Section 9:
Technology Roadmap
Roger Linfield

Technology Risk Matrix

Technology Readiness Levels (TRLs)

Coronagraph

Interferometer

TPF Technology Development Approach (from RFP, early 2000)

1.8 Provide requirements for proposed architecture technology development consisting of:

- 1.8.1 A listing of technology needs
- 1.8.2 A roadmap for technology development
- 1.8.3 Metrics for assessing technology maturity and readiness
- 1.8.4 Identification of technologies requiring flight validation
- 1.8.5 Specification of the requirements that the architecture places on formation-flight space demonstration for those architectures that are based on formation-flying

TPF Technology Development Approach (Direction as of July, 2001)

- Bring discriminating technologies to a level (TRL 4-5) to facilitate architecture selection
  - Consider four current architecture classes through end of current studies
  - Assume down-selection to two competing architectures in mid-FY'02
  - Assume down-selection to final architecture at the end of FY'06
- Pursue a range of technological approaches
  - Best ideas identified from pending OSS NRA studies
  - JPL competitively selected industry and university proposals
  - In-house JPL efforts where unique competencies exist
- Implement an integrated plan for development, validation and selection of enabling TPF technologies
  - From bench-top breadboard demos, through testbeds & flight validations
  - Consistent with available budgets and on a schedule to support key TPF project decision points culminating with the NAR/PDR in FY 2010

TPF Technology Roadmap -- Impact of Science Precursor Data on Arch. Choice

		Abundance of Earth-like Planets (e.g. from Kepler mission)	
		Low (< ~8% of stars)	**Medium to High** (> ~8% of stars)
Level of exo-zodiacal emission around target stars (e.g. from CODEX, Keck interferometer, LBT)	**Low** (most are <10 zodis)	**Interferometer w/ large baseline & apertures**	**Either coronagraph or interferometer**
	High (most are >10 zodis)	**Neither in the near future**	**Coronagraph**

Science precursor input is needed **first**, to decide which technology should be used. We should keep studying both architectures to refine our understanding of technology readiness and cost

Tallest TPF Technology Tentpoles

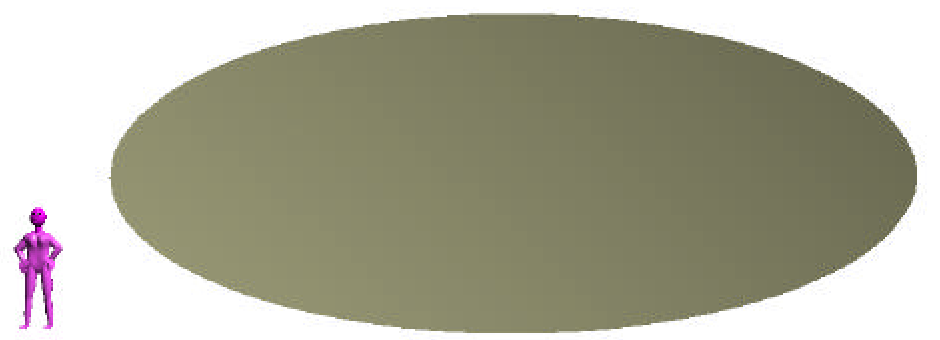
- Coronagraph
  - Large optics - very lightweight, very high precision
  - Thermal control and structural motion - changes over several hours must result in ~0.3 Å or less wavefront errors, RMS, at critical spatial frequencies
  - Amplitude uniformity & stability - ? 10^{-4} level, for enough spectral bandwidth
  - Deformable mirrors - control to <1 Å rms over wide range of scales
  - Wavefront sensing - adequate for <1 Å control
  - 3 m space coronagraph would demonstrate all key technologies
- Interferometer
  - Cryogenic nulling - 10^{-5} or 10^{-6} depth across ~1 octave
  - Wavefront & amplitude control - spatial filter in mid-IR (+ DM for low spatial freqs) + control of thermal & vibration effects + acc. amplitude measurement
  - Beam transport issues (rejection of stray light at small angles)
  - Autonomous Formation Flying likely, with ~ 5 spacecraft
  - StarLight mission will demonstrate autonomous formation flying and stray light rejection at visible wavelengths

Risk Matrix for Coronagraph

Coronagraph Technology	Risk Level
Large Optics	Moderate
Wavefront Stability	Moderate
Amplitude Uniformity	Moderate
Graded Focal Plane Masks (option)	Moderate
Wavefront Sensing	Low
Deformable Mirrors	Low
Binary Pupil Masks (option)	Low

TPF Technology Roadmap -- Coronagraph Architecture

- Large optics



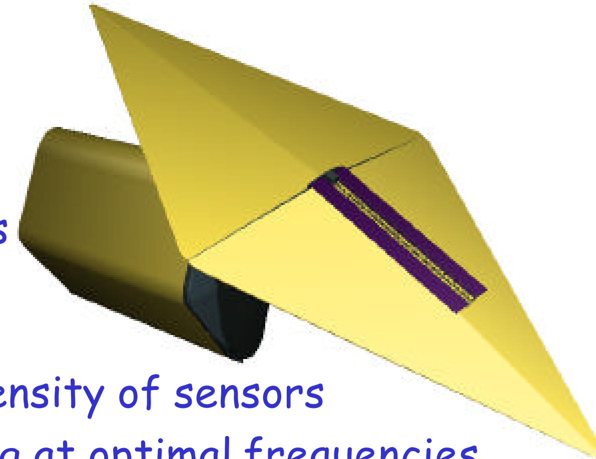
  - Requirements
    - > 4 x 10 m size, < 25 kg/m^2 (mirror glass only)
      - Nominally monolithic, but segmented structure not ruled out
    - <u><7 nm rms at critical spatial frequencies</u> (3-130 cycles/aperture)
      - Accuracy; stability in a controlled environment must be 100 x better
    - Actuators on back surface for low spatial frequency adjustment

