Overview of Affordability Assessment Approach

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Overview

- The Aerospace Corporation frequently asked to assess the cost and schedule realism of projects at different points in the project lifecycle
- Tools used to evaluate numerous proposals and conduct Independent Cost Estimates (ICEs) for a variety of NASA missions and programs
- Different cost and schedule estimating methods apply depending on stage of the project
- Suite of tools exists to assess cost and schedule based upon available information
- These analyses form the basis for strategic analysis of affordability (so-called “Sand Charts”) providing assessment of projects within a portfolio of missions

Agenda

- Overview
- Magnitude of Cost and Schedule Growth
  - *Evolution of Concepts Over Time*
- Assessing Project Cost and Schedule
  - *Multiple Methods at Various Levels*
- Assessing Program Affordability
  - *Sand Chart Tool Overview*
- Application, Observations & Challenges
  - *Decadal Support and Review of HSF Plans Committee*

Forty NASA Robotic Science Missions Experienced 27% Cost and 22% Schedule Growth During Development


United States General Accounting Office

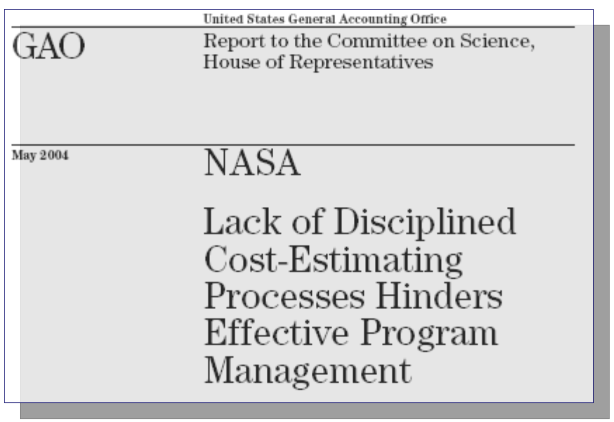
GAO

Report to the Chairman, Subcommittee on Investigations and Oversight, Committee on Science, Space, and Technology, House of Representatives

December 1992

NASA PROGRAM COSTS

Space Missions Require Substantially More Funding Than Initially Estimated


United States General Accounting Office

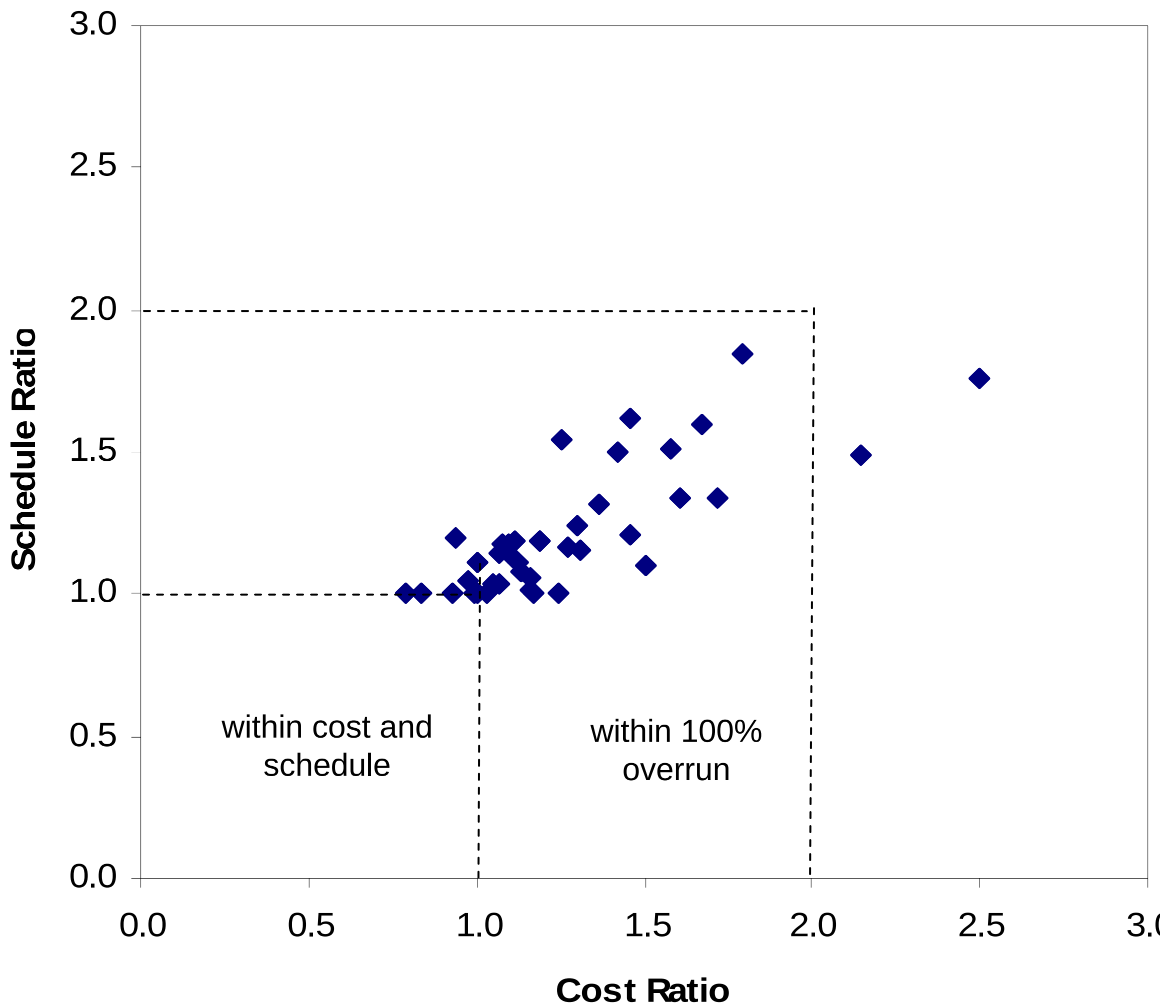
GAO

Report to the Committee on Science, House of Representatives

May 2004

NASA

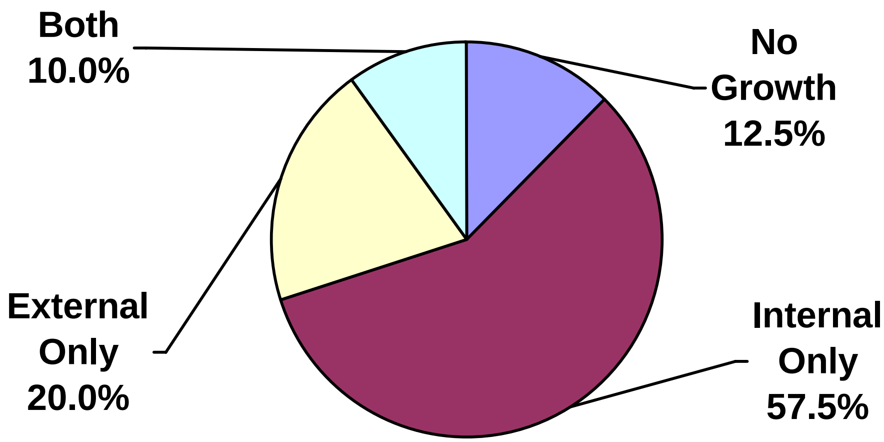
Lack of Disciplined Cost-Estimating Processes Hinders Effective Program Management



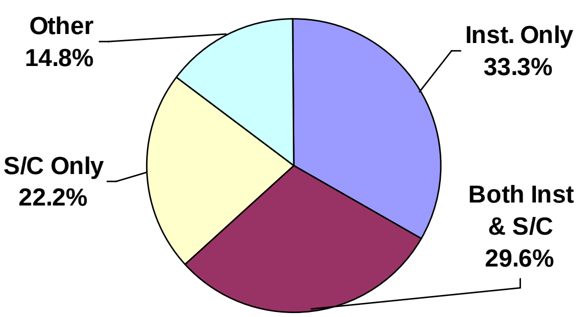
Reasons for Growth - Study of 40 NASA Missions: Internal versus External Factors Driven-Growth

- Internal Growth (within Project's control)
  - *Technical*
    - Spacecraft development difficulties
    - Instrument development difficulties
    - Test failures
    - Optimistic heritage assumptions
  - *Programmatic*
    - Contractor management issues
    - Inability to properly staff an activity

Distribution of Growth

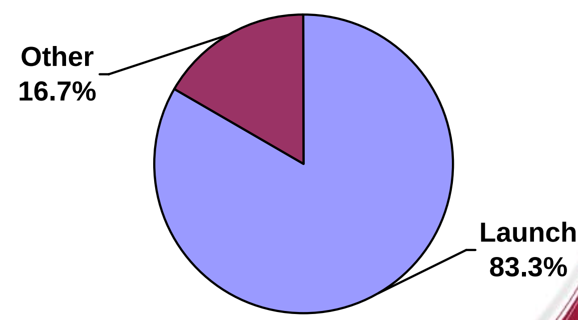


- External Growth (outside Project's control)
  - *Launch vehicle delay*
  - *Project redesign*
  - *Requirements growth*
  - *Budget constraint*
  - *Labor strike*
  - *Natural disaster*



Distribution of Internal Growth

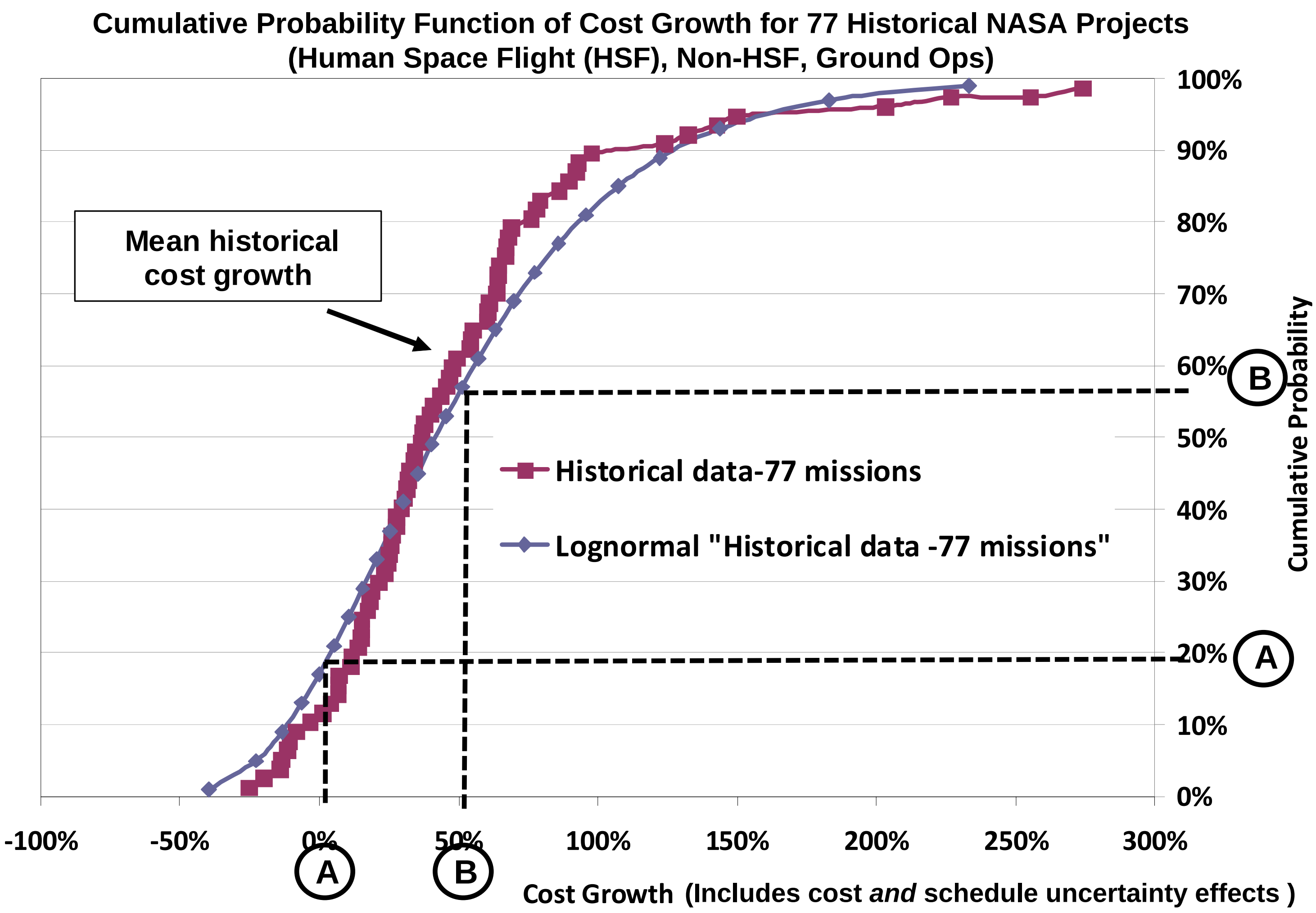
Distribution of External Growth



77 Historical NASA Projects Demonstrated ~51% Cost Growth from Formulation Start to Launch

(A) 0% average cost growth corresponds to 17% confidence on lognormal approximation to data.
17%-tile = 0 % historical cost growth (no reserves).

(B) 51% average cost growth corresponds to mean of lognormal approximation to data.
Mean = 51% historical cost growth.

