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Outstanding Research Issues in Systematic Technology Prioritization for New Space Missions

Workshop Proceedings

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Contents

1. Workshop Objectives

A workshop entitled "Outstanding Research Issues In Systematic Technology Prioritization for New Space Missions" was held April 21-22, 2004 in San Diego, California on behalf of NASA Program Managers Robert Pearce (Code R Division of Strategic Planning) and Doug Craig (currently in the Human and Robotic Technology Program of Code T). The purpose of this meeting was to explore the state-of-the-art in decision analysis in the context of being able to objectively allocate constrained technical resources to enable future space missions and optimize science return.

The participants in this workshop are listed below:

John. D. Azzolini	Goddard Space Flight Center	**Louis Lollar**	Marshall Space Flight Center
Jacob Barhen	Oak Ridge National Laboratory	**Jon Neff**	Aerospace Corporation
David Bearden	Aerospace Corporation	**Stephen Prusha**	Jet Propulsion Laboratory
Doug Comstock	NASA HQ Code BX	**Guillermo Rodriguez**	Jet Propulsion Laboratory
Jason Derleth	Jet Propulsion Laboratory	**Paul Schenker**	Jet Propulsion Laboratory
Mark Drummond	Ames Research Center	**Jeffrey Smith**	Jet Propulsion Laboratory
Alberto Elfes	Jet Propulsion Laboratory	**Raphael Some**	Jet Propulsion Laboratory
Joseph Fragola	Science Applications Inc.	**Mark Steiner**	Goddard Space Flight Center
Dave Beals	Langley Research Center	**Charles Weisbin**	Jet Propulsion Laboratory
Jalal Mapar	Science Applications Inc.	**Alan Wilhite**	Georgia Institute of Tech.
Othar Hansson	Thinkbank, Inc.	**Giulio Varsi**	NASA HQ Code S

2. Invited Talks

Several invited speakers presented their approach and results of recent experience to provide background for the ensuing group discussions.

The need for systematic technology assessment and prioritization was motivated in the talk entitled, **"Strategic Investments Overview" by Doug Comstock**, Director of Strategic Investments for NASA Code BX. Emphasis was on the demonstration of alignment of theme plans with the broader Agency Strategic Plan, and development of common analysis standards.

Then, each of the two mornings was comprised of presentations from the following speakers:

- **"Estimating the Risk of Technology Development," Alan Wilhite**, Professor, Georgia Institute of Technology/National Institute of Aerospace. This talk discussed the characterization of risk through a matrix of probability and consequence. The probability was in turn, decomposed into probability of achieving technological maturity, and probability of achieving performance specifications, for a given resource allocation and schedule. An analytical hierarchical process is used to elicit data from experts. Specific case studies were used to illustrate these concepts.
- **"Technology Assessment of NASA Lidar Missions: A Pilot Study," Mark Steiner**, NASA Goddard Space Flight Center. This is a technology investment case study leading to a next generation LIDAR instrument. Science measurements needs were determined, and physics models developed which would enable mapping between technology performance and instrument performance. Future extensions were suggested in terms of

broadening the entire architecture trade space and combining available data/tools into a unified system.

- **"The Atlas Decision Support System," Louis Lollar,** NASA Marshall Space Flight Center. This talk discussed plans for the ATLAS system, intended as a single (high level) desk top tool which would integrate information concerning missions, architectures, technologies etc. with coverage across the full life cycle, and would recommend relative ranking of technological candidates. The system currently uses system mass (surrogate for cost) as the major discriminator.
- **"The Earth Science System Analysis Model," Othar Hansson** (Thinkbank, Inc.). This talk presented a 3-part investment model of technology change, impact assessment, and prioritization in the framework of an influence network for improved reliability of weather prediction. The example included 13 candidate technologies as they influence 12 system characteristics (of the 13 x 12 = 156, only 18 are non-zero), with projected impact on 5 major system performance and cost metrics. An important consideration is that priorities depend on customer perspectives and there are often many different stakeholders (e.g. those interested in science, those interested in economics, those interested in safety etc.).
- **"Multi-Mission Strategic Technology Prioritization Study," Charles Weisbin**, Jet Propulsion Laboratory, California Institute of Technology. This is a comprehensive JPL study to date on technology assessment and prioritization. The START methodology described in section 1 demonstrated this approach can be used to assess a wide range of missions and technologies and is capable of inter-program trades. The study comprised 13 missions and 167 technology performance parameters in 23 technology areas. Technology investment recommendations were provided at technology task and technology area level as a function of resources available. At any level of resource investment, the likelihood of missions being technologically enabled was also presented.

The slides for these presentations are given in Appendix A.

3. Group Discussions

Each of the two afternoons was devoted to breakout sessions, addressing important questions and issues of current interest. Appendix B contains a detailed record of these discussions prepared by the breakout groups. Some of the more important highlights of these discussions are summarized below.

Question 1: In prioritizing technology development for missions, how should the relative values of the missions be assessed and quantified?

- **Should mission (= flight project) value be assessed at all?** *Value is always assigned: current processes do this in a non-traceable, non-auditable way. It has to be done, so that we can improve on today's process.* To do this, focus on functional objectives. The tool should allow for externally prescribed inputs about mission value.

  There will always be a difference between valuation theory and results versus a final assessment by the decision-maker. In making a final assessment, the decision-maker can augment the evaluation results with other factors external to the analysis. Identifying the decision analysis process as a tool for mission and technology portfolio selection reduces political sensitivity about the relative position in the launch queue.

- **Who should do it? Can it be done?** There is the problem of different stakeholders. Possible approaches are: (1) *Code B assesses relative value of missions* (they allocate resources to Enterprises). An example may be to consider the 18 theme areas and 3 mission areas, and given them each a high, medium, or low ranking; (2) Enterprises: *Code B apportions resources as a block to Enterprises, Enterprises prioritize missions,* with inputs from Science Groups and Project Managers; and (3) *Executive Council, Joint Strategic Assessment Committee performs the prioritization.*

- **How should it be done?** *There were many alternative suggestions offered.* Stakeholders can assess mission values in a process not unlike that used to rank departments at various academic institutions. Project managers can be surveyed to provide input to this process. Another option is to count the strategic goals within the NASA Strategic Plan that are satisfied, and use this as a factor in assessing mission value. In another option, mission cost can be used as a surrogate for value, and relative prioritization can be expressed through budget deltas by theme from year to year. Yet another option is to assign value on the basis of classifying missions into those that enable entirely new scientific discoveries, and those that enhance scientific knowledge about phenomena that have been previously discovered. *The NASA Strategic Plan should identify the "owner" of the prioritization process.*

Question 2: There are many architectural options to enable a mission, but at the early formulation stage, how might we best select among them, and perform a functional decomposition to determine quantified capability requirements?

- **It is possible to obtain mission capability requirements for missions that are at the early formulation stage.** *In many cases, particularly where there may be a vast spectrum of previous missions from which to draw data, requirements for new undefined missions can often be obtained by projected evolution.* One can assume an evolution from the technological state of the art (technology push) and iterate between what the technology might be able to achieve, and the corresponding new mission requirements that can be satisfied. *A functional decomposition is derived from mapping mission capability requirements to technology performance metrics. The functional decompositions from each new advanced concept study might be stored in a NASA database.* Capability requirements for missions can be obtained to whatever level of detail may be available. Mapping relevant technologies to capability requirements can identify technology gaps, and these gaps can be used to derive performance metrics for technologies. The fulfillment of requirements can be evaluated by modeling and simulation or by analyzing the degree to which relevant figures of merit are satisfied. A relative value to various figures of merit may be assigned by parametric weighting of mission values and by conducting iterative sensitivity analysis. *Don't over-weigh optimizations but consider the level of precision; reserve some fraction for visionaries and spontaneous discoveries.* Consider approaches from other sectors (government, non-NASA, public, etc.).

- **There are advantages and disadvantages of establishing requirements.** "Requirements" are not ironclad, but have to be adaptive and negotiable. *Requirements have to be coupled* *with affordability and serve as a basis for negotiation among mission and system designers and the related technology developers. Requirements should ideally be expressed quantitatively.* Requirements are different from specifications. Quantification of requirements can bring problems, but can also allow one to know when one is done.

- **Defining mission concepts involves working in a very large trade space.** How do you search it? *Search trade space hierarchically, keeping the number of options low at each level. Delay decisions on final designs*: NASA tends to dive into a specific point design too early. A more extensive assessment of the trade space, keeping uncertainties and options open, allows a broader, more valuable set of technologies to be developed. On the other hand, there are huge costs associated with keeping options open.

Question 3: How do we systematically acquire credible information, such as cost and performance estimates about technology development, which might seek to satisfy capability requirements.

- **Strive to make the data models and assumptions traceable and transparent.** One of the key features in achieving data quality is to undertake an *independent review of the data, by a team external to the data generation process.* Workshops can be used to enhance credibility of the data collected.

- **Strive to obtain statistically significant samples in the data set.** *For high-risk or non-legacy technologies, the data should include estimates of uncertainty.* In matching capability requirements to technology tasks, the data estimates should *include as many valid viewpoints as possible to reduce the influence of inevitable uncertainties in individual data values.* The larger the number of viewpoints represented in the data, the greater the robustness of the conclusions that can be drawn from it.

- **Strive to implement a data collection process that is sustainable.** *The POP process is a good programmatic vehicle to request data generation and to implement incentives for proper response to such requests.* Iterations should be easier than the first bounce. The process for data collection should be continually reevaluated. Quarterly reviews of the information should be conducted with researchers, technology developers, and mission experts.

Question 4: What is the best methodology to perform technical risk assessment, management and mitigation? Is the representation needed for risk management technologies fundamentally different to that needed for discipline-product technologies, such as sensing, manipulation, and thermal control?

- *The representation and assessment of risk estimation and software technologies should be made consistent with those of the discipline product technologies (e.g., sensing, manipulation, mobility, etc.), in order to allow comparative analysis.* It is important to have researchers state what kind of performance metrics they hope to impact; missions should provide goals.

- *Risk manifests itself in terms of cost and schedule (as well as performance) and these impacts must be assessed in an integrated fashion.* Software and hardware might be combined at a capability level as opposed to a discipline level.

- State of the art can be characterized, but the whole 'ecosystem' of software should be looked at, not just an algorithm, for instance.

Question 5: What are the criteria management will use to judge the results of a structured technology prioritization analysis?

The analysis and its results have to support and defend the eventual decision to stakeholders such as OMB, GAO, and others. The analysis should be traceable, transparent, understandable, and presented in a concise way. The analysis should document explicitly the important issues, assumptions and approximations, and should identify major uncertainties and other problem areas. The analysis has to address what the decision-maker cares about, including metrics and alternative options. *The analysis should have the objective of providing decision-support tools and should provide options instead of point-solutions.* The results should be cast as trades between risk and cost or between benefit and cost. The analysis should result in preferred recommendations and justifications spanning the decision space, not just negatives and consequences. The analysis products should be digestible and tuned for interpretation at the appropriate level.

4. Recommendations for Future Activities

The meeting concluded with a discussion of potential future activities, which included:

- *Formulate and conduct a pilot application project, in partnership with a selected theme and program management representing mission, technology, and financial planning organizations. Increase the fidelity of the data and analysis, if necessary by initially narrowing the scope of mission and technology options*

- *Report on workshop results to the NASA multi-center System Analysis Consortia*

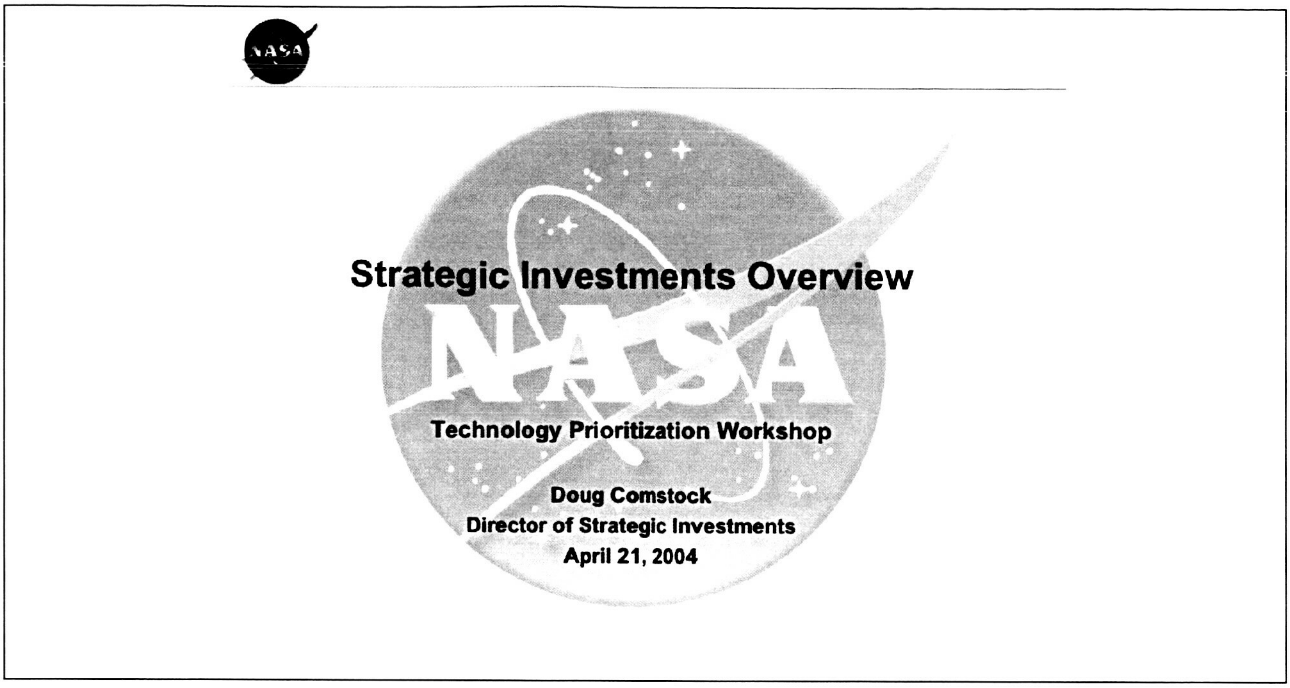
- *Provide input to POP guidance next February (e.g. types of inputs required)*

- Provide additional organized opportunities for further technical discussion and exchange on such topics as risk assessment and decision analysis methods (e.g., partial completion of tasks, handling of reserves, etc.)

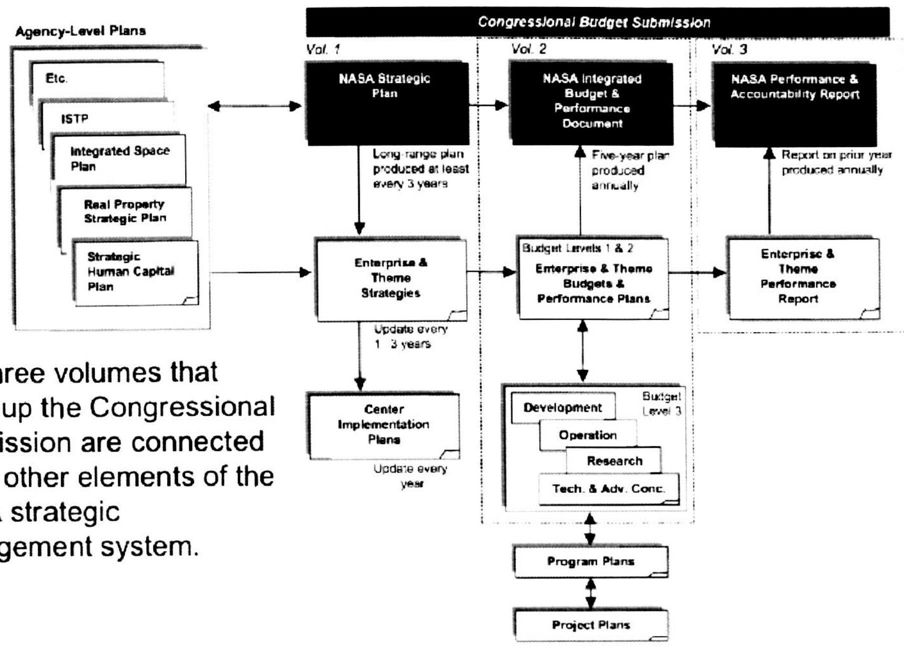
- Investigate potential concurrent applications of technology prioritization methods to other government agencies (e.g., Homeland Security). Address prototypical questions of potential benefit to others.

Appendix A: Slides of Invited Talks

- **Doug Comstock**



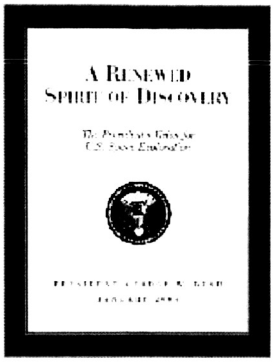
NASA Strategic Management Documents



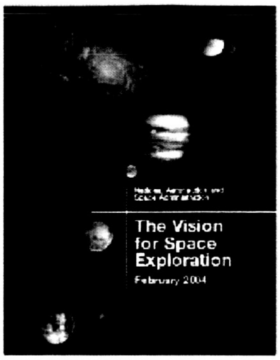
The three volumes that make up the Congressional Submission are connected to the other elements of the NASA strategic management system.

The Congressional Submission – FY 2004

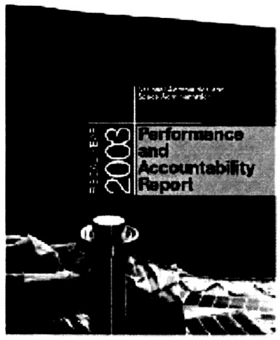
Key Documents – FY 2005 Budget Request



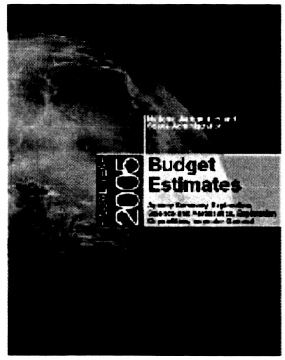
President's Policy Directive



The Vision for Space Exploration



FY 2003 Performance and Accountability Report



Congressional Budget Justification

New Building Block Investments

Overcoming Barriers that Constrain Research and Discovery

Technological Barriers

Power: Providing ample power for propulsion and science

Transportation: Providing safe, reliable, and economical transportation to and from space, and throughout the solar system

Human Capabilities: Understanding and overcoming human limitations in space

Communications: Providing efficient data transfer across the solar system

Building Blocks

Ongoing Efforts

Nuclear Systems Initiative
- Greatly increased power for space science and exploration

Integrated Space Transportation Plan
- Orbital Space Plane
- Extended Shuttle operations
- Next-generation launch systems

In-Space Propulsion Program
- Efficient solar system transportation

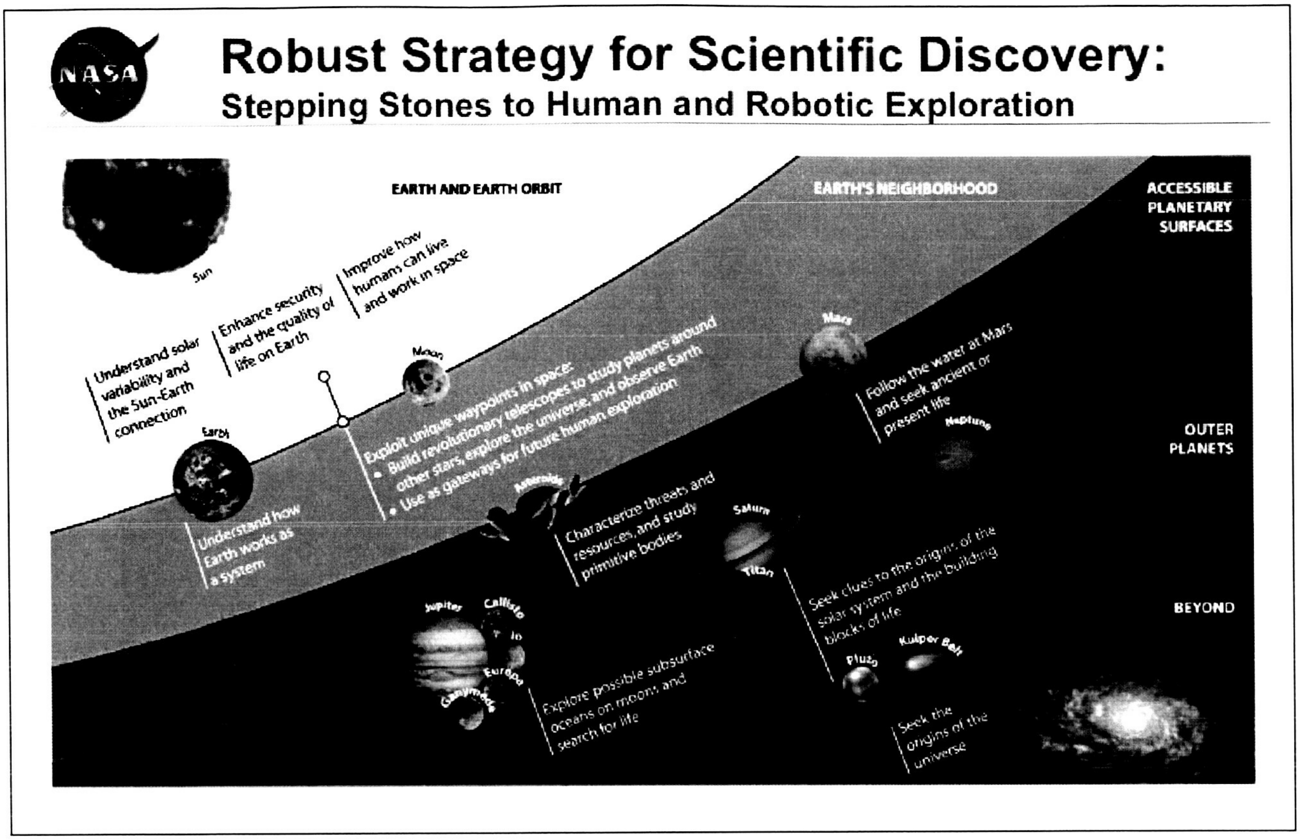
Space Station Restructuring
- Research priority focused
- Management reforms
- Sound financial base

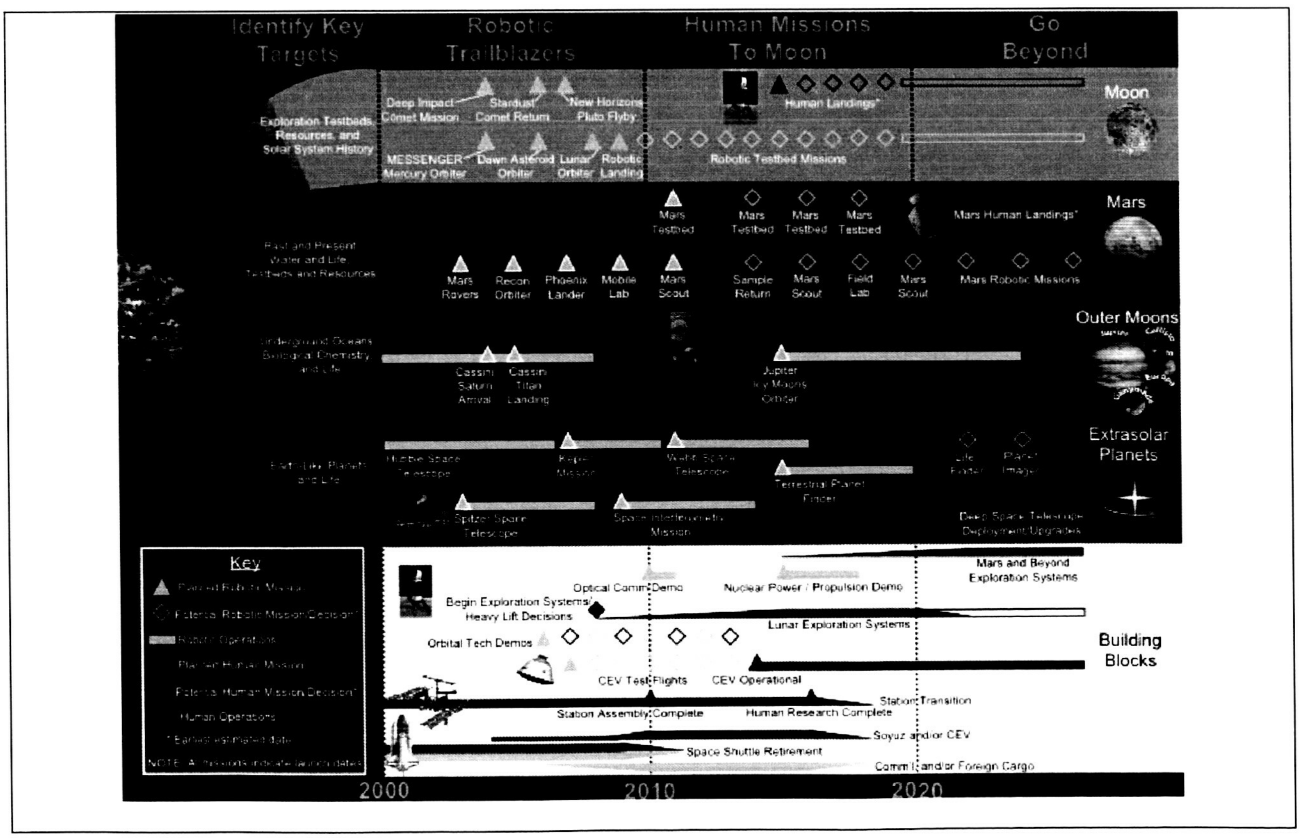
New Efforts

Project Prometheus
- Nuclear Power and propulsion for revolutionary science and orbital capabilities
- First mission to Jupiter's moons