Kodak development plans for large optics

Advanced Mirror Technology			Technology Maturity (01–10)
Title	**Description**	**Technology Performance Metrics**	**01 02 03 04 05 06 07 08 09 10**
AMSD ULE Mirror Assembly	ULE Mirror, Reaction Structure Force Actuators ***Funded Program***	15 kg/m^2 at 1.4m 2 kg Actuator Range	*Mirror assembly*
TPF Proof of Principle	Process 0.5 m Segmented Core & Faceplates flat mirror	Faceplate joint processing mid-spatial f goal: 2nm rms over 3-130 cycles/A	*Plano Mirror*
TPF Demonstration Mirror Assembly	1m Segmented Core & Faceplates powered mirror on actuators	Faceplate joint processing mid-spatial f goal: 2nm rms over 3-130 cycles/A	*Mirror assembly*
TPF Subscale Mirror Assembly	1/4 scale of 4x10 m TPF mirror, actuators & structure	Build and test to TPF optical specifications Goal of 35 kg/m^2 for assembly	*Mirror assembly*
Advanced Force Actuator	Lightweight, Improved Performance Actuator	12kg Total Range · 0.5g resolution <0.15 kg weight · Redundancy	*Prototype*
High Volume Water Jet Core	Develop Advanced Water Jet Capability for large mirrors	Multiple Heads Multiple Machines · $>5\ m^2$ per month	*Feasibility demo*
Large Area Mirror Processing	Develop, Demonstrate Capability To Process large surface area	Polishing Technology · multiple heads mid-spatial f · $>5\ m^2$ per month	*Development*
In-Situ Optical Metrology	Develop, Demonstrate In-situ Metrology For Off-Axis Aspheres	Goal to test large optics in process to 2nm rms from grinding through polishing	*Development*

TPF Technology Roadmap -- Coronagraph Architecture

- Wavefront stability
  - Wavefront errors accumulated during ~ several hours must be less than ~ 50% of total error budget (<1 Å at critical spatial frequencies)
  - Ongoing integrated modeling will quantify the wavefront stability from temperature variations and from vibrations
- Development plans
  - Design trade for large, NGST-like sunshield
  - Investigate network of temperature sensors and local heaters
    - Integrated model can quantify expected performance, as a function of the density of sensors
  - Design a system with reaction wheels running at optimal frequencies (not near any resonances)
    - Investigate options without reaction wheels
    - Investigate active isolation mechanisms



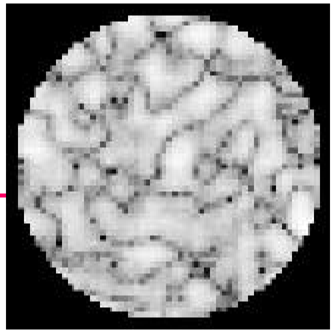
TPF Technology Roadmap -- Coronagraph Architecture

- Amplitude uniformity
    - Needed to maintain stray light rejection over a spectral bandwidth wide enough to detect the exoplanet signal in a moderate integration time
- There is a bandpass limitation in using phase (~ 1/ ?) correction to achieve amplitude (~ constant vs. ?) uniformity
- To achieve acceptable bandpass, we require 10^{-4} amplitude uniformity at relevant spatial frequencies
    - Passively: currently a big challenge
    - Actively: not intrinsically difficult to do, but requires some care to protect the wavefront quality
    - Thus amplitude control is a technology development issue
- Examples of options for active control of spatial amplitude variations:
    - Photosensitive coating
    - Interferometric amplitude modulator (same problems as phase correction)
    - LCDs
    - Physical edge control (for shaped-pupil concepts)

TPF Technology Roadmap --
Coronagraph Architecture

- Wavefront Sensing
  - Requirements

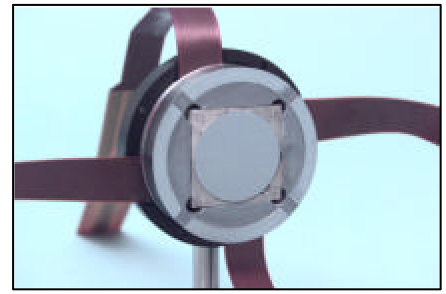
    Science camera measurements adequate for control to 0.07 nm rms in the range 3-130 cycles per aperture (CPA)



    - Coronagraphic Field Occulter (CFO) reflection measurements adequate for control to 1.6 nm rms (0-3 CPA)
  - Past Work
    - CODEX proposal simulations: adequate for 0.2 nm rms
      - Iterative algorithm (similar to CLEAN in radio interferometry), using residual image to adjust deformable mirror
  - Development Plans
    - Princeton-led proposal for further simulations
    - Full lab test if study leads to additional funding
    - Perhaps fly a CODEX-type (HST coronagraph) or other space demo

TPF Technology Roadmap --
Coronagraph Architecture

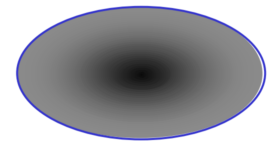
- Deformable Mirrors
  - Requirements
    - <u>Relative positioning precision of 0.075 nm rms</u>, looser for low spatial frequencies (< 3 CPA)
    - Stable at the same level for >>1 hour, in space
    - (Likely needed at low spatial frequencies for interferometer)



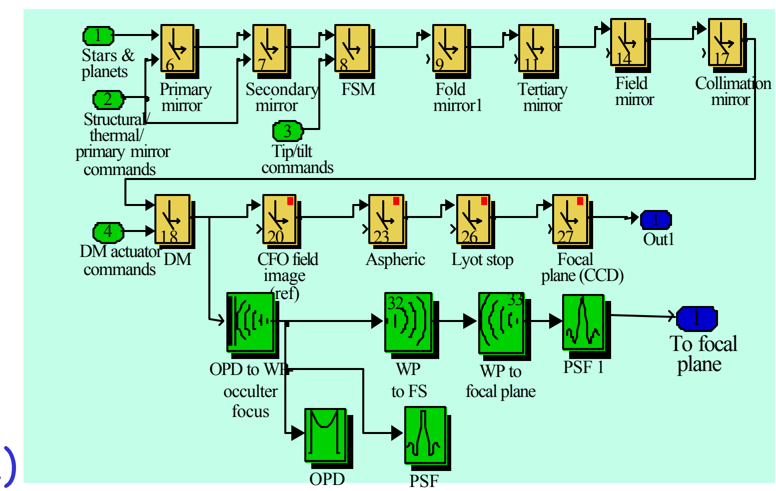
  - Current Status (lab measurements in vacuum, DMs from Xinetics)
    - 0.025 nm rms setting precision, high actuator density: 1 mm pitch
    - Stable at 0.1 nm rms for a few weeks, open loop
      - requires 10 mK temperature control
  - Development Plans
    - Continuing work with ground-based Adaptive Optics systems
    - Lab work at JPL (J. Trauger)
      - Accelerated life test, demonstrate DM with size ? 128 x 128
    - Proposed lab work at Princeton
    - Possible CODEX flight (HST Coronagraph) or other space demo