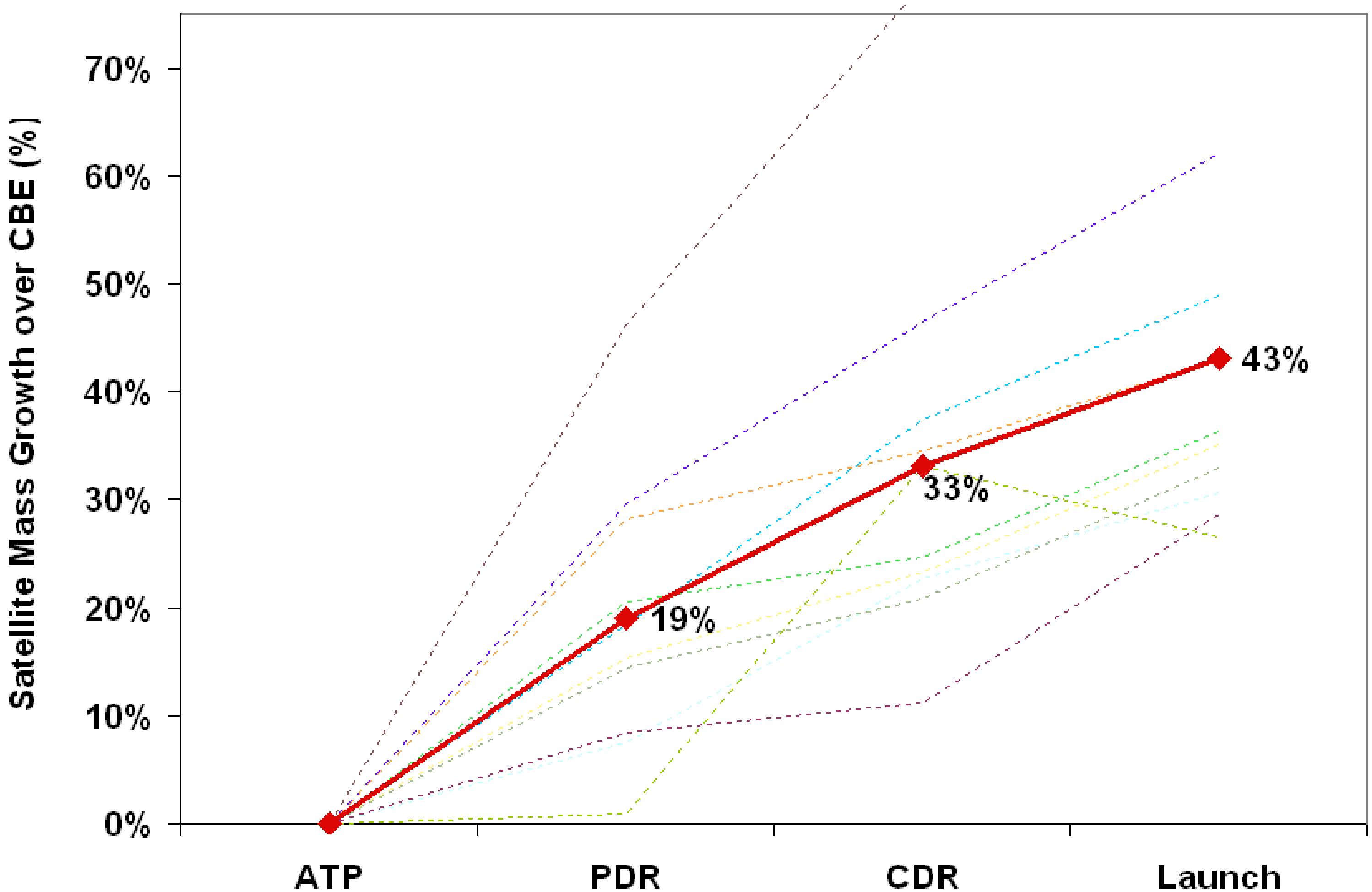


Evolution of Mission Concepts Over Time Can Lead to Estimation of a “Moving Target” at Each Milestone

- Potential causative factor for cost growth is evolution of mission over time
- Results in underestimation of technical specifications such as mass, power, data rate, and complexity of a system
- Underestimation of system resources leads to underestimation of the cost of the mission
- Success oriented schedules often shorter than historical comparisons would indicate
- Cost estimators, in effect, trying to estimate “moving target” as requirements evolve and system resources grow

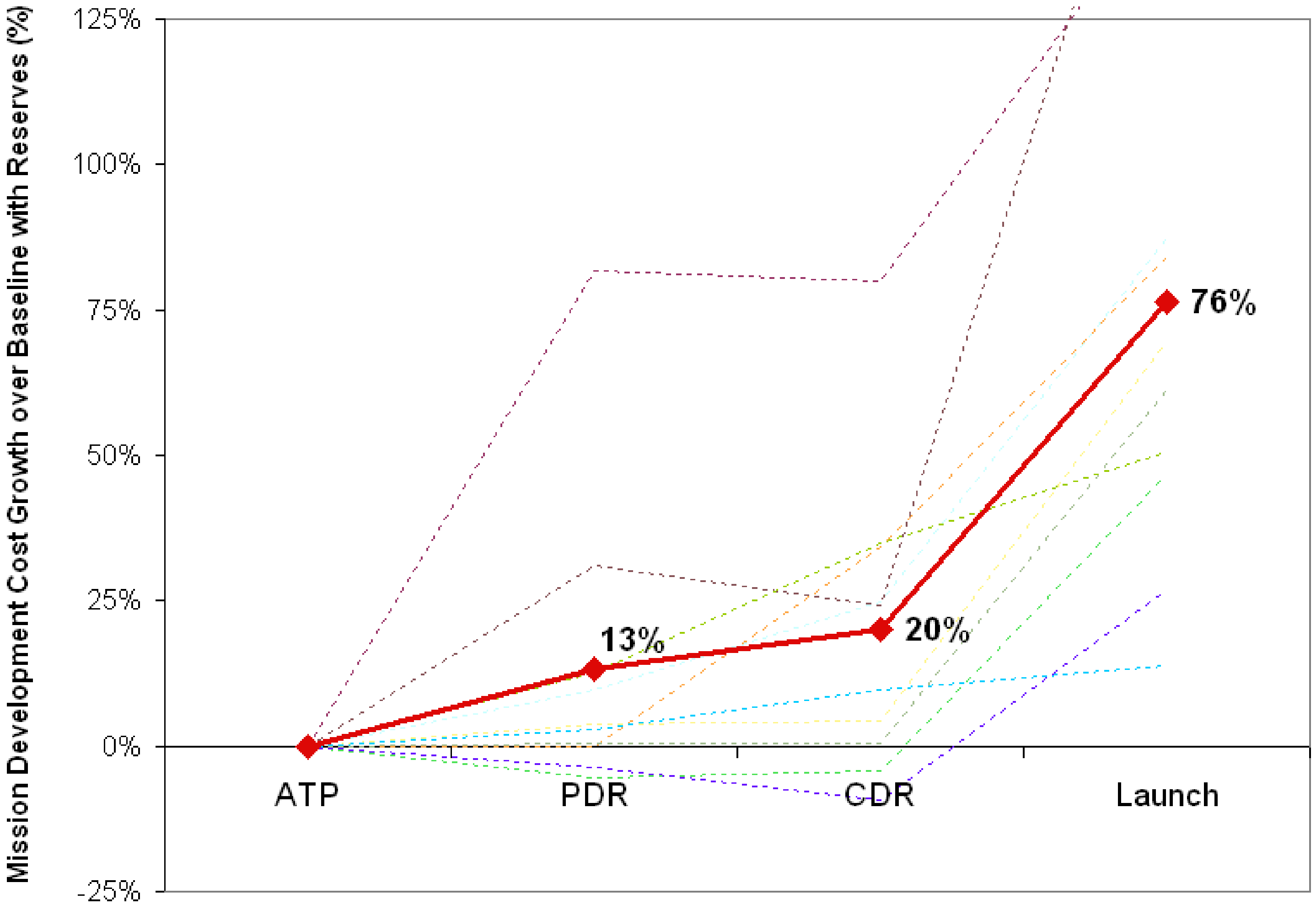
Summary of Ten NASA Science Missions Show that Mass Growth Exceeds Typical Reserve Guidance

- Average mass growth (43%) for ten missions exceeds typical guidelines of mass reserves (30% over CBE) at start of Phase B



Realization of Cost Growth Occurs Primarily After CDR as Programmatic Baseline Catches Up to Technical Baseline

- Average cost growth for ten missions studied is 76% over baseline with reserves (and 113% over baseline without reserves)



Example: Substantial Differences Exist between Science Definition Team (SDT) and Final Configuration

	STEREO	STEREO
Programmatics	**SDT**	**Final**
Schedule (months)	40	70
Launch Vehicle	Taurus	Delta II
Technical		
Mass (kg)		
Satellite (wet)	211	612
Spacecraft (dry)	134	414
Payload	69	133
Power (W)		
Satellite (Orbit Average)	152	515
Payload (Orbit Average)	58	108
Other		
Transponder Power (W)	20	60
Downlink Data Rate (kbps)	150	720
Data Storage (Gb)	1	8

SDT Configuration

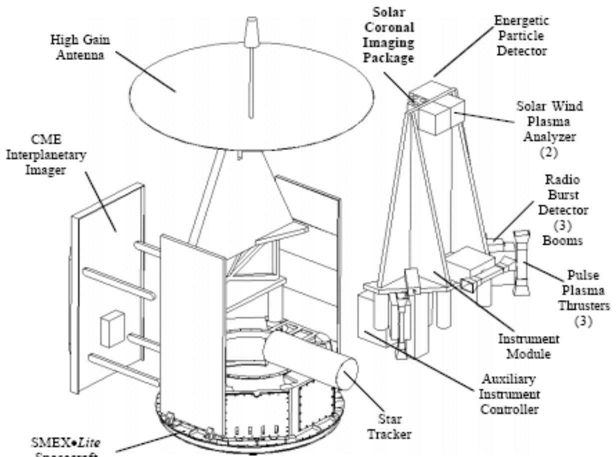
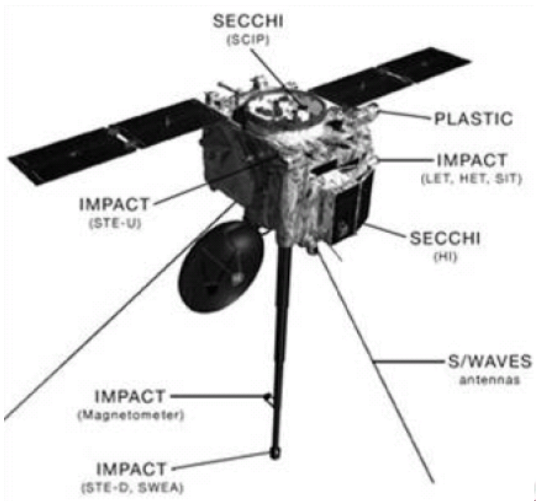