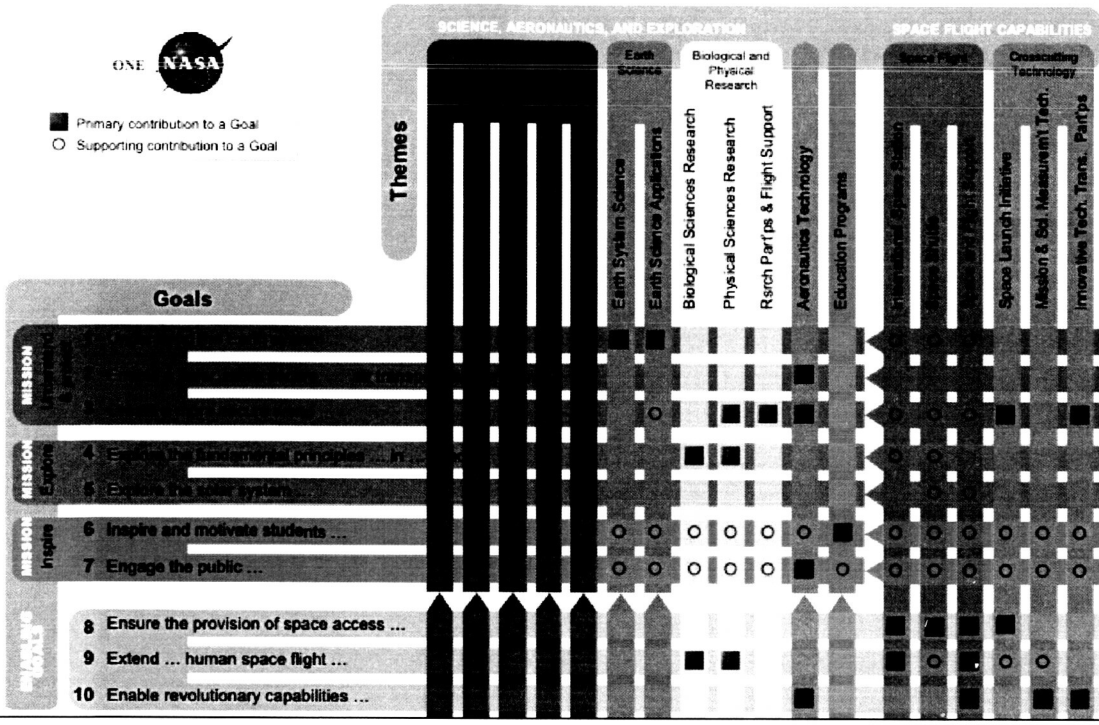
Human Research Initiative
- Accelerate research to expand capabilities
- Enable 100+ day missions beyond low-Earth orbit

Optical Communications
- Vastly improved communication transform science capability
- First demonstration from Mars


Robust Strategy for Scientific Discovery:
Stepping Stones to Human and Robotic Exploration
NASA
EARTH AND EARTH ORBIT
EARTH'S NEIGHBORHOOD
ACCESSIBLE PLANETARY SURFACES
OUTER PLANETS
BEYOND
Sun
Earth
Moon
Mars
Neptune
Saturn
Titan
Jupiter
Callisto
Io
Europa
Ganymede
Asteroids
Pluto
Kuiper Belt
Understand solar variability and the Sun-Earth connection
Enhance security and the quality of life on Earth
Improve how humans can live and work in space
Understand how Earth works as a system
Exploit unique waypoints in space:
• Build revolutionary telescopes to study planets around other stars, explore the universe, and observe Earth
• Use as gateways for future human exploration
Characterize threats and resources, and study primitive bodies
Follow the water at Mars and seek ancient or present life
Explore possible subsurface oceans on moons and search for life
Seek clues to the origins of the solar system and the building blocks of life
Seek the origins of the universe


Identify Key Targets
Robotic Trailblazers
Human Missions To Moon
Go Beyond
Exploration Testbeds, Resources, and Solar System History
Deep Impact Comet Mission
Stardust Comet Return
New Horizons Pluto Flyby
MESSENGER Mercury Orbiter
Dawn Asteroid Orbiter
Lunar Orbiter
Robotic Landing
Human Landings*
Robotic Testbed Missions
Moon
Mars Testbed
Mars Human Landings*
Mars
Mars Rovers
Recon Orbiter
Phoenix Lander
Mobile Lab
Mars Scout
Sample Return
Field Lab
Mars Robotic Missions
Outer Moons
Cassini Saturn Arrival
Cassini Titan Landing
Jupiter Icy Moons Orbiter
Extrasolar Planets
Spitzer Space Telescope
Terrestrial Planet Finder
Key
Building Blocks
Mars and Beyond Exploration Systems
Optical Comm Demo
Nuclear Power / Propulsion Demo
Begin Exploration Systems Heavy Lift Decisions
Lunar Exploration Systems
Orbital Tech Demos
CEV Test Flights
CEV Operational
Station Transition
Station Assembly Complete
Human Research Complete
Soyuz and/or CEV
Space Shuttle Retirement
Comm'l and/or Foreign Cargo
2000
2010
2020

The Strategic Organization



Performance: Accountability

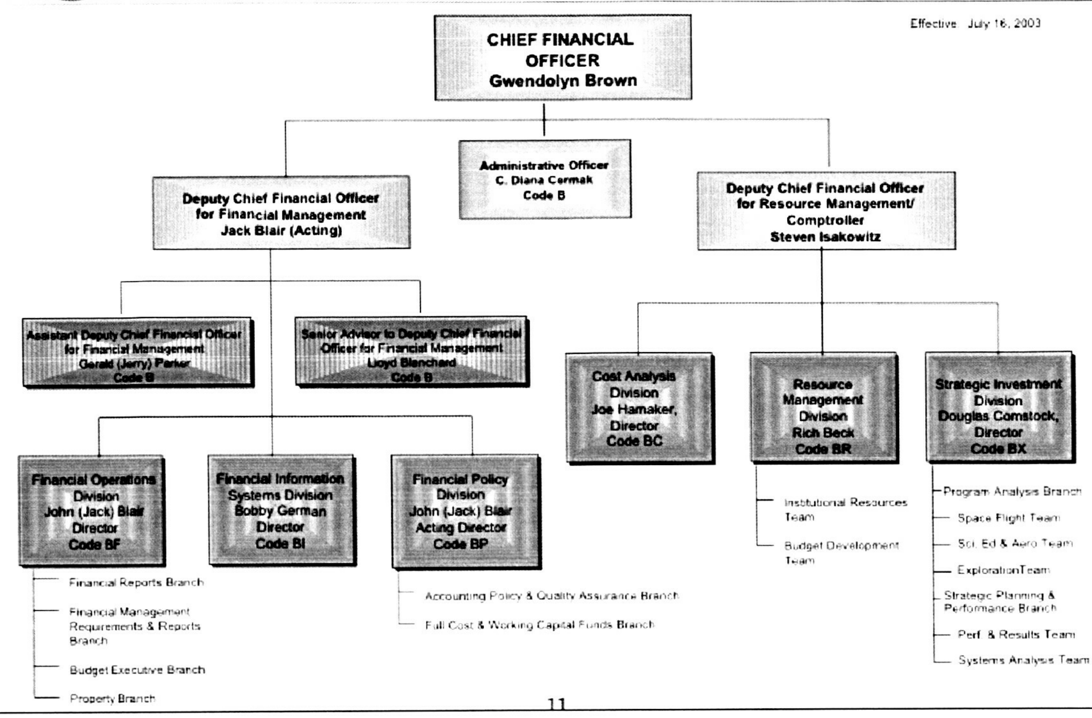
Strategic Plan

Vision	All performance must be tied to the NASA Vision
Mission	One NASA: Many Themes support each of 3 NASA Missions
Goal	7 Goals tied to the Mission + 3 enabling Goals
Objective	What is to be accomplished; owned by a single Theme.

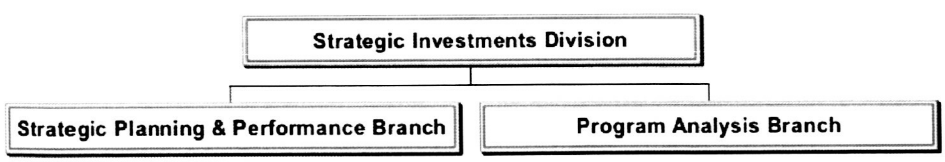
Performance Plan

Outcome	An important multi-year step on a Theme's roadmap.
Annual Performance Goal	Indicates annual progress towards achieving outcomes. Tied to a Theme's budget investment.

Office of the Chief Financial Officer (Code B)



Strategic Investments Division



Performance and Results Team
- Strategic Plan
- Integrated Planning
- Performance Measurement
- Performance Reporting
- Budget & Performance Integration
- Strategic Management

Systems Analysis Team
- Standards for Systems Analysis
- Analytical tool development
- Support to Space Architect
- Cross-Enterprise analysis

Space Flight Team
- Space Shuttle
- Space Station
- Space & Flight Support

Science, Education & Aero Team
- Space Science
- Earth Sciece
- Biological & Physical Research
- Education
- Aeronautics

Exploration Team
- Transportation
- Human and Robotic Technology

Code BX Products

Annual Budget Request – Integrated Budget and Performance Document (IBPD)

- Code BX led the design, development and integration of the IBPD
- Totally revamped Congressional justification – well received
- Page count less than half with more information than before
- Integrates budget with performance, setting government-wide benchmark

Performance and Accountability Report (PAR)

- Code BX leads the formulation, integration, production of the PAR
- Met aggressive OMB schedule
- On schedule for meeting even more aggressive OMB schedule this year

Strategic Plan

- Code BX led the formulation, integration and production of the plan
- High quality plan, seven months ahead of schedule

Integrated Planning

- Code BX developed and implemented the plan for integrated Agency planning in support of the Associate Deputy Administrator for Technical Programs
- Integrated set of planning documents being produced for the first time, including Enterprise Strategies and Center Implementation Plans
- A planning 'community' has been established with significantly improved communications
- Working with other Agencies to share best practices

Code BX Products

- **Budget Amendments and Supplemental Requests**
  - Code BX leads/supports strategy, drafting, integration and advocacy
  - FY 2003 Budget Amendment
    - Approved by OMB, adopted by appropriators
  - FY 2004 Supplemental Request
    - Approved by OMB and now appropriated
- **Performance Plans**
  - Pre-IBPD FY 2003 performance plan was re-mapped to new strategic framework for the Agency
  - FY 2004 performance plan revised to increase measurability of outcomes
- **Management Tool Development**
  - Code BX working with IFM Program and Chief Engineer to establish requirements and implementation plans for Erasmus

Systems Analysis

- The systems analysis community across the Agency is often called upon to assess investment strategies.
  - "How do we demonstrate alignment with the Agency Strategic Plan in a standard way?"
  - Wide range of analysis: ISTP, technology portfolios, cross Enterprise activities, spacecraft mission trades, etc....
- There are no "best practices" or common analysis standards to enable "apples to apples" comparisons of results.
  - Decision makers and analysts will both benefit from an open and transparent approach to performing and employing analysis products.
  - Have found that such standards are welcomed and encouraged.
- Code BX is seeking to catalyze a systems analysis 'community' among existing organizations dispersed across the Agency.
  - Budget process is a consumer of a great deal of Agency systems analysis products.
  - Currently engaged in dialog with systems analysis and systems engineering groups around the Agency on developing standards and a community.
  - Collecting inventory of tools, approaches, and environments from around the Centers.
  - Will conduct workshops and develop standards this year.
  - Goal is improved communications and strengthened capabilities, leading to better investment decisions.

15

Summary

Significant changes are underway

- **Integration among the vision and mission, strategic plan, budget, and performance planning and reporting**
  - Closer linkage of our budget estimates with our strategic plan, performance measures and institutional needs
  - Systems analysis efforts to improve linkage for better decisions
- **Integrated budget and performance information in a single document, linked to strategic plan objectives through new budget structure arranged in "themes"**
  - Ensures consistency among critical documents
- **Annual and long-term performance measures directly traceable through the strategic plan to the vision and mission**
  - Clear accountability for results through themes
- **Defined agency goals requiring multiple enterprises and themes, with interdependencies and shared accountabilities**
  - Reflects the One NASA philosophy

These changes will help NASA to achieve our Vision and Mission

- **Dr. Alan W. Wilhite**

Estimating the Risk of Technology Development

Dr. Alan W. Wilhite
Langley Distinguished Professor/Systems Architectures and Analysis
Georgia Institute of Technology/National Institute of Aerospace

256.683.2897

Center for Aerospace Systems Analysis (CASA)

When do you do risk analysis ?

Risk analysis and response planning must be done during the initial planning phase of the project. Ideally, risk analysis and response planning is done during the project proposal phase and revisited on a regular basis.

"70% of a project's cost at completion is committed by the time the first 5% of the project's budget is actually spent."

The Elements of Risk

Risk is composed of TWO elements:

1.) The UNCERTAINTY (expressed as a probability (Pf) of achieving a project performance objective

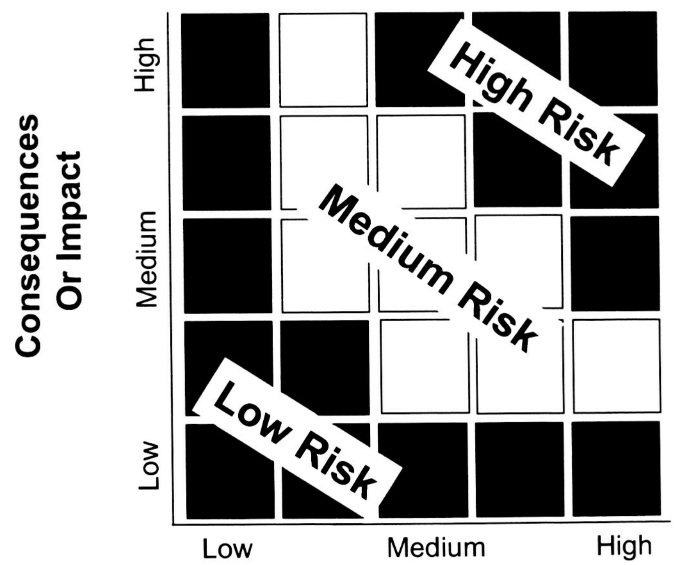
AND,

2.) The CONSEQUENCES (Cf) of a risk event

Risk= Pf x Cf

Caution is needed, of course in using this approach. It is necessary to be wary of multiplying 2 pieces of information together to produce a figure which may ,make an account's eyes light up but be of little practical value to a project manager.

Risk Assessment Matrix



Probability of Failure
(1 – Probability of Success)

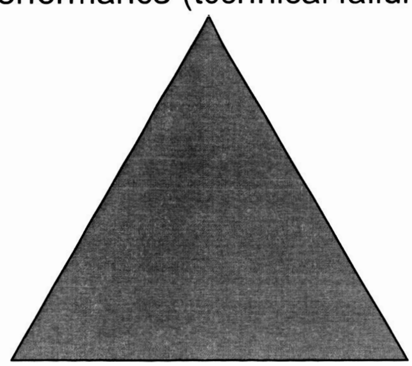
Characterization of Technology Risk

(utilization for system development)

- Probability of failure to:
  - Reach maturity for system integration (programmatic failure)
  - And meet Technical Performance Measures goals (technical failure)
- Impact on overall system performance of failing to meet TPM goals

Measures of Probability of Failure

- The Probability of Failure is measured by the three measures used for programs or projects - cost, schedule, and performance.



Measures of Programmatic Failure

- **Development difficulty**
  - **Technology Readiness Level Gap (Initial to TRL6)**
  - Research and Development Degree of Difficulty
  - TPM gap
- **Requirements, requirements flowdown, interface requirements, etc.**
- **Schedule**
  - Defined schedule showing maturity increasing/adequate analysis and testing
  - Critical Path
  - Adequate slack
  - High risk items, work around
  - Exit criteria for every milestone
- **Cost**
  - Defined cost for all milestones
  - Costs include NASA and contractor
- **Management and technical team (experienced)**

NASA's TECHNOLOGY READINESS LEVEL (Scale for Tracking Risk Reduction)

9 - Actual system "flight proven" on operational flight

8 - Actual system completed and "flight qualified" through test and demonstration

7 - System prototype demonstrated in flight

6 - System/Subsystem (configuration) model or prototype demonstrated/validation in a relevant environment

5 - Component (or breadboard) verification in a relevant environment

4 - Component and/or breadboard test in a laboratory environment

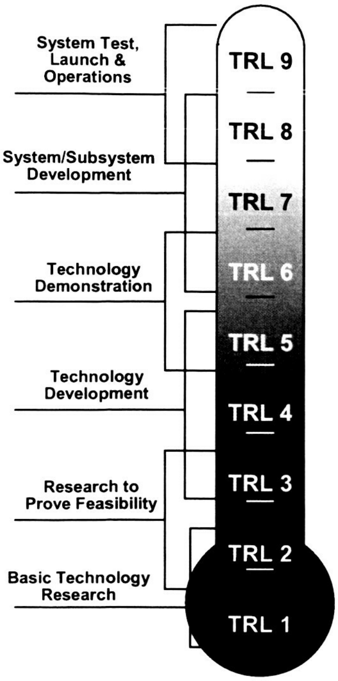
3 - Analytical & experimental critical function, or characteristic proof-of-concept, or completed design

2 - Technology concept and/or application formulated (candidate selected)

1 - Basic principles observed and reported

Technology Readiness Level of 6 is usually required for Development

NASA's Technology Readiness Levels (Software)



TRL 9: Actual system "mission proven" through successful mission operations *Thoroughly debugged software readily repeatable. Fully integrated with operational hardware/software systems. All documentation completed. Successful operational experience. Sustaining software engineering support in place. Actual system fully demonstrated.*

TRL 8: Actual system completed and "mission qualified" through test and demonstration in an operational environment *Thoroughly debugged software. Fully integrated with operational hardware and software systems. Most user documentation, training documentation, and maintenance documentation completed. All functionality tested in simulated and operational scenarios. V&V completed.*

TRL 7: Initial system demonstration in high-fidelity environment (parallel or shadow mode operation) *Most functionality available for demonstration and test. Well integrated with operational hardware/software systems. Most software bugs removed. Limited documentation available.*

TRL 6: System/subsystem prototype validated in a relevant end-to-end environment *Prototype implementations on full scale realistic problems. Partially integrated with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.*

TRL 5: Module and/or subsystem qualified in relevant environment *Prototype implementations conform to target environment / interfaces. Experiments with realistic problems. Simulated interfaces to existing systems.*

TRL 4: Module and/or subsystem qualified in laboratory environment *Standalone prototype implementations. Experiments with full scale problems or data sets.*

TRL 3: Analytical and experimental critical function and/or characteristic proof-of-concept *Limited functionality implementations. Experiments with small representative data sets. Scientific feasibility fully demonstrated.*

TRL 2: Technology concept and/or application formulated *Basic principles coded. Experiments with synthetic data. Mostly applied research.*

TRL 1: Basic principles observed and reported *Basic properties of algorithms, representations & concepts. Mathematical formulations. Mix of basic and applied research.*

Measures of Programmatic Failure

- **Development difficulty**
  - Technology Readiness Level Gap (Initial to TRL6)
  - **Research and Development Degree of Difficulty**
  - TPM gap
- **Requirements, requirements flowdown, interface requirements, etc.**
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  - Exit criteria for every milestone
- **Cost**
  - Defined cost for all milestones
  - Costs include NASA and contractor
- **Management and technical team (experienced)**

Research and Development Degree of Difficulty (RD^3)

R&D^3

I A very low degree of difficulty is anticipated in achieving research and development objectives for this technology.

Probability of Success in "Normal" R&D Effort > 99%

II A moderate degree of difficulty should be anticipated in achieving R&D objectives for this technology.

Probability of Success in "Normal" R&D Effort > 90%

III A high degree of difficulty anticipated in achieving R&D objectives for this technology.

Probability of Success in "Normal" R&D Effort > 80%

IV A very high degree of difficulty anticipated in achieving R&D objectives for this technology.

Probability of Success in "Normal" R&D Effort > 50%

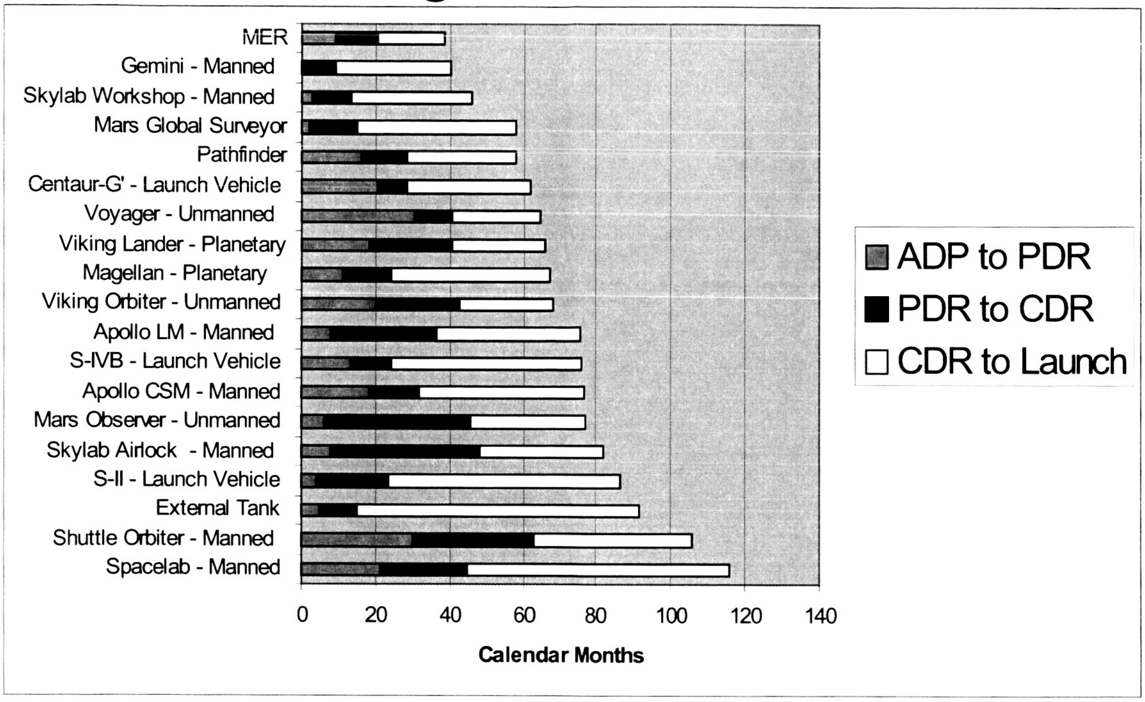
V The degree of difficulty anticipated in achieving R&D objectives for this technology is so high that a fundamental breakthrough is required.

Probability of Success in "Normal" R&D Effort > 20%

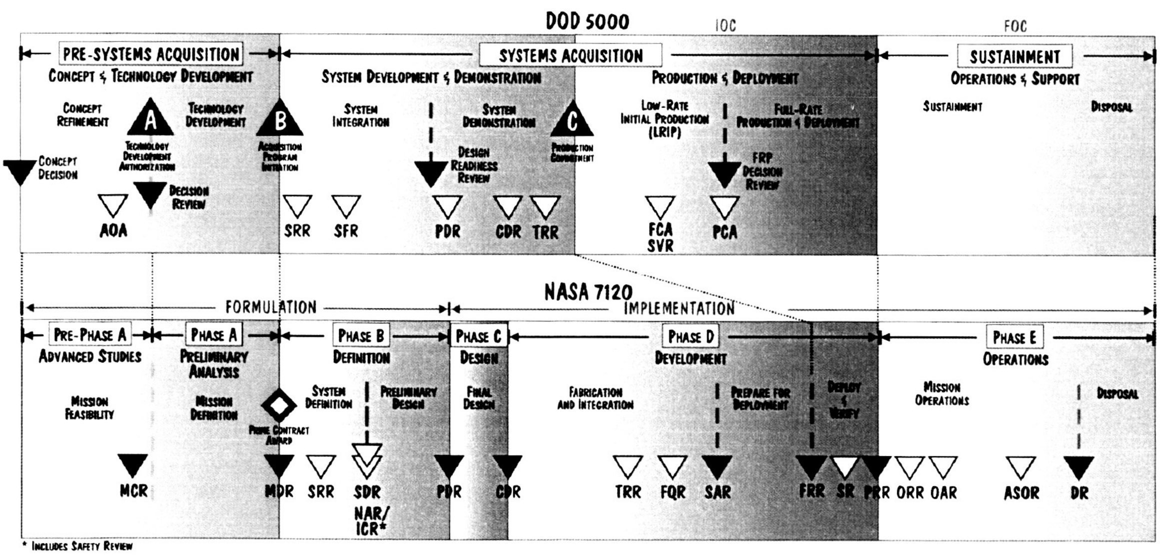
Measures of Programmatic Failure

- **Development difficulty**
  - Technology Readiness Level Gap (Initial to TRL6)
  - Research and Development Degree of Difficulty
  - TPM gap
- **Requirements, requirements flowdown, interface requirements, etc.**
- **Schedule**
  - Defined schedule showing maturity increasing/adequate analysis and testing
  - Critical Path
  - Adequate slack
  - High risk items, work around
  - Exit criteria for every milestone
- **Cost**
  - Defined cost for all milestones
  - Costs include NASA and contractor
- **Management and technical team (experienced)**

NASA Program Schedule Actuals



Life Cycle Milestones



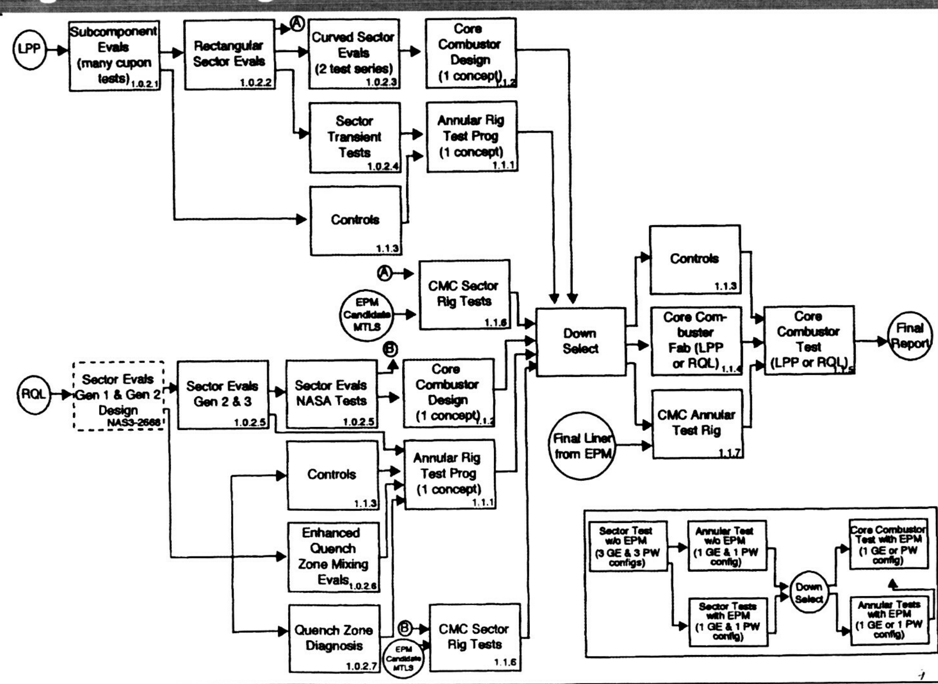
AOA	ANALYSIS OF ALTERNATIVES	IOC	INITIAL OPERATIONAL CAPABILITY	SAR	SYSTEM ACCEPTANCE REVIEW
ASOR	ANNUAL SYSTEMS OPERATIONS REVIEW	MCR	MISSION CONCEPT REVIEW	SDR	SYSTEM DESIGN REVIEW
CDR	CRITICAL DESIGN REVIEW	MDR	MISSION DESIGN REVIEW	SFR	SYSTEM FUNCTIONAL REVIEW
DR	DECOMMISSIONING REVIEW	NAR	NON-ADVOCATE REVIEW	SR	SAFETY REVIEW
FCA	FUNCTIONAL CONFIGURATION AUDIT	OAR	OPERATIONAL ACCEPTANCE REVIEW	SRR	SYSTEM REQUIREMENTS REVIEW
FOC	FULL OPERATIONAL CAPABILITY	ORR	OPERATIONAL REQUIREMENTS REVIEW	SVR	SYSTEM VERIFICATION REVIEW
FQR	FORMAL QUALIFICATION REVIEW	PCA	PHYSICAL CONFIGURAION AUDIT	TRR	TEST READINESS REVIEW
FRR	FLIGHT READINESS REVIEW	PDR	PRELIMINARY DESIGN REVIEW		
ICE	INDEPENDENT COST REVIEW	PRR	PRODUCTION READINESS REVIEW		