TPF Technology Roadmap --
Other Coronagraph Technologies

- Masks (Pupil and Focal-Plane)
  - Precision attenuation in focal plane masks



    - DM can correct for small amplitude errors over ~30% BW over half the plane
  - Adjustable shape in pupil masks - broadband correction of amplitude errors
  - Advanced lab work needed
    - Kasdin et al. lab test proposal
- High-fidelity integrated model
  - High order structural/thermal/optical
  - Full attitude control simulation
  - Simulations used for design trades
    - (e.g., temperature control network)
  - Advanced system in place at Ball



TPF Technology Roadmap --
Interferometer Architecture

- Cryogenic nulling
  - Requirements
    - 10^{-5} or 10^{-6} depth over 1 octave (amplitude, delay, polariz. control)
    - Compound nuller for wide ($?^4$ or $?^6$) null
  - Technology status
    - Cryogenic actuators have been developed
      - Ball proprietary lubrication technology
      - Application: delay lines, fast steering mirrors
  - Development plans
    - Lab work in visible and (future) mid-IR nulling
    - Proposed study for space demonstation

TPF Technology Roadmap -- Interferometer Architecture

- Beam Transport
  - Requirements
    - Rejection of sunlight glint from other spacecraft
      - Difficult because only few arcminutes from starlight beam
    - Rejection of thermal emission from other spacecraft
      - Also rejection at small angles from starlight beam
    - Scattered light from all surfaces
  - Development plans
    - StarLight mission will have similar geometry and must reject sunlight glint
      - Much milder requirements than for TPF
    - Thermal emission shielding required for NGST

Technology Maturity and Readiness

NASA Technology Readiness Levels

	Technology	Current TRL	Future work	Estimated Completion Date	Resulting TRL
Coronagraph	Large, lightweight optics	3	Lab demo of scale models	2005	6
	Wavefront sensing with science camera	3	Possible CODEX flight on HST	2004	6
	Deformable Mirrors	5	lifetime tests in lab	2003	6
	Thermal Control	4	NGST validation	2008	7
	Binary Pupil Masks with adjustable borders for amplitude uniformity	2	Lab demo of full scale masks	2005	6
	Integrated model of full optical system	6	NGST validation	2008	8
Interferometer	Cryogenic Actuators	5	NGST validation	2008	7
	Cryogenic Nulling System	3	Possible flight demo	2007	6
	Beam Transport	3	StarLight mission	2006	6
	Autonomous Formation Flying	3	StarLight mission	2006	6

Highest Priorities for Technology Development

- Large Optics
  - ~ 50% scale model, demonstrating figure precision
  - Laboratory work needed
  - **Longest lead time item - work (and funding) must start soon**
- Thermal and Structural Motion Control (for Wavefront Stability)
  - Space demo of temporal stability
  - NGST will do this with large optics
- Pupil and Focal Plane Masks, and Amplitude Uniformity
  - Adjustable border capability of binary masks
    - Control amplitude errors in pupil plane
  - Graded focal plane masks - lab demo of manufacturing accuracy

Technologies Requiring Flight Validation

- Vibration control and isolation of structures in space
  - Coronagraph - 0.1 nm level important for low-mid spatial frequencies, lower sensitivity to bulk displacements
  - Interferometer - 2-3 nm level important; this <u>does</u> apply to bulk displacements
  - It is not obvious which requirement is harder
- Formation Flying
  - Interferometer only - StarLight will validate most aspects needed by TPF
- Large, light-weight, precision optical systems
  - Coronagraph only - construction and delivery to space
  - Partial validation by NGST

Requirements for Formation Flying Demonstration (Interferometer only)

- Sensor suite
  - Robust, full sky coverage, no ambiguities (RF sensors)
  - High precision angular metrology for delay and delay rate (laser and starlight sensing)
- Controls
  - Translation and attitude deadbands
  - Autonomous collision avoidance
- StarLight mission validation
  - Many of the key issues
- What StarLight won't do
  - Angular metrology is far too crude for TPF astrophysics mode
  - Sensor suite design/validation only for face-to-face configuration
  - Contamination of optical surfaces with multiple spacecraft

