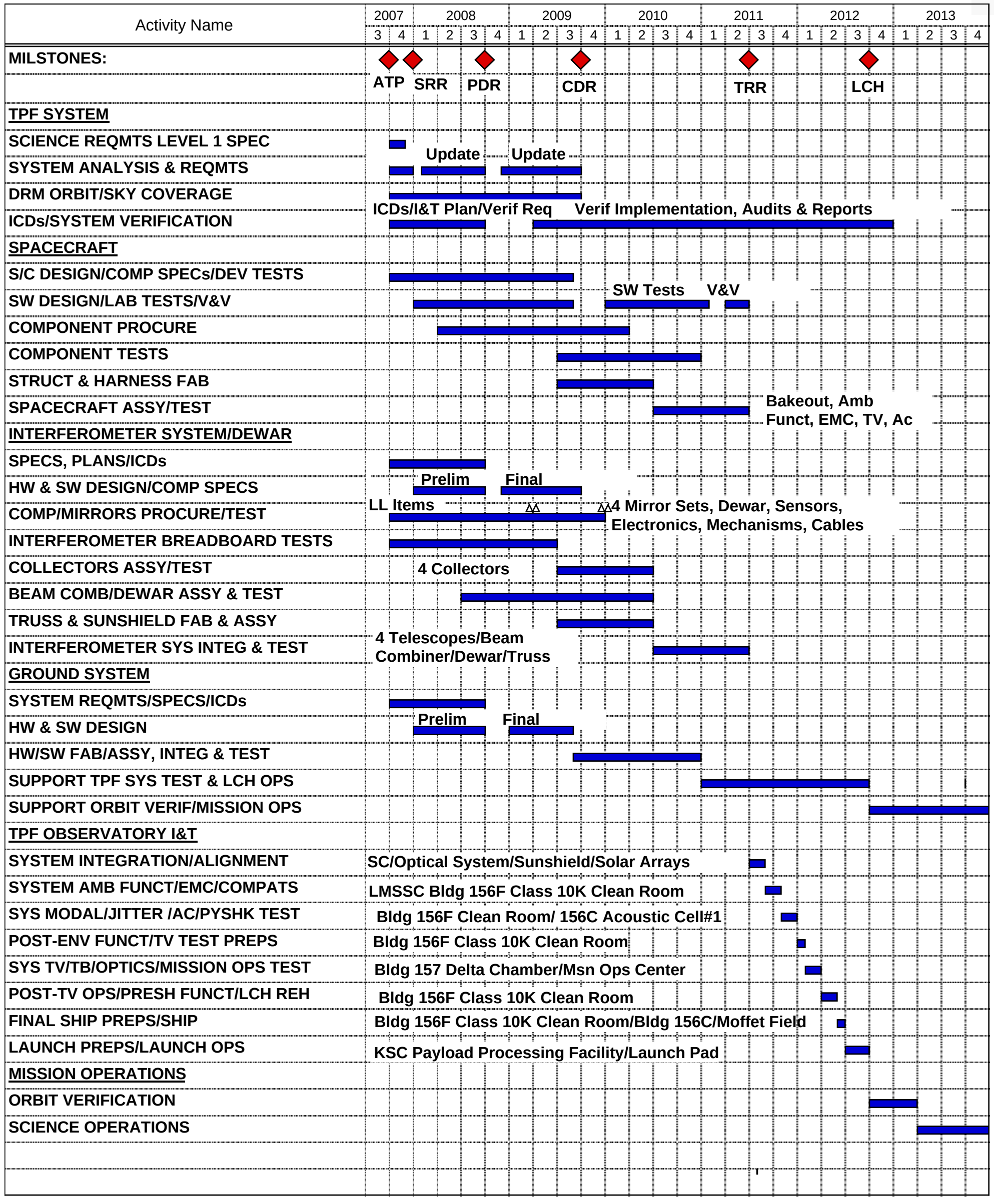
Lockheed Team TPF Schedule