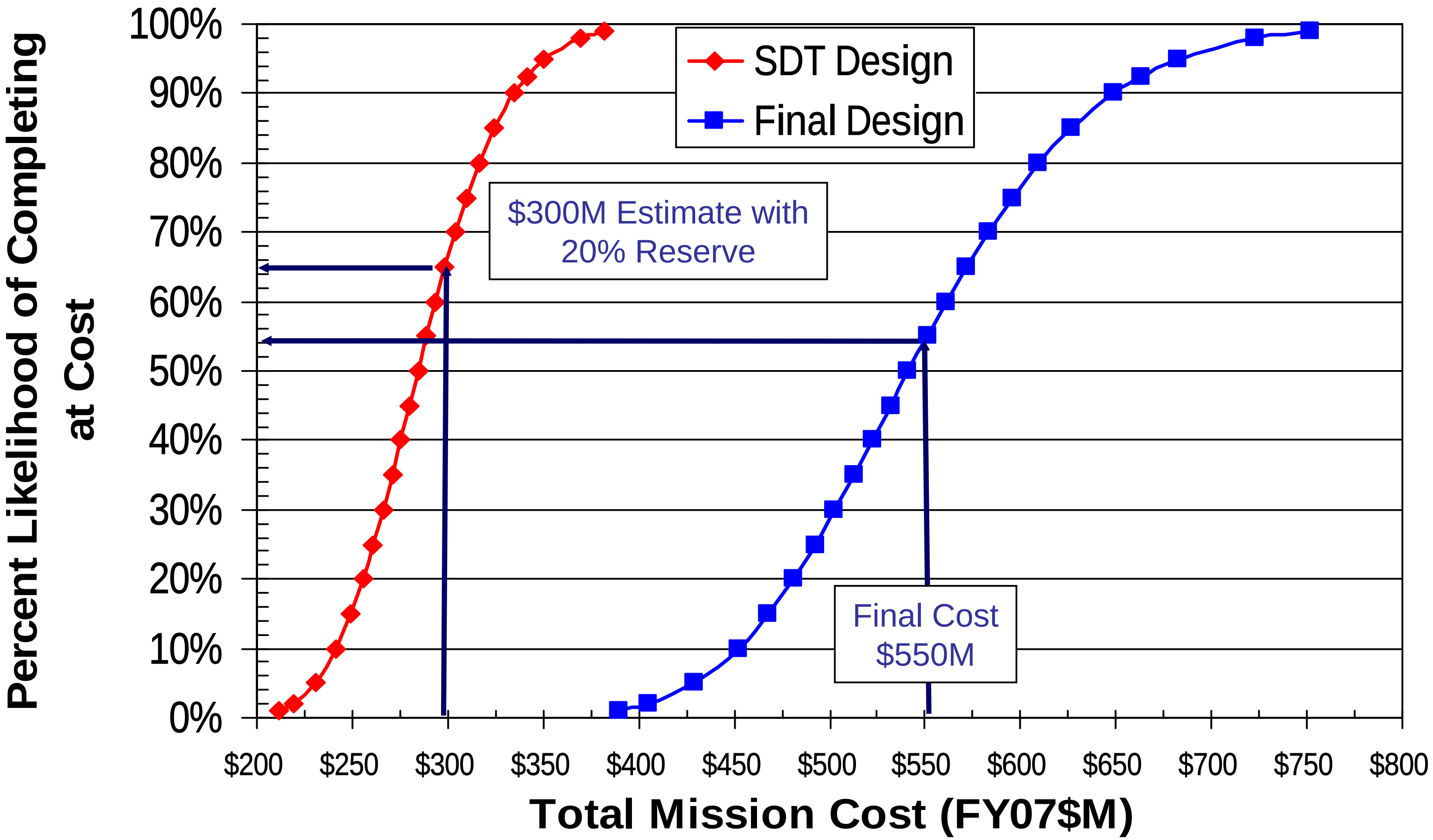
Figure 10. STEREO Configuration Details

Final Configuration

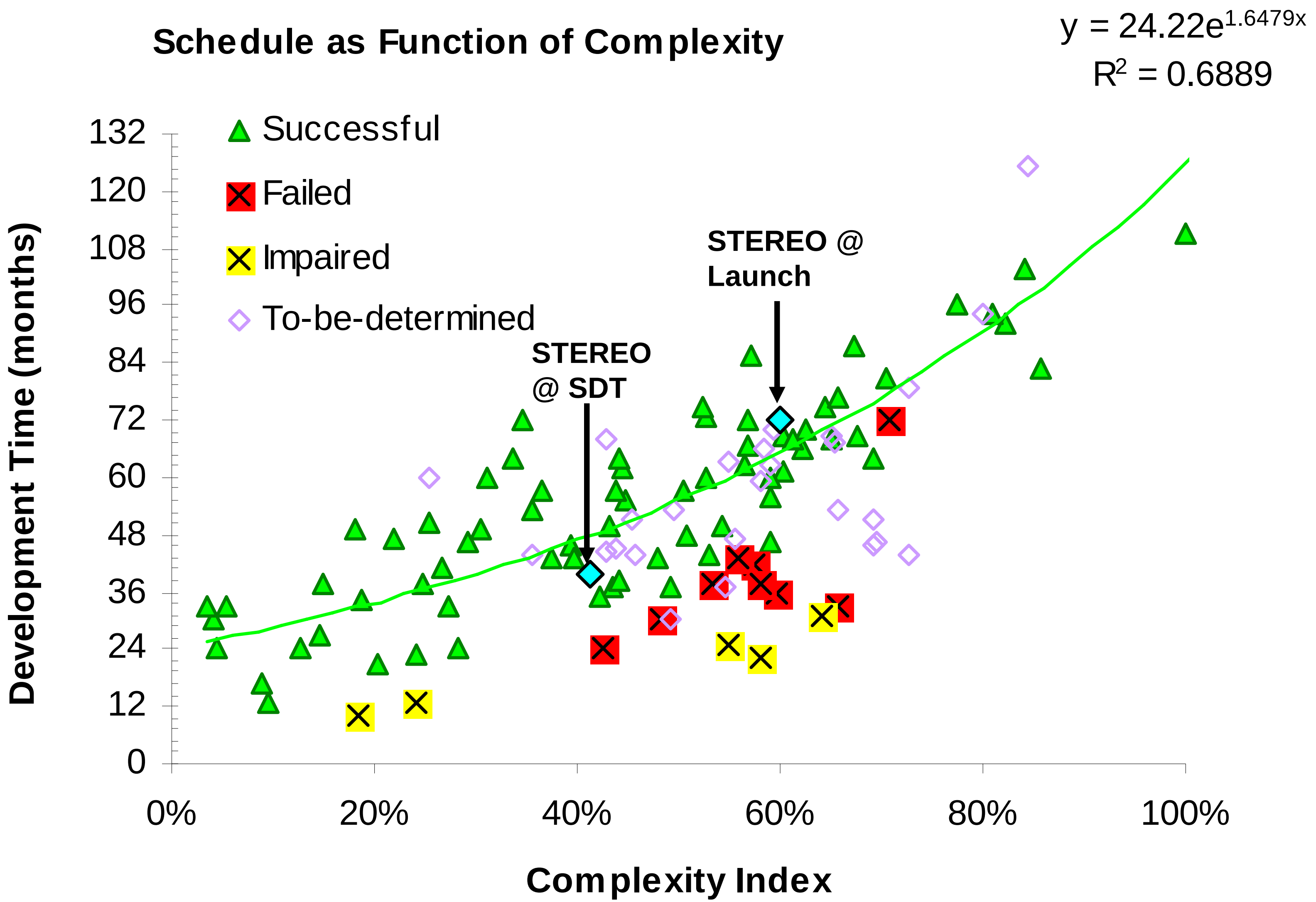


Illustrations reprinted courtesy of NASA

Typical Cost-risk Analyses Won't Capture Large Changes During Concept Evolution



Effect of Increased Complexity on Development Time: STEREO Complexity Increased from 40% to 60%



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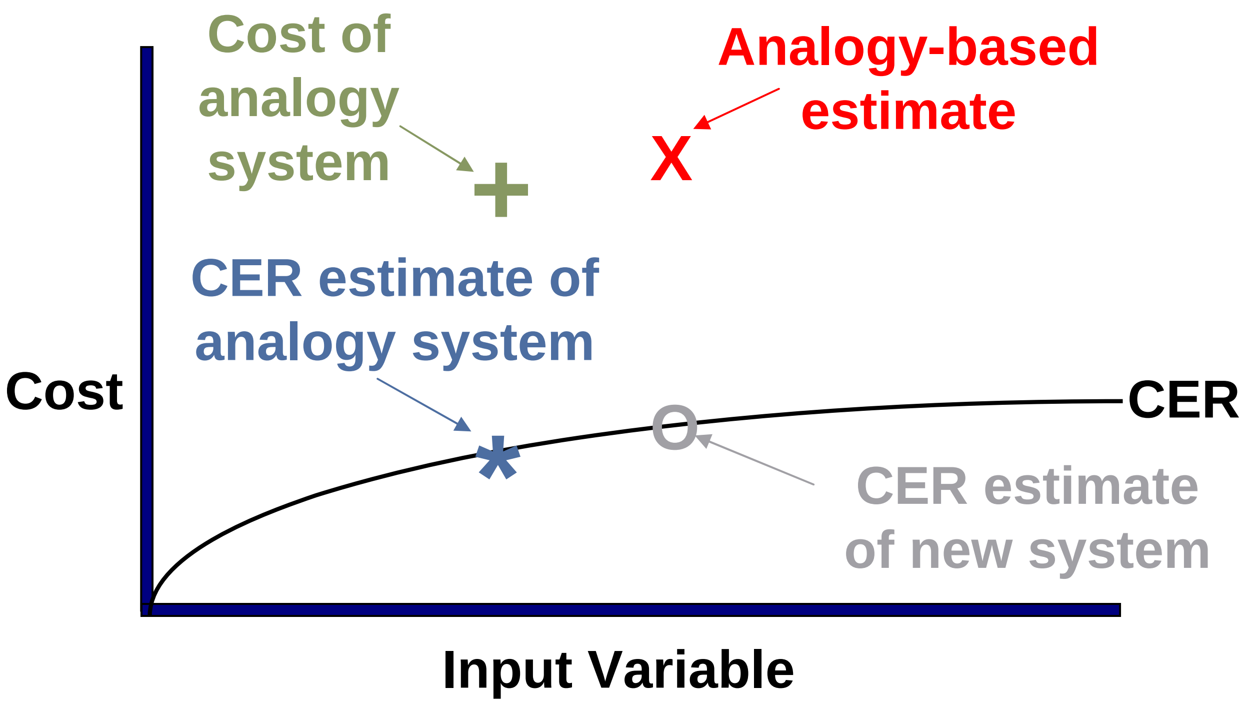
Primary Tenants of Cost Estimating to Establish Robust Estimates

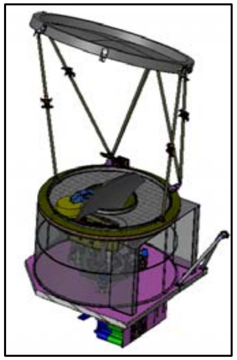
- Use Multiple Methods
  - *Ensures that no one model/database biases the estimate*
    - Industry Standard Methods
    - Aerospace Developed Models

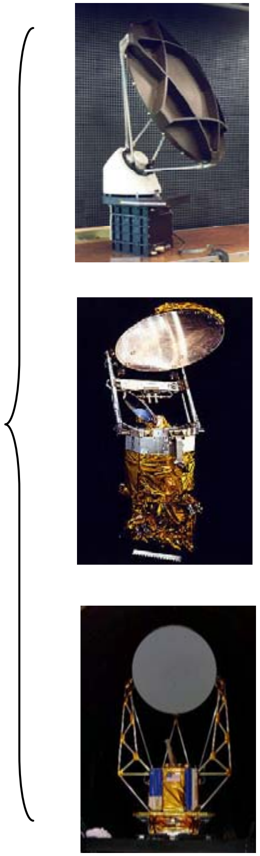
- Use Analogy Based Estimating
  - *Ties cost to systems that have been built with known cost*
  - *Allows contractor specific performance to be addressed*
  - *Forces estimator and project to look at cost and complexity of new concepts with respect to previously built hardware*

- Use Both System Level and Lower Level Approaches
  - *Ensures that lower level approaches do not omit elements or underestimate overall cost relative to system level complexity*

Analogies Anchor to Actual Cost Data Adjusted Based on Functional Cost Estimating Relationships



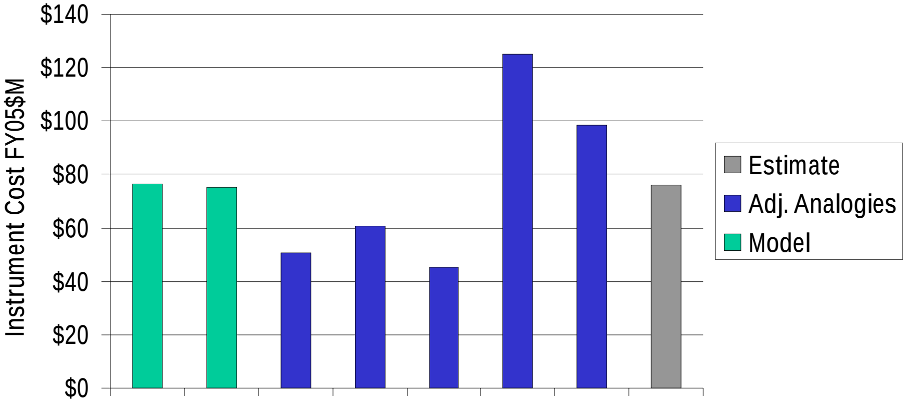


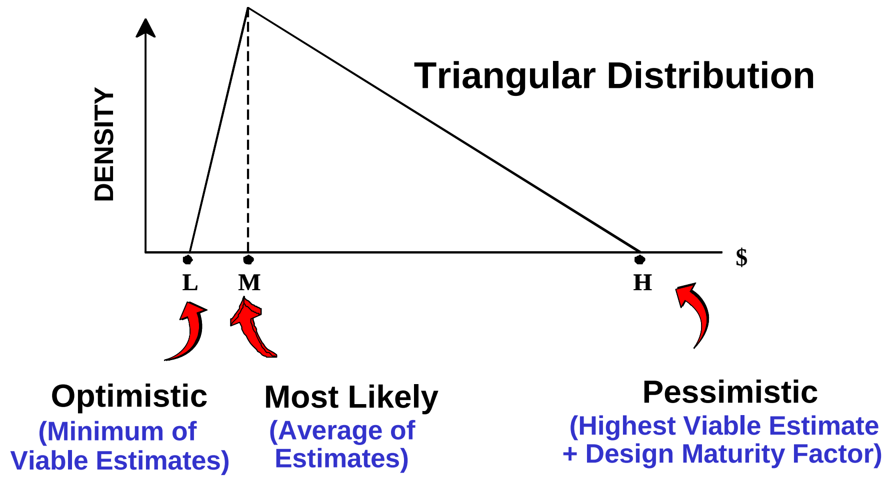


- Use analogies as the basis for an estimate
- Every historical program has “unique” aspects that affect cost
- Use multiple analogies to average out impacts of unique aspects

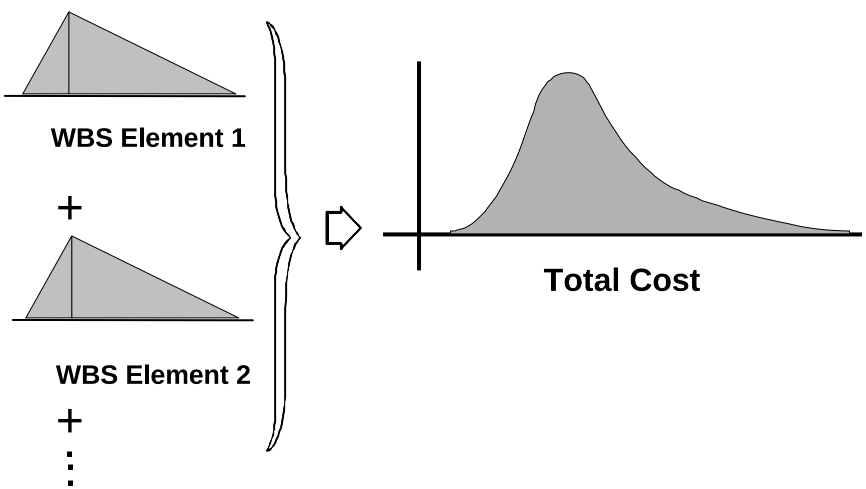
Cost Risk Process Uses Multiple Methods to Provide a Distribution of Possible Outcomes

Example of Multiple Cost Estimates

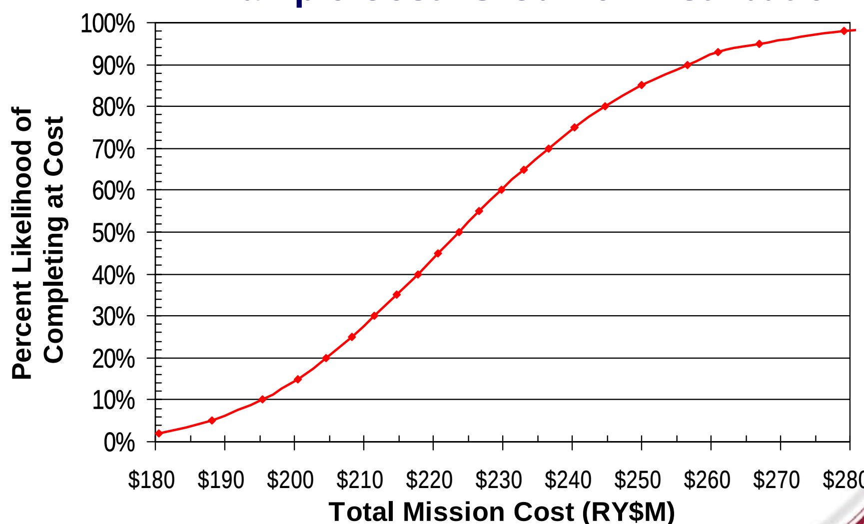




Total Distribution is a Combination of Cost Distributions for WBS Elements



Example Cost "S-Curve" Distribution



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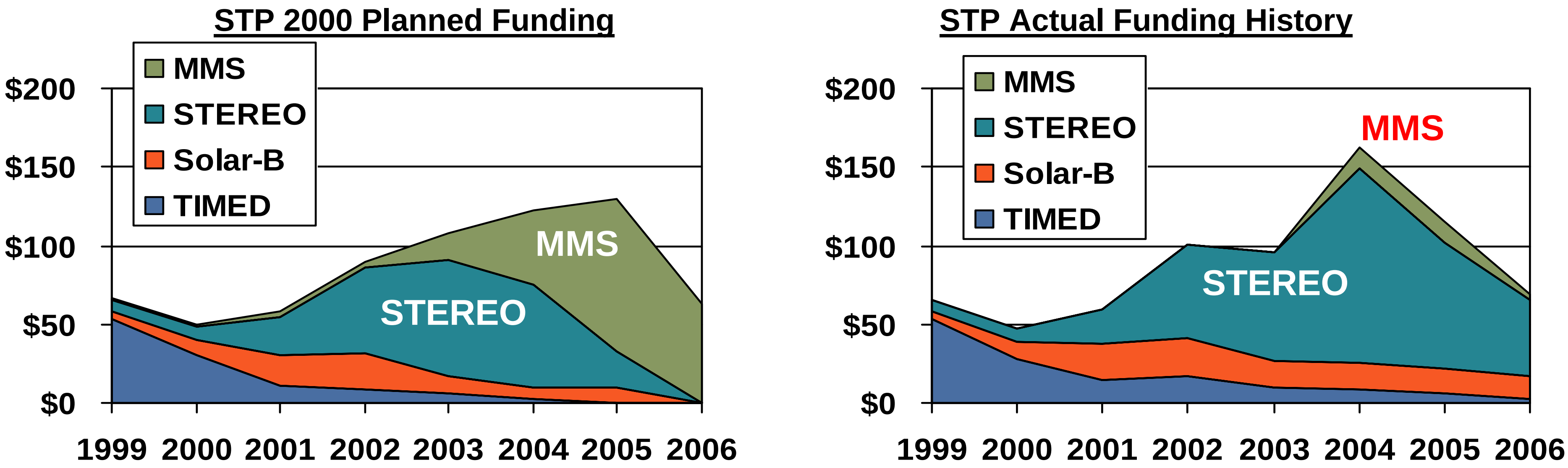
Inadequate Budget for One Project Results in a Domino Effect for Other Projects in Program Portfolio