TPF Visible-Light Coronagraph Technology Development Program -- Schedule & Cost

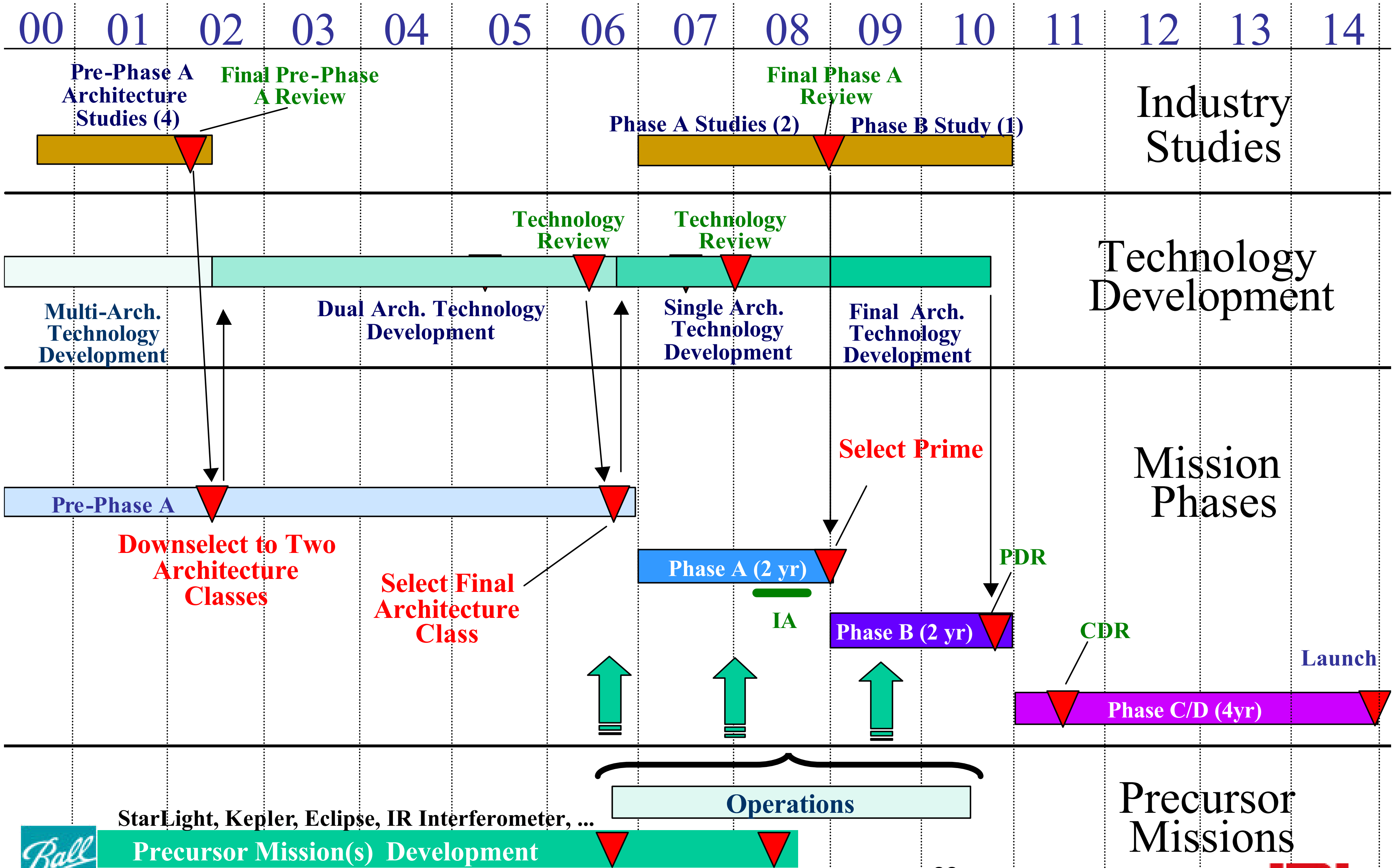
	Fiscal Year	2002	2003	2004	2005	2006
$50M	TPF C/G Tech. Program:	5	10	10	15	10
20	Large Optics & Test Technol. →	2	4	4	6	4
11	Wave-front Stability →	1	2	2	4	2
8	Mask Optim-ization →	1	2	2	2	1
11	Other Techs. →	1	2	2	3	3
	NASA Space Precursors & Lab Demos →		NRA Studies	Eclipse-type		