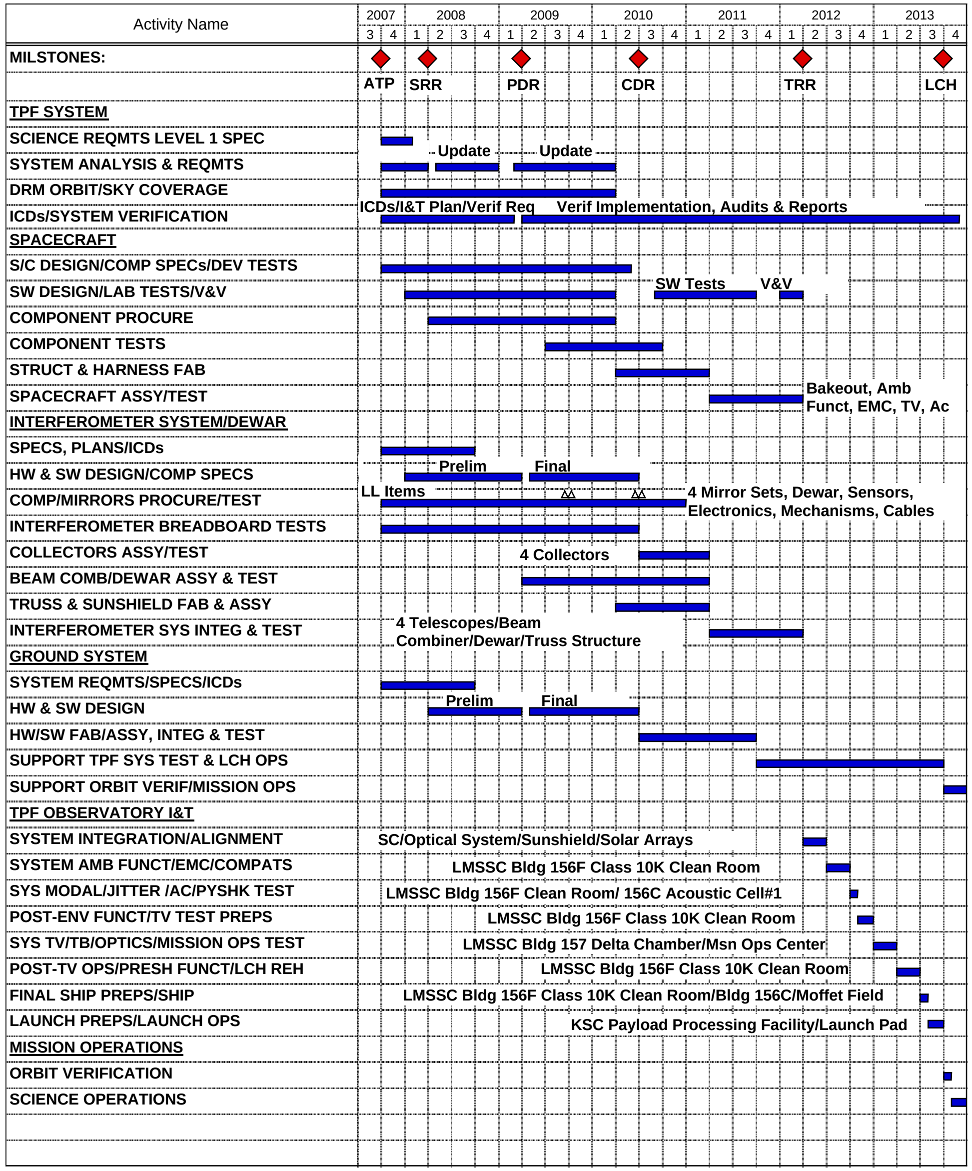
9 meter SCI Four-Year Development Phase B/C/D