Total Program Funding 1999-2006

- Planned = $690M
- Actual = $715M

Although the total program funding remained consistent over this time period, implementation of successive missions substantially affected

Affordability Analysis ("Sand Chart") Needed to Support Long Term Decision Making Process

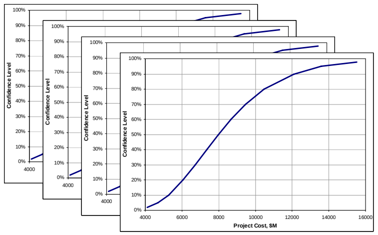
- Simulate portfolio of related projects, based on the individual projects' cost-risk and program funding constraints
  - *Monte-Carlo analysis, using S-Curves, simulates cost growth*
  - *Algorithms derived from historical behavior of past projects*
  - *Schedule interdependencies combined with individual project cost growth*

- Portfolio forced to fit within available funding
  - *Shift start of projects, modify duration between milestones, or eliminate projects to create new plan within available funding*
  - *Projects with significant fixed costs (e.g. workforce/facility requirements), may see increased cost if forced to stretch over longer duration*
  - *Cost reductions and milestone delays can lead to increased costs due to inefficiencies (e.g. contract modifications, workforce costs, etc.)*

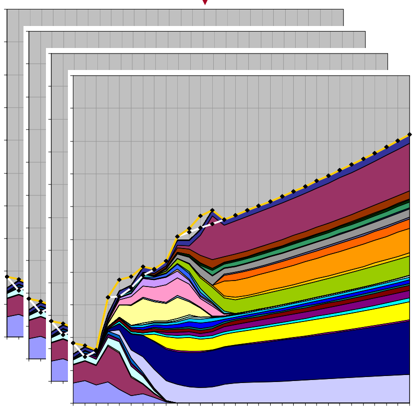
- Cost and schedule outputs probabilistic
  - *Typically reported at 65-70% confidence level*

Designed to Evaluate Scenarios for Given Program/ Portfolio or Develop Plan Given Individual Elements

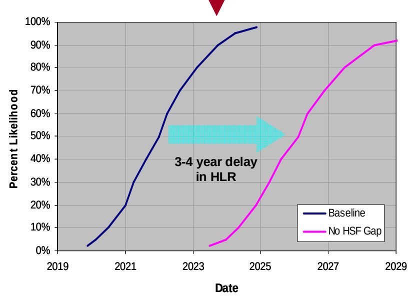
Evaluation



Input:
baseline plan, cost likelihood curves, program linkages

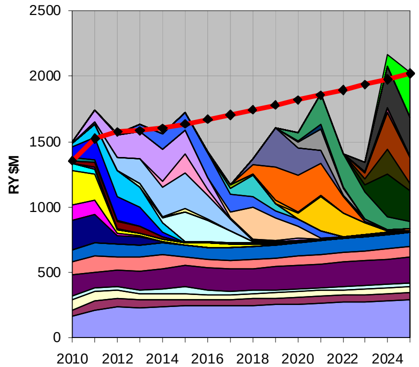


Perform Monte Carlo probabilistic analysis



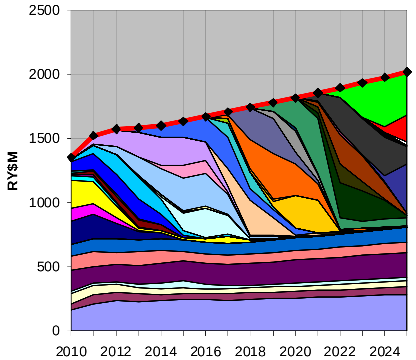
Output:
schedule likelihood curves, # of missions complete, etc.

Planning



Input:
baseline plan, program linkages

Apply Stretch Algorithms



Output:
***New* strawman plan that fits budget available**

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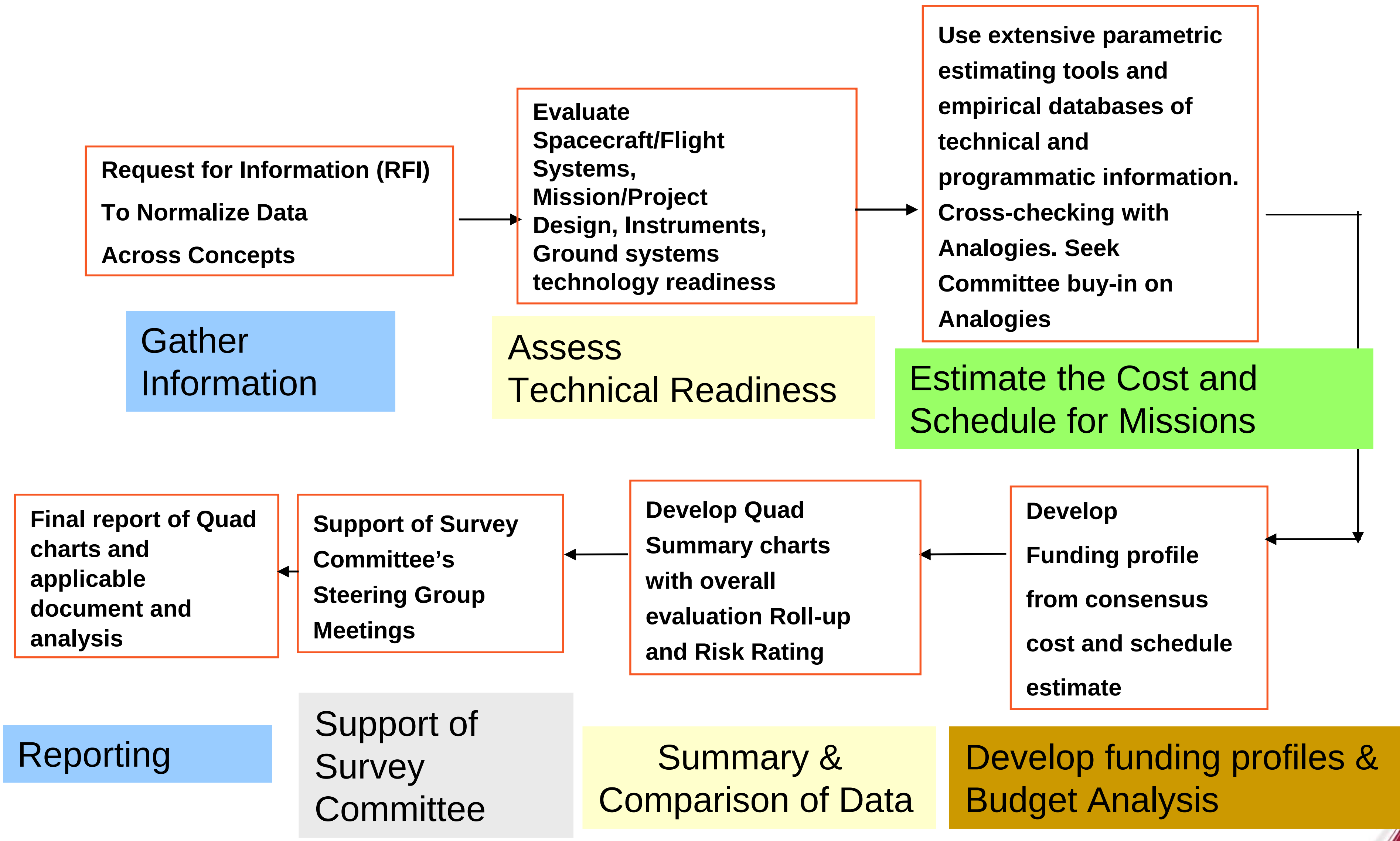
Observations & Challenges
Review of HSF Committee and Decadal Support

- Decadal Survey Support
  - *Objective is to apply a uniform and historical data informed affordability analysis to each of the activities examined*
  - *Historical mass, power & schedule growth used to assess potential cost "threats"*
  - *Limited data for ground based projects*
  - *Limited project/activity interactions – due to timeline and scope*

- Review of HSF Plans Committee Work
  - *Objective to apply uniform and historical data informed affordability analysis methodology to each option at a high level*
  - *Traditional cost estimates not performed*
  - *Need to compare in-development systems with "paper concepts"; some project elements had little design analysis performed*
  - *Historical cost growth from project formulation (SDR or Phase B) while many project elements considered had not reached SDR*

Decadal Support Flow Diagram



Decadal Technical, Cost and Schedule Assessment

Concepts

Evaluate Responses

- Technical
- Cost
- Schedule

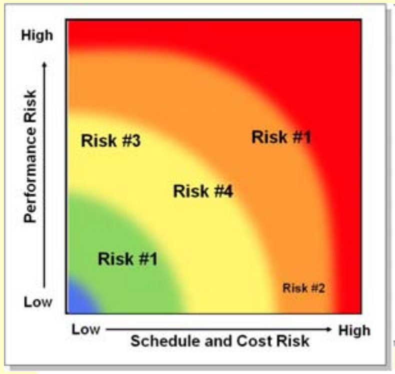
Multiple Iterations and Interaction

Concept Maturity
Implementation
Development
Heritage
Contingency

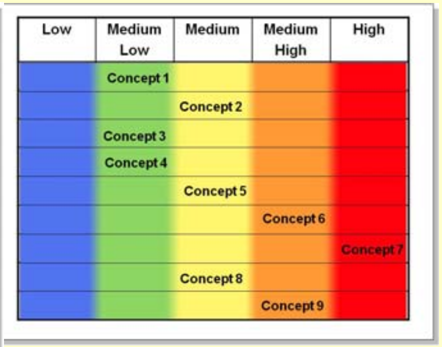
Analogies
Models
Reserve
Cost Estimate
Cost Threats

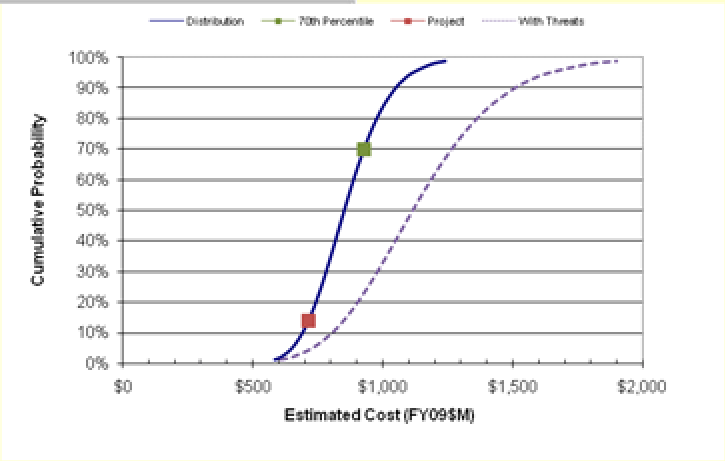
Project Phases
Critical Path
Analogies

Concept Risks



Leveled Technical Rating



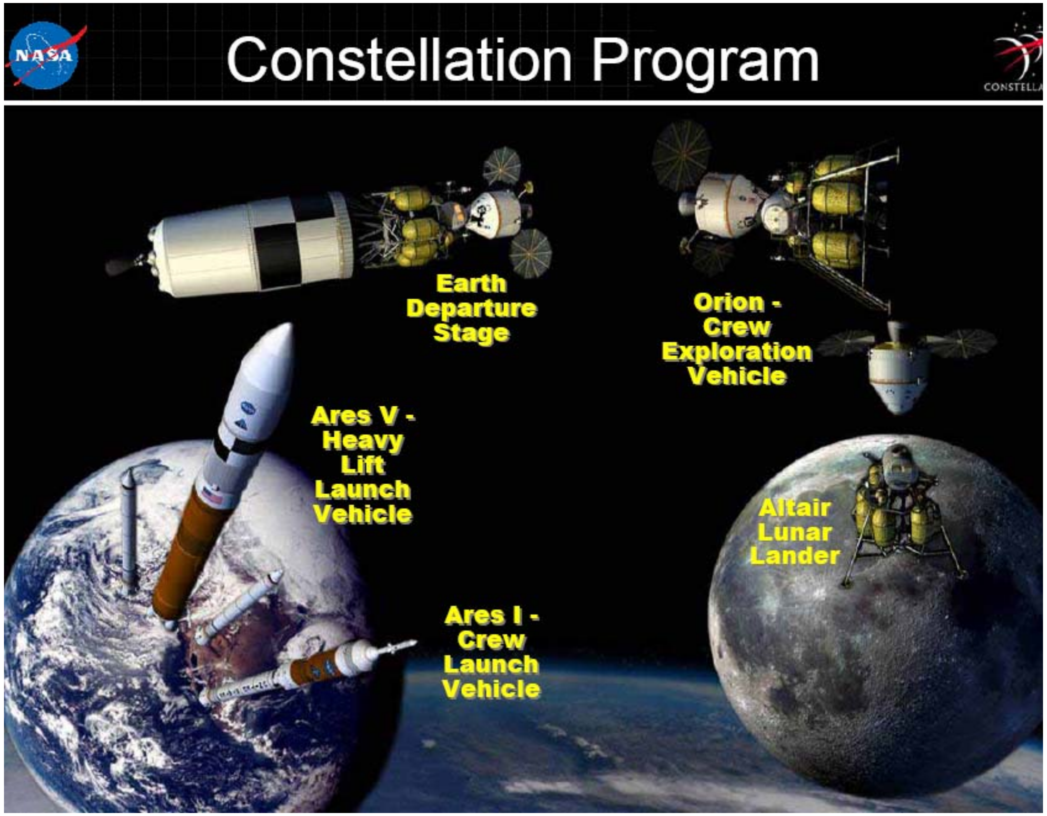


Double S-Curve Bounds Cost Threats

- **Mass maturity impact on LV Cost**
- **Schedule slippage impact on Cost**
- **Mass & Power reserve impact on Cost**

Future of U.S. Human Spaceflight in the Upcoming Decades Formulated in Terms of Five Key Questions

1. What should be the future of the Space Shuttle?
2. What should be the future of the International Space Station (ISS)?
3. On what should the next heavy-lift launch vehicle be based?
4. How should crews be carried to low-Earth orbit?
5. What is the most practicable strategy for exploration beyond low-Earth orbit?