Measures of Programmatic Failure

- **Development difficulty**
  - Technology Readiness Level Gap (Initial to TRL6)
  - Research and Development Degree of Difficulty
  - TPM gap
- **Requirements, requirements flowdown, interface requirements, etc.**
- **Schedule**
  - Defined schedule showing maturity increasing/adequate analysis and testing
  - Critical Path
  - Adequate slack
  - High risk items, work around
  - Exit criteria for every milestone
- **Cost**
  - Defined cost for all milestones
  - Basis of costs (FTEs, facilities, hardware, etc.)
- **Management and technical team (experienced)**

Low NOx Combustor

1-Pager Work Logic



Low NOx Combustor

1-Pager Work Logic Description

1.0.2.1 LPP Subcomponent Evals

- Many cupons tested
- Feeds sector test prog
- Continues during sector test prog
- Used for sector design refinement
- Essentially complete by FY95
- GE/NASA

1.0.2.2 CPP Rectangular Sector Evals

- Combines components for integrated evals
- 3 configurations tested
- Primary feed to annular test program design
- Secondary feed to core combustor test program design
- Uses non EPM materials
- GE/NASA

1.0.2.3 LPP Curved Sector Evaluation

- Added shape fidelity over rectangular evals
- Two test series of single configuration
- Feed core combustor test program design
- GE

1.0.2.4 LPP Sector Transient Test

- Evaluation of rectangular sector configurations
- Primary feed to annular test program design

1.0.2.5 RQL Sector Combustion Rig

- 3 generation tests of progressively complex design
- Gen I tests and Gen II design from separate contract
- P&W test feed annular rig test program design
- NASA test feed core combustor test program
- Uses non EPM materials
- P&W/NASA

1.0.2.6 Inhanced Quench Zone Mixing

- Applies to RQL configuration
- P&W/NASA participation
- Feeds annular rig test program design

1.0.2.7 Quench Zone Diagonistics

- Same as 1.0.2.6
- P&W participation

1.0.2.8 Analytical Code Dev

- Feed products to test programs as developed
- NASA

1.0.2.9 Emission Minimizing Completion Controls

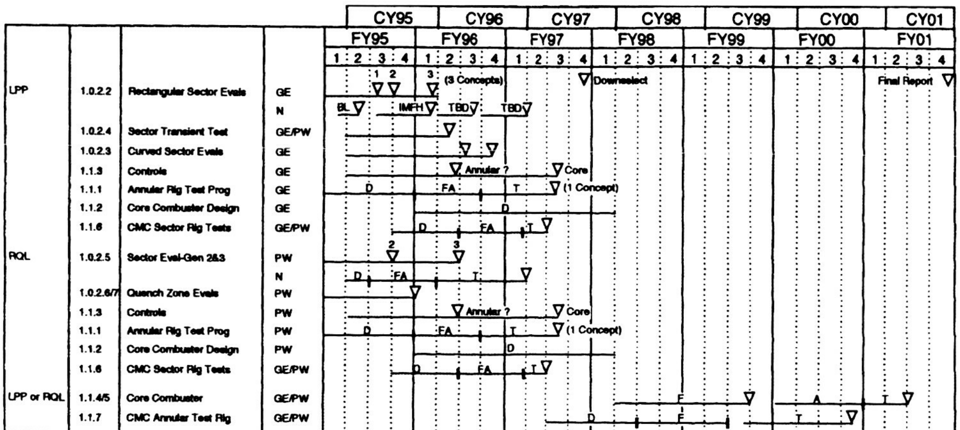
- Feed products to test programs as developed
- NASA

1.0.2.10 Grants

- Feed products to test programs as developed
- Universities

Low NOx Combustor

1-Pager Work Schedule



		FY95	FY96	FY97
Models	Designed	11	2	2
Models	Fabed	7	7	
Tests	Completed	7	12	8
Analysis	Completed	4	13	10
Simulations	Completed	7	4	1

		FY95	FY96	FY97	FY98	FY99	FY00	FY01	Total
1.0.2	Combuster Supporting Tech Tests	9.4	6.0	2.0	1.2	1.1	.1		19.8
1.1.1	Annular Rig Test Prog	7.1	9.5	1.9					18.5
1.1.2	Core Combuster Design	.4	4.5	5.6	1.8	.9	.7	.5	14.5
1.1.3	Controls	1.4	1.1	.9	.7	1.0	.9	.3	6.3
1.1.4	Core Combuster Fab				.6	2.6	.5		3.8
1.1.5	Core Combuster Assy & Test				.6	1.2	7.2	4.5	13.5
1.1.6	CMC Sector Rig Tests	.3	.9	1.7					3.0
1.1.7	CMC Annular Rig Tests		.3	.9	.7	2.8	1.5	.1	6.3
	Total	18.6	22.3	13.0	5.5	9.6	10.9	5.4	85.7

Low NOx Combustor

1-Pager Cost Distribution

			94	95	96	97	98	99	00	01	02	Total
1.0.2	Combustor Supt Tech	P	.3	3.6	.4	-	-	-	-			4.2
		G	-	2.5	2.5	-	-	-	-			5.0
		N	-	3.3	3.1	2.0	1.2	1.1	.1			10.8
		T	.3	9.4	6.0	2.0	1.2	1.1	.1			20.1
1.1.1	Annular Combustor Rig	P	.4	2.9	2.6	.4	-	-	-			6.3
		G	.2	4.3	6.8	1.5	-	-	-			12.9
		N	-	-	-	-	-	-	-			-
		T	.6	7.1	9.5	1.9	-	-	-			19.2
1.1.2	Core Combustor Design	P	-	.2	3.0	3.6	1.1	.8	.6	.4	-	9.9
		G	-	.2	1.5	2.0	.7	.1	.1	.2	-	4.6
		N	-	-	-	-	-	-	-	-	-	-
		T	-	.4	4.5	5.6	1.8	.9	.7	.5	-	14.5
1.1.3	Low NOX Combustor Controls Dev	P	-	.4	.5	.6	.4	1.0	.9	.3	-	4.0
		G	.1	.8	.4	.1	.2	-	-	-	-	1.6
		N	-	.2	.2	.2	.1	-	-	-	-	.7
		T	.1	1.4	1.1	.9	.7	1.0	.9	.3	-	6.3
1.1.4	Core Engine Combustor Fab	P	-	-	-	-	.5	1.0	.5	-	-	2.1
		G	-	-	-	-	.1	1.6	-	-	-	1.7
		N	-	-	-	-	-	-	-	-	-	-
		T	-	-	-	-	.6	2.6	.5	-	-	3.8
1.1.5	Core Engine Test	P	-	-	-	-	.5	.1	3.4	3.3	-	7.3
		G	-	-	-	-	.1	.2	.3	.1	-	.6
		N	-	-	-	-	-	.9	3.5	1.0	.1	5.5
		T	-	-	-	-	.6	1.2	7.2	4.5	.1	13.5
1.1.6	CMC Combustor Sector Rig	P	-	.3	.7	1.6	-	-	-	-	-	2.7
		G	-	-	.2	.1	-	-	-	-	-	.3
		N	-	-	-	-	-	-	-	-	-	-
		T	-	.3	.9	1.7	-	-	-	-	-	3.0
1.1.7	CMC Annular Combustor Rig Test	P	-	-	.1	.1	-	.2	.2	-	-	.7
		G	-	-	.2	.8	.7	2.6	1.3	.1	-	5.6
		N	-	-	-	-	-	-	-	-	-	-
		T	-	-	.3	.9	.7	2.8	1.5	.1	-	6.3
	Total	P	.7	7.4	7.3	6.3	2.5	3.1	5.6	4.0	-	36.9
		G	.3	7.8	11.6	4.5	1.8	4.5	1.7	.4	-	32.6
		N	-	3.52	3.5	2.2	1.3	2.0	3.6	1.0	.1	17.2
		T	1.0	18.6	22.3	13.0	5.6	9.6	10.9	5.4	.1	86.7

Minimal Technology Data Sheet

Contact Information			
Person Providing Data: Phone: Email Address:		Secondary Contact: Phone: Email Address:	

Capability:	
Capability Impact:	(see chart 1-10)
Impact Rationale:	

Technology Project Name:	
Description	Objectives,Scope, State of the Art and Improvements to SOA (Gap assessment), Heritage of Technology (evolution or revolution path)

Technology Maturity	
Current TRL (1-6)	(List/Describe Characteristics of Technology or Your Rationale for Qualifying it at the TRL noted.)
Time to mature to TRL=6, yrs	(use technology development schedule to show TRL progression)
Total cost to obtain TRL=6	(full cost including workforce, contracts, hardware, infra-structure, test facilities use and/or improvements, etc
Research Degree of Difficulty (1-5)	(List/Describe Characteristics of Technology or Your Rationale for Qualifying it at the RD^3 noted.)

Dependence on other technologies to meet capability expectations			
Technologies	Developers	Funded or Unfunded	

Technical Performance Measures	State of Art Value	Projected Value	Probability
(e.g. weight, power, etc.) and Units		Value at end of development program.	Probability of meeting performance by technology development date.

Technology Development Schedule			
Year	Milestone	TRL	Cost

Impact

Cost and Credibility

Difficulty

Meets architecture ATP schedule

Assessing Technology Risk Using AHP (Analytical Hierarchical Process)

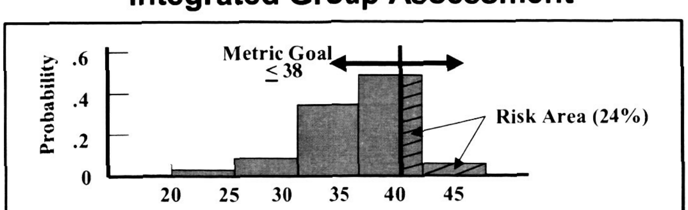
- The AHP is based on the hierarchical decomposition of the prioritization or forecasting criteria down to the level at which the decision or forecast alternatives can be pair-wise compared for relative strength against the criteria.
- The pair-wise comparisons are made by the participating experts and translated onto a numerical ratio scale.
- The AHP mathematical model then uses the input pair-wise comparisons data to compute priorities or forecast distributions as appropriate.

Analytical Hierarchical Process

Individual Assessment

Metric Interval	Most Likely	Relative Likelihood	
20 to 25 Units	○	5%	As likely as 35 to 40
25 to 30	○	25%	As likely as 35 to 40
30 to 35	○	75%	As likely as 35 to 40
35 to 40	●	100%	Most likely interval
45 to 50	○	10%	As likely as 35 to 40

Integrated Group Assessment



Technology Risk Assessment – Phase 3
Summary Of Airframe Risk Assessments

TA	TECHNOLOGY PROJECT	COST	SCHED	TECH
2	STRUCTURAL HEALTH MONITORING – NORTHROP GRUMMAN			
2	METALLIC CRYOTANK - BOEING			
2	CERAMIC MATRIX HOT STRUCTURES - MRD			
2	DURABLE ACREAGE CERAMIC TPS - BOEING			
2	DURABLE ACREAGE METALLIC TPS - OCEANEERING			
2	INTEGRATED AERO-THERMAL & STRUCTURAL THERMAL ANALYSIS - NASA			
2	STRUCTURAL & MATERIALS/TANK/TPS INTEGRATION - NASA			
2	STAGE SEP & ASCENT AERO-THERMODYNAMICS - NASA		No Data	
2	MATERIALS & ADVANCED MANUFACTURING: PERMEABILITY RESISTANCE - NASA			
2	LIGHTWEIGHT INFORMED MICRO-METEOROID RESISTANT TPS - NASA			
2	ULTRA HIGH TEMPERATURE SHARP EDGE TPS - LMC			
2	CERAMIC MATRIX COMPOSITE – SOUTHERN RESEARCH			

Technology Risk Assessment – Phase 3
Structural Health Monitoring (Shm)

TA-2 Airframe **Northrop Grumman**

MAJOR RISKS

Cost – Cost of 8,000 sensors for full scale SHM could be very high, but is understood.

Schedule – Critical schedule issue is availability of Composite Cryo-tank for testing. SHM starting at TRL 4 in 2002. No development issues affecting schedule.

Technical

- Reliability – Integration of 8,000 sensors into one reliable SHM is a risk
- Testability - Availability of Full Scale Composite Cryo-tank for testing to achieve TRL 6

CONTINGENCY PLAN SUGGESTION

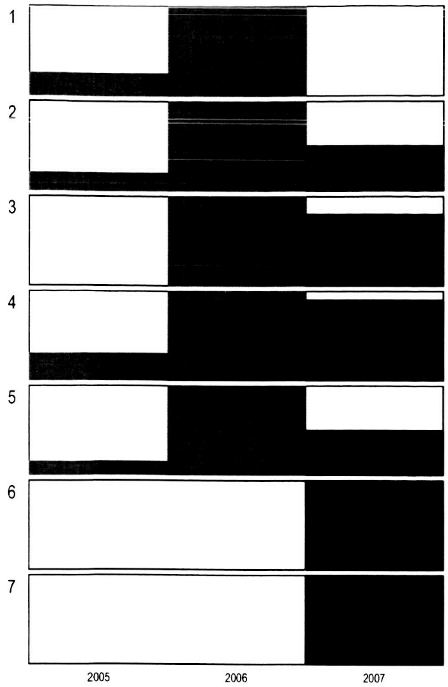
Use a subscale tank (18 to 20 ft diameter) to test SHM system

NOTE: Only new or updated comments are contained in this report. Refer to Phase 2 report for complete evaluation. No significant change in evaluation from Phase 2.

Show Stopper – Lack of Funding for Composite Cryo-tank for Testing

Structural Health Monitoring (Northrop Grumman)

Development Schedule



Goal: 2006 years

1: They should meet this goal based on present information.

2: NGC is starting with the SHM technology at a TRL level of 4 in 2002. They have plans to develop a structural health monitoring system and integrate it into a full-scale composite cryotank and complete test in 2005 timeframe. So the critical element of this is really having available a full-scale composite tank with this system integrated into it in 2005. That's the biggest concern because the funding level could get cut on the full-scale development of a composite tank that is in a separate technology development/funding under GEN2. So, there are no major issues with respect to developing the SHM system that NGC is proposing here. The issue is with respect to the availability of a full-scale composite cryotank in 2005/2006 which could face some serious funding issues given that GEN2 is probably not going to carry two tanks to TRL = 6 (metallic and composite).

5: If funding is maintained for the duration of the project, it is probable that it will come in on schedule.

7: There is a trade-off that should be made between the amount of health monitoring and robustness of design/analysis. As the vehicle is used for repeated flights some of the health monitoring sensors will become inoperable and others will produce data that has increasing errors. At some point a decision will need to be made relative to how many flights can be achieved before the health monitoring system itself must be inspected and checked out for adequate performance. The cost of maintaining the health monitoring system should be weighed against the cost of increasing the robustness of design thereby reducing the need for health monitoring. The reliability of the health monitoring system must consider the sensors, the data system and everything that is needed to transfer the data from the sensor to the data system. The lowest reliability part of the system may be the vehicle installed data transmission lines (quite a nest of lines) which must pass through the vehicle requiring compromises to be made in other disciplines of the vehicle design.

Technology Success Data

Technology Area: Airframe Technologies

Technology Development: Composite Cryotank (Northrop Grumman)

Probability of Success

Metric	Units	Weight	Low	High	Goal	EV	EV Dev.[1]	Success
Development Cost	Million $	0.50	85	235	115	137	-19%	12%
Development Schedule	years	0.50	2005	2007	2006	2006.9		50%
[2] **Weighted Programmatic Success:**		31%						
External Inspection Interval	missions	0.09	0	[illegible]	125	86	-31%	30%
Flight Mission Life	missions	0.13	0	50[illegible]	400	232	-42%	15%
Internal Inspection Interval	missions	0.09	[illegible]	120	60	42	-30%	26%
Leak Rate	SCIM	0.11	0	1200	200	399	-100%	28%
Operating Pressure	PSI	0.1[illegible]	10.0	50.0	30.0	30.7	2%	58%
Reliability	%	0.11	99.99900	100.00000	99.99950	99.99952	0%	52%
Weight/Volume	lb/cu ft	0.13	0.100	0.900	0.220	0.376	-71%	13%
[2] **Weighted Technical Success:**		31%						
[3] **Combined Weighted Success:**		31%						

EXAMPLE

Expected Value – Mean or average value of the estimated probability distribution. It is the value of the metric expected by the evaluators

Expected Value Deviation – Deviation of the EV from the goal, calculated as follows:

Absolute Value: $\dfrac{EV - Goal}{Goal}$

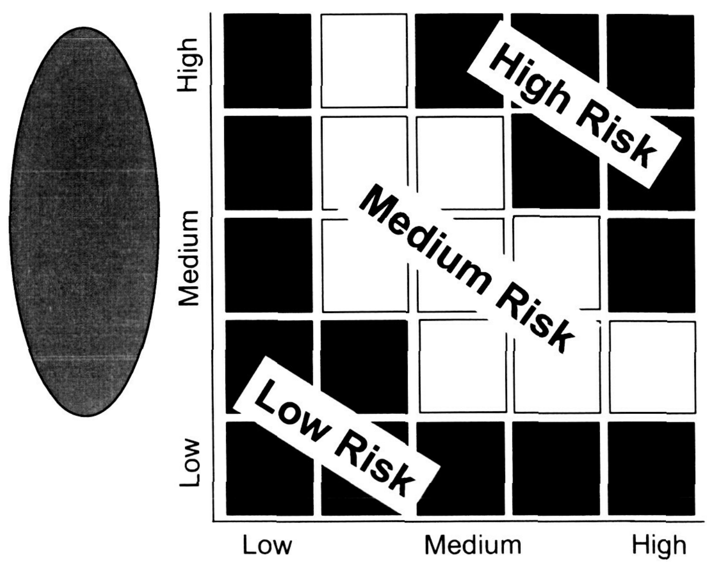
A minus sign in front of the calculated value indicates that the EV is worse than the goal.

Assumption: The Low to High range contains 100% of the possible values of the metric.

[1] EV Deviation show by how much the EV misses the goal. It is omitted for certain metrics.
[2] Weighted Success is the average success probability of the metrics.
[3] Combined Weighted Success is average of technical and programmatic Weighted Success.

0% - 20%   20%-50%   50%-100%

Risk Assessment Matrix



Probability of Failure
(1 – Probability of Success)

Launch Vehicle Propulsion Technology Selection

	Delta Isp, sec	Cost	Delta Isp/Cost	TRL	RD^3	Probability of Failure
Metalized Hydrogen	15	200	0.075	2	5	25
Advanced Materials	10	150	0.067	3	4	16
Chamber Pressure	8	100	0.080	3	4	16
Combustion Efficiency	6	90	0.067	4	3	9
Nozzle Efficiency	4	50	0.080	4	2	6
O/F Ratio	2	65	0.031	5	2	4

What is the your investment order?

Weighted Technology Impact Ranking

(Quantitative assessment after tech portfolio selected and funded)

Technologies / **Requirements**

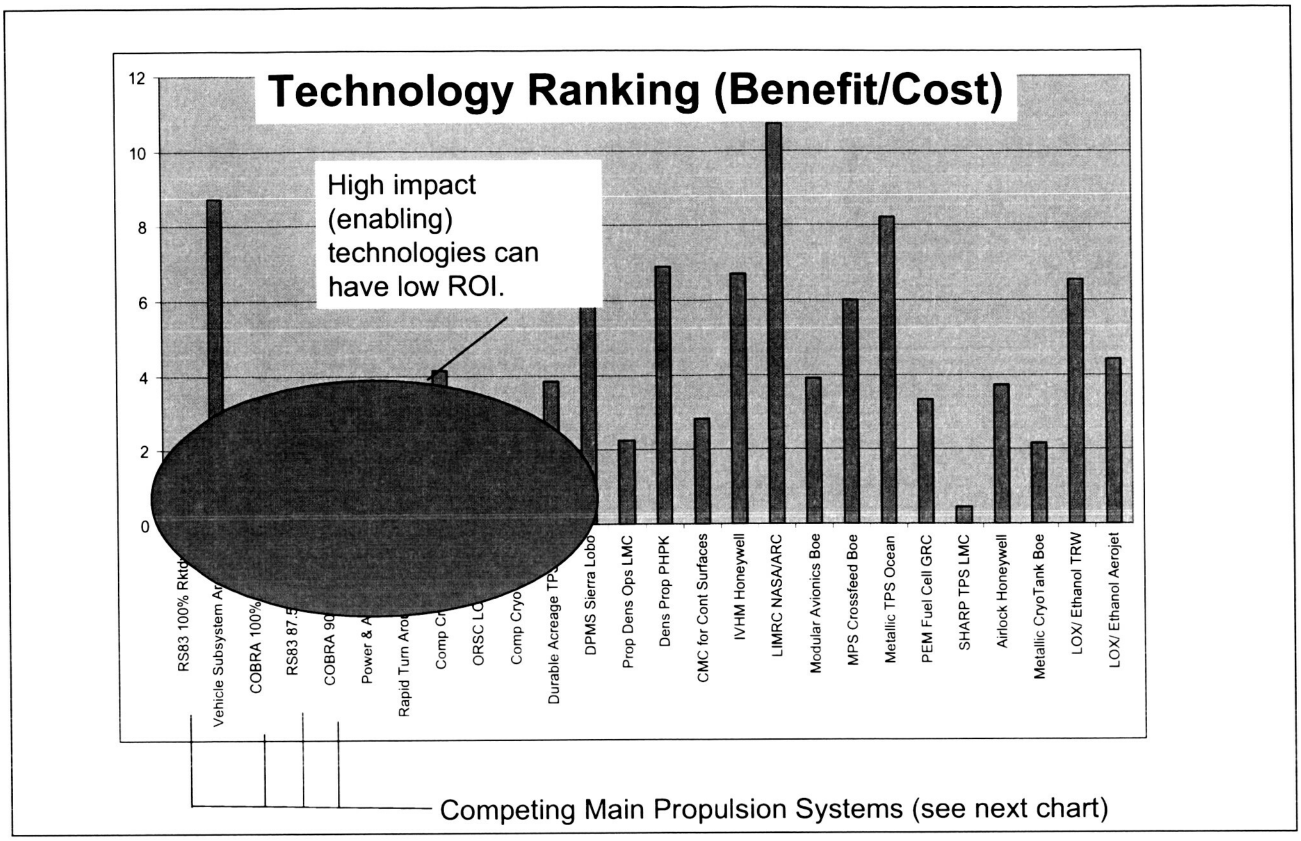
Requirements	RS83 100% Rktdyne	RS83 87.5% Rktdyne	COBRA 100% P&W/AJ	COBRA 90% P&W/AJ	ORSC LOX/RP 86%	Vehicle Subsystem Arch Boe	Power & Actuator LMC	Rapid Turn Around TPS Boe	reage TPS Boe	S Ocean	ywell	Tank Boe	Tank NG	a Lobo	Ops LMC	PHPK	nt Surfaces	LIMRC NASA/ARC	Modular Avionics Boe	MPS Crossfeed Boe	Airlock Honeywell	SHARP TPS LMC	Metallic CryoTank Boe	PEM Fuel Cell GRC	LOX/ Ethanol TRW	LOX/ Ethanol Aerojet
Safety (45%)	0.45	0.45	0.45	0.45	0.45	0.37	0.37	0.18	0.18	0.18	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.10	0.07	0.07
Loss of Crew								0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3			
Loss of Vehicle											0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3		
Loss of Mission								0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Loss of Payload						0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
$/lb (35%)	0.19	0.11	0.13	0.09	0.02	0.16	0.11	0.23	0.11	0.09	0.14	0.16	0.11	0.11	0.08	0.08	0.11	0.11	0.11	0.11	0.08	0.06	0.02	0.11	0.06	0.02
Launch Availabilit	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3
DDT&E - Average							0.3	0.3	0.3			0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3				0.3		
1st Unit Prod. Cos							0.3		0.3			0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3		0.3	0.3	
Annual Ops Cost (		0.3	0.3	0.3		0.3	0.3		0.3				0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3			0.3	0.3	
Facilities Cost (10		0.3	0.3			0.3	0.3		0.3				0.3	0.3			0.3	0.3	0.3	0.3	0.3	0.3		0.3		
Technical (20%)	0.20	0.03	0.06	0.00	0.00	0.14	0.06	0.10	0.10	0.00	0.06	0.20	0.17	0.14	0.14	0.14	0.10	0.06	0.06	0.06	0.03	0.06	0.06	0.06	0.00	0.00
Vehicle Empty Wei		0.3	0.3				0.3	0.3	0.3		0.3						0.3	0.3	0.3	0.3		0.3	0.3	0.3		
Vehicle GLOW			0.3				0.3				0.3							0.3	0.3	0.3	0.3	0.3	0.3	0.3		
Total Weighted Score	0.84	0.59	0.64	0.54	0.47	0.67	0.54	0.51	0.39	0.27	0.34	0.50	0.41	0.38	0.36	0.36	0.34	0.30	0.30	0.30	0.25	0.26	0.22	0.27	0.13	0.09