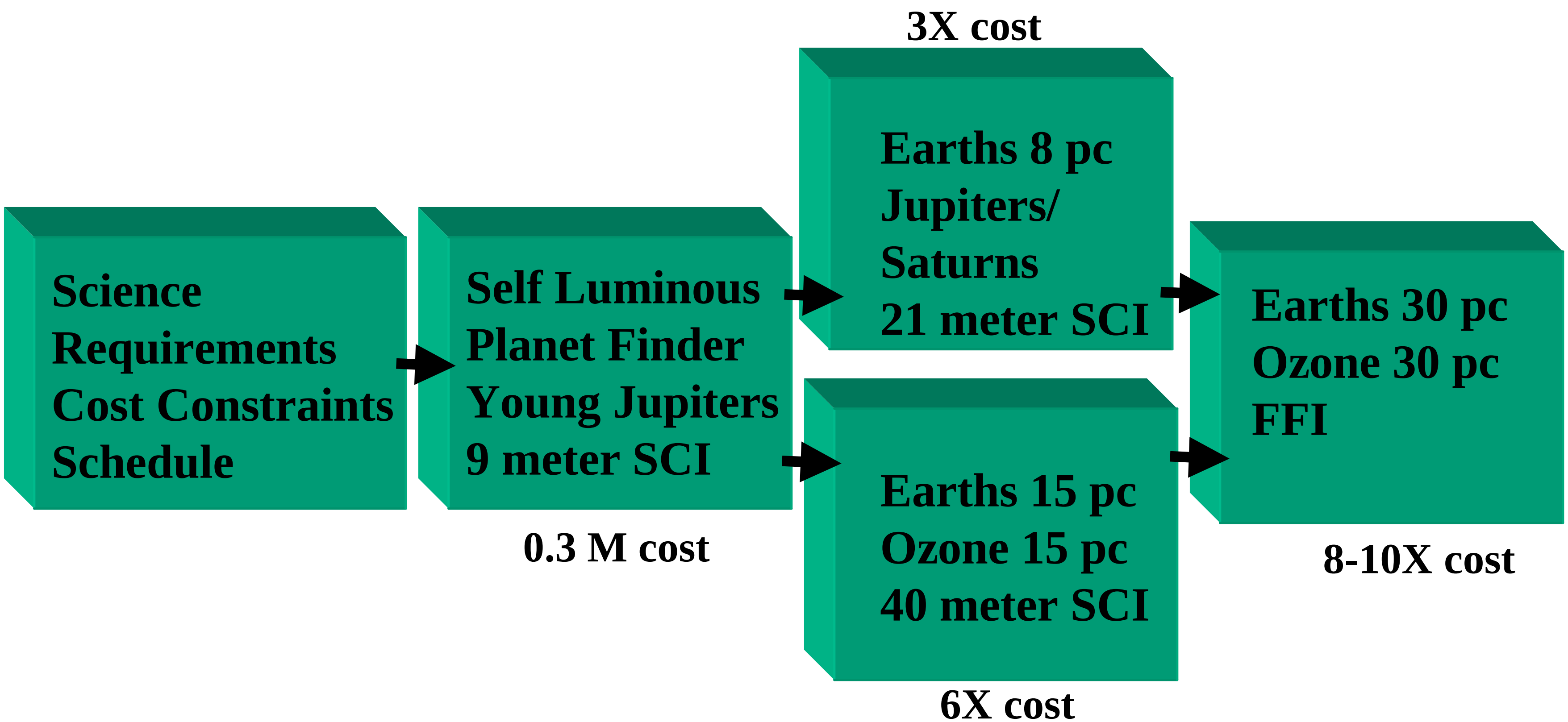
21 meter SCI Five-Year Development Phase B/C/D