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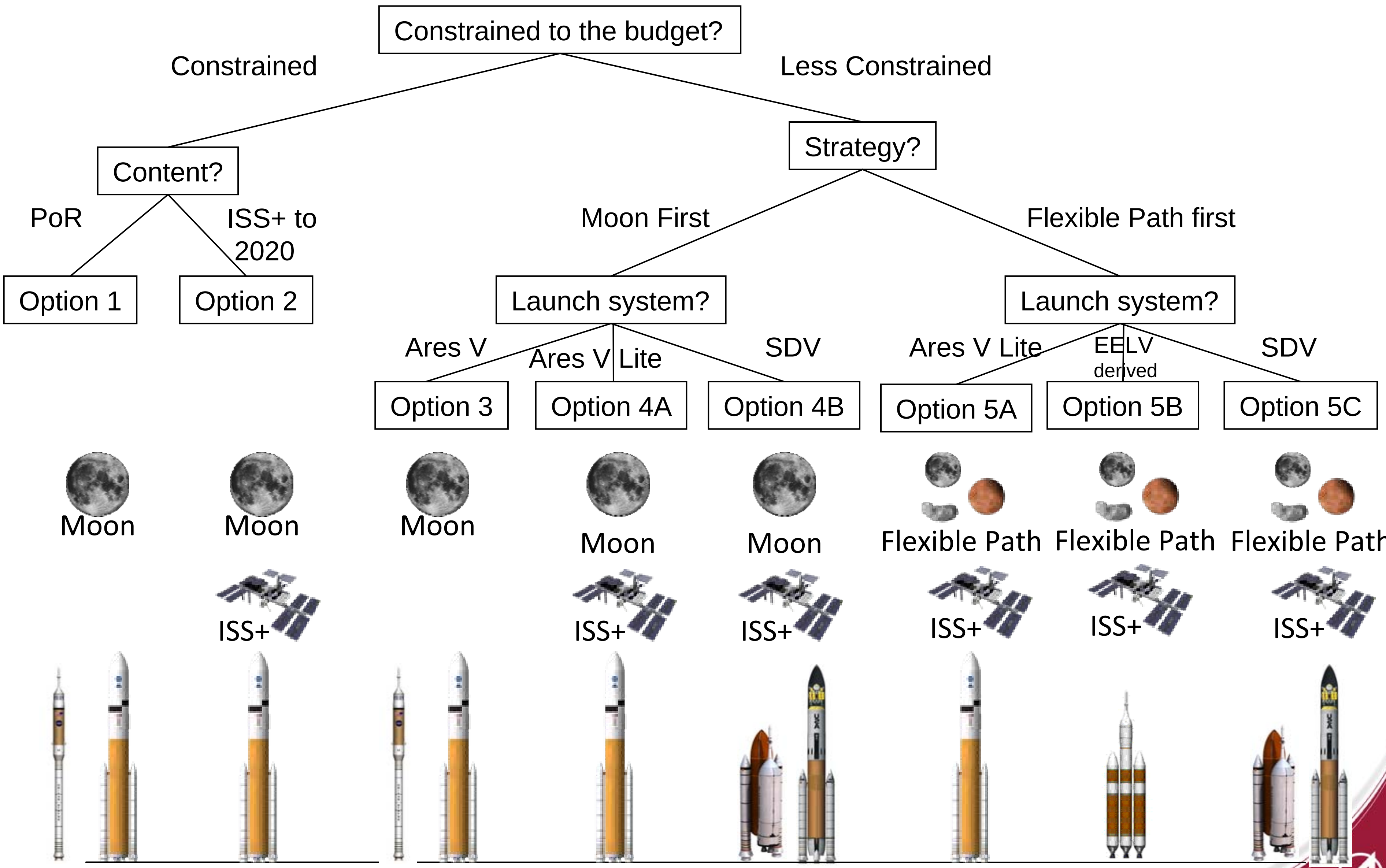
Summary of Integrated Options Evaluated by Review of HSF Committee

	Budget	Shuttle Life	ISS Life	Heavy Launch	Crew to LEO
Constrained Options					
Option 1: Program of Record (constained)	FY10 Budget	2011	2015	Ares V	Ares I + Orion
Option 2: ISS + Lunar (constrained)	FY10 Budget	2011	2020	Ares V Lite	Commercial
Moon First Options					
Option 3: Baseline - Program of Record	Less constrained	2011	2015	Ares V	Ares I + Orion
Option 4A: Moon First - Ares Lite	Less constrained	2011	2020	Ares V Lite	Commercial
Option 4B: Moon First - Extend Shuttle	Less constrained	2015	2020	Directly Shuttle Derived + refueling	Commercial
Flexible Path Options					
Option 5A: Flexible Path - Ares Lite	Less constrained	2011	2020	Ares V Lite	Commercial
Option 5B:Flexible Path - EELV Heritage	Less constrained	2011	2020	75mt EELV + refueling	Commercial
Option 5C: Flexible Path - Shuttle Derived	Less constrained	2011	2020	Directly Shuttle Derived + refueling	Commercial

Note: Program-of-Record-derived options (Options 1 and 3) do not contain a technology program; all others do.

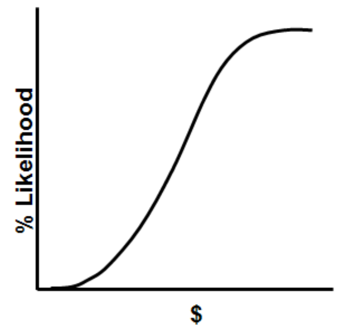
Integrated Option Decision Analysis Tree



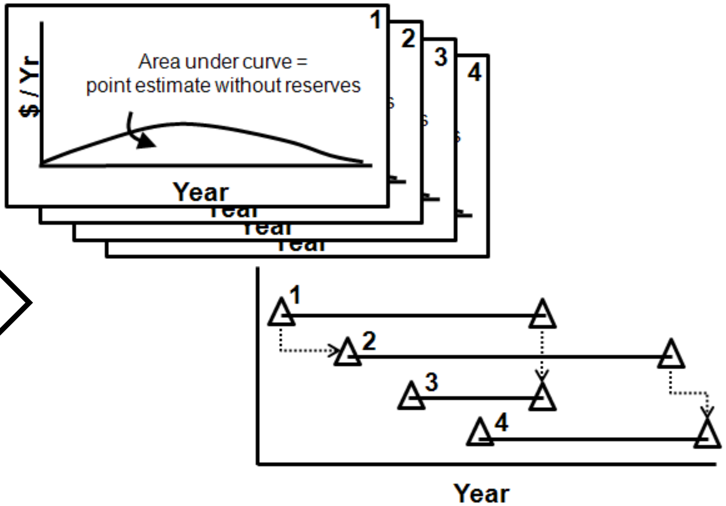
Used with Permission of Review of US Human Space Flight Plans Committee

Methodology Overview: Review of Human Space Flight (HSF)

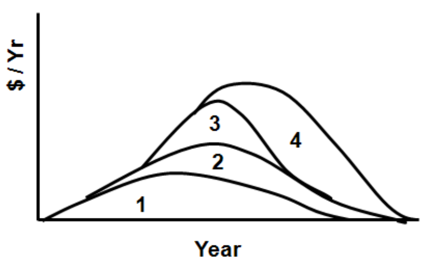
1. Point Estimate Without Reserve



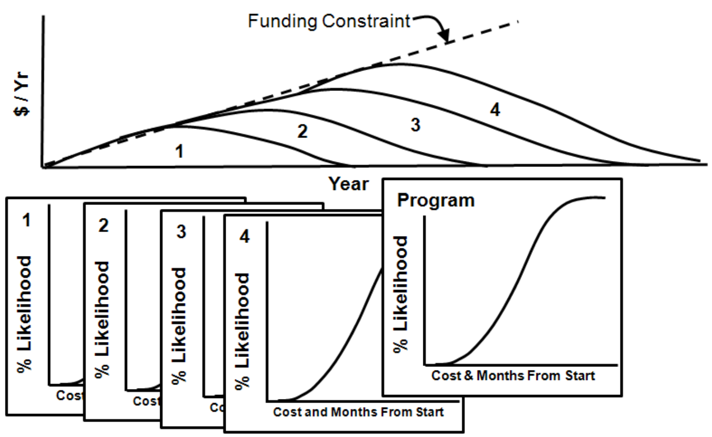
2. Cost-Risk Curve Informed by Historical Program Experience



3. Starting Project Budget Profiles and Schedule Dependencies



4. Assembled Program Architecture Budgets



5. Program Budget Under Funding Constraints

Source of Point Estimates

1. **Program of Record (POR) Elements**

<u>Basis of Estimate</u>

- PMR '08 Rev 1B, without reserves, for Phase B or later projects
- PMR’09 without reserves, for pre-phase B projects

2. **Non-POR Elements**

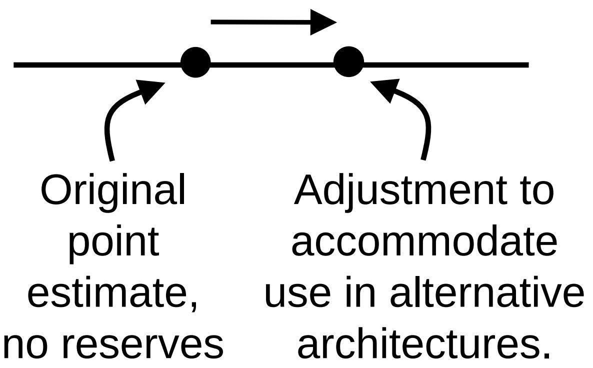
<u>Basis of Estimate</u>

- Related program data (e.g. EELV)
- Historical analogy data
- Prior NASA studies on similar or related program elements
- HSF Committee discussion

<u>Review of Basis of Estimate</u>

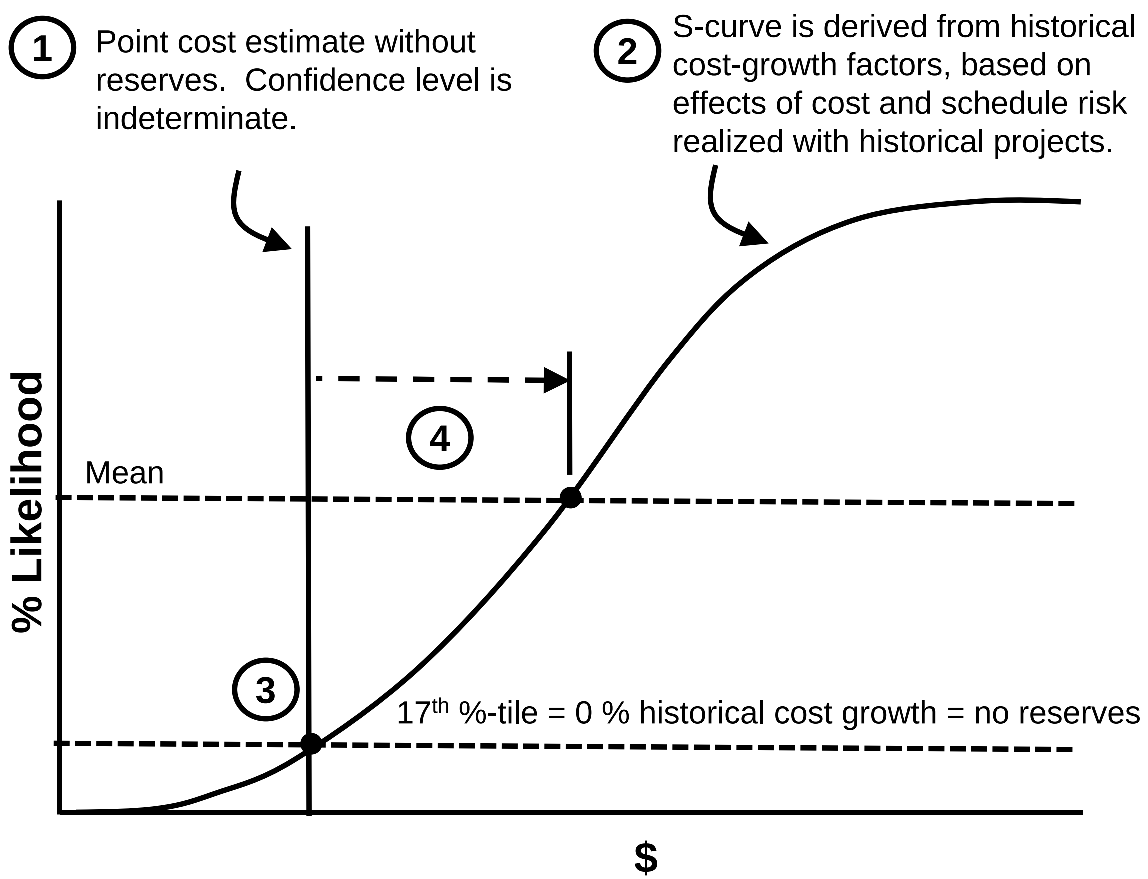
- Iterative discussions on basis of estimate and assumptions with NASA
- Pedigree review of source data
- Comparison to analogy or reference data

Point estimate, without reserves, adjusted to account for additional work required to accommodate interface changes for new architectures