Section 10: Schedule & Life-Cycle Cost

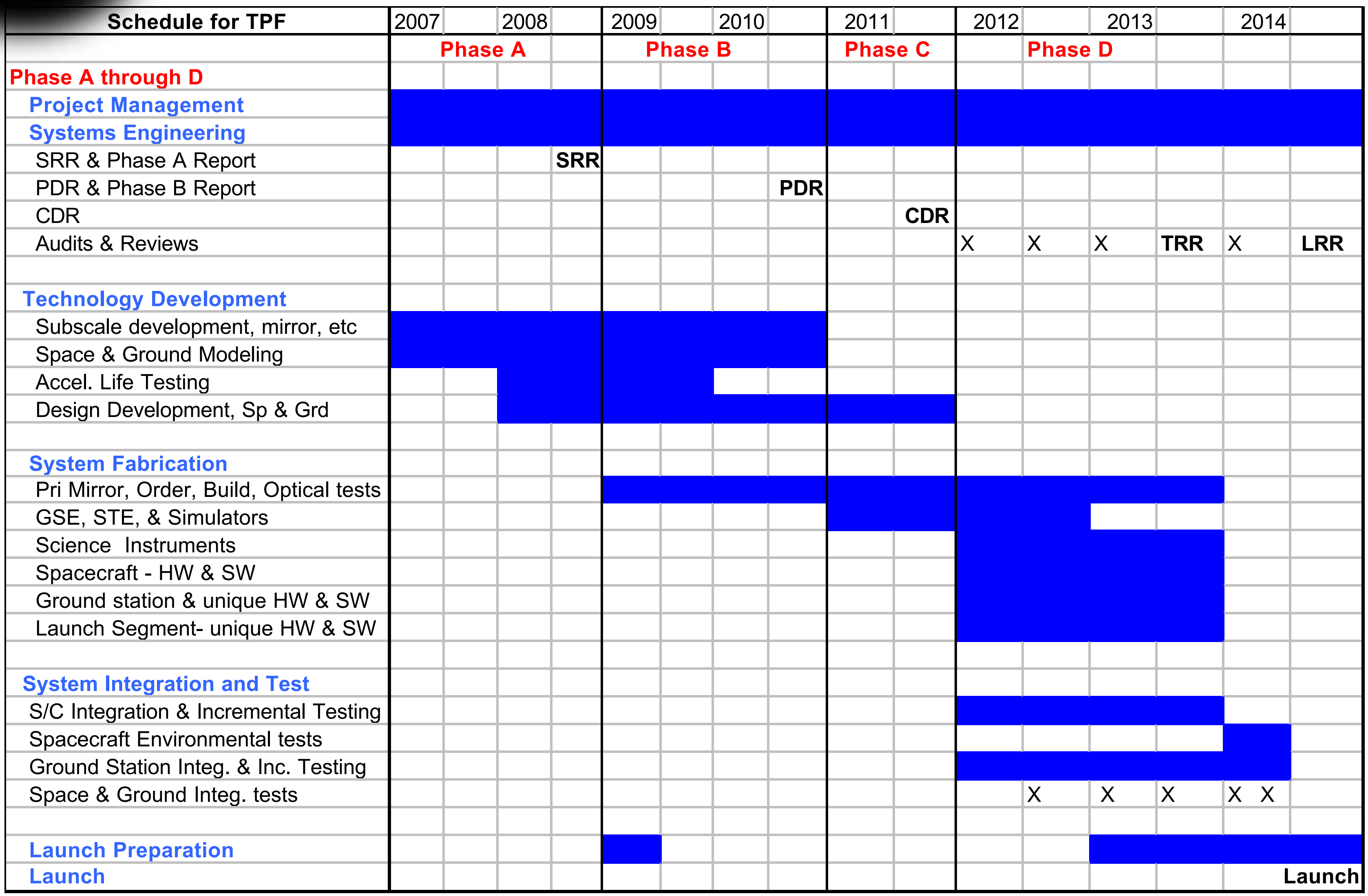
Dave Fischer, Jim Crocker

Costing Approach
Top-down results
Bottoms-up results
Comparison of Cost Models
Risk Items

Revised TPF Schedule from JPL / NASA



Implementation Schedule, Phases A-D



Life-Cycle Cost Estimate -- Statement-of-Work Requirements

1.7 Provide a life-cycle cost estimate for the following:

1) technology development,

2) formulation,

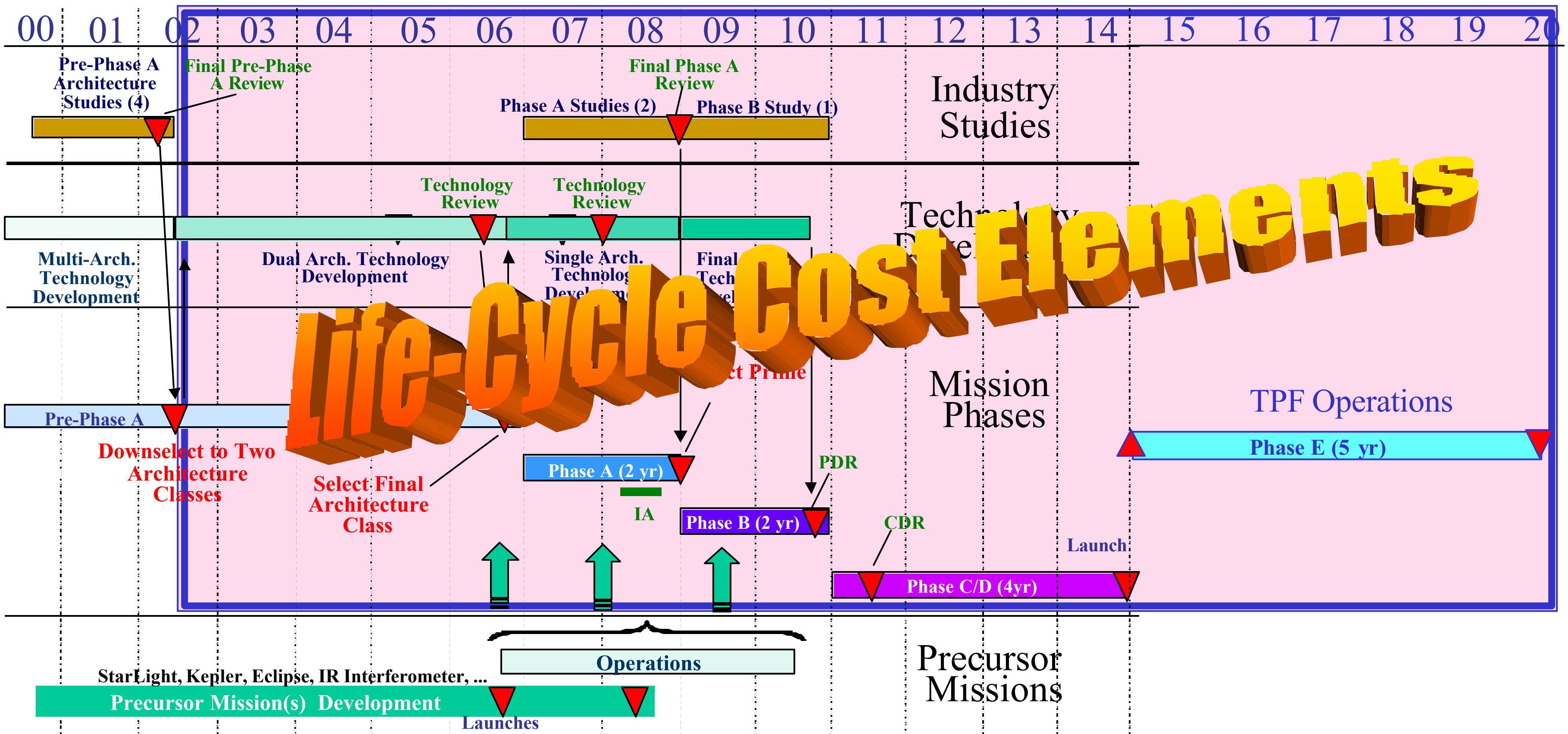
3) implementation,

4) launch and deployment, and

5) mission operations phases

Life Cycle Cost Estimate -- What's Included

(Following JPL NMI 7120.4 & NHB 7120.5) **This estimate is for Pre-Phase A (Technology Development), Phases A & B (Formulation), Phases C, D, & E (Implementation, consisting of Design, Build, Test, Launch, Deployment, & Mission Operations)**



Simplified Cost Estimating

- Many people have used a principle that the cost of a space system is a simple function of spacecraft mass (including instrument)
- NASA has a few simple cost models based almost entirely on mass. Here, from using the JSC website, are the following results from two models for the subsystem masses of our TPF concept:
  - Spacecraft/Vehicle Level Cost Model
    - A 1800 kg spacecraft vehicle should cost $270 M, a 1650 kg instrument (telescope) $120 M, and 1400 kg of science instruments $110M
    - We could add on $50 M for technology development, $220 M for launch, and $ 200 M for mission operations and operations facilities
    - That would give a total life-cycle cost of $970 M
  - Advanced Mission Cost Model, physics & astronomy S/C, dry mass 5365 kg
    - Cost estimated at $2.0 B, plus the above $50 M, $220 M, and $200 M,
    - That would give a total life-cycle cost of $2.5 B
- We should try to do our estimating somewhat better than this