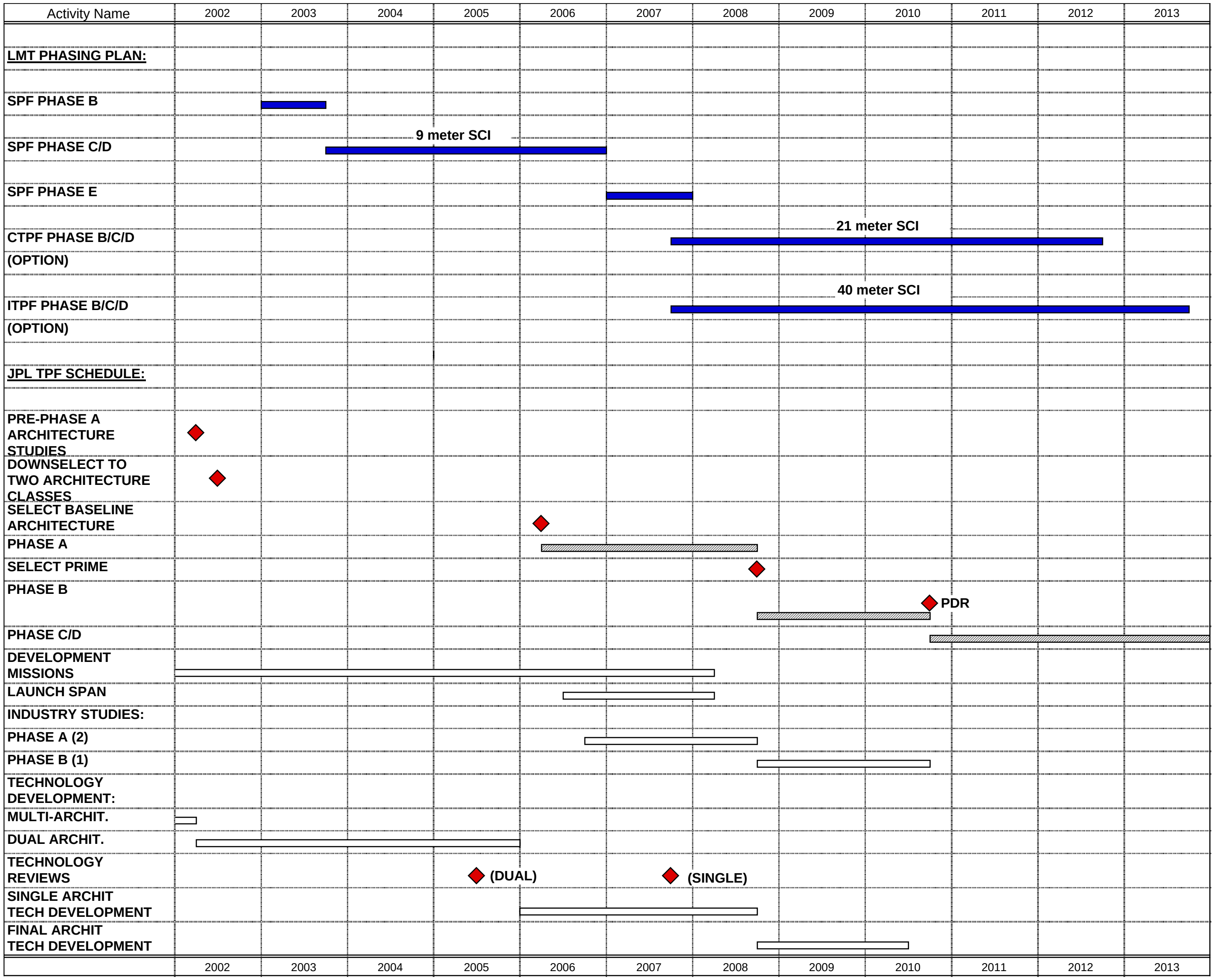
40 meter SCI Six-Year Development Phase B/C/D