Point Estimate to Cost Risk

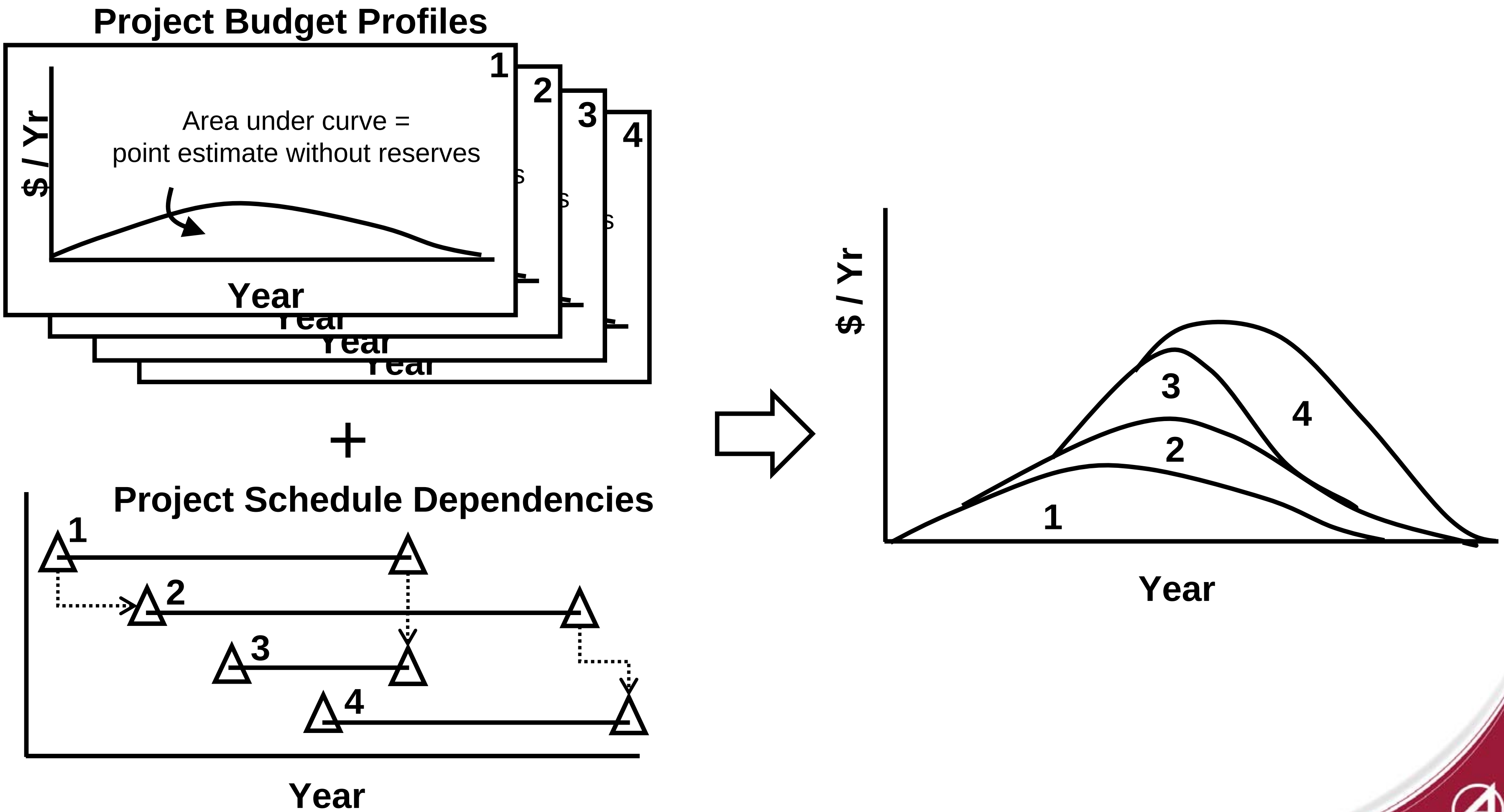
- **Point estimates for POR elements past Phase B start from PMR08 Rev 1B**
- **Point estimates for POR elements before Phase B start from PMR09**
- **Point estimates for non-POR elements from NASA, Aerospace, and Committee sources**



1. Point estimate, without reserves.
2. S-curve is derived from historical cost-growth factors.
3. 17%-tile confidence is aligned with point estimate
4. Mean is aligned to average cost growth (**<u>51%</u>**). < 51% historical cost growth from PMR09 cost-to-go for POR elements past Phase B.

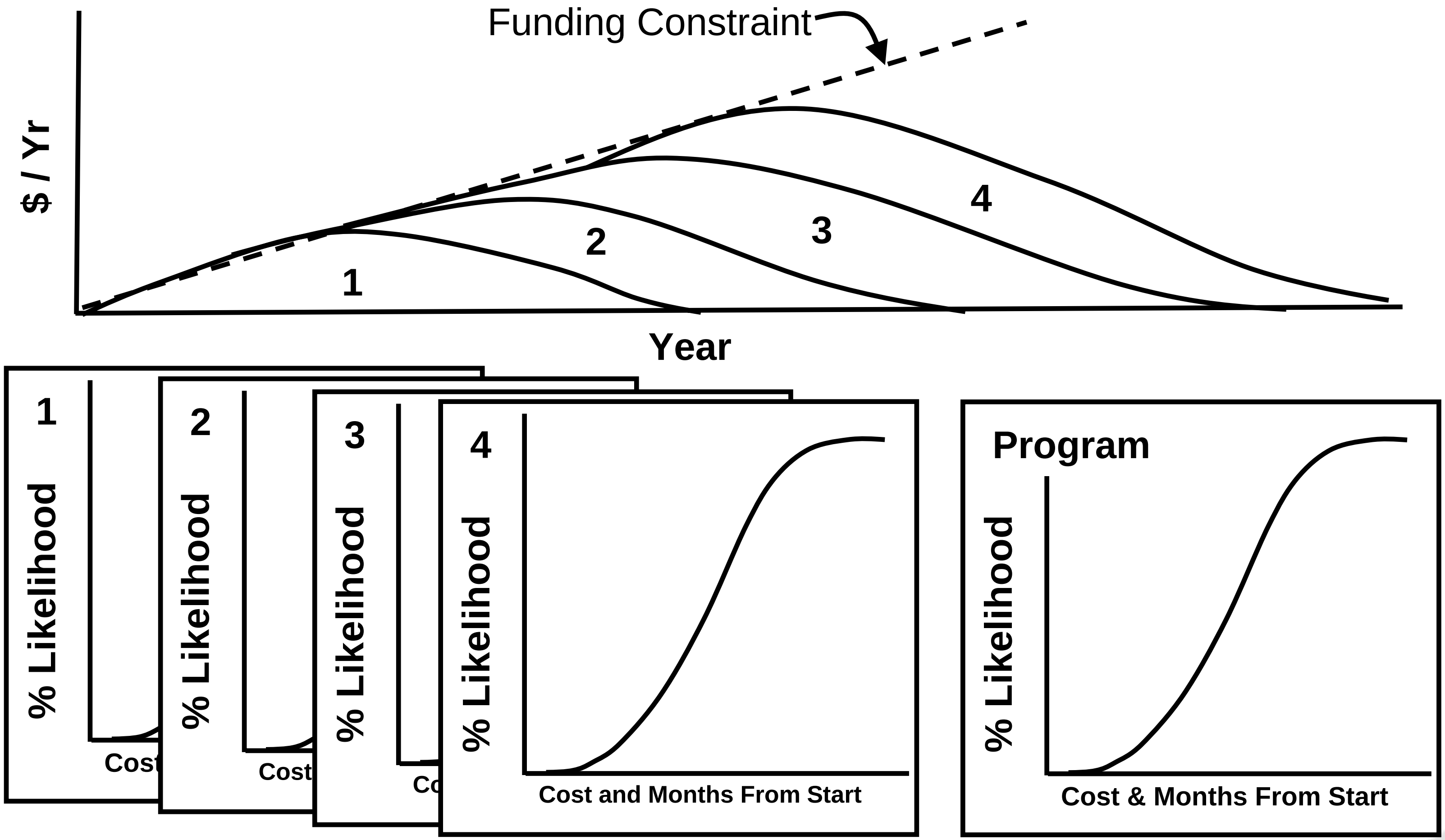
Establish starting budget profiles for each project in program, and assemble program

- **Assemble project funding wedges into architecture / program**
- **Schedule dependencies establish precedence and constraints**
- **Schedule unaffected by funding availability (unconstrained budget)**

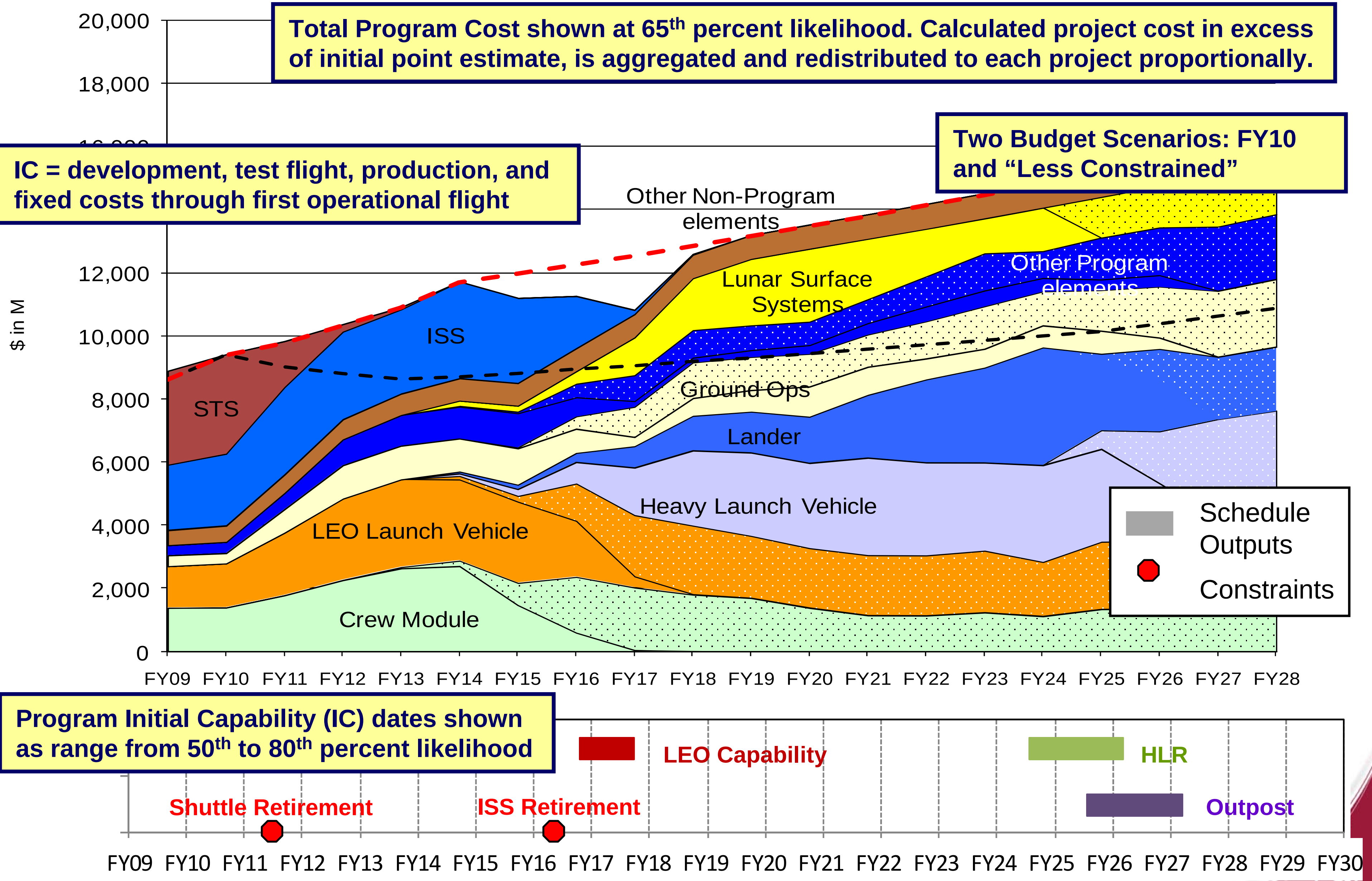


Constrain to Budget Scenario

- **Monte-Carlo based on cost risk curve for each project element**
- **Program dependencies and funding constraints determine project phasing**
- **Total cost increases to accommodate inefficiencies with adjusted schedule**
- **Outputs: realized cost/schedule, cost and schedule confidence S-curves**



Notional Sand Chart Used for Program Assessment



Summary – Re-cap

- Initial project estimates may be unreliable due to design and technology immaturity and inherent optimism
- While estimates become more accurate as project matures, the greatest growth manifests itself late in project development
- Methods exist to estimate cost and schedule at the conceptual phase albeit with some level of uncertainty
- Cost estimating process includes use of multiple methods, adjusted analogies, and system level and lower level approaches
- These analyses feed strategic analysis (“Sand Chart”) capabilities providing a long term, robust assessment of projects and their effect on a portfolio of programs and missions
- Decadal Study and Review of HSF Plans Committee support demonstrate application of and challenges with program-level affordability analysis

Backup

References and Further Reading

1) Bearden, David A., “A Complexity-based Risk Assessment of Low-Cost Planetary Missions: When is a Mission Too Fast and Too Cheap?”, Fourth IAA International Conference on Low-Cost Planetary Missions, JHU/APL, Laurel, MD, 2-5 May, 2000.

2) Bearden, David A., "Small Satellite Costs", *Crosslink Magazine*, The Aerospace Corporation, Winter 2000-2001.

3) Bitten R.E., Bearden D.A., Lao N.Y. and Park, T.H., “The Effect of Schedule Constraints on the Success of Planetary Missions”, Fifth IAA International Conference on Low-Cost Planetary Missions, 24 September 2003.

4) Bearden, D.A., “Perspectives on NASA Robotic Mission Success with a Cost and Schedule-constrained Environment”, Aerospace Risk Symposium, Manhattan Beach, CA, August 2005

5) Bitten R.E., Bearden D.A., Emmons D.L., “A Quantitative Assessment of Complexity, Cost, And Schedule: Achieving A Balanced Approach For Program Success”, 6th IAA International Low Cost Planetary Conference, Japan, 11-13 October 2005.

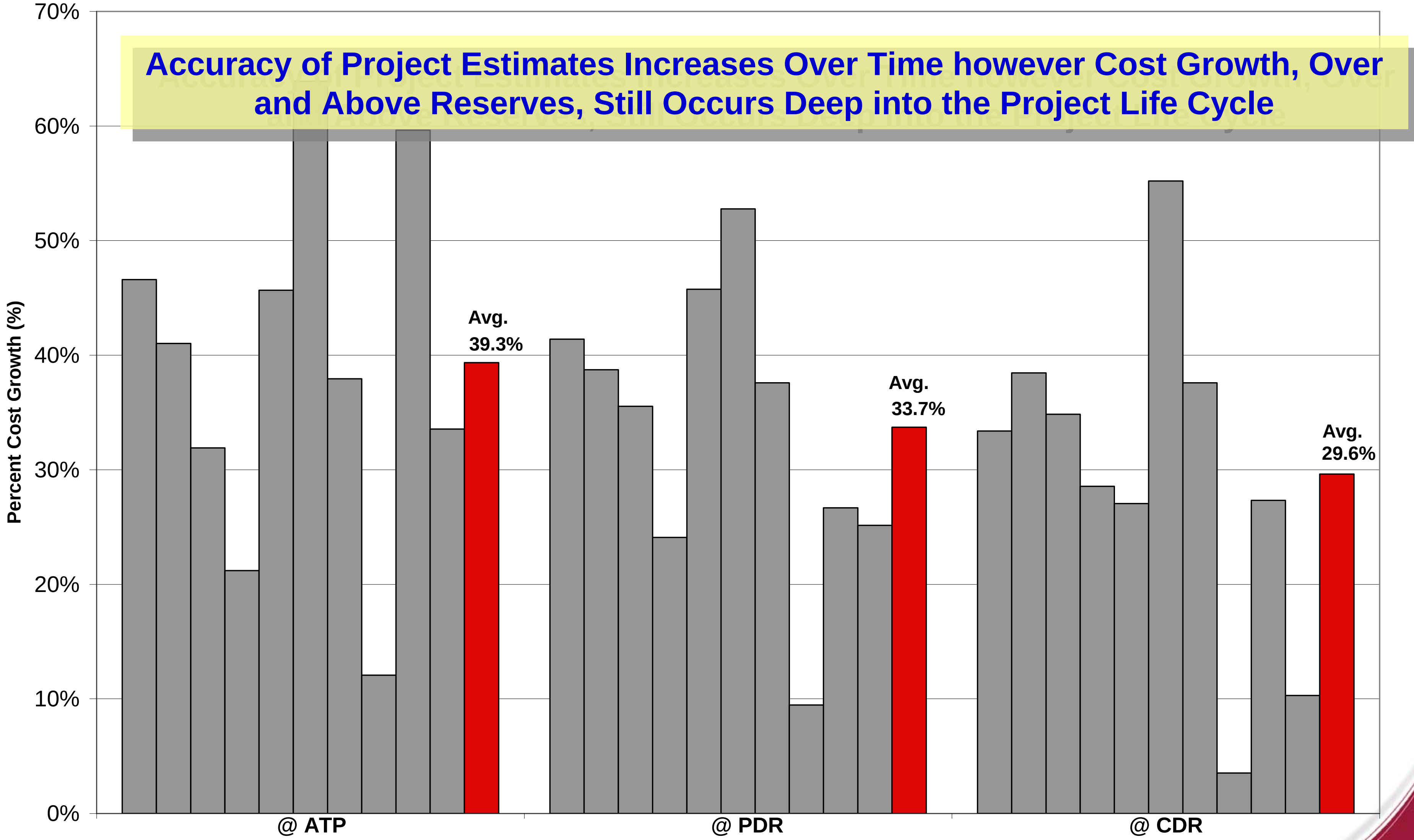
6) Bitten R.E., “Determining When A Mission Is "Outside The Box": Guidelines For A Cost- Constrained Environment”, 6th IAA International Low Cost Planetary Conference, October 11-13, 2005.