Impact Assessment

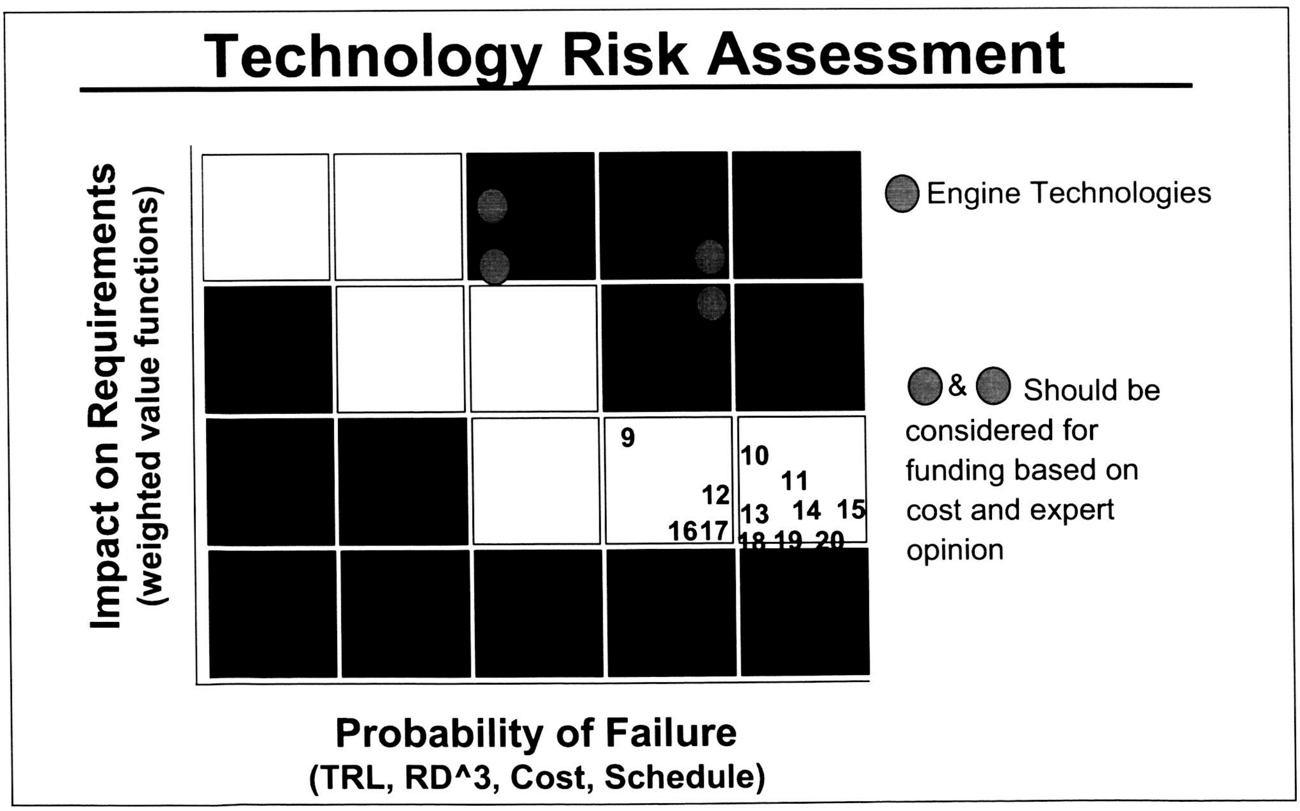
High   Medium   Low :

Comments on Investment Strategy and Impact Assessment Method

- Very poor choice of technology portfolio (~two-thirds of technologies have low or negative impact)
- Wrong requirements were developed
- Systems analysis did not model the technologies correctly

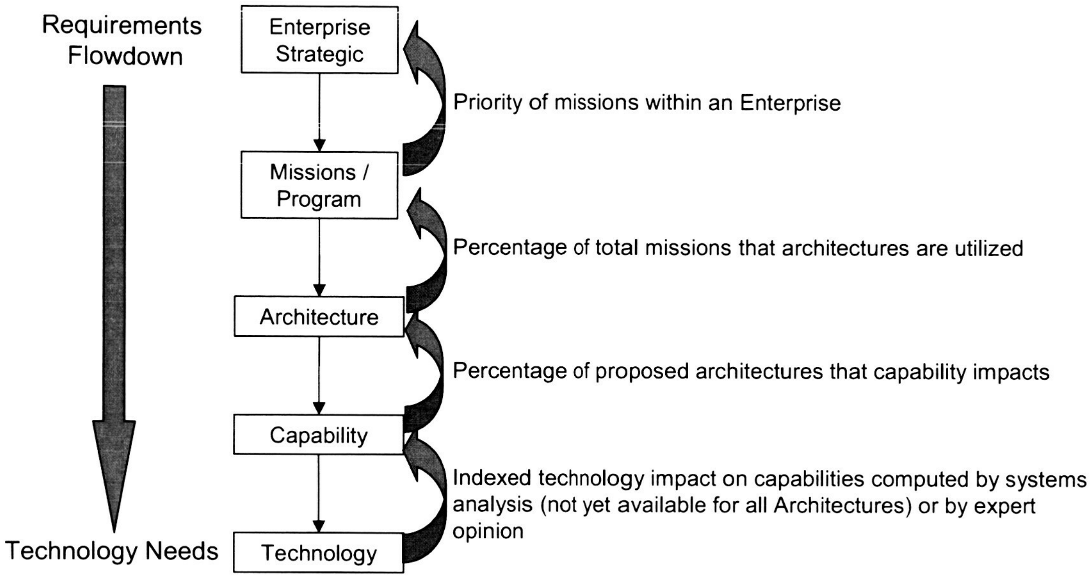


Technology Ranking (Benefit/Cost)
High impact (enabling) technologies can have low ROI.
12
10
8
6
4
2
0
DPMS Sierra Lobo
Prop Dens Ops LMC
Dens Prop PHPK
CMC for Cont Surfaces
IVHM Honeywell
LIMRC NASA/ARC
Modular Avionics Boe
MPS Crossfeed Boe
Metallic TPS Ocean
PEM Fuel Cell GRC
SHARP TPS LMC
Airlock Honeywell
Metallic CryoTank Boe
LOX/ Ethanol TRW
LOX/ Ethanol Aerojet
Competing Main Propulsion Systems (see next chart)



Technology Risk Assessment
Impact on Requirements (weighted value functions)
Probability of Failure (TRL, RD^3, Cost, Schedule)
Engine Technologies
& Should be considered for funding based on cost and expert opinion
9
10
11
12
13 14 15
1617

Technology Agency Impact Model



$$\text{Technology Impact} = \text{Capability Impact} \bullet \text{Architecture Impact} * \text{Mission Impact} * \text{Enterprise Impact}$$

Summary Technology Risk Assessment

- **Technology risk is based on the probability of technology development success versus the impact of the technology on the system**
- **Technology development probability of failure is similar to any project. Should have defined WBS, requirements, schedule, cost, etc.**
- **Expert opinion is used for assessment; AHP is one method to obtain and integrate the opinions.**
- **Expert opinion or systems analysis can be used to define the impact of the technology on the system.**
- **For total Agency impact, future enterprise missions need to be prioritized to assess technology global impact and risk.**

• **Mark Steiner**

Systematic Technology Planning - GSFC Perspective

April 21, 2004

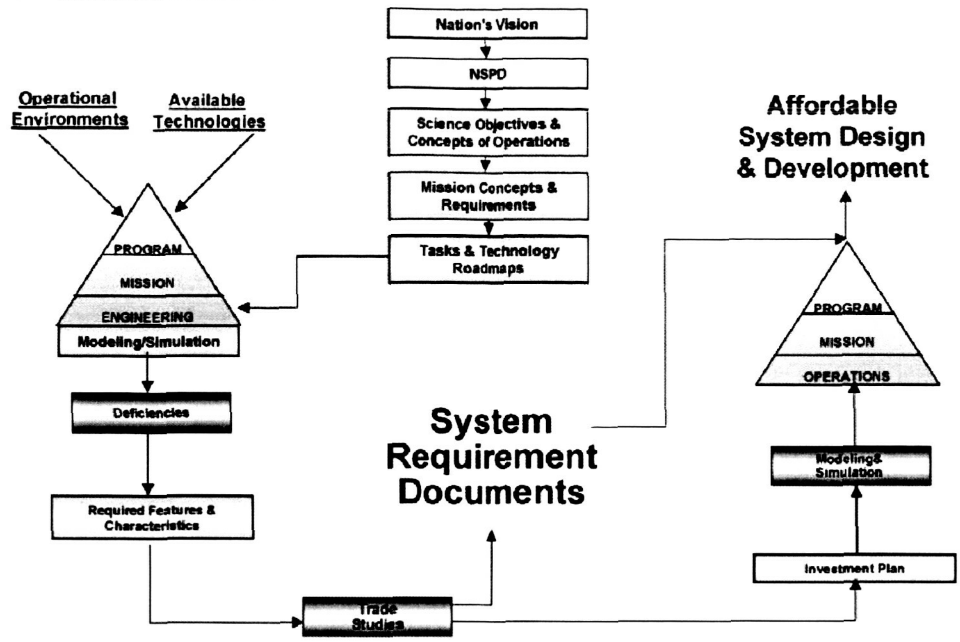
Mark Steiner
Goddard Space Flight Center
Greenbelt, MD 20771

Introduction

How do we integrate systematic technology investment planning into the process of architecting NASA's new space missions?

- GSFC perspective based on:
  - Exploration Initiative and current mission planning environment
  - FY 2003 Lidar Technology Pilot Study w/ LaRC
  - FY 2004 TAA study w/ JPL
- Goddard's vision as to what needs to be done next

Strategy-to-Task-to-Technology Process



Engineering and Technology Support Across Life Cycle

Strategic technology investment analysis enhances ...

Pre-formulation/Formulation

- Roadmap generation and review
- Advanced concept development and review
- Refinement of roadmaps, advanced concepts, technologies, etc.
- Proposal development and review
- Technology development and review
- Tracking and execution of roadmaps, advanced concepts, technologies, etc.
- Requirements and Systems Analysis

Cross Life Cycle Activities

- Risk management
- Project/Program cross-coordination and cross-coupling
- Independent technical/management review
- Lessons Learned Identification & Feedback

Implementation & Decommissioning

- Requirements management
- Design and development of missions, instruments, systems, technologies, etc.
- Product and service delivery
- Integration & test
- Launch, early-orbit check-out
- Operations & sustaining engineering
- Technology Commercialization

Approval

- Technology planning
- Approval review engineering and product support
- Program/Project plan support

... sound decisions across mission and program life cycles.

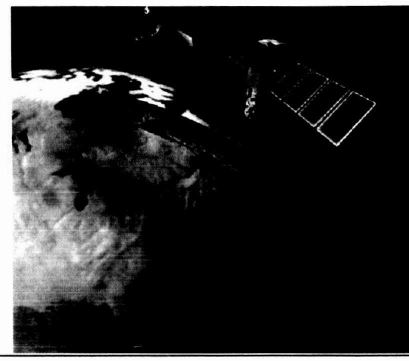
Lidar Pilot Study: Charter from Code R

Code R tasked GSFC and LaRC to perform a technology assessment study of Lidar missions with the following objectives:

1. Develop a process for assessing the system-level benefits of new technology investments to guide program investment decisions.
2. Establish performance goals for evaluating the progress of technology development & risk relative to the state of the art.
3. Identify high-payoff crosscutting technologies that are enabling for sets of future mission concepts with similar scientific objectives.

GSFC and LaRC performed this Technology Assessment Analysis (TAA) pilot study 2003

- Used system engineering approach to determine expected return on technology investments that could ultimately be used at the mission, enterprise, or agency level
- Allowed specific technologies to be evaluated for their impact on life cycle cost



Study Flow - 1

Science inputs

Captured science goals for aerosol Lidar -

- Examined ESTIPS database to establish science objectives for next generation Lidar and found that more detailed information was needed.
- Performed survey of aerosol-climate community and Lidar experts to fully populate domain of science measurement goals (e.g., detect aerosols and clouds and obtain their optical characteristics).

Derived science measurement needs that drove the integrated instrument performance requirements (such as SNR for atmospheric area of interest).

Study Flow - 2

Science inputs

↓

Technology inputs

Captured technology options that would improve Lidar performance

Surveyed technologists and grouped results into generic Lidar system component options.

Study Flow - 3

Science inputs

↓

Technology inputs

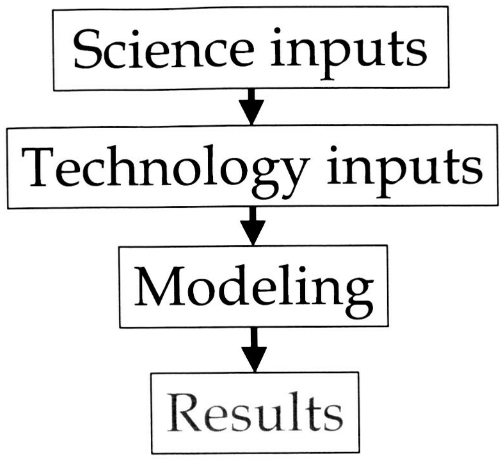
↓

Modeling

Developed model of aerosol and cloud Lidar instruments: maps technical performance into instrument performance in area of atmosphere to be measured.

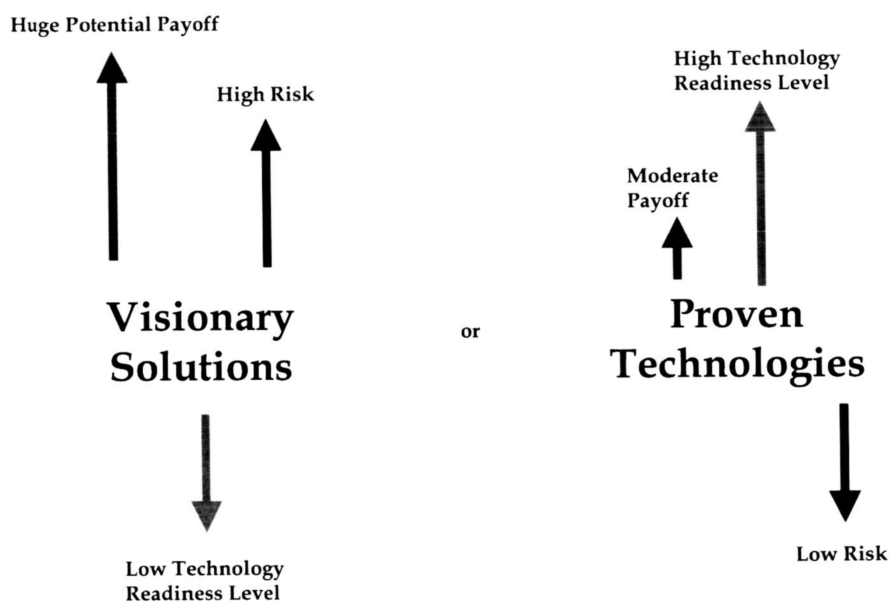
Developed technology development model (from starting TRL to TRL 6): maps development risk and investment plan to technology performance over time.

Study Flow - 4



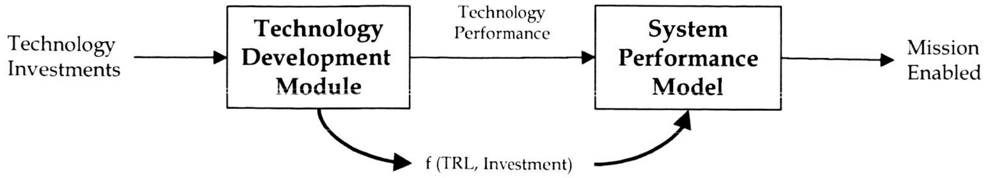
Linked models and used them to trade off cost, development risk, and instrument performance to optimize technology investment plan.

Technology Development Risk



Always a Trade-Off in Technology Investments

Technology Development Modeling

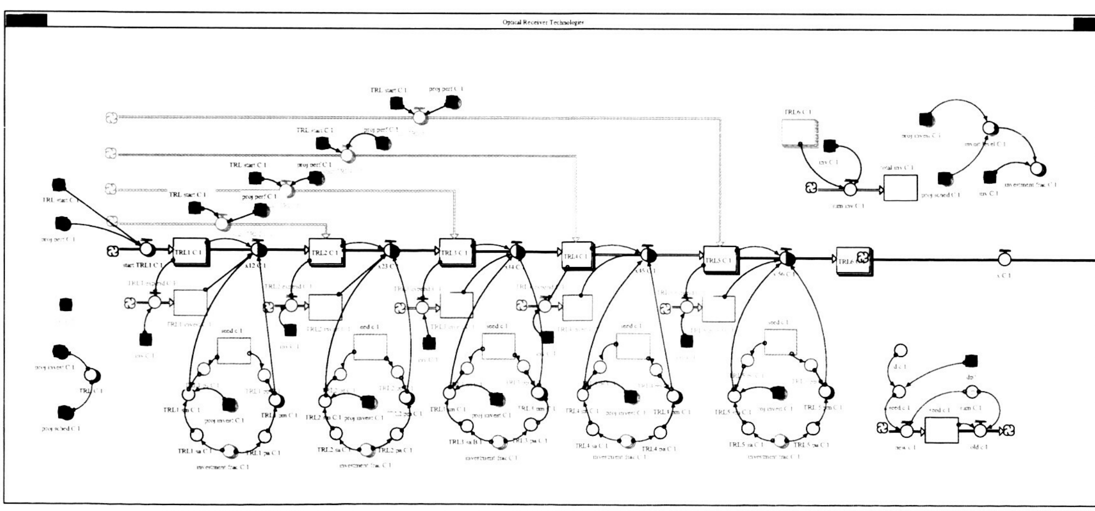


Technology Development Model (from starting TRL to TRL 6) maps development risk and investment plan (estimated schedule and budget) to technology performance over time.

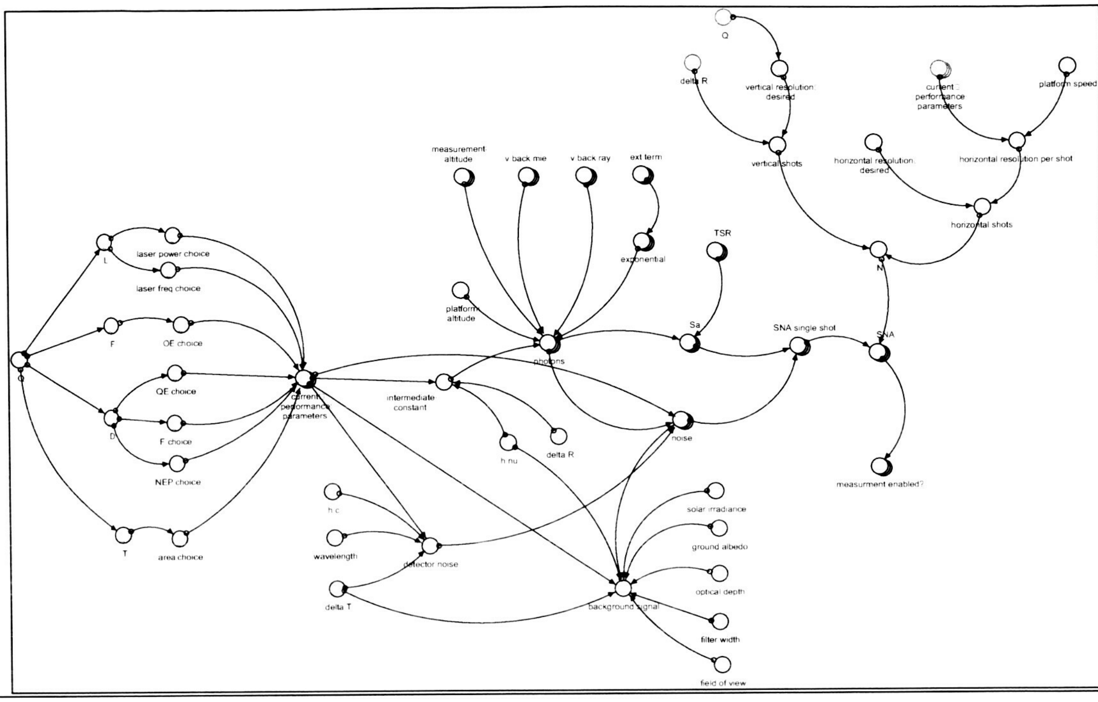
System Performance Model maps technology performance into system performance

Link models and use them to trade off cost, development risk, and system performance to optimize technology investment plan.

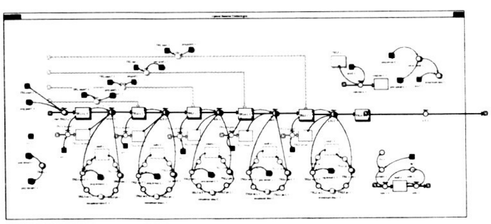
Systems Dynamic Modeling – Technology Development



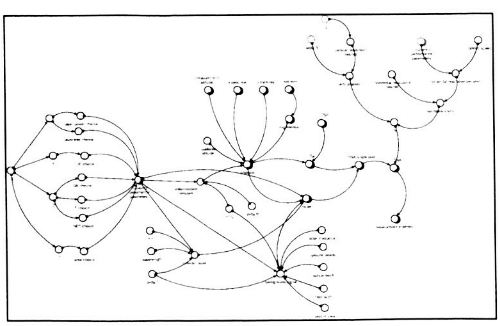
Systems Dynamic Modeling – Lidar Performance



The Study Methodology Enables

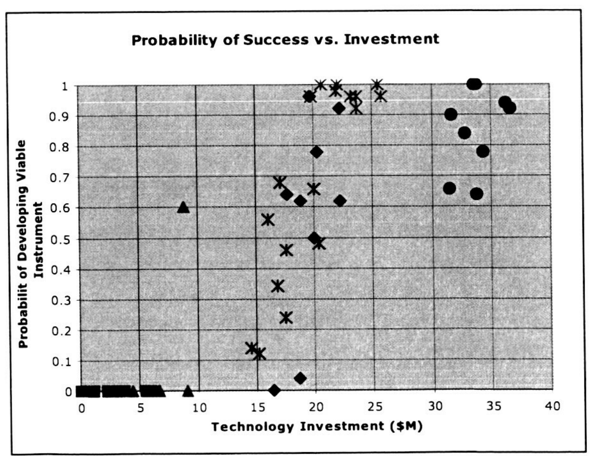


Combining lidar technology development modeling . . .



. . . and lidar performance modeling . . .

. . . to determine return on investment . . .



and provide best estimate as to which group of technologies would enable the mission, reduce cost, and be most likely to enhance overall value.

FY04 TAA Study

Lidar Pilot Study FY03:

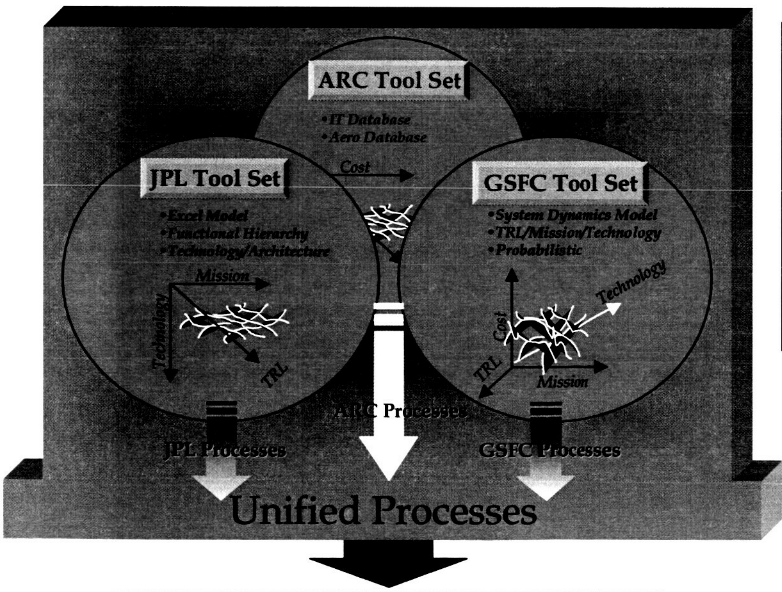
- Develop an approach to maximize the value of NASA's technology investment.
- Understand process of gathering information, developing models, and presenting results:
- Develop a general approach for optimizing technology investments and apply to LIDAR measurements

Expansion in FY04:

- Partner with JPL to extend process to space architect's Design Reference Missions
- Work with other centers (LaRC, ARC) to broaden technology databases, share processes, share results
- Extend performance modeling to include instrument accommodations (spacecraft and ground system)

Unified Agency-Wide Technology Assessment Framework

Unified Technology Assessment Framework



Features

- ***Toolbox approach***
- ***Each tool is unique***
- ***Different views based on same data***
- ***Each tool optimizes over a specific dimension, depending on question being asked***
- ***Convergence results in Unified Process and helps V&V tools***

Quantifiable and Risk Based Technology Investment Strategy

Reference Missions & Grand Challenges

Reference Missions (not listed in order of priority)	Grand Challenges
Orbital Aggregation and Space Infrastructure Systems (OASIS)	Modular, Distributed Structures, Human Protection, Robotic Assembly
Mars Surface Missions (e.g. Mars Science Laboratory; Astrobiology Field Lab; etc.)	Long-Range Mobility on Ice; Deep Drilling; Automated Return Launch; Risk Mitigation (Pre-Phase A)
Lunar Survey Study Mission	Sensor Webs & Data Fusion: Lidar/Radar Instrument Systems; Multi-Spectral Scanner; Model-Driven Multi-Measurement-Validated Data Reduction
Earth Biomass (surface, mid-canopy, and canopy heights.	Lidar/Radar Instrument Systems; Multi-Spectral Scanner
Sensor Webs & Data Fusion	Model-Driven, Multi-Measurement- Validated, Data Reduction
RASC - L2 Earth Observing Telescope	Large deployable mirrors, membrane type shape control, formation flying
Venus Surface Missions	Extreme Environments (460C temp; 90 bar pressure; sulfuric acid clouds at 50 km)
Generic Critical Design Review requirements derived from Pathfinder, Space Station or other recent mission	Quantify mission-level impact of ECS technologies, such risk management and human organization, whose primary contribution is to the design process, and that are not necessarily embodied within a hardware or software flight system

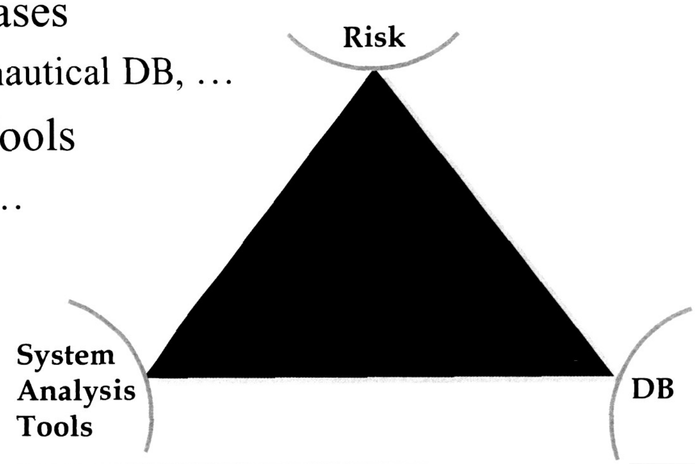
NOTE: GSFC and JPL will share performance data on all reference missions.