TPF Program Evolution

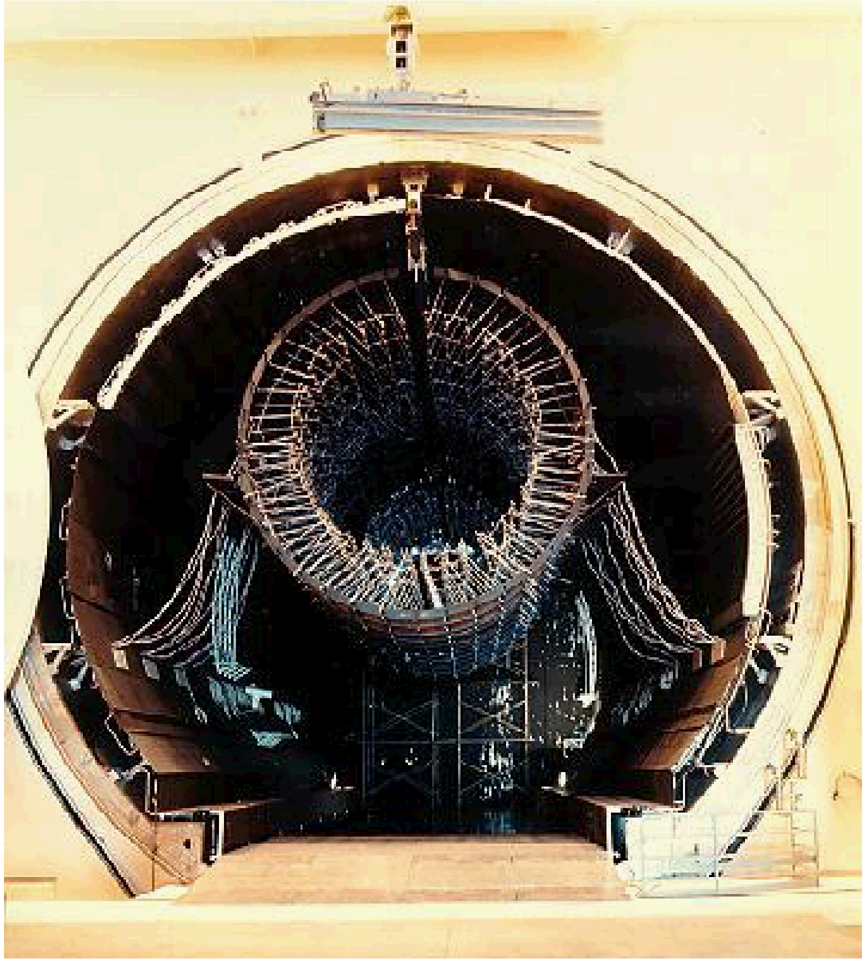


TPF PROGRAM PHASING

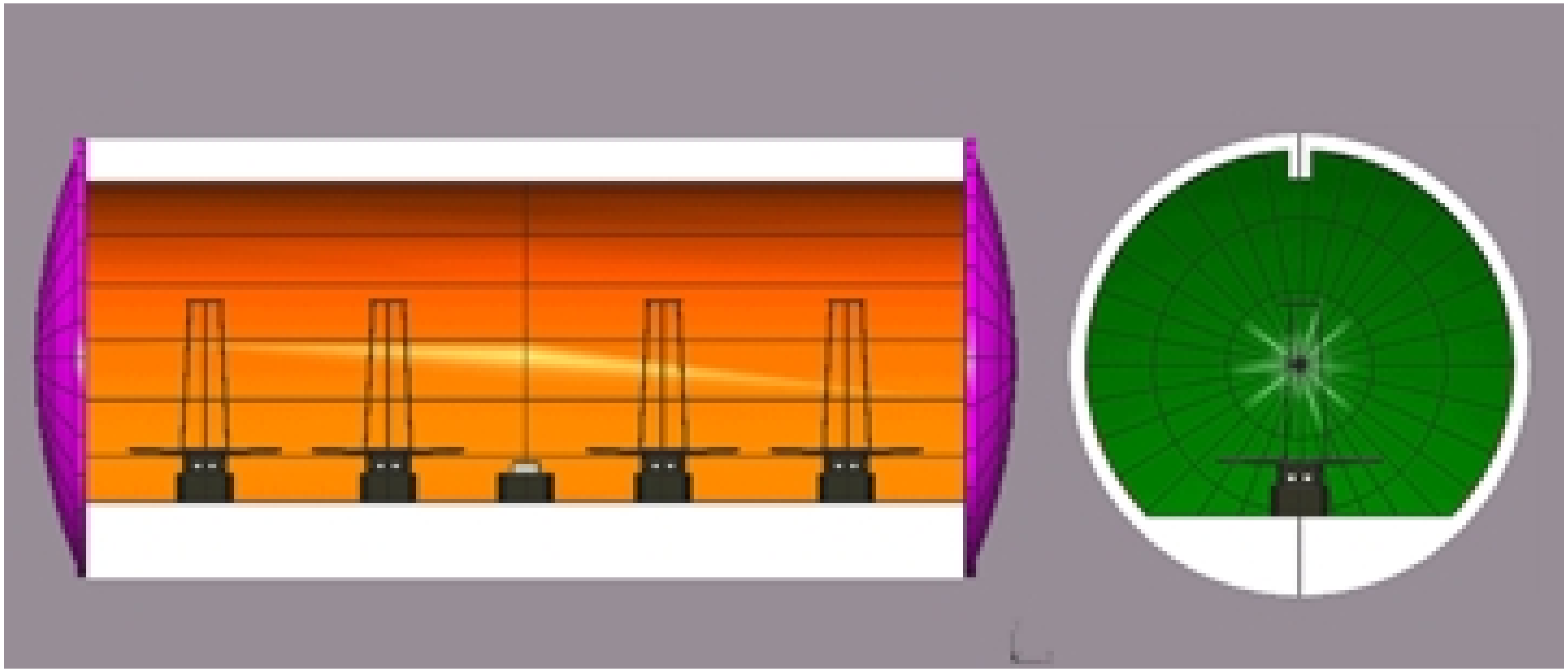


LMMS Delta Chamber

- Size: 26-ft Dia X 80-ft long
- Dual entry chamber
- Capable of performing thermal vacuum, thermal balance and solar simulation tests
- Liquid nitrogen coldwall system and 2 cryogenic vacuun pumping systems
- Can be modified to accommodate the He test equipment
- Achieves 10^{-7} torr in 12 hours
- Adjacent class 100K cleanroom with 50-lb bridge crane



TPF TV Test Configuration



Commonality/Heritage

Interferometers:	9m SCI	21m SCI	40m SCI	Free Flyer Interferometer
Project Management/System Engineering	Product Teams	Product Teams	Product Teams	Product Teams
Program Schedule	4 yrs	5 yrs	6 yrs	7-10 yrs
Spacecraft &Software	LM900	LM900	LM900	LM900
Detector Dewar	Solid H2	Solid H2	Solid H2	Solid H2
Beam Combining	In Dewar	In Dewar	In Dewar	In Dewar
Telescopes	.6m-2	1.7m-4	3.5m-4	3.5/6m-4
Truss/Sunshield	Gr-Ep	Folded GE	Folded GE	Attached SS
Integration & Test	DELTA Chamber	DELTA Chamber	DELTA Chamber (2X)	DELTA Chamber (4X)
Launch Vehicle	Delta II Atlas III	Atlas 5	Atlas 5	Atlas 5 (Multi)

Mission Overview (vs. SIRTF)

Feature	SIRTF	SPF (9 m)	40 m
Telescope	One 85-cm cryogenic (5.5K), 3.5 µm - 160 µm	Two 60-cm cryogenic (60K), 4 µm - 12 µm	Four 75-cm cryogenic (40K), 7 µm - 17 µm
Cryogen	super-fluid Helium	solid Hydrogen	solid Hydrogen
Instruments	3	1	1