7) Bitten R., Emmons D., Freaner C., “Using Historical NASA Cost and Schedule Growth to Set Future Program and Project Reserve Guidelines”, IEEE Aerospace Conference, Big Sky, Montana, March 3-10, 2007.

8) Emmons D., “A Quantitative Approach to Independent Schedule Estimates of Planetary & Earth-orbiting Missions”, 2008 ISPA-SCEA Joint International Conference, Netherlands, 12-14 May 2008.

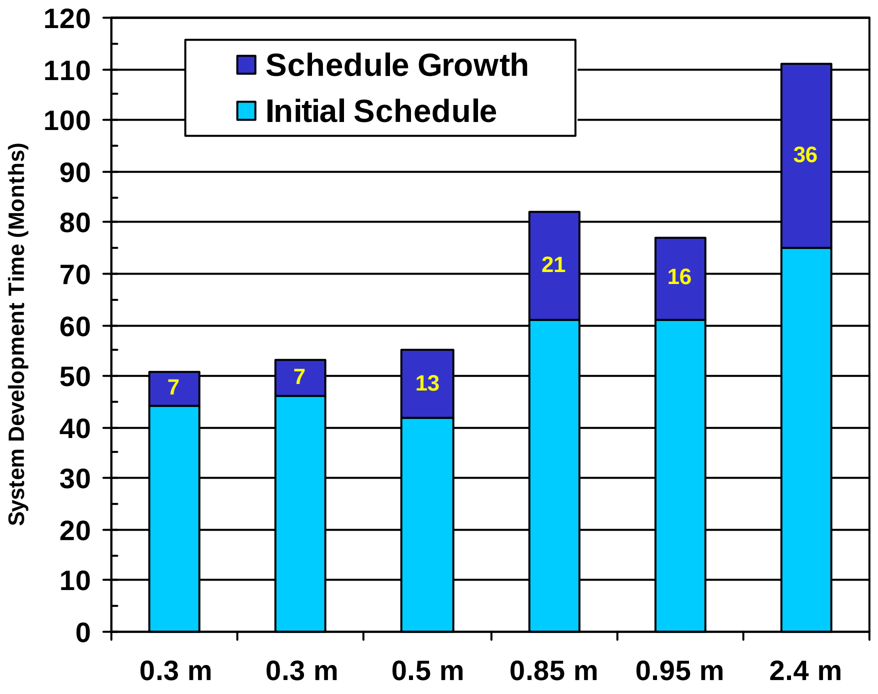
9) Freaner C., Bitten R., Bearden D., and Emmons D., “An Assessment of the Inherent Optimism in Early Conceptual Designs and its Effect on Cost and Schedule Growth”, 2008 SSCAG/SCAF/EACE Joint International Conference, Noordwijk, The Netherlands, 15-16 May 2008.

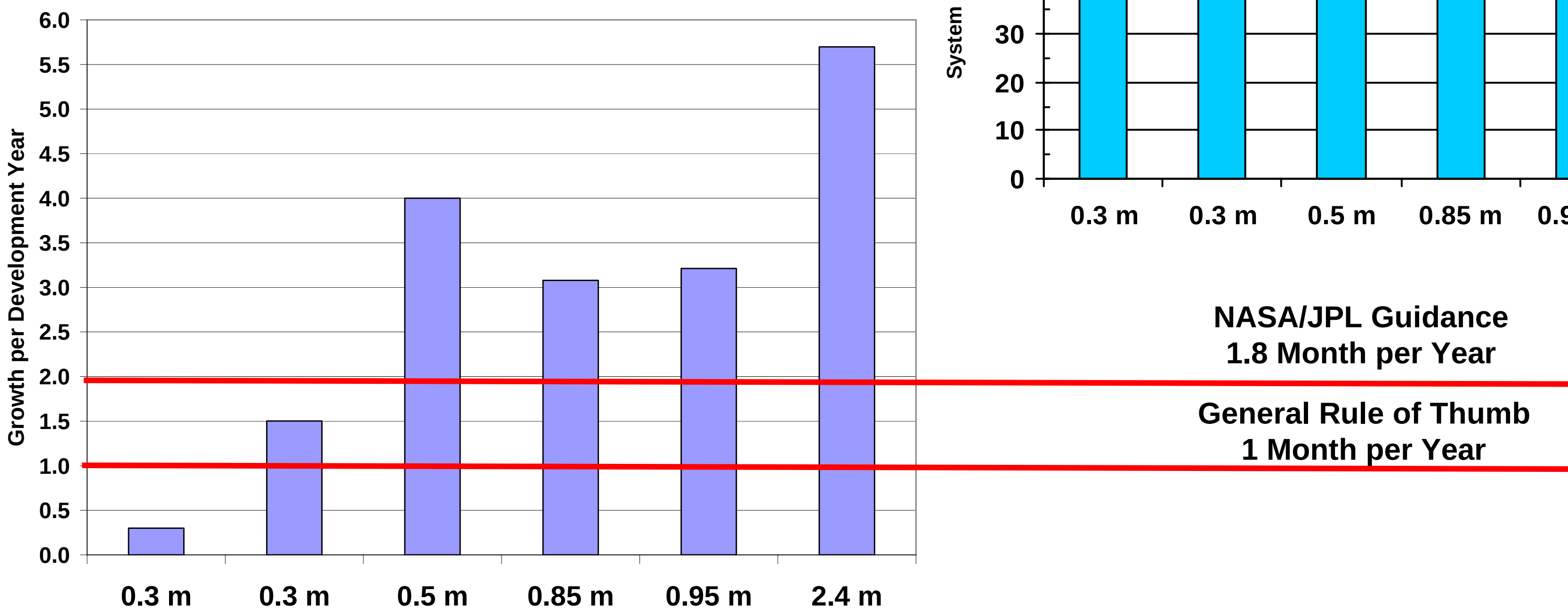
How Reliable are the Projects' Estimates at Conceptual Design Stage and How Does Confidence Progress?



Comparison of Schedule Growth Data with Agency Guidelines: NASA Telescope Missions

Four of Six Telescope Missions Exceeded Common Schedule Reserve Guidelines



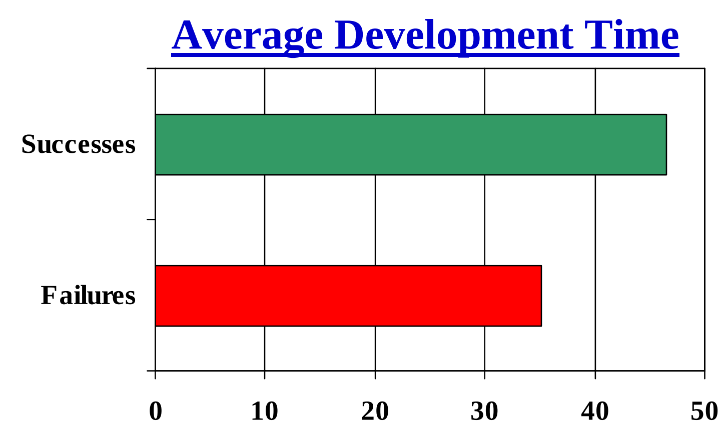


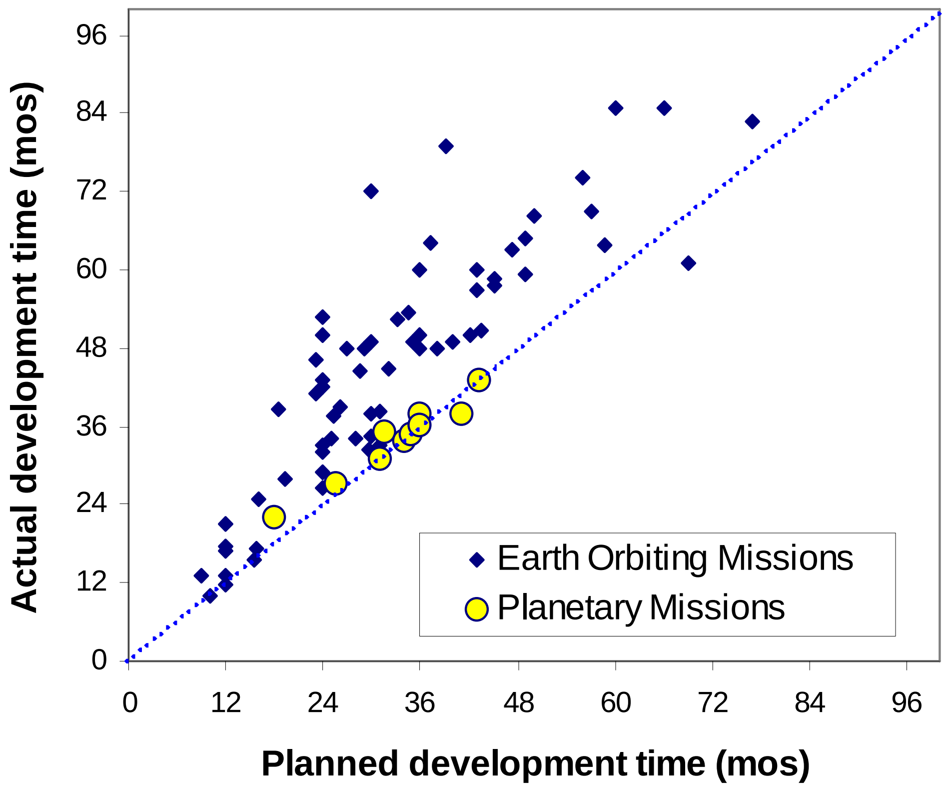
Comparison of Schedule Growth and Success for Planetary Missions vs. Earth-orbiting Missions

- Development times for Planetary missions less than Earth-orbiting missions due to constrained launch windows
- Planetary missions experienced less schedule slip on average than earth-orbiting missions
- However, planetary missions failed or impaired more often

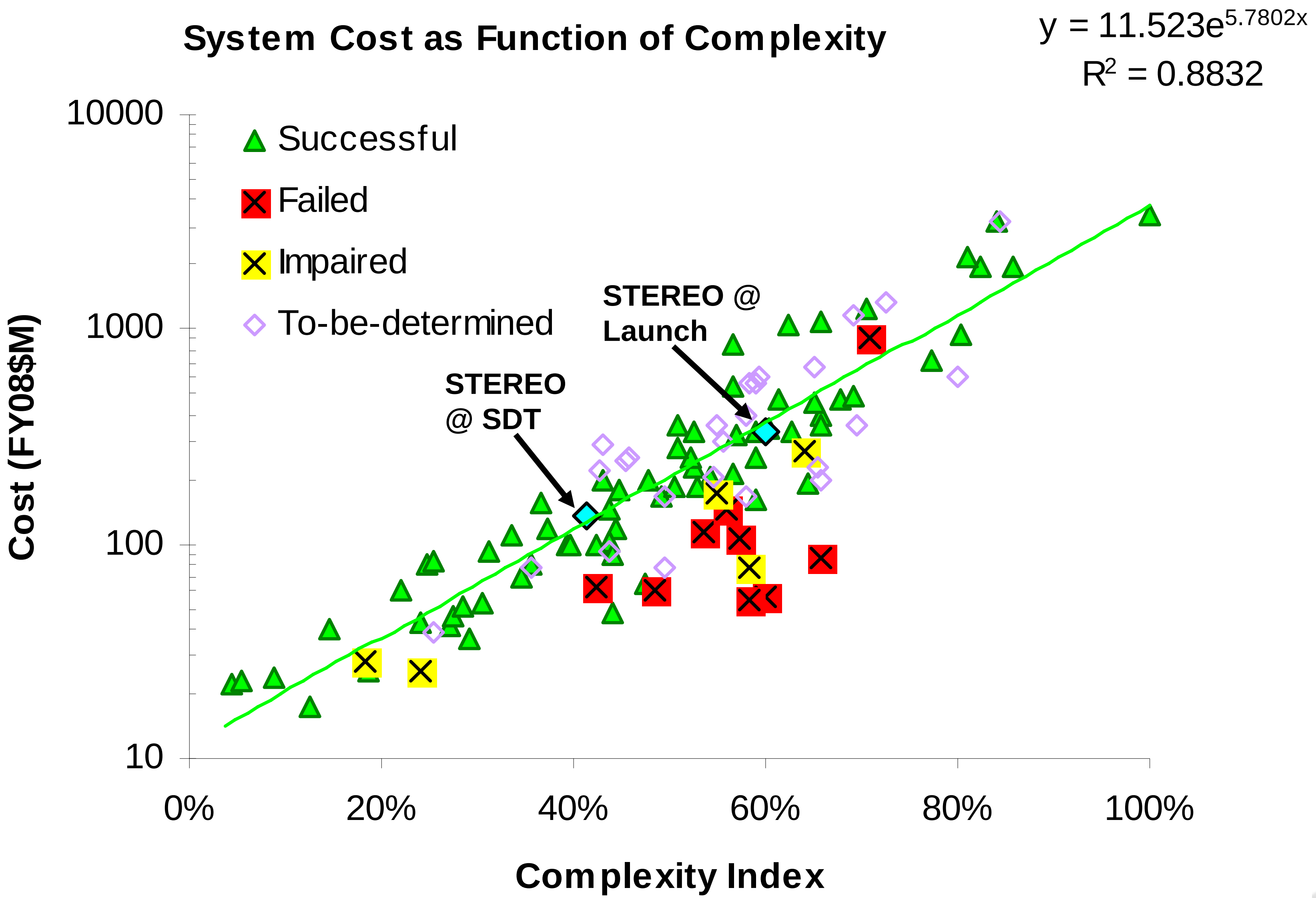
	Planetary	Earth-Orbiting
Sample Size	10	56
Schedule Growth	3.9%	38.3%