Study Data Gathering

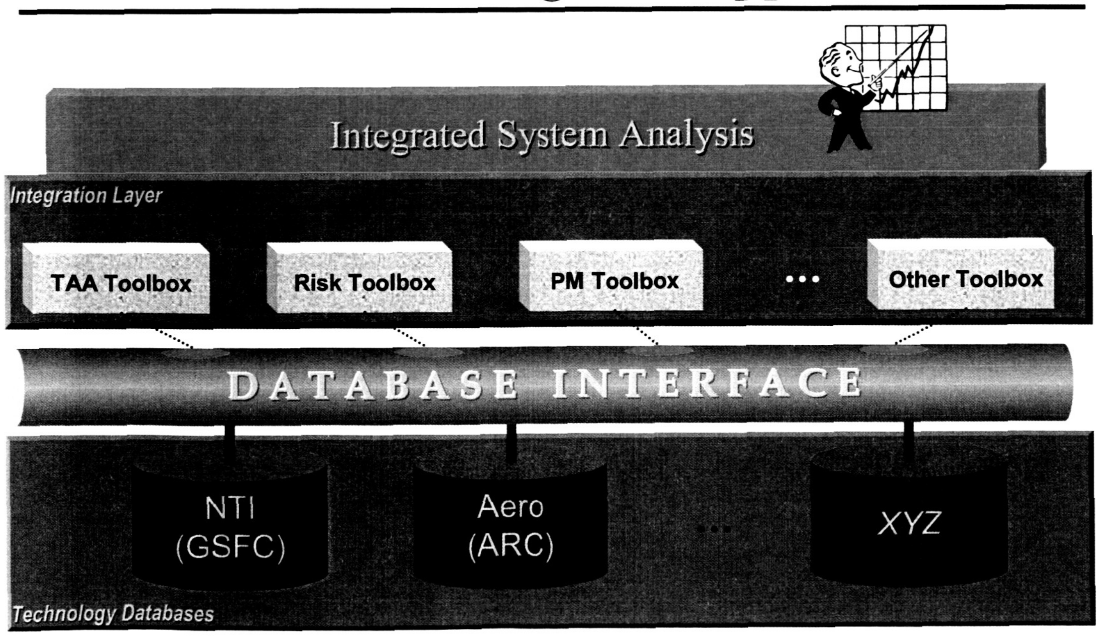
- **Have developed a technology list in cooperation with JPL**
  - **Shows who will gather technology information in which areas**
- **Have common technology data gathering template, based heavily on Space Architect work**
- **Common technology data template and sharing of this and the reference mission performance information will allow JPL and GSFC to run common data through both sets of tools and provide results for comparison**
- **Analyze differences between tools, since view problem from different but complementary angles:**
  - **JPL – good for matrixing many technologies across many mission sets**
  - **GSFC – good for in-depth analysis of technology development within particular mission (performance parameter) set**

Integration of Risk into Technology Planning

- Risk
  - Tools and methodology
- Technology Databases
  - NTI, ESTO, Aeronautical DB, …
- System Analysis Tools
  - TAPS, JPL Tool, …



Ideas for an Integrated Approach



Guesswork/Gut Feel Replaced with Integrated System Analysis

Considerations for NASA

Currently -

- We conduct deterministic and probabilistic assessment of existing systems based on mission requirements
  - Probabilistic sensitivity analysis for point solutions (Shuttle, Station, ...)
    - *system decision trees are often complex and may not capture everything*

Future -

- Assessment of entire architecture trade space to include technology development risk, programmatic risk, operational risk (vehicle, etc.) and cost
  - Effect of technology on system design/development/cost/schedule
- Models to develop probability distribution of expected outcome
  - Probability based Genome Model will integrate TRL to provide a powerful view into future mission strategies and architectures.

Next Steps for NASA

- Get all technology players to play together
- Integrate processes and tools as makes sense to answer questions at the appropriate level
- NASA Technology Assessment Technical Committee??

Unified Agency-Wide Technology Assessment Framework

- **Louis Lollar**

"ATLAS"
Advanced Technology Life-cycle Analysis System

April 2004

Louis F. Lollar
Advanced Projects Office of the Flight Projects Directorate
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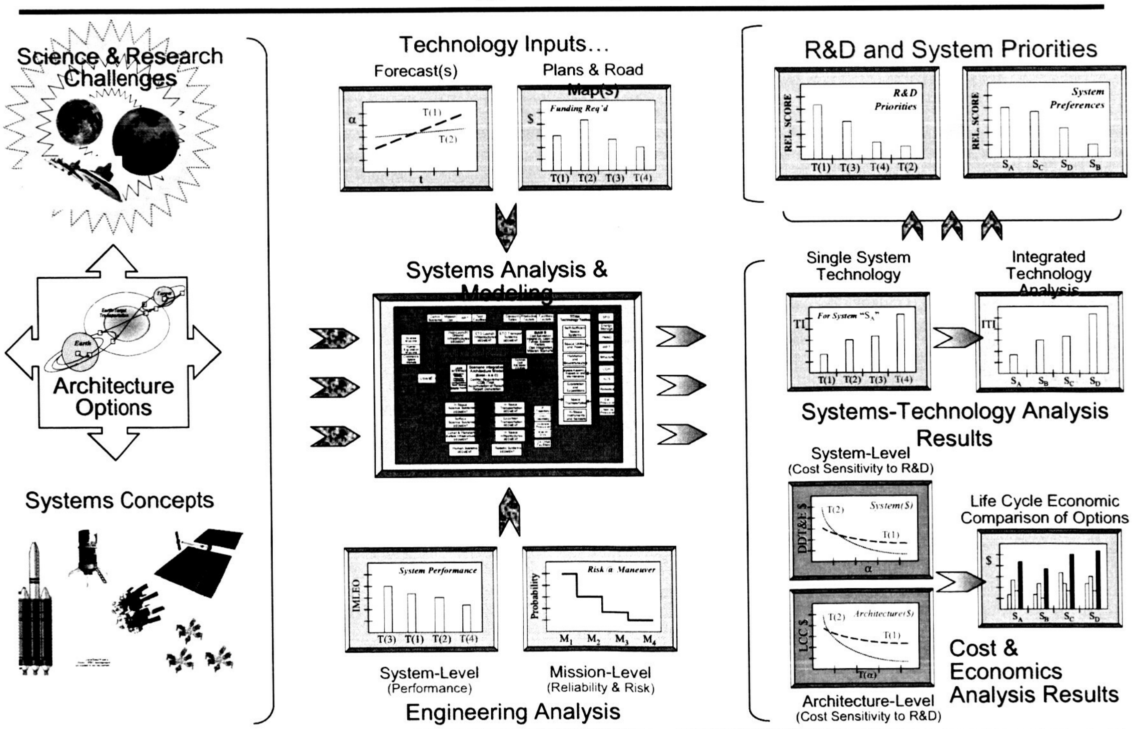
Contents

Overview

- **Making good decisions concerning research and development portfolios—and concerning the best systems concepts to pursue—as early as possible in the life cycle of advanced technologies is a key goal of R&D management**
- **This goal depends upon the effective integration of information from a wide variety of sources as well as focused, high-level analyses intended to inform such decisions**
- **The presentation provides a summary of the Advanced Technology Life-cycle Analysis System (ATLAS) methodology and tool kit…**
  - ATLAS encompasses a wide range of methods and tools
  - A key foundation for ATLAS is the NASA-created Technology Readiness Level (TRL) systems
  - The toolkit is largely spreadsheet based (as of August 2003)
- **This product is being funded by the Human and Robotics Technology Program Office, Office of Exploration Systems, NASA Headquarters, Washington D.C. and is being integrated by Dan O'Neil of the Advanced Projects Office, NASA/MSFC, Huntsville, AL**

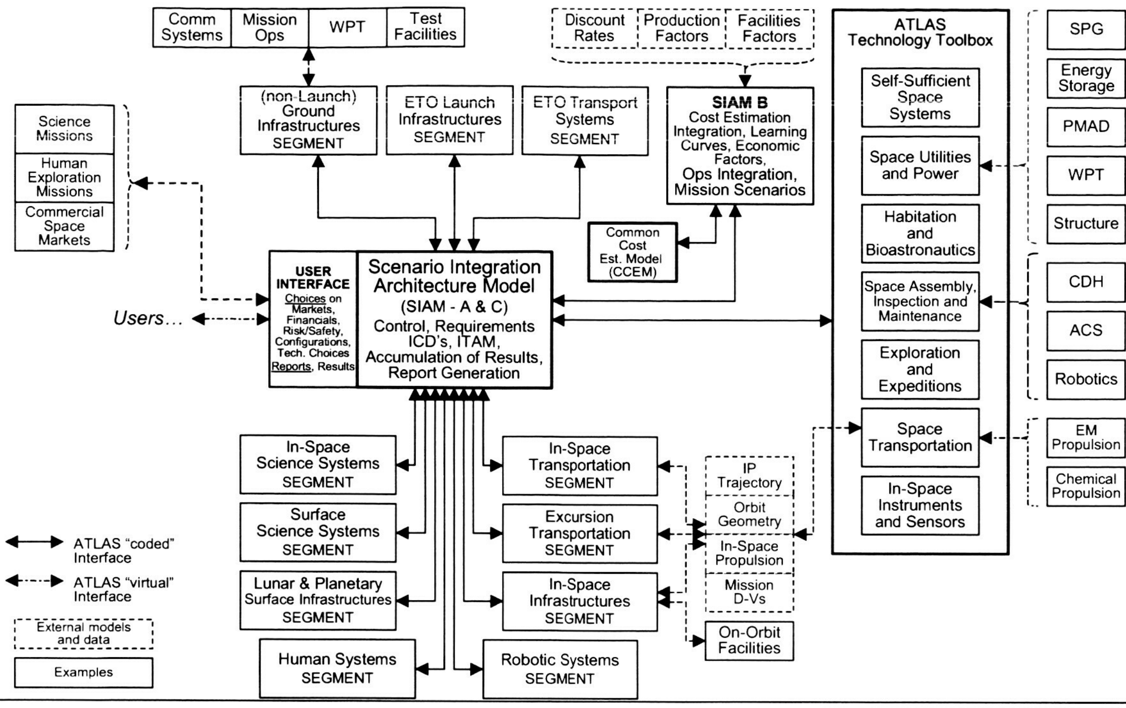
"ATLAS" Approach

Advanced Technology Life-cycle Analysis System



Advanced Technology Life-cycle Analysis System (ATLAS) Model

Architecture Overview



Notional Example Analysis

Lunar Rover to Collect Ice from the Lunar Craters

- **Notional Scenario**
  - Launch elements to LEO for construction
  - LEO to Lunar Orbit
  - Base system/Rover to "Edge of Crater"
  - Rover descends into the crater to retrieve some ice
  - Rover brings the ice back to the base unit
- **Analyst chooses(with help from ATLAS)**
  - Launch Vehicle
  - LEO Base Configuration
  - Orbital Transfer Vehicle
  - Base Vehicle
  - Lunar Rover
- **Output Data from ATLAS**
  - Mass statement(s) for each subsystem and/or 18 subsystems
  - DDT &E (6 year cycle)
  - Cost for each system and/or 18 subsystems
  - Theoretical first unit cost
  - Life cycle costs
  - Views of the intermediate steps of the process

Summary

- **A central challenge in the management of innovation lies in making good decisions in the absence of complete information**
  - The conundrum is that the earliest decisions have the greatest affect on project outcomes, and yet they must be made at the time when there is the least detailed information available
- **The ATLAS modeling system is being developed to contribute to the resolution of this challenge**
  - By providing a single (high-level), desk-top tool that integrates information on, and analytical relationships among various missions, architectures, systems, technologies and associated metrics, and costs
- **Although considerable work remains, it appears likely that ATLAS will begin operations—and to make meaningful contributions to Agency decisions—during FY 2004**

- **Othar Hansson**

The CICT Earth Science Systems Analysis Model

COMPUTING
INFORMATION &
COMMUNICATIONS
TECHNOLOGY

Barney Pell, Joe Coughlan,
Bryan Biegel, Ken Stevens,
Othar Hansson, Jordan Hayes

NASA Ames Research Center
& Thinkbank, Inc.
April 2004

The ESSA Team

- Task leads:
  Barney Pell (Lead), Bryan Biegel (Co-lead),
  Joe Coughlan (Science Lead),
  Walt Brooks (Science Co-Lead)
- Subcontractor:
  Othar Hansson & Jordan Hayes, Thinkbank
- ARC team:
  Ken Stevens, Peter Cheeseman, Chris Henze,
  Samson Cheung, et al.

Enough About Me

- Research collaborations with NASA Ames since 1989 (heuristic search, data-mining, planning/scheduling).
- PhD (Computer Science), Berkeley.
  Using decision analysis techniques for search control decisions in science planning/scheduling systems.
- Thinkbank:
  custom software development,
  software architecture consulting,
  technology due-diligence for investors.

Agenda

CICT Systems Analysis

Our modeling approach

- a 3-part schematic investment model of technology change, impact assessment and prioritization

A whirlwind tour of our model

Lessons learned

Systems Analysis in CICT

- Demonstrate "systematic and thorough investment decision process" to HQ, OMB and Congressional Decision Makers
- Increase awareness and substantiate CICT's impact to missions. Road map CICT projects to missions and measurement systems
- 4 teams in FY03:
  - 2 pilot studies (Earth Science [me]; Space Science [Weisbin]): explore models for ROI of IT.
  - TEAM: map from NASA Strategic Plan to IT capability requirement; technology impact assessment
  - Systems Analysis Tools (COTS/GOTS)

Earth Science Pilot Study

How do we characterize and quantify a science process?

Can we build a model of how CICT technology investments impact ROI in a NASA science process?

What modeling approach is suitable for making such analyses understandable and repeatable?

Current State

What have we learned? (FY03)

- Decision analysis modeling techniques can be applied to systems analysis of CICT project areas. Built model of weather-prediction data pipeline.

What don't we know? (FY04)

- How much time/expense needed to build a full model
- How such a full model fits into a real NASA program context (CDS: Collaborative Decision Systems)

Pilot Study Focus

- Criteria for science process to study
  - Important to a major customer base,
  - Significantly drives technology investments
  - Generalizes to a class of related processes
  - Amenable to quantitative analysis.
- 2010 Weather Prediction process
  - Critical Earth Science process with relevance not only to NASA scientists but to the nation at large.
  - Stretch goals require technology breakthroughs.
  - Strong technology driver for other science problems
  - Starting point: analyses from ESE computational technology requirements workshop (4/02)

Pilot Study Accomplishments

- Identified modeling formalism (influence diagrams)
  - Clear semantics accessible to both ES & CICT experts
  - Tools exist for sensitivity analysis, decision-making, etc.
    We chose Analytica as our modeling tool.
  - Successfully transferred/applied to Space Science pilot study as well.
- Built a model with an understandable, simple structure (after much research and many iterations).
- Demonstrated the kinds of analyses made possible by the model

Agenda

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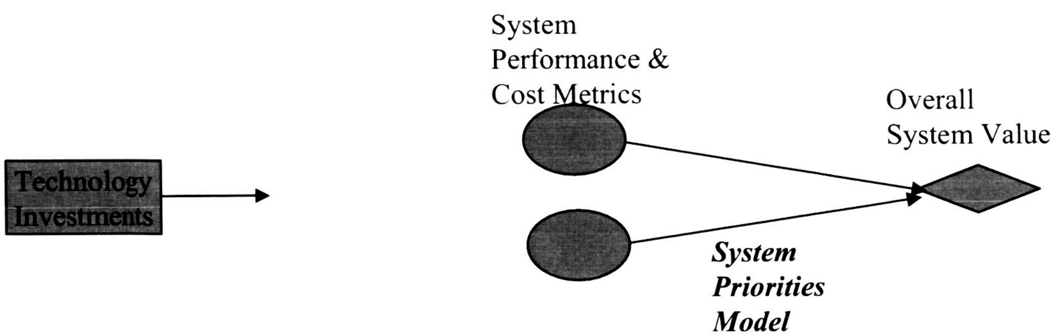
Lessons learned

Methodology: Decision Model

Q1: Which technology investments should I make?

Q2: How does each technology investment improve overall system/mission value (including cost considerations)? Choose investments with highest value.

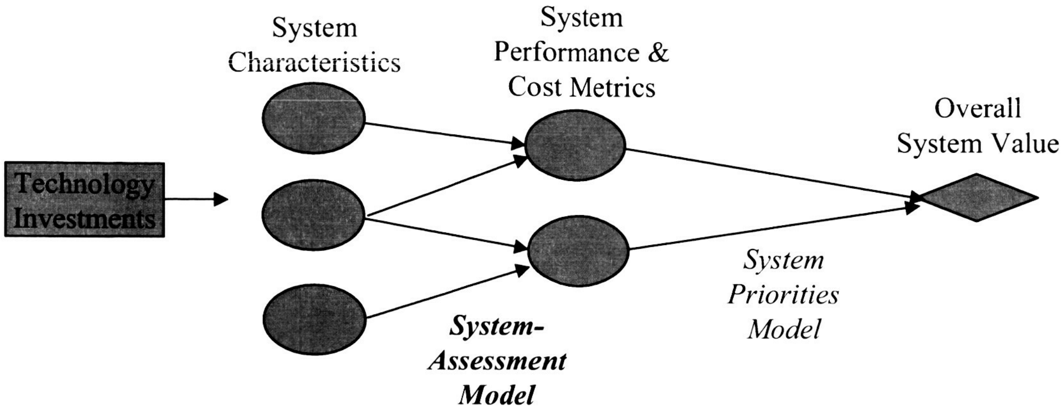
Filling in the Decision Model



System value is a function of a set of metrics (accuracy, fidelity, cost, etc.). We can model the priority among the metrics independent of the technologies used.

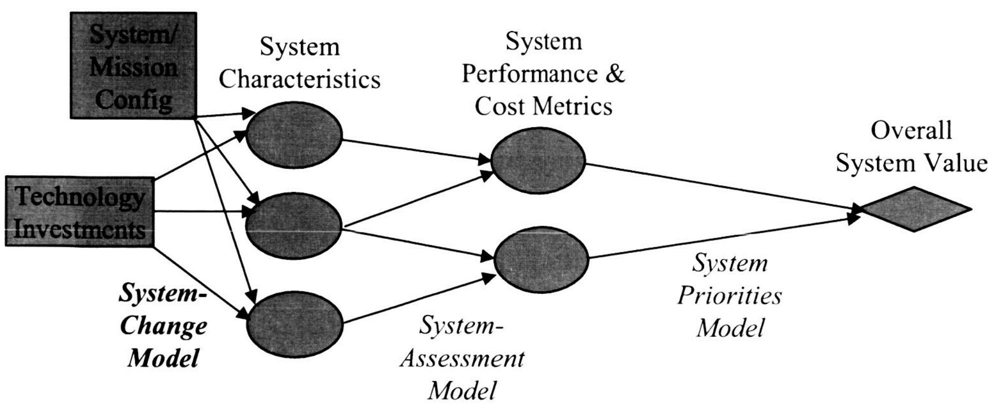
Technology investments have value in that they improve these metrics.

Filling in the Decision Model



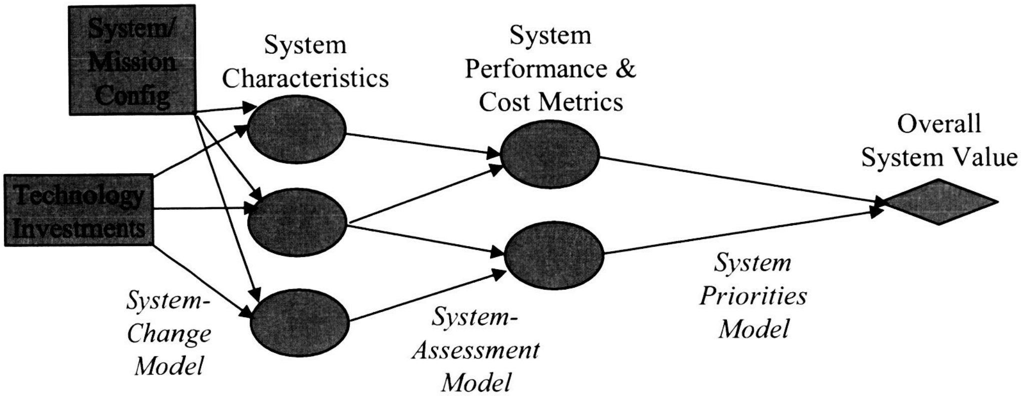
The metrics can be modeled in terms of abstract system characteristics (data volume, algorithm accuracy, processing speed, model fidelity, ...).

Filling in the Decision Model



Technology investments, together with some mission-specific parameters, influence the system characteristics. A technology investment (such as data visualization research) has value in that it improves system characteristics (such as model fidelity).

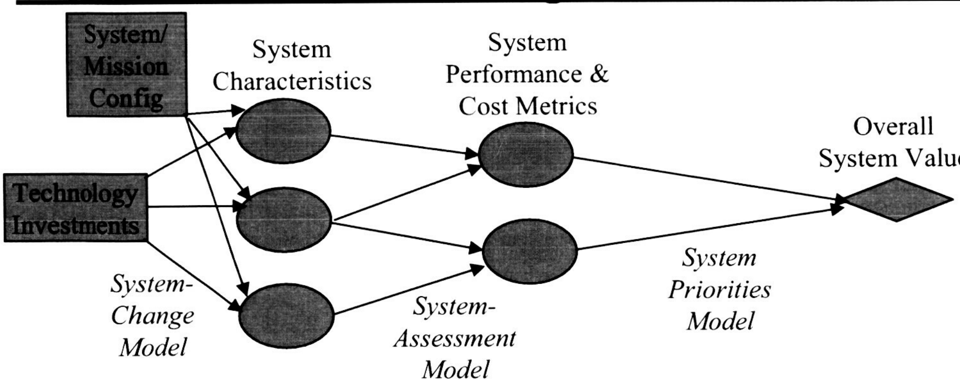
Methodology: Influence Diagrams



We've sketched an "influence diagram" model of the decision.

Q: What tech. investments maximize expected overall system value?
Q: Value of model refinement: How sensitive to assumption A?
Q: Value of information: what if we knew that project P would succeed?
Q: Value of control: what if we could reduce risk of project P failing?

Influence Diagram Details



Influence diagram tools (such as Analytica) allow you to specify and evaluate these models. Diagram structure and decision analysis techniques speed specification of required parameters.

"What-if" and optimization questions reduce to the problem of computing functions of conditional prob. distributions:
"best" technology investment is:

argmax [E(Overall System Value | Technology Investments)]

Agenda

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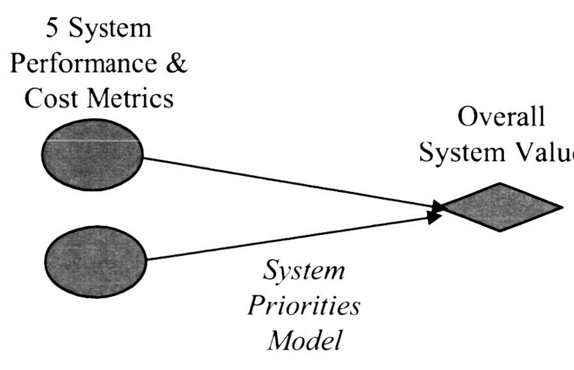
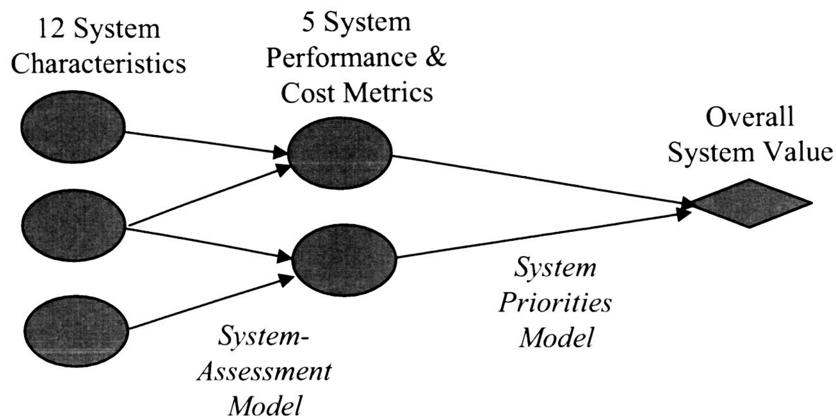
The ESSA Model



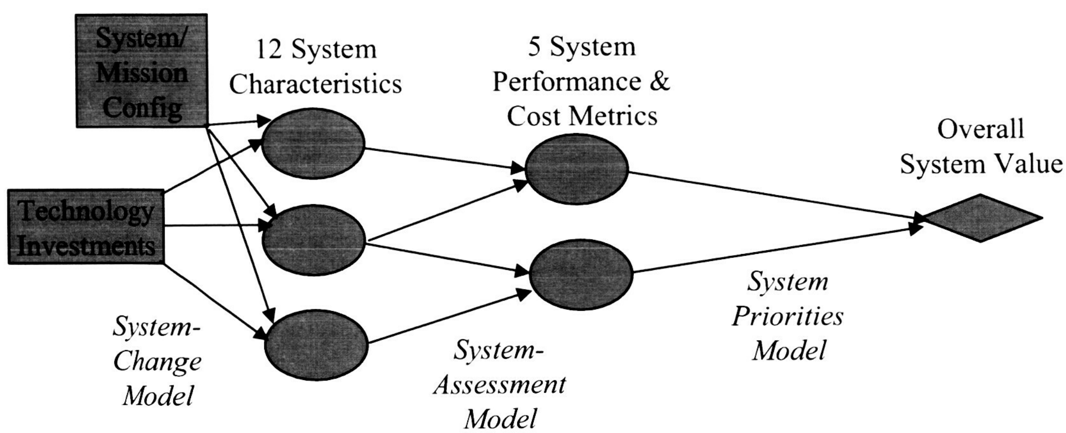
Our set of 5 metrics include:
development cost, operations cost, accuracy, model fidelity, etc.

The ESSA Model



Our 12 System Characteristics include:
observation density, assimilation efficiency, cpu efficiency, etc.

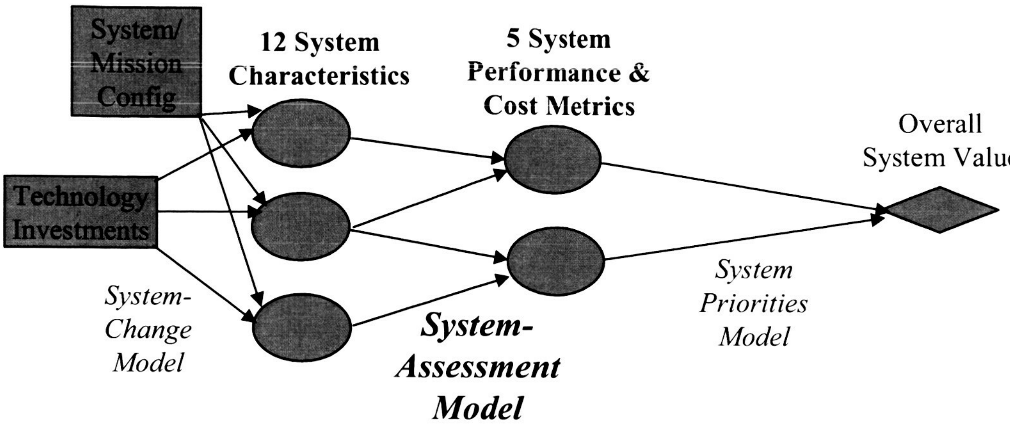
The ESSA Model



Our 13 technology investments include: data-mining, launching a new data source, targeted observing, etc.

Each represents a research area, summarizing a range of individual research tasks or proposals.