We Use Three Methods to Develop our Preferred Life-Cycle Cost Estimates

1. Parametric estimates, based on other related programs
2. A Top-Down ("Delphi", named after the oracle) method, based on similarities to, and differences from, NGST
3. A Bottoms-up model, based on the project schedule, size, and complexity

Parametric Cost Estimate

1. Our Parametric estimating method brackets the expected cost, based on comparisons to actual built systems in terms of their:

- Mass (which includes impact of aperture, and scales linearly to cost)
- Orbit (low-earth easier, but environment harsher; modest cost impact)
- Performance (pointing accuracy a good measure, also modest cost impact)
- Complexity (no. of instruments, serviceability, lifetime, reliability)
- Cost in 2002 dollars; also need $470M for tech. devlpt., launch & mission ops

Comparison Mission & Weighting	Mass Factor	Orbit Factor	Performance Factor	Complexity Factor	Cost (2002 $)	TPF Cost
Hubble Space Tel - 4	2	1.1	0.9	1.4	$3B	$1.1B
Terra - 2	0.9	0.9	0.7	1.2	$1.2B	$1.7B
Chandra - 2	0.8	1	0.9	1	$1.2B	$1.7B
QuickBird - 1	--	--	--	--	--	$1.4B
Weighted Average TPF Cost, with added tech. devlpt., launch & mission ops						$1.9B

Top-Down Cost Estimate

2. Our Top-Down (Delphi) method brackets the expected cost, based on:

- Engineering Judgement
- Similarity to other programs
- Special hardware needs and cost risks

- We began with NGST as a baseline, polled experts on the technical and costing efforts, and accounted for differences in technical approaches such as:
  - The instrument suite
  - Primary Mirror fabrication and polishing
  - Deformable Mirror technologies
  - Environmental tests

Top-Down Cost Estimate Results

Our Top-Down Estimate provides a high-level comparison by hardware elements

	(in FY02 M dollars)
1.0 Technology Development	50
2.0 Preliminary Analysis (Phase A, x 2)	30
3.0 Instrumentation	520
1.1 Instrument Suite	**325**
1.2 Backplane	**35**
1.3 Primary Mirror	**130**
1.4 Deformable Mirror	**30**
4.0 Spacecraft	145
2.1 Bus	**120**
2.2 Sunshade/Baffle	**25**
5.0 I&T	120
6.0 Launch Services	220
7.0 MO&DA (Phase E)	200
Total	**1.28 B**

Bottoms-Up Model Cost Estimate

3. Our model is an industry-standard model calibrated to our business area

   We modeled the TPF cost using these inputs:

   - The project schedule
   - A detailed and complete WBS for the mission
   - Special care to account for critical technology items
   - Level-of-effort estimates for labor throughout the program
   - Similarity to other programs

Bottoms-Up Cost Modeling Assumptions

Mission assumptions:

- Long life (5-yr mission, ideally 10-yr lifetime)
- High reliability
- Complex optics development

Cost assumptions:

- We didn't assume cost savings due to technology flow-downfrom other projects
- Low-risk sparing philosophy

Cost Model assumptions:

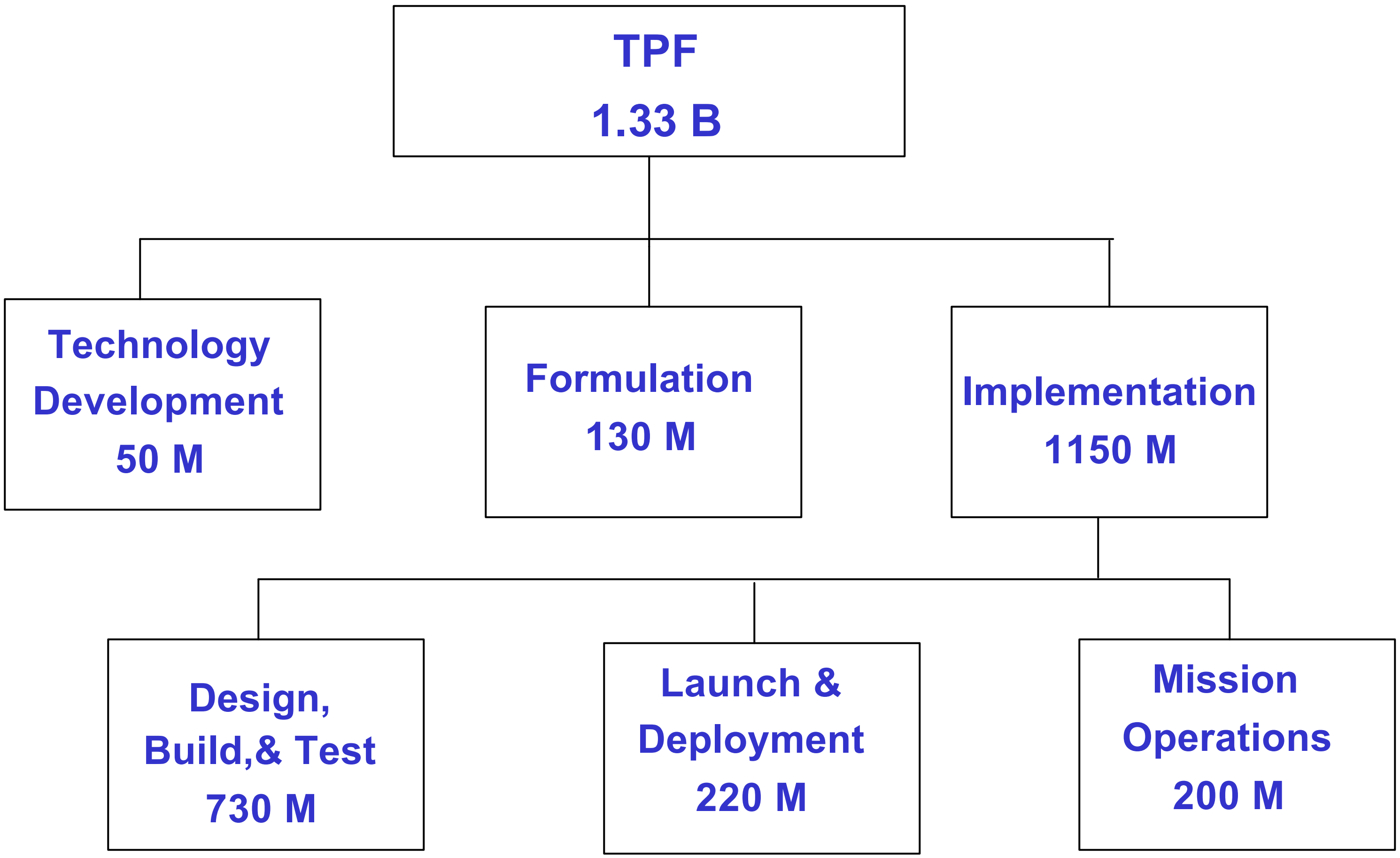
- We based our spacecraft costs on recent calibrations to Price H for newly estimated spacecraft
- We assumed optics and the science instruments are highly complex
- We used current rates and factors and calculated all costs in constant year FY2002 dollars
- We did not include cost reserves in the estimate