Outcome	Planetary	Earth-orbiting
% Successful	30%	84%
% Partial	40%	7%
% Catastrophic	30%	9%

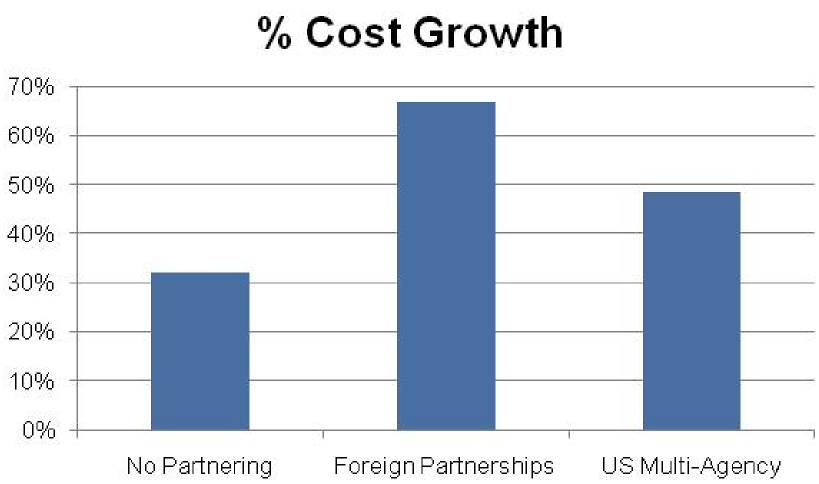


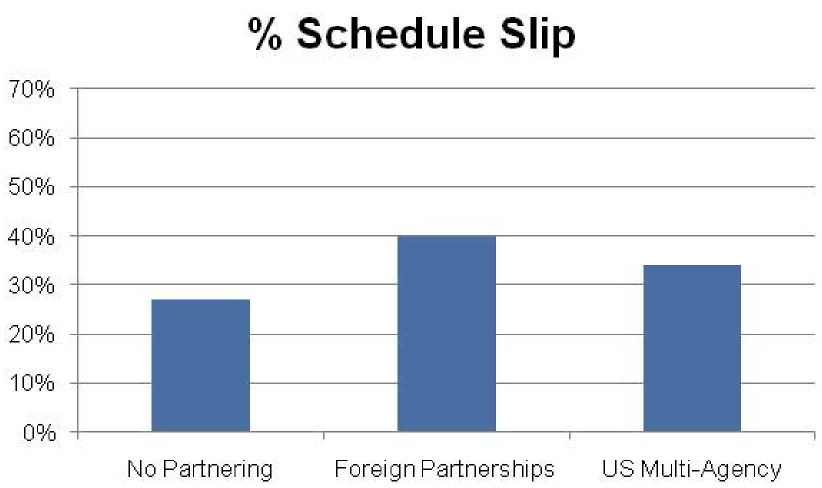


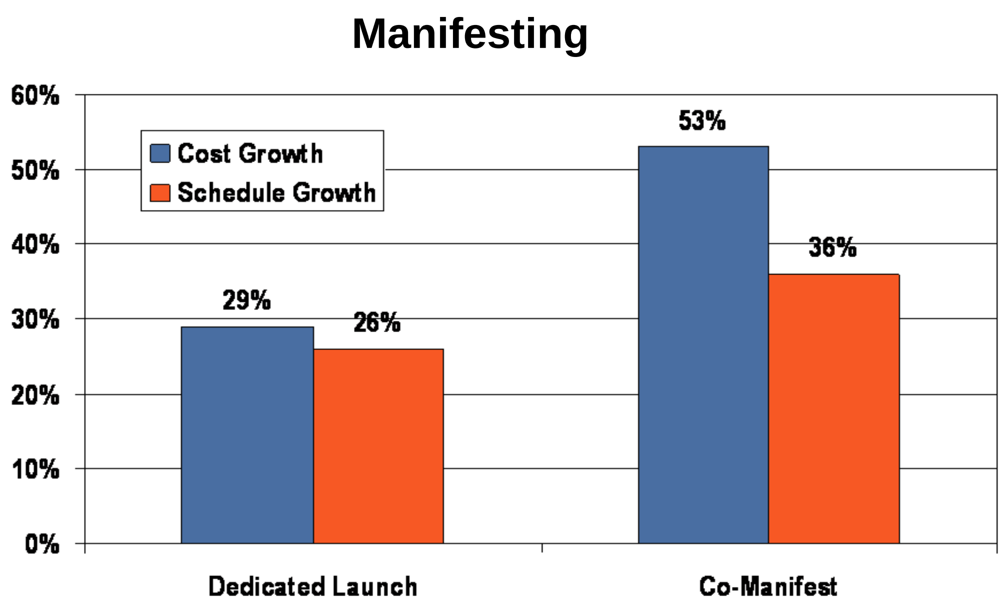
Effect of Increased Complexity on Flight System Cost: STEREO Complexity Increased from 40% to 60%



Partnering Arrangements - Implications for Cost and Schedule growth





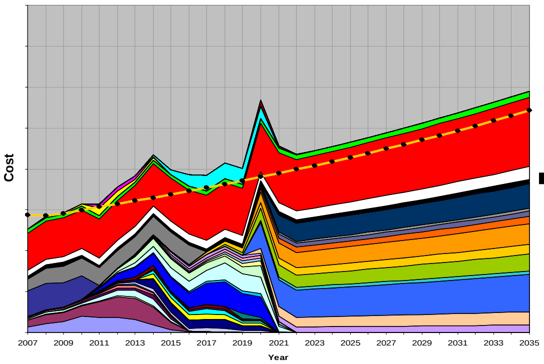


<u>Data sources:</u>

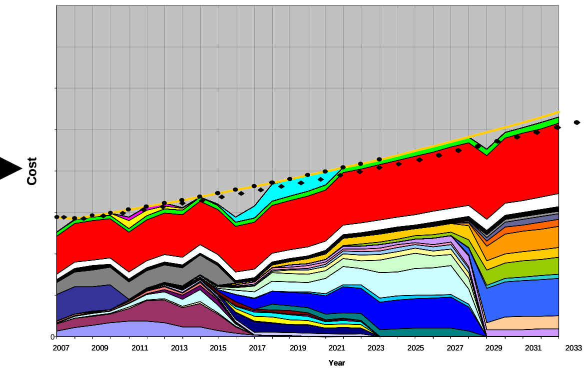
- 77 NASA missions (primarily robotic, non-human missions)
- 40 NASA robotic missions

Sandchart Applies Real World Penalties to Projects Based on Performance of Other Elements in Portfolio

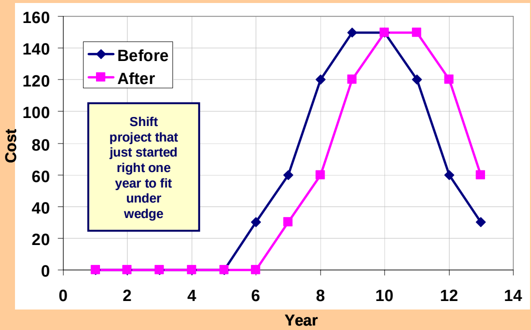
With Cost Overruns Included



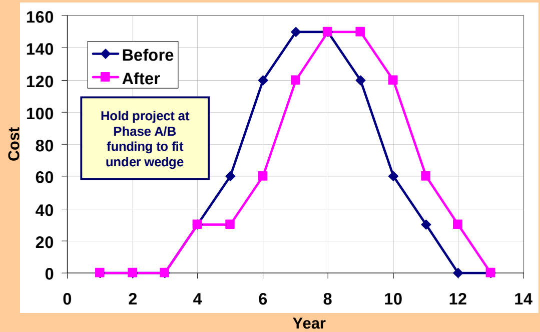
Adjusted to Fit Budget



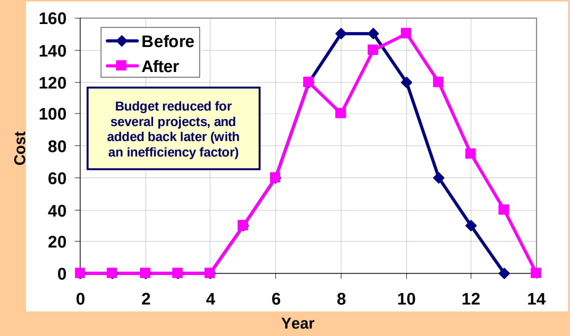
Apply Penalties



Penalty 1: Delay Start



Penalty 2: Phase A/B Hold



Penalty 3: Funding Reduction

Allows realistic assessment of interaction of multiple program elements or multiple missions within a given portfolio

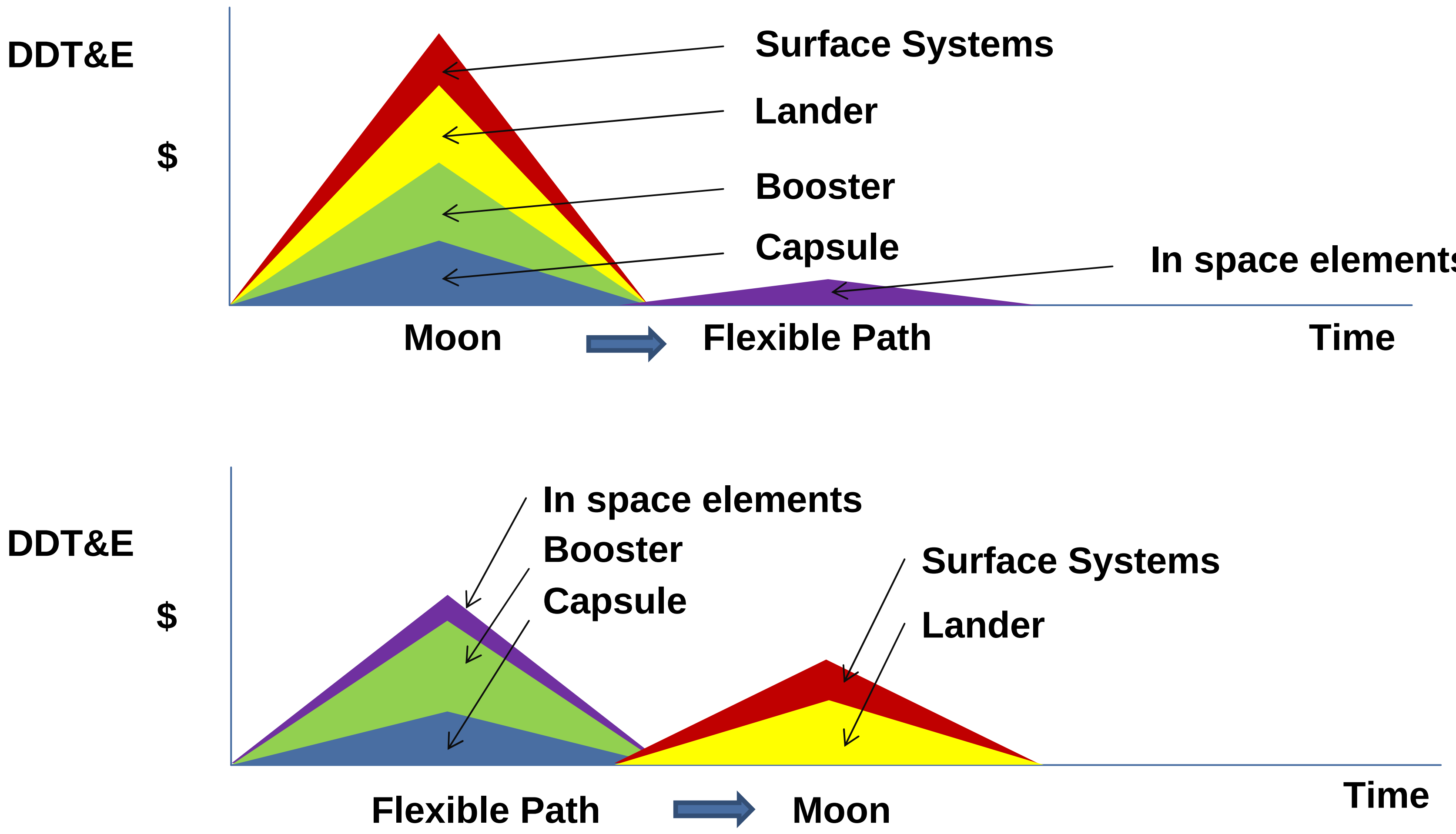
Key Phases of Astro2010 CATE Process

- Develop Request for Information
  - *Technical implementation and required technology development*
  - *Concept maturity and basis of cost and schedule estimates*
- Evaluate concepts in a Leveled process
  - *Technical, cost and schedule assessment performed in parallel*
  - *Discussion and interaction between disciplines important*
  - *Concepts have different levels of maturity which impacts technical and cost risk*
  - *Quantified cost threats identified based on:*
    - Schedule maturity and optimism
    - Technical maturity based on mass and power contingencies
- Present Initial findings to each panel
  - *Discuss concepts and receive immediate and written feedback*
- Re-evaluate, where appropriate, and provide final results
  - *Level all concepts*
  - *Summary charts for committee and detailed charts for each panel*

Project Funding Profiles and Schedule Milestone Constraints

- Sand Chart requires that cost point estimates are spread over time into budget profiles
  - *For POR elements, development cost phasing, milestones, and project duration defined by the PMR '09 funding profile*
  - *For non-POR elements, development cost phasing, milestones, and project duration defined by assuming 40/50 beta curves (40% cost at midpoint) spread over several years (depending on element)*
  - *Operations cost profiles calculated by assuming both marginal/unit costs (tied to a flight manifest) and fixed/year costs (when appropriate).*
  - *Costs are modeled in FY09$, and converted to RY$ using the NASA New Start inflation index. Future costs - beyond 2009 - were inflated using 2.4% inflation factor consistent with the budget inflation factor.*
- Schedule linkages are used to link projects when necessary
  - *Example: Used to ensure that launch vehicle (e.g. Ares I) and crew capsule (e.g. Orion) finish at the same date*
  - *Example: Used to push out costs for starting operations (fixed/yr, marginal/unit) when development experiences schedule delays*

Development Cost Phasing: Lunar vs. Flexible



Used with Permission of Review of US Human Space Flight Plans Committee