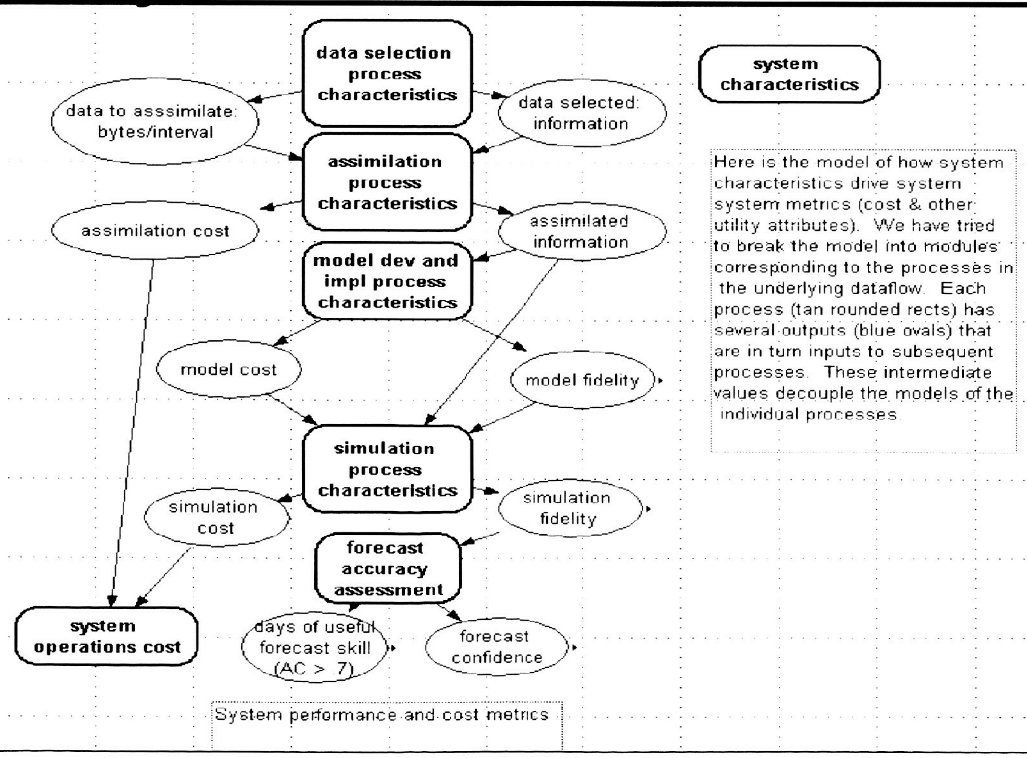
Diving Down into the Model



System-Assessment Model: the most stable part of the model, owned/designed by a customer domain expert who understands the behavior of the system/mission being analyzed.

System-Assessment model computes System Metrics from System Characteristics

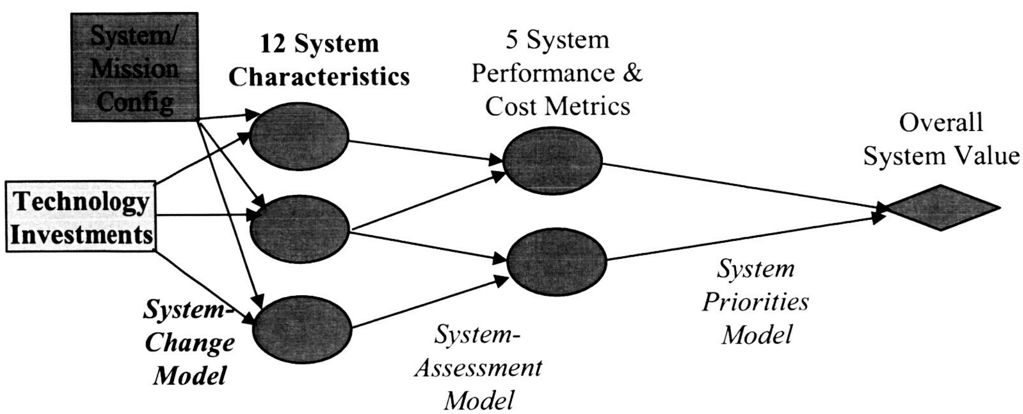
System-Assessment Model



Example System Characteristics

Assimilation efficiency	0-1 scale: how much information is retained despite approximations in data assimilation?
CPU efficiency	>0 : percentage speedup in CPUs due to R&D investments
Data efficiency	0-1 scale: how much information is present in each bit of data selected?
Ensemble efficiency	0-1 scale: how much improvement in forecast skill do we get from using ensemble algorithms?
Model framework	0-1 scale: how much fidelity is present in our models?
Observation density	0-1 scale: how many of the available observations do we make?
Postprocessing effectiveness	0-1 scale: how much improvement in forecast skill do we get from using post-processing?
Simulation efficiency	> 0: percentage speedups in simulation due to R&D investments

Instantiating the Model



System-Change Model: owned/designed by a program manager who understands the feasibility and impact of different research areas.

System-Change model computes System Characteristics from the set of Technology Investments chosen (and system/mission config parameters)

System-Change Model

- "Impact matrix" quantifies the changes to system characteristics that will occur if individual research projects succeed.
- "Cost matrix" quantifies cost breakdown for each research area.
- Portfolio of research areas determines what impacts will be felt.
- (In an extended model, cost and impact could vary over time.)

System-Change: Research Areas

- **Data-efficient simulations (same data size)**
  choose a more informative set of observations to improve forecast skill at the same computational cost
- **Data-efficient simulations (less data)**
  reduce number of observations (and reduce computational cost) w/o reducing forecast skill
- **Targeted Observing**
  ditto, but also gather more targeted observations based on ensemble accuracy estimates (e.g., the SensorWeb concept)
- **Adaptive grid methods**
  reduce number of grid points by using regional forecast as boundary conditions
- **Improvements in ensemble methods**
  reduce number of ensembles needed to get similar accuracy estimates (e.g., through use of particle filter technology)
- **Data-mining of model outputs**
  increased skill from same model output via data analysis & visualization (intelligent data understanding)

System-Change: Research Areas

- **Modeling tools**
  ESMF and other initiatives to make modeling efforts more productive
- **System Management/Tuning tools**
  Auto or Semi-Automatic Parallelization tools, Benchmarking, Cluster management, etc.
- **Instrument models**
  tools for creating more accurate instrument models.
- **Launch new data source**
  collect additional types of observation data by launching a new instrument.
- **Launch replacement data source**
  collect a new type of observation data, but keep the total amount of data processed the same.
- **Higher resolution models**
  develop higher resolution models and move to higher resolution simulation

Research Area Impact

Impact matrix has a value for each pair (13 research areas x 12 system characteristics): 156 possible, but only 18 are nonzero.

Impact can be positive or negative:

Impact(targeted observing, observation density) = low neg.

Impact(launch new data source, observation density) = low

Some more examples:

Impact(targeted observing, targeting efficiency) = low

Impact(system mgmt/tuning, cpu efficiency) = low

Impact(adaptive grid, simulation efficiency) = medium

Impact Matrix

	Assimilation efficiency	Assimilation density	Cpu efficiency	Data efficiency	Downlink density	Ensemble efficiency	Model framework	Observation density	Observation efficiency	Postprocessing effectiveness	Simulation efficiency	Targeting efficiency
data-efficient simulations (same data size)				■								
data-efficient simulations (less data)				■				(lo)				
targeted observing				■				(lo)				lo
adaptive grid methods											■	
improved ensemble methods						■						
data-mining of model outputs										■		
modeling tools							■					
system mgmt/tuning			lo									
launch new data source				■				lo				
launch replacement data source				lo								
instrument models	lo											
higher resolution models		lo					lo				(lo)	

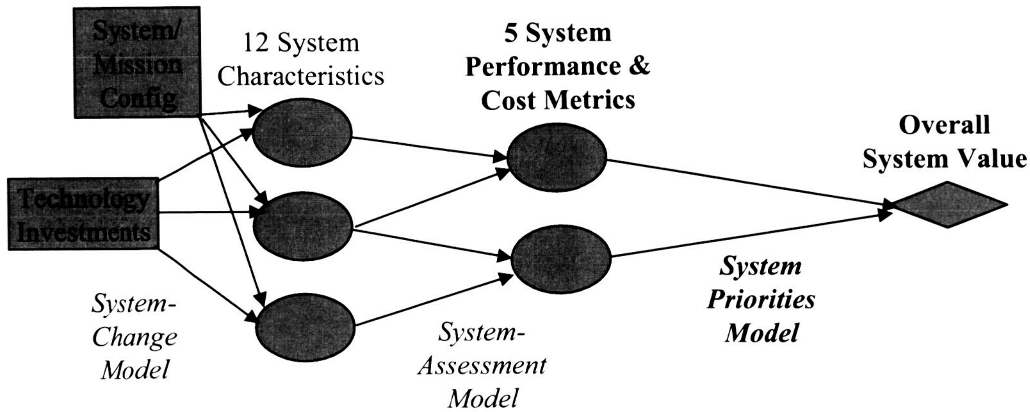
Qualitative → Quantitative

Impact is parameterized qualitatively (lo, med, hi). This qualitative scale is then quantified inside the model.

Each of the parameters has a different interpretation under the four scenarios (pessimistic, consensus, optimistic, ideal). This allows us to compare in a best-case vs. worst-case manner.

	pess.	cons.	optim.	ideal
Lo	.05	.1	.15	1.0
Med	.2	.3	.4	1.0
Hi	.3	.5	.7	1.0

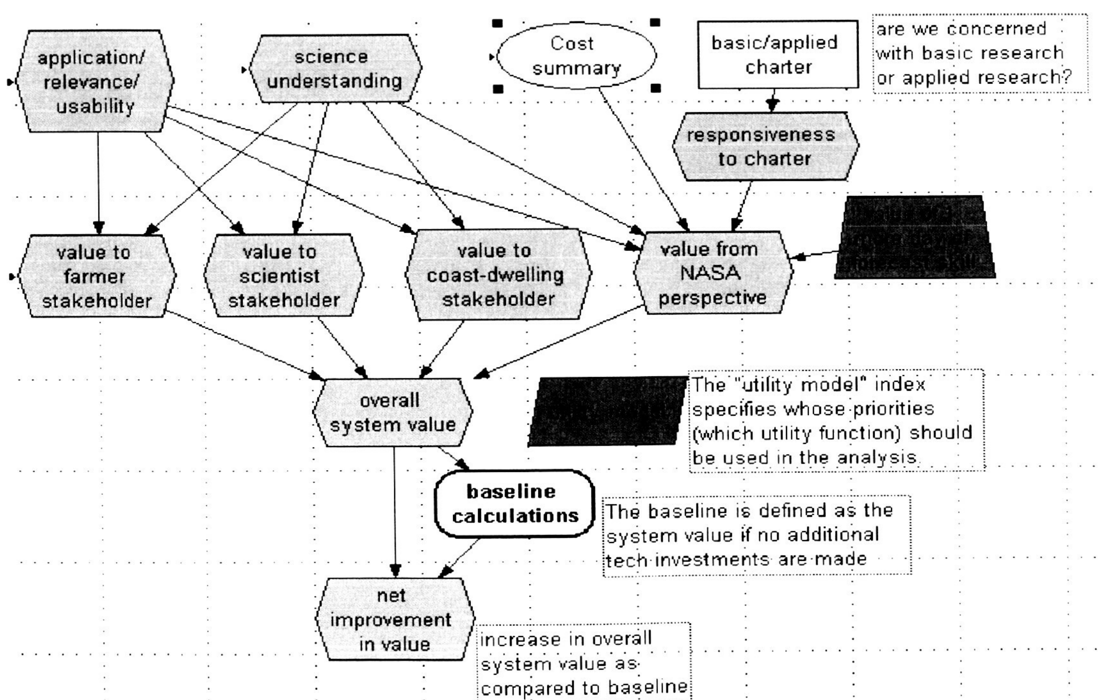
Instantiating the Model



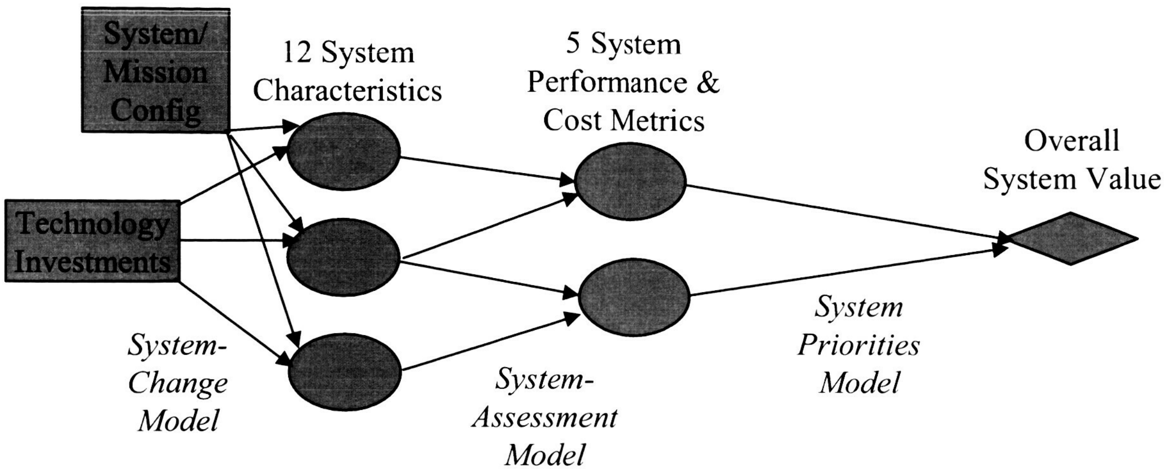
System Priorities Model: designed/owned by program manager cognizant of NASA priorities

System Priorities Model computes overall System Value given the System Metrics.

System Priorities Model



Review: Combining the Models



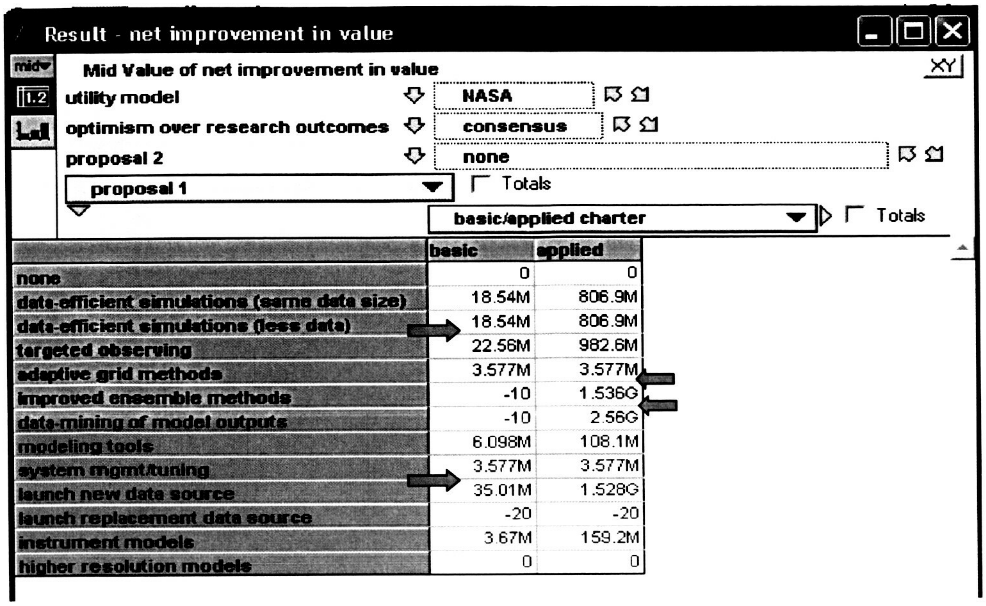
Results: Caveat

Remember: results (evaluations, ROI, etc.) must be understood as a function of the inputs used to calculate the results:

f(model, assumptions, priorities)

Priorities depend on perspective: we model basic (science value only) versus applied (economic value only)

Evaluating Research Areas



Result - net improvement in value

Mid Value of net improvement in value

utility model: NASA

optimism over research outcomes: consensus

proposal 2: none

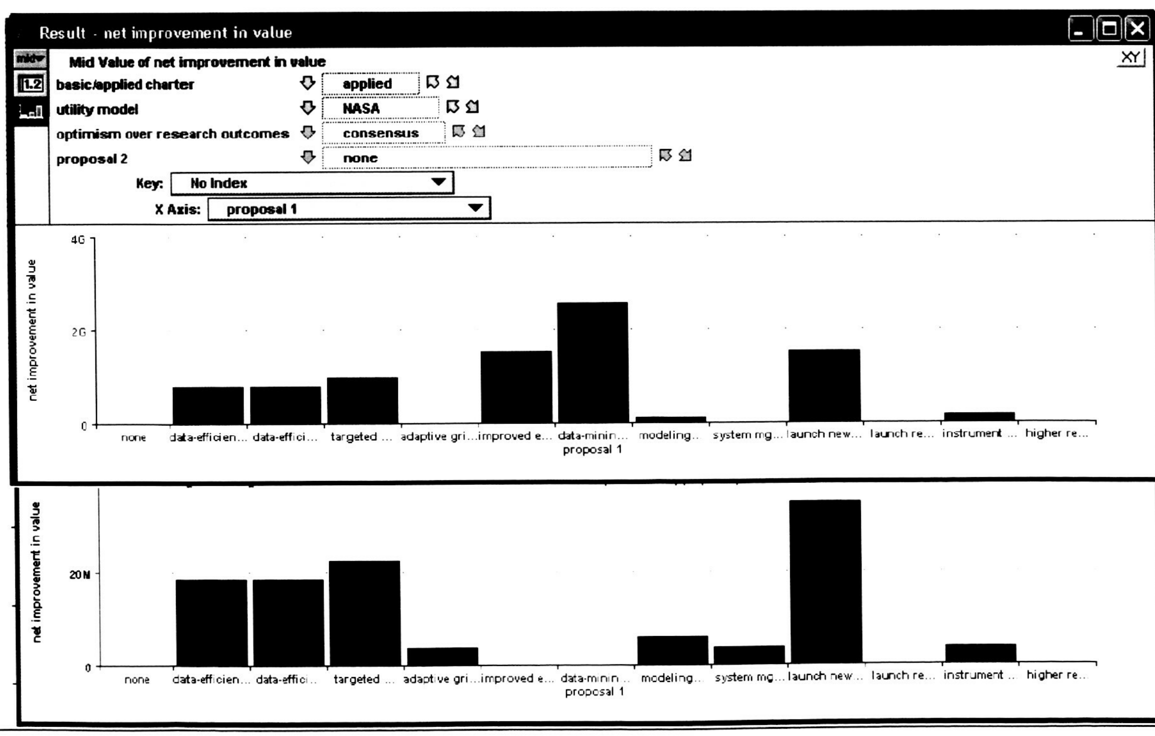
proposal 1 ; basic/applied charter

	basic	applied
none	0	0
data-efficient simulations (same data size)	18.54M	806.9M
data-efficient simulations (less data)	18.54M	806.9M
targeted observing	22.56M	982.6M
adaptive grid methods	3.577M	3.577M
improved ensemble methods	-10	1.536G
data-mining of model outputs	-10	2.56G
modeling tools	6.098M	108.1M
system mgmt/tuning	3.577M	3.577M
launch new data source	35.01M	1.528G
launch replacement data source	-20	-20
instrument models	3.67M	159.2M
higher resolution models	0	0

Basic: launch new data source (35M) & targeted observing (22M)

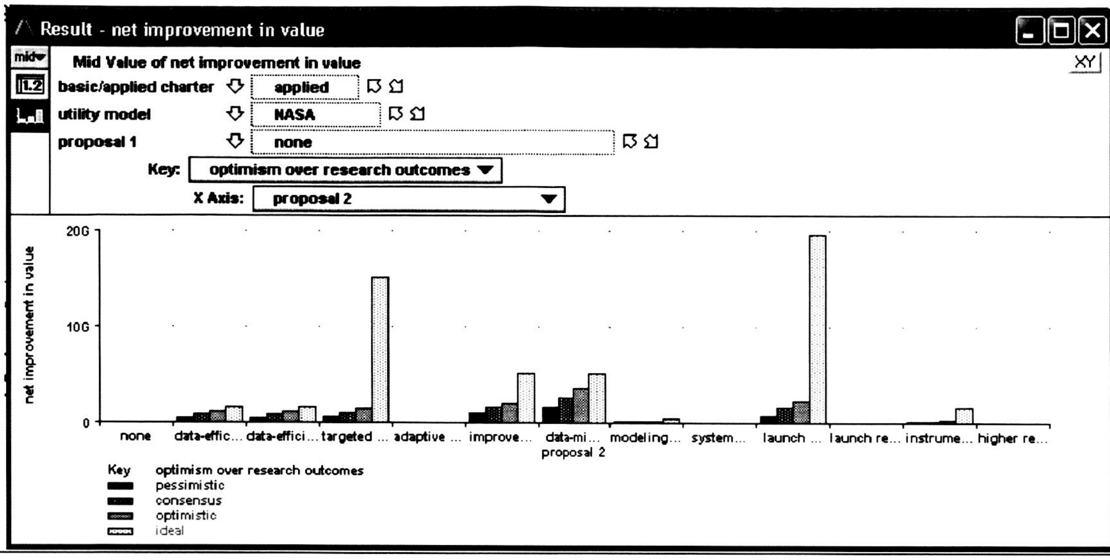
Applied: data-mining (2.5B) & improved ensemble methods (1.5B)

Evaluating Research Areas



Sensitivity Analysis

Sensitivity to "optimism" variable: two research areas have vastly higher potential impact under ideal assumptions. Pessimistic view of data-mining exceeds optimistic assessment of other areas.



Synergy Between Research Areas

We can look for synergies by finding pairs of research areas with much higher value than the two areas individually...

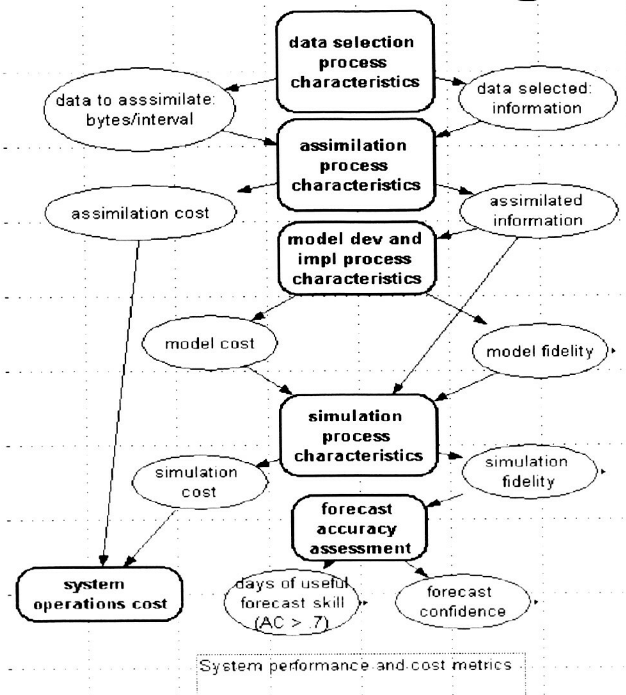
Under the applied research focus:

Biggest synergies

Launch new data source ($1.5B)
+ targeted observing ($1B)
yields a synergy of $700MM

Launch new data source ($1.5B)
+ data-efficient simulations ($800MM) yields a synergy of $400MM

Understanding the Model



BLUE OVALS summarize the way that system changes flow through the assessment model. We can diagnose our assumptions by analyzing how these variables vary as we vary research area.

Agenda

CICT Systems Analysis

Our modeling approach

– a 3-part schematic investment model of technology change, impact assessment and prioritization

A whirlwind tour of our model

Lessons learned

Modeling lessons learned...

Model and modeling technology should be:

- understandable and easy to use

and should support:

- varying levels of detail (qualitative→quantitative)
- varying scope (cross-cutting value as well as mission-specific value)
- development of models by distributed stakeholders
- multiple uses / answer multiple questions
- varying assumptions/priorities
- communication/debate/collaboration

Lessons learned...

- Model preferences of different stakeholders explicitly
- Allow for easy variation in assumptions ("what if our model is wrong? ...our estimates overly optimistic?")
- Compare impact of each technology to a no-investment baseline
- Make models modular and decoupled:
  technology investments →
    system characteristics →
      performance metrics →
        "return" or "mission value"
  (three arrows == three submodels)

End of workshop talk…

Full report is available at
http://support.thinkbank.com/essa-final

- **Chuck Weisbin**

Multi-Mission Strategic Technology Prioritization Study

C. R. Weisbin, G. Rodriguez, A. Elfes, J. Derleth, J.H. Smith, R. Manvi, B. Kennedy, and K. Shelton

"Systematic Technology Prioritization For New Space Missions"

Humphrey's Half Moon Inn, San Diego, CA

Jet Propulsion Laboratory
California Institute of Technology
April 22, 2004

Acknowledgements

- **C. Moore, Y. Gawdiak, D. Craig, M. Hirschbein for encouragement and support in undertaking this study**
- **M. Steiner, J. Azzolini for providing data about remote observation instrument technology**
- **P. Troutman for assisting in collection of data for the OASIS reference missions, and E. Kolawa for data about extreme environments**
- **S. Prusha for assisting in selection of ECS technologies to analyze; M. Feather for providing information about correlations of tasks and needs**

Study Staff & Roles

- **JPL**
  - J. Derleth, Mission & Technology Portfolio Optimization
  - A. Elfes, ECS Data & Analysis
  - B. Kennedy, ECT Data & Analysis
  - R. Manvi, Tech Life Cycle & Risk Management Model
  - K. Shelton, Mission & Technology Data Base
  - J. H. Smith, Integrated Risk Analysis
  - G. Rodriguez, System Analysis
- **GSFC staff** (M. Steiner, J. Azzolini, J. Mapar, C. Stromgren)

Study Objectives

- **Perform a pilot study of sufficient breadth which demonstrates in an auditable fashion how advanced space technology development can best impact future NASA missions**
  - Include wide spectrum of missions & technologies
  - Can add new missions & technologies easily
  - Optimize technology portfolios
  - Lead to rapidly prototyped example
- **Show an approach to deal effectively with inter-program analysis trades**
- **Explore the limits of these approaches and tools in terms of what can be realistically achieved (scope, detail, schedule, etc.)**

Technology Portfolio Optimization Approach

- Collect performance data for many individual technologies; each data input is viewed as a statistical sample representing an expert assessment
- Group the technological data into a tree-like hierarchical model to predict "integrated" system, mission, and multi-mission impact of individual technologies
- Search computationally for technology portfolios with optimal science return, risk and cost impact
- Investigate sensitivity of the optimal portfolio to changes in available budget levels

Major Study Challenges

- Reference Missions: assess mission value; characterize capability requirements
- Technology Projections: characterize performance; manage widely dispersed and non-uniform data
- Uncertainty: incorporate & manage widespread uncertainty
- ROI Measures: formulate suitable value function for portfolio analysis
- Layers of Abstraction: choose and maintain appropriate level of analytical abstraction
- Technological Boundaries: boundaries of technology domains not clearly marked
- Many Scales: large differences in cost and performance scales for different technologies
- Performance Parameters: not fully understood for some technologies
- .....