Arrays	4×256^2, 5×128^2, 32x32, 2x20, for imaging and spectroscopy	1×128^2, for imaging and spectroscopy 1×256^2, for phase detection	1×256^2, for imaging and spectroscopy
Orbit	solar orbit, trailing Earth and receding at 0.12 AU/year	solar orbit, trailing Earth and receding at 0.12 AU/year	solar orbit, trailing Earth and receding at 0.12 AU/year
Lifetime	2.5 years, goal of 5 years	2.5 years, goal of 4 years	5 years, goal of 10 years
Ground Station	DSN	DSN	DSN
On-board Storage	Up to 4 Gbits per 12 hours	Up to 4 Gbits per 12 hours	Up to 4 Gbits per 12 hours
Max. Downlink Rate	2.2 Mbps	2.2 Mbps	2.2 Mbps

SPF mission is similar to SIRTF, with simpler instrument

Cost Summary

Structurally Connected Interferometers:	9 meter	21 meter	40 meter
Spacecraft & Truss System	$98M	$173M	$304M
Optical System	$47M	$168M	$558M
Launch Vehicle	$75M	$100M	$120M
Phase E/Science	$30M	$300M	$500M
Totals (with 30% Contingency):	$293M	$843M	$1741M

Free Flyer >$2.5B

Summary

- Program risk reduction with science rich, low cost, low risk 9 meter SCI development mission launched in December 2006
- Intermediate TPF version (21 meters) identified and costed
- TPF science planetary detection requirements met with 40 meter SCI
- Technology development identified
- Program costs identified for each option
- Free Flyer Interferometer system identified for future TPF missions covers planetary and astrophysics science