Bottoms-Up Cost Model Results by Program Element

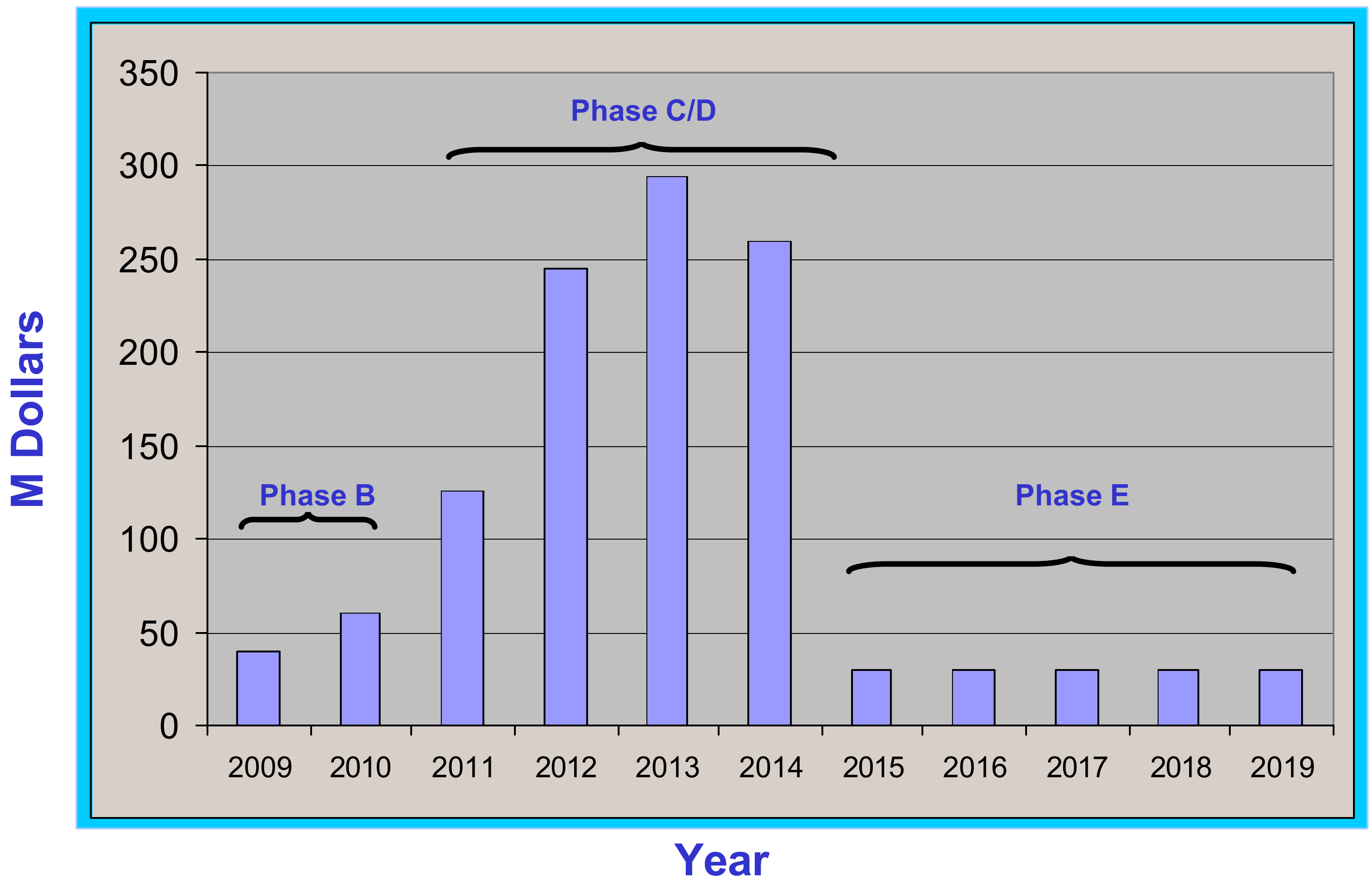
Project Management, Systems Engineering, and Profit all have been allocated into the element costs listed below

	(In FY02 M dollars)
1.0 Technology Development	50
2.0 Preliminary Analysis (Phase A, cost for 2 contractors)	30
3.0 Instrument (includes primary mirror, DM, and backplane)	560
4.0. Spacecraft Bus (includes sunshade)	160
5.0. System I&T	110
6.0 Launch Services	220
7.0. MO & DA (Ph. E)	200
Total	1.33 B

Bottoms-Up Model Cost Estimate -- Results by JPL Program Phase Elements



Bottoms-Up Model Results -- Time-Phased Graph (Phases B to E)