Implementation Approach

- **Iterative in three phases (keep eye on big picture early, and continuously)**
  - Phase 1 minimalist multi-mission set; ECT/ECS technologies
  - Phase 2 more extensive set of missions & technologies (June 04)
  - Phase 3 completion of full study (December 04)
- **Maintain high degree of connectivity**
  - Space Architect
  - Revolutionary Mission Concepts
  - Advanced Space Technology Programs
  - Enterprises
  - Centers
  - Etc.

Pilot Study Reference Missions

(Organized by Science-Site Location)

Pilot Study Reference Missions

- **Inner Solar System**
  - Venus Surface (1-site land)
  - Venus Surface (Multi-site-land)
  - Comet Sample Return
- **Earth Observation**
  - Biomass**
- **Earth's Moon**
  - OASIS*
  - Lunar Sample Return
  - Remote Lunar Survey**
  - Lunar Precursor Resource Survey
- **Mars**
  - Mars Science Lab
  - Mars Scout Line
  - Mars Astrobiology Lab
  - Mars Sample Return
- **Outer Solar System**
  - Titan Surface
  - Europa Lander

➢ Initial reference mission set as of April 15, 2004

➢ More missions and enabling technologies will be added throughout the period of performance of the study

* OASIS is a near Earth transportation infrastructure that enables access to the Moon. It consists of: a Hybrid Propellant Module, a Chemical Propulsion Module, a Solar Electric Propulsion Module, and a Crew Transport Vehicle.

** GSFC contribution to this study focuses on these missions

Reference Missions & Major Challenges

(Minimalist Mission Set for PHASE I)

Reference Mission Classes (not listed in order of priority)	Major Challenges
Earth's Moon: Orbital Aggregation and Space Infrastructure Systems (OASIS); Lunar Remote Survey; Lunar Surface Missions; etc.	Deep Space Robotic Rendezvous & Docking; Long Term Cryogenic Fuel Storage in Space (>2 years); Long Life Ion Engines(>15 K-hours)
Mars Surface: (e.g. Mars Science Laboratory; Astrobiology Field Lab; Mars Sample Return; etc.)	Long-Range, Long-Life Mobility (10's of kilometers, >600 sols); Substantive Sample Collection and Return (>1kg, 0<depth<100m subsurface)
Earth Observation: Biomass	Lidar/Radar Instrument Systems; Multi-Spectral Scanner; Sensor Webs & Data Fusion
Outer Solar System: Titan Surface; Europa Lander	Extreme Environments; Sub-Surface Ice Mobility
Inner Solar System: Venus surface; comet sample return	Extreme Environments (460C temp; 90 bar pressure; sulfuric acid clouds at 50 km)

➢ **Technologies to be evaluated will include:**

- Technological products in several discipline fields (aimed at operational flight system implementation (e.g. advanced materials, structures, etc.)
- Risk assessment tools and infrastructure to allow for risk quantification, and risk mitigation during an entire mission life-cycle, but that do not necessarily appear in the flight system implementation (e.g. risk management methods)

Enabling Technologies for Which Data Has Been Collected to Date

- **Extreme Temp & Pressure Components, Thermal Control, Pressure-Vessel-Encapsulated Electronics (Venus)**
- **Electric & Chemical Propulsion; Reaction Control; Multifunction Structures; Fuel Storage & Control; Syntactic Foams, Formation Flying (OASIS)**
- **Entry Descent & Landing; Surface,Aerial,Subsurface Mobility; Manipulation, Drilling, Sampling (Mars, Titan, Comet, Lunar Surface)**
- **In-Space Inspection, Maintenance, Assembly (OASIS, Large Observatory Platform, Gateway, Space Solar Power)**
- **Risk Methods, Tools and Workstation; Mishap Anomaly Data Base; Complex Systems Research; Risk Characterization & Visualization; etc. (All Reference Missions)**

Enabling Technology Areas

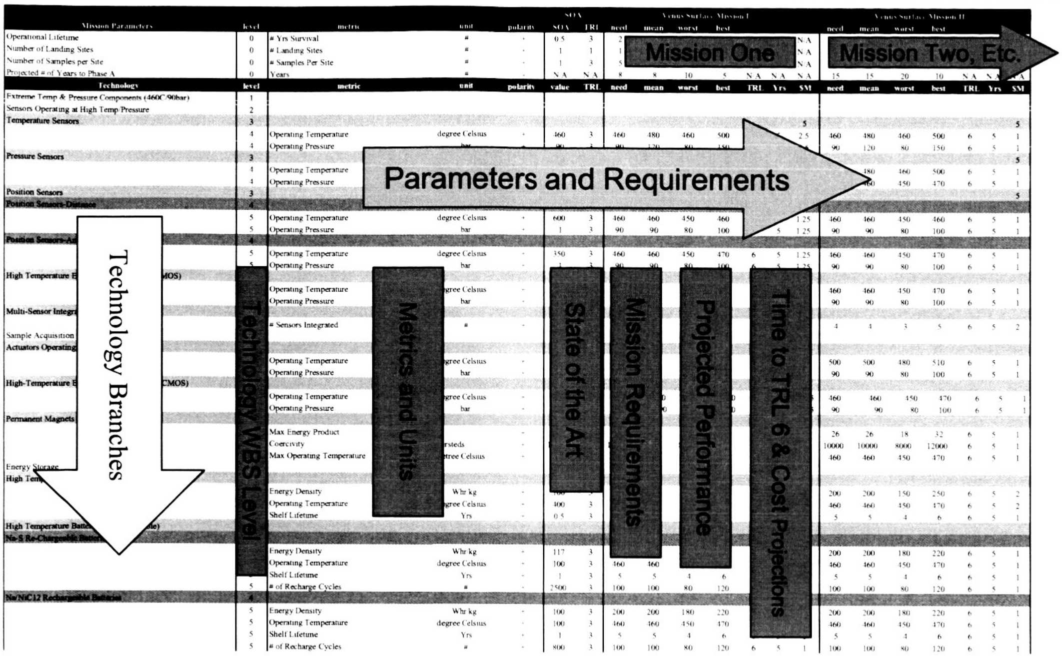
(for which data has been collected to date)

Enabling Technology Areas	Missions
Electric & Chemical Propulsion; Reaction Control; Multifunction Structures; Fuel Storage & Control; Syntactic Foams, Formation Flying; In-Space Robotic Inspection, Maintenance, Assembly	OASIS
Entry Descent & Landing; Surface, Aerial,Subsurface Mobility; Manipulation, Drilling, Sampling	Mars, Earth's Moon, Titan, Comet
Risk Methods, Tools & Workstation; Mishap Anomaly Data Base; Complex Systems Research; Risk Characterization & Visualization; etc.	All
Extreme Temp & Pressure Components, Thermal Control, Pressure-Vessel-Encapsulated Electronics	Venus, Titan, Europa

Technology Areas are Decomposed into Many Sub-Areas & Performance Parameters

A Few Typical Technology Areas	A Few Typical Technology Sub-Areas	A Few Typical Performance Parameters
Multi-Function Structures	Modular, Distributed Structures, Deployable Structures, etc.	Contract/Extend (cm), Power per Mass (W/kg), etc.
Fuel Storage & Control	On Orbit Cryrogenic Fuel Transfer, Tank Pressure Control, Fuel Storage, etc.	Flow Rate (kg/min), Pressure (kPa), Time (yrs), etc.
Subsurface Ice Mobility	Range, Radiation Dose, Payload Capacity, Ambient Pressure, etc.	Distance (km, mRads), Mass (kg), Pressure (atm), etc.
Extreme Temperature & Pressure Components	High Temperature Electronics, Permanent Magnets, Energy Storage, etc.	Temperature (Celsius), Pressure (Bars), Energy Density (Whr/l) etc.
Risk Methods, Tools & Workstation	Model Based Risk Analysis, Mission Risk Profiling Capability, etc.	Accessibility, applicability to multiple mission phases, risk mitigation coverage

Mission & Technology Data Base



This is an early draft for April 15th, 2004. Please do not distribute.

Mission & Technology Data Base

-- Current Size Summary --

- **Size of Mission & Technology Capability Data Base (as of April 15, 2004)**
  - 13 missions covering wide spectrum of NASA strategic plans
  - 23 technology areas (structures, energetics, extreme environments, surface mobility, etc.)
  - 86 technology sub-areas (batteries, payload capacity, thermal control, etc.)
  - 167 technological performance parameters (power density, operating temperature, etc.)
- **Remarks About Data Base**
  - Current data set is more detailed in some areas than in others
  - More technologies & detail will be collected in subsequent phases
  - Our analysis methods can handle data sets with non-uniform detail

This is an early draft for April 15th, 2004. Please do not distribute.

Risk Related Requirements

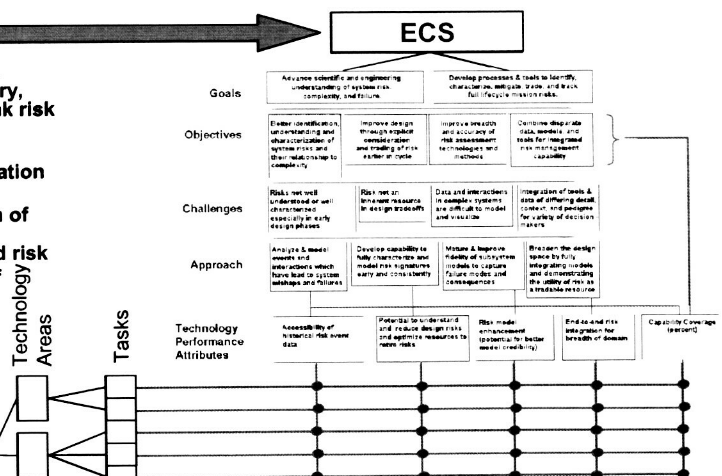
(from Point of View of a Project Manager)

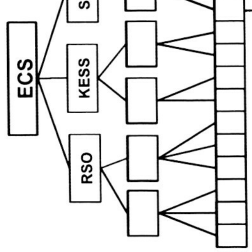
- **Risk Management Must:**
  - Delineate major risks: Technical, Human, Organizational, Budgetary, and Schedules ;estimate and rank risk levels
  - Provide ways to visualize risk elements, time profile, and mitigation strategies
  - Assure that the systems and trade analysis includes cost, performance, and risk
  - Provide auditable benefit/cost of implementing begin-to-end risk mitigation strategies

Connecting Risk Technologies to Requirements

Requirements:

- ❑ **Delineate major risks: Technical, Human, Organizational, Budgetary, and Schedules; estimate and rank risk levels**
- ❑ **Provide ways to visualize risk elements, time profile, and mitigation strategies**
- ❑ **Assure that a substantial portion of the design space is explored including cost, performance, and risk**
- ❑ **Provide auditable benefit/cost of implementing end to end risk mitigation strategies**





ECS: Engineering of Complex Systems

➢ SRRM: System Reasoning and Risk Management

- KESS: Knowledge Engineering for Safety and Success
- RSO: Resilient Systems and Operations

System Reasoning and Risk Management (SRRM) Project Executive Summary

Goals	Advance scientific and engineering understanding of system risk, complexity, and failure.		Develop processes & tools to identify, characterize, mitigate, trade, and track full lifecycle mission risks.		
Objectives	Better identification, understanding and characterization of system risks and their relationship to complexity	Improve design through explicit consideration and trading of risk earlier in cycle	Improve breadth and accuracy of risk assessment technologies and methods	Combine disparate data, models, and tools for integrated risk management capability	
Challenges	Risks not well understood or well characterized, especially in early design phases	Risk not an inherent resource in design tradeoffs	Data and interactions in complex systems are difficult to model and visualize	Integration of tools & data of differing detail, context, and pedigree for variety of decision - makers	
Approach	Analyze & model events and interactions which have lead to system mishaps and failures	Develop capability to fully characterize and model risk signatures early and consistently	Mature & improve fidelity of subsystem models to capture failure modes and consequences	Broaden the design space by fully integrating models and demonstrating the utility of risk as a tradable resource	
Technology Performance Attributes	Accessibility of historical risk event data	Potential to understand and reduce design risks and optimize resources to retire risks	Risk model enhancement (potential for better model credibility)	End-to-end risk integration for breadth of domain	Degree of Alignment (Effectiveness in percent)

Attribute Definitions

Accessibility of risk data	Best Case	10	Easy to use DB spans multiple mission/projects with risk events categorized for search.
		5	DB may be limited to specific category or series of missions.
	Worst Case	0	Supporting data/verifications are anecdotal (narrative) format without categories of risk events for easy search. May require further processing to another format.
Potential to reduce design risks	Best Case	10	Technology helps to identify and reduce risks during early phases of project (Phase A/B) with potential to dramatically reduce overall project costs by reducing rework.
		5	Technology helps identify/reduce mission risks for Phase C/D; Large potential cost benefits if used. Provides a screen that limits potential risks from passing CDR.
	Worst Case	0	Technology helps identify technology development or subsystem risks, but may or may not influence overall system risk.
Risk model enhancement	Best Case	10	Technology provides new approach for addressing design risk life-cycle or part of life-cycle not previously addressed (e.g., mgmt, org. risks)
		5	Technology either provides new, more effective approach for risk analysis or fills missing gap in temporal or breadth of risk analyses (but not both)
	Worst Case	0	Technology does not address missing gap in design life-cycle.
End-to-end risk integration	Best Case	10	Technology provides synergistic integration with other tools and databases fully compatible with emerging design environments (temporal and breadth).
		5	Risk technology allows interaction with common databases but cannot be integrated with other stand-alone applications.
	Worst Case	0	Technology is stand-alone; focused, narrow; little breadth or temporal range, databases are separated with little or no connectivity. Integration difficult.

All SRRM Technology Areas Are Included for the Pilot Study

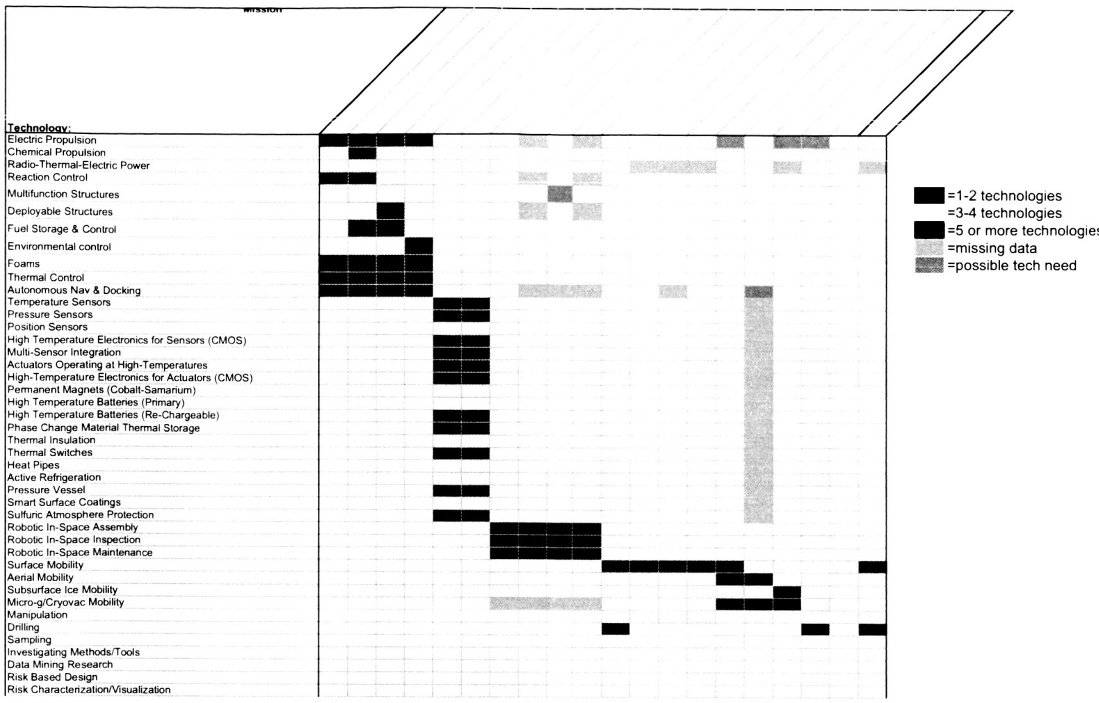
1. Risk Methods/Tools (RMT)
2. Risk Workstation (RWS)
3. Mishap/Anomaly Database (MAIS)
4. Model-Based Hazard Analysis (MBHA)
5. System Complex Research (SCR)
6. Risk Characterization/Visualization (RCV)
7. Risk-Based Design (RBDO)
8. Data Mining Research (DMR)
9. Investigation Methods/Tools (IMT)

Typical SRRM Technology Area Data*

Technology	Level	Metric	Unit	Polarity	SOA	Low	ML	High	$M
		How performance is measured	What unit performance is measured in	+ = Better if performance is higher - = Better if performance is lower	Current state-of-the-art for similar technologies	Technologist's estimate of low, most likely, and high values of what will be provided to the mission			How much the technologist needs to achieve TRL 6 in $M
ECS	1								
SRRM	2								
RISK Methods & Tools	4	Accessibility of Historical Risk Event Data	0-10	+	4	7	8	9	2
		Potential to Understand and Reduce Design Risks and Optimize Resources to Retire Risk	0-10	+	1	7	8	9	
		Risk Model Enhancement (Potential for Better Model Credibility)	0-10	+	2	9	10	10	
		End-to-end Risk Integration for Breadth of Domain	0-10	+	2	8	9	10	
		Extent of Needs Covered	0-1	+	0.5	0.7	0.8	0.9	

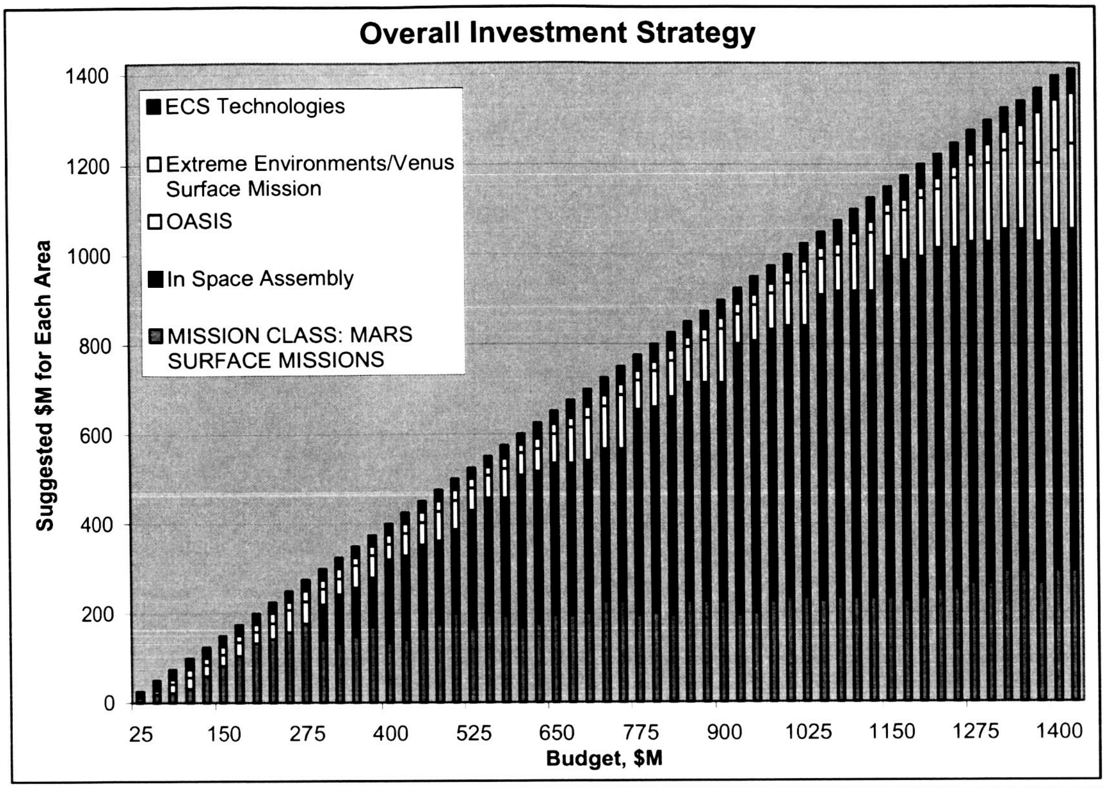
*SRRM data cast in same format used for all other technologies (shown in slide 14)

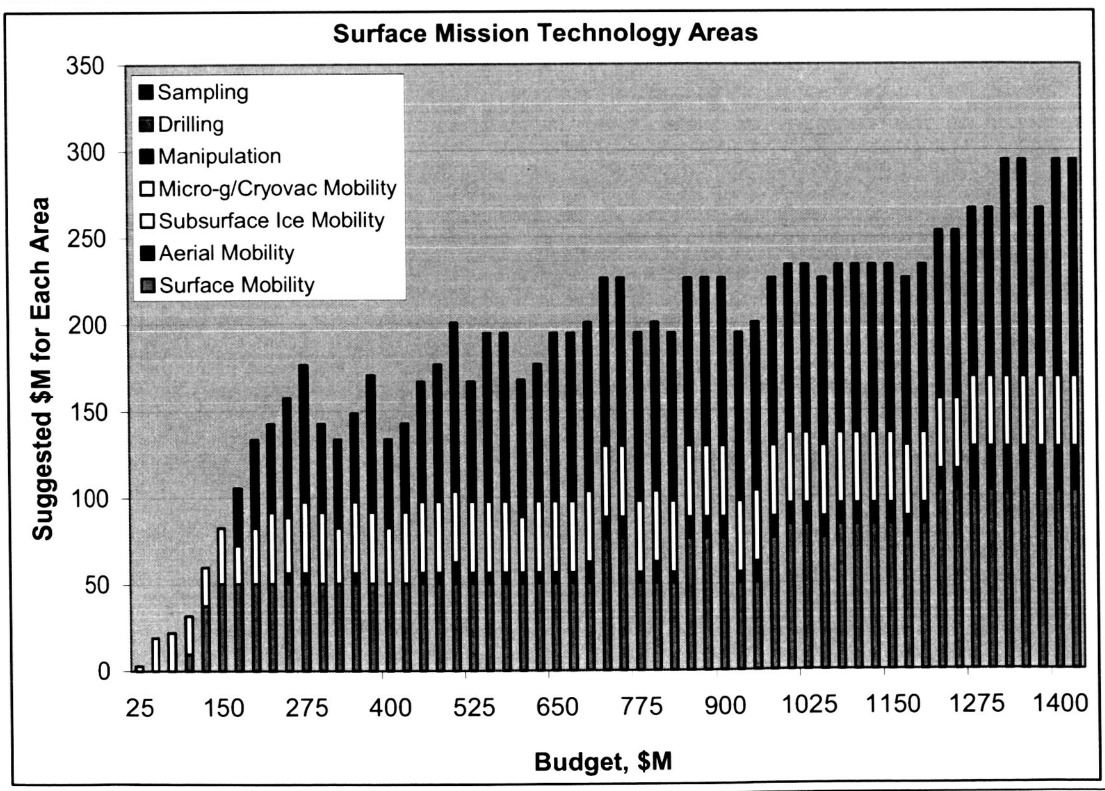
Mission-Technology Complexity Map

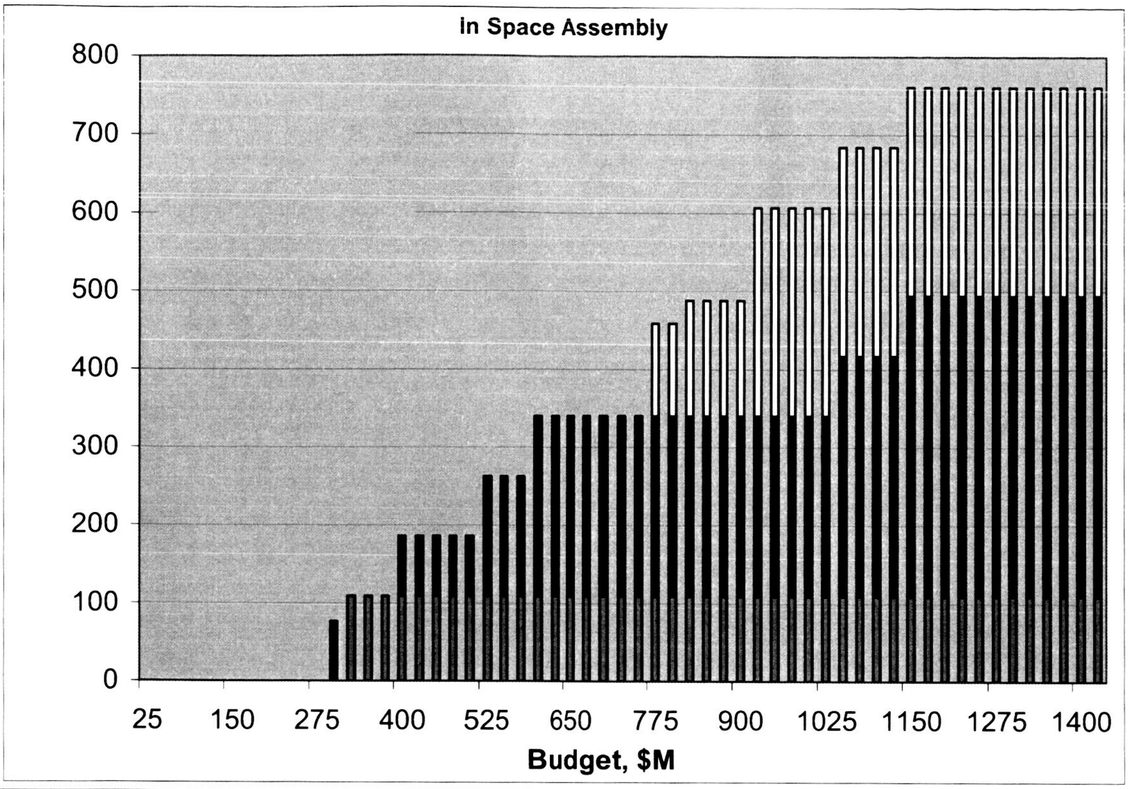


Analysis Options Used to Get Typical Results in Slides 25-30

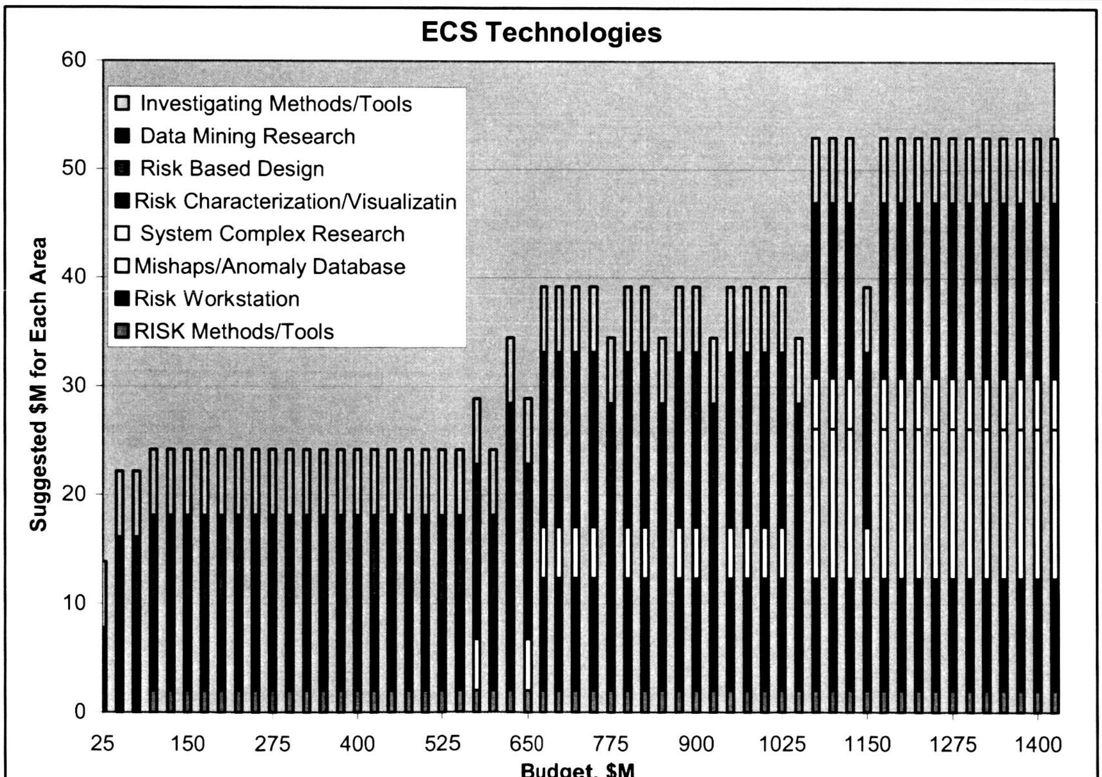
Analysis Options Used	Other Options Available
Uniform science-return value for all missions	Can assign non-uniform science return value (user prescribed)
Uniform value for all technologies at the same hierarchical level; "democratic" hierarchy	Can prescribe general technology organizations; based for example on mission and system decomposition
Technology correlations and co-dependencies set to zero	Can explicitly include correlation & co-dependency parameters when available
Risk estimates based only on performance uncertainty	Can include cost, schedule and other risk factors
Identical development time (~10 yrs) for all technologies	Can vary technology development time as a model parameter
TRL data not included in technology projections	Can analyze TRL data within existing analysis framework