Cost Risks

- Uncertainties in the cost include:
  - Final Performance Requirements
  - Eventual results from ongoing modeling and design work
  - Progress in key technology developments
  - Definition of the science instruments and the astrophysics mission
- Cost risk relatively minor because of this concept's considerable similarity to previous programs such as HST

Cost Summary

- We've modeled costs by three methods which agree with each other to within 34% Std. Deviation:
  - Parametric $1.9 B
  - Top-Down $1.28 B
  - Bottoms-Up $1.33 B
  - Average Estimate = $4.5 B / 3 = $1.5 B
    - and the Std. Deviation of this average is 24%
- Though TPF will present technical challenges, we understand the scope and risks, and have developed credible costs
- A defensible summary total life-cycle cost estimate for the TPF visible-wavelength coronagraph option is $1.5 B

Section 11:
Conclusions and Recommendations
Steve Kilston, Bob Brown

Summary of Key features
Thanks
Recommendations

TPF Architecture Evaluation Criteria -- all well met by Visible-Light Coronagraph

- #1: Sensitivity in finding and characterizing exoplanets
- #2: Richness of astrophysical science opportunities
- #3: Technology development needed
- #4: Life-cycle costs
- #5: Risk of cost, technology, schedule, on-orbit failures
- #6: Reliability and robustness
- #7: Alignment with technology path to future exoplanet-study missions

Visible-Light Coronagraph Architecture for TPF has Many Advantages

1. Many stars can be surveyed, & planets characterized, within system lifetime
2. Broad capability to investigate properties of all planetary system constituents, e.g., both gas giant and terrestrial planets, and debris disks
3. Covers wavelengths not visible with other extremely high-resolution instruments
4. High sensitivity to faint signals close to zodi, noise, or confusion sources
   - > 3 x shorter integration time than best MIR performance
5. Multiple science instruments; plus, valuable astrophysics while observing planets
6. Technology -- few "tall poles", strong inheritance, simple readiness tests
7. Single-dish telescope: moderate number of parts & subsystems, low combined risk
8. Low overall system cost per Earth-like planet found and characterized
9. Multiple orbit / instrumentation approaches as backup
10. Large visible-light system proves technology essential to future Origins programs

A Unified Plan for the Further Detection and Characterization of Exoplanets

- Premises:
  - Technology and money will increase with time
  - Gradually we'll look for exoplanets farther & farther away from us
- Phase 0 -- circa 2008 -- ~$400M-- a first space coronagraph for exoplanets
- Phase 1 -- circa 2015 -- ~$1.5B
  - We want to find nearby exoplanets with technology little beyond today's
  - With likely planet statistics, terrestrial planets in nearby habitable zones can be seen for the least money by using a large visible-light coronagraph
    - Covers IWD range of 500 to ~40 mas; G-star distances from 1.3 to 20 pc
- Phase 2 -- circa 2025 -- $3B +
  - More expensive & difficult technologies can extend our range & check M stars
  - IR adds biomarkers; interferometer gives variable baseline
    - Can cover G-star distances up to 30 pc, but then need large apertures
- Phase 3 -- circa 2035 -- $6B +
  - Very expensive and large interferometers can extend distance beyond 30 pc

Future Plans to Make TPF a Reality

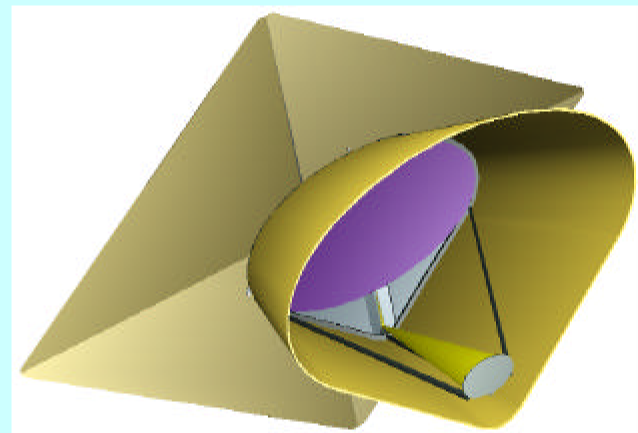
- Work on IRAD, NRA Studies, related relevant systems, and TPF Technology Development Program to bring both Coronagraph and IR Interferometer technologies forward toward TRL 4/5
  - Highest maturity & lowest risk must guide 2006 final architecture selection
- Assist successful development & operation of TPF technology & science precursors
  - StarLight
  - NGST and its science instruments
  - Kepler
  - Eclipse or larger coronagraph
  - Ground-based IR nulling interferometers (Keck, LBT)
  - Nulling space interferometer
- Contribute to increased scientific understanding of extrasolar planetary systems
- Form and participate in highly capable and comprehensive multi-institution team to succeed in Phase A Proposal and Study, beginning in 2006
- Get long-lead items, e.g, large primary mirror, started as soon as possible
- Win Phase B/C/D TPF design and implementation contract, and work like hell on it

The Ball TPF Team Thanks our Customers

- Our great thanks to JPL & NASA for sponsoring and funding this study which has been even <u>more</u> fun to work on than we presciently predicted
- Thanks to Dan Coulter and Chas Beichman for keeping a steady hold on the helm, and for directing the study to balanced and fruitful emphases
- Special thanks to Chris Lindensmith for his great helpfulness, cheerful attitude, and careful daily shepherding of the 4 cantankerous teams
- And, of course, we thank the U.S. taxpayers who maintain an enthusiastic interest in scientific discoveries sufficient to keep the whole NASA enterprise afloat (or, better, ad astra)

Final Chart

- What, exactly have we done and learned?
  - We have assembled an incredibly good coronagraph team
  - We've understood much of what needs to be done to help achieve the next stage of highly advanced space optical systems
  - We've enjoyed terrific intellectual fun



- We've tried hard to be nonpartisan & fair
- We've uncovered very tough challenges and approaches to their solution
  - But we recognize fully that we don't yet have all the answers
- With a modest expenditure of time and money so far, we have retired a great many of the previous concerns about a coronagraph architecture