Overall Investment Strategy
ECS Technologies
Extreme Environments/Venus Surface Mission
OASIS
In Space Assembly
MISSION CLASS: MARS SURFACE MISSIONS
Suggested $M for Each Area
0
200
400
600
800
1000
1200
1400
25
150
275
400
525
650
775
900
1025
1150
1275
1400
Budget, $M

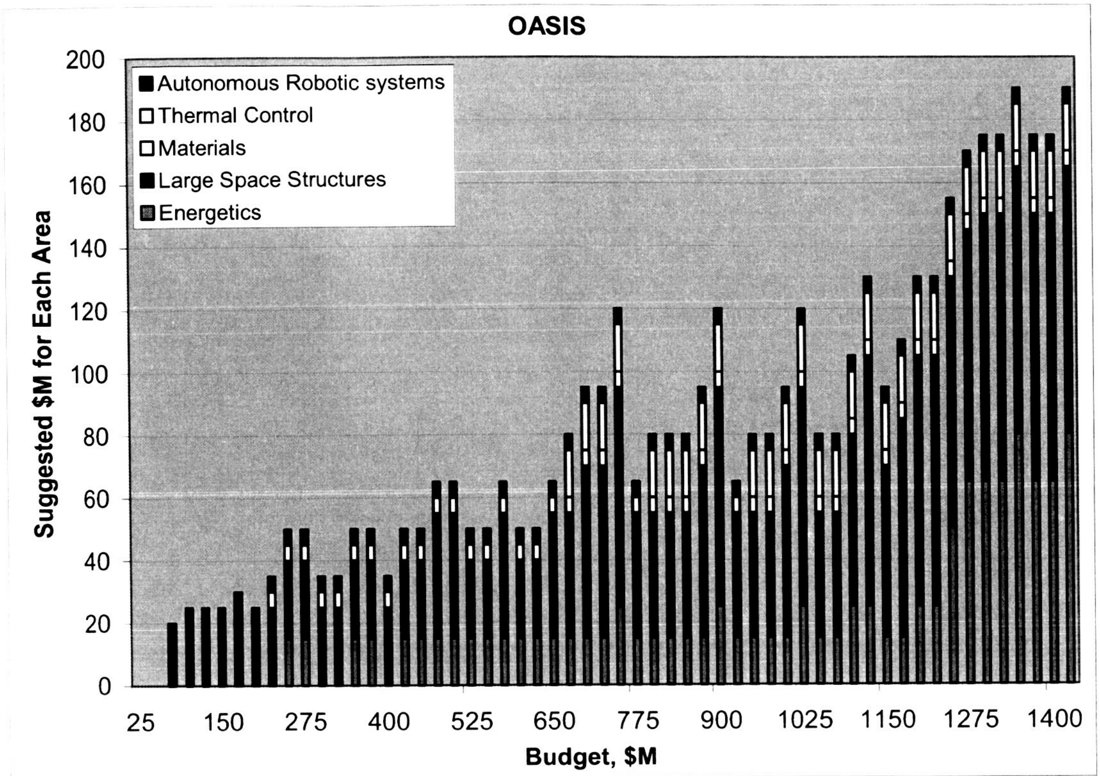

Surface Mission Technology Areas
Sampling
Drilling
Manipulation
Micro-g/Cryovac Mobility
Subsurface Ice Mobility
Aerial Mobility
Surface Mobility
Suggested $M for Each Area
0
50
100
150
200
250
300
350
25
150
275
400
525
650
775
900
1025
1150
1275
1400
Budget, $M

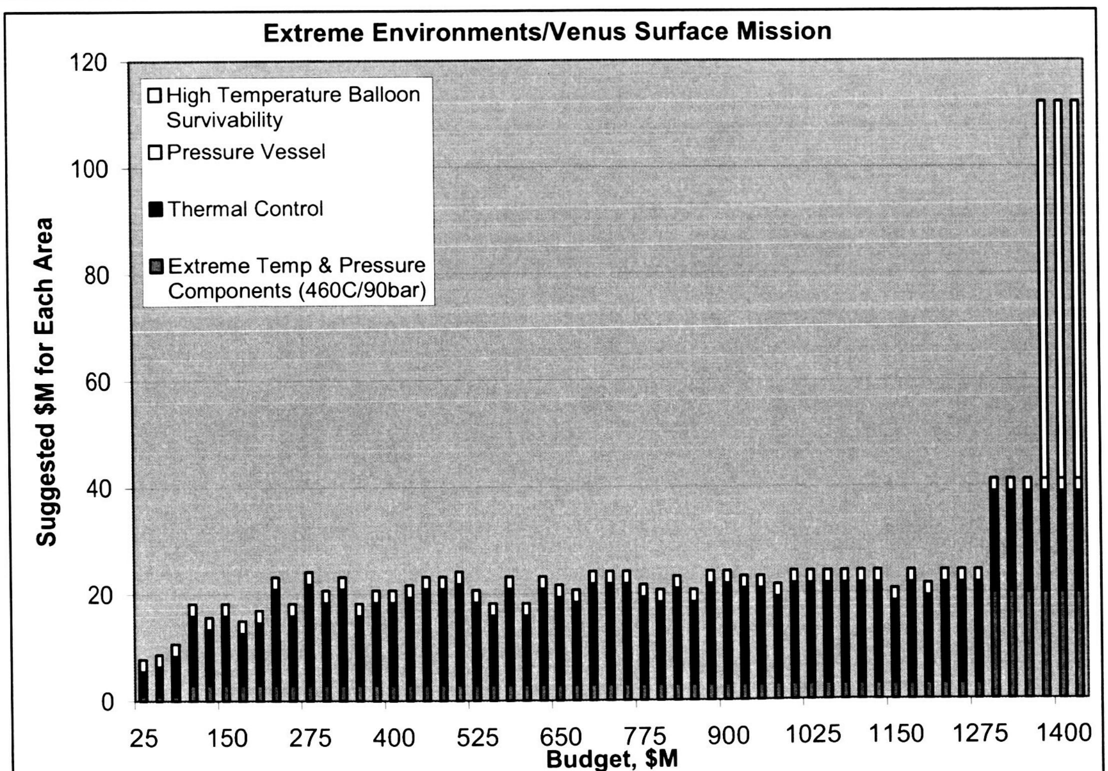


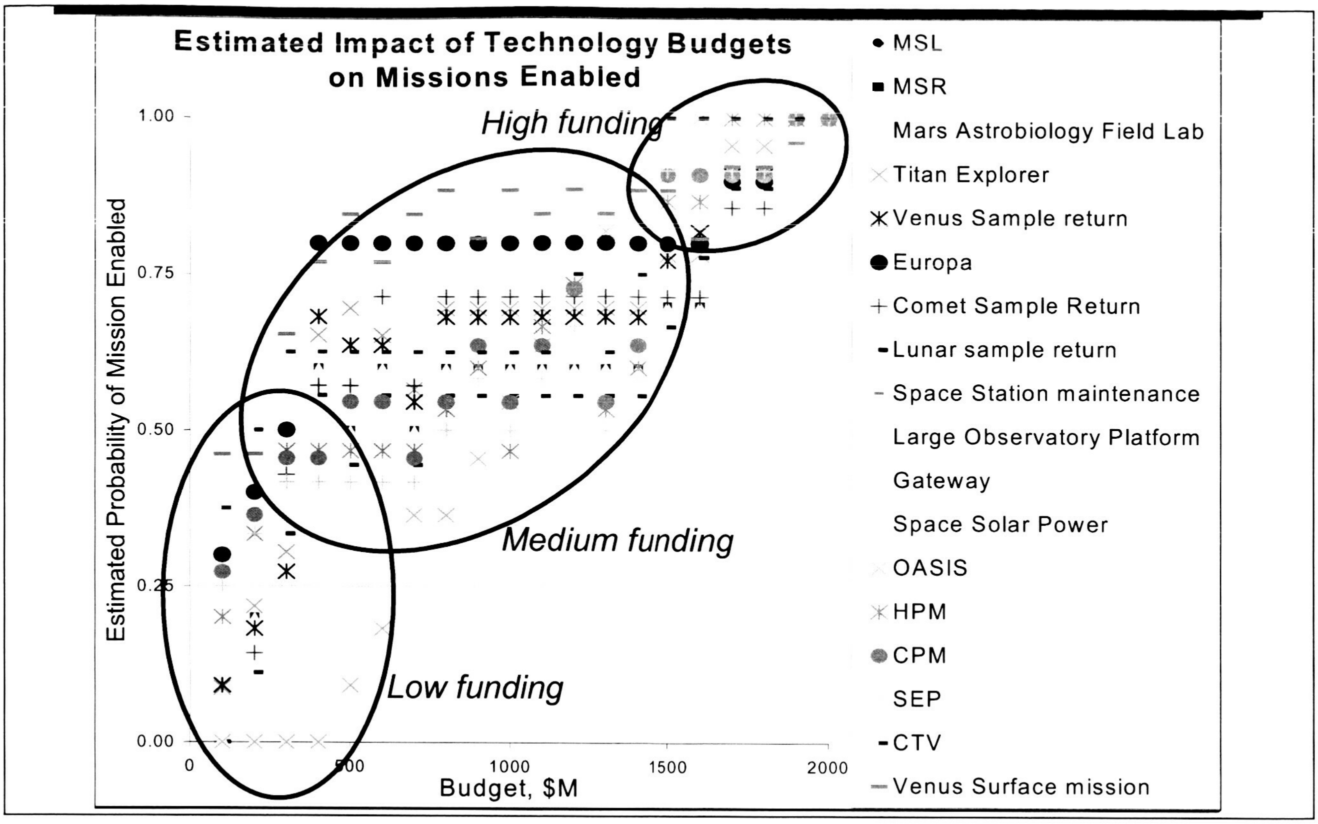
In Space Assembly
800
700
600
500
400
300
200
100
0
25
150
275
400
525
650
775
900
1025
1150
1275
1400
Budget, $M

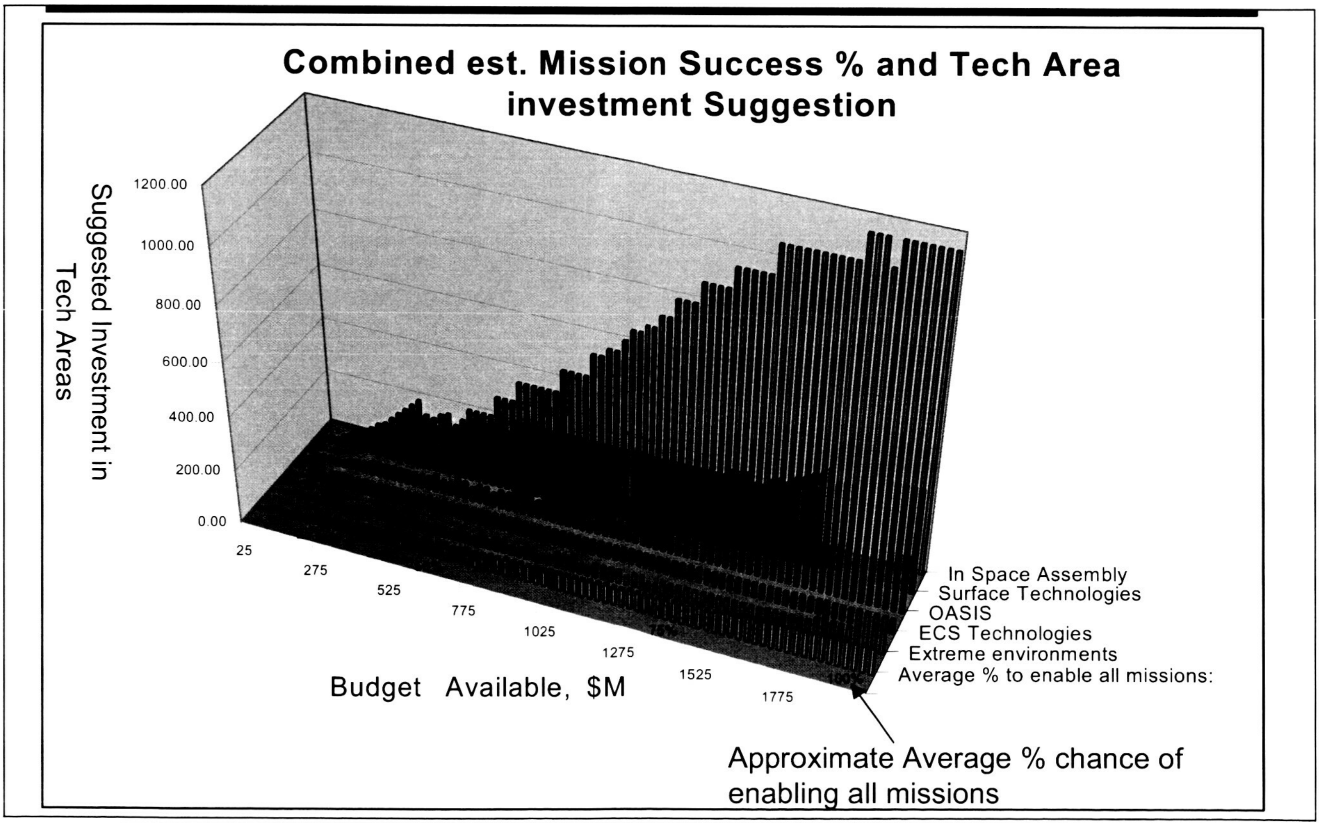


ECS Technologies
Investigating Methods/Tools
Data Mining Research
Risk Based Design
Risk Characterization/Visualizatin
System Complex Research
Mishaps/Anomaly Database
Risk Workstation
RISK Methods/Tools
Suggested $M for Each Area
60
50
40
30
20
10
0
25
150
275
400
525
650
775
900
1025
1150
1275
1400
Budget, $M


OASIS
Autonomous Robotic systems
Thermal Control
Materials
Large Space Structures
Energetics
Suggested $M for Each Area
200
180
160
140
120
100
80
60
40
20
0
25
150
275
400
525
650
775
900
1025
1150
1275
1400
Budget, $M


Extreme Environments/Venus Surface Mission
High Temperature Balloon Survivability
Pressure Vessel
Thermal Control
Extreme Temp & Pressure Components (460C/90bar)
Suggested $M for Each Area
120
100
80
60
40
20
0
25
150
275
400
525
650
775
900
1025
1150
1275
1400
Budget, $M


Estimated Impact of Technology Budgets on Missions Enabled
High funding
Medium funding
Low funding
Estimated Probability of Mission Enabled
1.00
0.75
0.50
0.25
0.00
0
500
1000
1500
2000
Budget, $M
MSL
MSR
Mars Astrobiology Field Lab
Titan Explorer
Venus Sample return
Europa
Comet Sample Return
Lunar sample return
Space Station maintenance
Large Observatory Platform
Gateway
Space Solar Power
OASIS
HPM
CPM
SEP
CTV
Venus Surface mission


Combined est. Mission Success % and Tech Area investment Suggestion
Suggested Investment in Tech Areas
1200.00
1000.00
800.00
600.00
400.00
200.00
0.00
25
275
525
775
1025
1275
1525
1775
Budget Available, $M
In Space Assembly
Surface Technologies
OASIS
ECS Technologies
Extreme environments
Average % to enable all missions:
Approximate Average % chance of enabling all missions

Concluding Remarks

- **Study Results to Date (January-March, 2004)**
  - Initial data base for 13 missions and 167 technology performance parameters in 23 technical areas, representing Code T,S,M,Y enterprises
  - Rapidly prototyped analysis capability to evaluate impact of technological investment on science and exploration return
- **Work Remaining (April-December, 2004)**
  - Expand data base to include more enabling missions and technologies (e.g. modular distributed structures, etc.)
  - Conduct more in-depth analysis of the representation and fidelity of the existing data set, and a more detailed treatment of the consistency and integration across program elements
  - Calibrate data base and analysis with extensive WHAT-IF computational

Appendix B: Records of Group Discussions

- **Questions for Working Groups**

Questions for Working Groups

1. **In prioritizing technology development for missions, how should the relative values of the missions be assessed and quantified?** (one measure of relative worth is the value that NASA is willing to pay for these missions, but there may be better figures of merit in terms of information returned? How do you compare value of technology supporting Station to that supporting Mission to Planet Earth? Within Space Science, how would the value technology contribution to a Mars sample Return be compared to that which supports a Europa mission?

Possible Answers

1. **Should mission (= flight project) value be assessed at all?**
   - Value is always assigned: current processes do this in a non-traceable, non-auditable way.
   - Has to be done, so that we can improve on today's process.
   - Difference between valuation theory and results vs. x decision-makers final assessment.
2. **Who should do it? Can it be done? (problem of different stakeholders)**
   - Code B assesses relative value of missions (they allocate resources to Enterprises):
     - Ex: 18 theme areas and 3 mission areas: high, medium, low ranking.
   - Enterprises: Code B apportions resources as a block to Enterprises
     - Enterprises prioritize missions
   - Executive Council, Joint Strategic Assessment Committee.
     - Science Groups/Project Managers: Prioritize missions.

Possible Answers

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Questions for Working Groups

2. **There are many architectures that might purport to enable a mission concept, but at the early formulation stage, how might we best select among them, and perform a functional decomposition to determine quantified capability requirements?**
   - How do we get functional requirements at pre-phase A stage?
   - Are there better ways to define the science/ops interface than fitting the boxes a posteriori?

Possible Answers

1. **Is it possible to obtain mission capability requirements at this stage?**

    - Science mission concepts are typically more mature/have clearer objectives than human missions.
    - Assume new undefined missions requirements can be drawn from a spectrum of past missions
    - Assume that the requirements evolve from the technological state of the art (technology push) and iterate

2. **Advantages and disadvantages of requirements**

    - "Requirements" are not ironclad, have to be negotiable. Requirements have to be coupled with affordability and serve as a basis for negotiation.
    - Requirements should be expressed quantitatively. Requirements are different from specs. Quantification of requirements brings problems, but also allows one to know when one is done.

Possible Answers

3. **Defining mission concepts involves working in a very large trade space. How do you search it?**

    - Search trade space hierarchically, keeping the number of options low at each level.
    - Delay decisions on final designs: NASA tends to dive into a specific point design too early. A more extensive assessment of the trade space, keeping uncertainties and open options, allows a broader, more valuable set of technologies to be developed. On the other hand, there are huge costs associated with keeping options open.

4. **What technologies should be funded?**

    - General technology areas can be extracted from early mission concepts, and these should be funded.
    - Insist that each mission concept study provides one or more functional decompositions (stored in a database). Since there is only a limited number of feasible architectures, they can be specified and a common set of relevant technologies extracted. Also identify key enabling technologies and perform gap analysis.
    - Sustainability is essential, not just affordability. Reusability: define/develop technology building blocks that can be "robust" and used across different missions. Avoid cutting off early promising technology paths. Temporal impact of technologies has to be taken into account.

Questions for Working Groups

3. **How do we systematically acquire credible information on technology development (cost/performance estimates and associated uncertainty, temporal and functional correlations etc.) which might seek to satisfy capability requirements.**

Possible Answers

- Add extra fields as part of the Technology Inventory collection process
- Augment the existing CRAI activity with independent review.
- Examine the limits of what might be feasible; remember to strive for plausibility not perfect accuracy
- Have NASA pay for this data acquisition as part of system studies
- Develop models based on historical data

Questions for Working Groups

4. **What is the best methodology to perform technical risk assessments and mitigations; is the evaluation of these fundamentally different from the discipline product technologies (e.g. sensing, manipulation, mobility etc.).**

Possible Answers

- Based on experience, assess the objectivity and usefulness of quantitatively measuring relative reliability gain associated with improved risk methodologies
- Based on mission experience, determine whether new risk methodologies are needed.
- Risk technologies Can/Cannot be blended uniformly into a prioritization methodology

Questions for Working Groups

5. What are the criteria management needs to take and use the results of such a structured analysis.

Possible Answers

- Need a sense of confidence in the overall mission requirements and technological characterization
- Consistency with the unstated policies from NASA (re: value, pull/push,etc.)
- Timely response
- Data acquisition process needs to be feasible from the viewpoint of overall effort.

- **Questions – Day 1**

- **How do we systematically acquire credible information on technology development (cost/performance estimates and associated uncertainty, temporal and functional correlations, etc.) which might seek to satisfy capability requirements?**
  - Credible: presentation would be plausible as seen by an independent review team

- **Are the data models and assumptions traceable and transparent?**
  - Workshop for credibility review
  - Peer reviews/third party teams
  - Explicit inclusion of uncertainty for high risk or non-legacy items
  - Matching capability requirements to technology tasks
- **Sustainable process? (i.e., are iterations easier than first bounce?)**
  - POP process as a vehicle for data generation -- incentives for proper behavior
  - Continuing reevaluating process
  - Quarterly review with researchers and mission experts
- **Are all valid viewpoints considered?**
- **Do you have an estimate of the robustness of the conclusions?**
- **Do independent review teams have recommendations?**

B. What is the best methodology...

- **How can the representation and assessment of risk estimation/software technologies be made consistent with those of the discipline product technologies (e.g., sensing, manipulation, mobility, etc.)?**
  - Important to have researchers state what kind of metric they hope to impact; missions should provide goals
  - Look at cost impacts as well as performance impacts
  - Combine software and hardware at a capability level as opposed to a discipline level
  - State-of-the-art *can* be characterized, but perhaps the whole 'ecosystem' of software should be looked at, not, for instance, an algorithm...

C. What are the criteria that management needs...

- **What are the criteria that management needs to take and use the results of such a structured analysis?**
  - Analysis has to support/defend the eventual decision to OMB and GAO and others
    - Traceable, transparent, understandable, presented in a concise way
    - Make issues explicit, identify problem areas
  - Analysis has to address what the decision maker cares about -- metrics, alternatives, etc.
  - Context is *decision support*
    - Cast as risk vs. cost; benefit vs. cost;
    - Provide options - not point solutions
      - Preferably with recommendations and justifications (not just negatives and consequences); span decision space
    - Digestible products tuned to appropriate level

- **Questions – Day 2**

Questions-Day 2

- ➢ **In prioritizing technology development for missions, how should the relative values of the mission be assessed or quantified?**
- ➢ **There are many architectures that might purport to enable a mission, but at the early formulation stage, how might we best select among them, and perform a functional decomposition to determine quantified capability requirements?**

How should the relative values of the missions be assessed?

- ➢ **In prioritizing technology development for missions, how should the relative values of the missions be assessed or quantified?**
  - "All missions are equal; some are more equal than others"
  - Aim for functional objectives
  - Missions fit under some exploration obj. Need a way to handle different msn approaches
  - Start with unity
  - Then apply dollar values to missions
  - Mission value parametric and subject to multiple interpretation
    - Position in launch queue
    - Normalize all to one
    - Alternative assumptions...etc.
    - Point is they can be varied

Architecture selection; functional decomposition

- **There are many architectures that might purport to enable a mission, but at the early formulation stage, how might we best select among them, and perform a functional decomposition to determine quantified capability requirements?**
- **Missions map to technologies that map to metrics**
- **Architectures are snapshots of different technology metric sets**
- **Compare the architectures indirectly by evaluating their technology portfolios and costs.**

Architecture selection; functional decomposition

- **Functional decomposition derived from mapping of mission capability requirements to technology metrics.**
  1. Obtain capability requirements from mission(s) to level available
  2. Get technology gaps from mission
  3. Map relevant technologies to capability requirements
  4. Derive performance metrics for technologies
  5. Evaluate fulfillment of requirements by performance (simulation, modeling, figures of merit)
  6. Weight by parametric mission values; sensitivity analysis
- **Don't over-weigh optimizations but consider level of precision; reserve some fraction for visionaries and spontaneous discoveries**
- **Consider approaches from other sectors (gov't., non-NASA, public, etc.)**

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13. ABSTRACT *(Maximum 200 words)*

A workshop entitled, "Outstanding Research Issues in Systematic Technology Prioritization for New Space Missions," was convened on April 21-22, 2004 in San Diego, California to review the status of methods for objective resource allocation, to discuss the research barriers remaining, and to formulate recommendations for future development and application. The workshop explored the state-of-the-art in decision analysis in the context of being able to objectively allocate constrained technical resources to enable future space missions and optimize science return. This article summarizes the highlights of the meeting results.

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