Solar System Planetary Science Decadal Survey and Missions in the Next Decade, 2013–2022

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Abstract—In 2010, the National Research Council Space Studies Board [1] established a decadal survey committee to develop a comprehensive science, mission, and technology strategy for planetary science that updates and extends the Board's 2003 Solar System Exploration Decadal Survey, "New Frontiers in the Solar System: An Integrated Exploration Strategy [2]." The scope of the survey encompasses the inner planets (Mercury, Venus, and Mars), the Earth's Moon, the giant planets (Jupiter, Saturn, Uranus, and Neptune), the moons of the giant planets, dwarf planets and small bodies, primitive bodies including comets and Kuiper Belt objects, and astrobiology.

Over this past year, the decadal survey committee has interacted with the broad solar system science community to determine the current state of knowledge and to identify the most important scientific questions expected to face the community during the interval 2013–2022. The survey has identified candidate missions that address the most important science questions and has conducted, through NASA sponsorship, concept studies to assess the cost of such missions as well as technology needs.

The purpose of this paper is to provide an overview of the 2012 Solar System Planetary Science Decadal Survey study approach and missions that were studied for implementation in the upcoming decade.[1,2] Final results of the decadal survey, including studies that were completed and the specific science, programmatic, and technology recommendations will be disclosed publically in the spring of 2011 and are not the subject of this paper.

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[2] IEEEAC paper #1072, Version 1, Updated October 14, 2010

1. INTRODUCTION

This Planetary Science Decadal Survey (PSDS) is the second such decadal survey to be undertaken. The initial survey was completed in 2003 and established priorities that drove the NASA planetary program [3]. With reference to the prior survey, the current committee indicated that those recommendations would be honored unless there is a compelling reason to overturn those results.

The survey is aimed at articulating a solar system program for the coming decade that represents as fully as possible the true consensus view of the planetary science community. The principal components of the survey report include:

- An overview of planetary science—what it is, why it is a compelling undertaking, and the relationship between space- and ground-based planetary science research;
- A broad survey of the current state of knowledge of the solar system;
- An inventory of the top-level scientific questions that should guide flight programs and supporting research programs;
- Recommendations on the optimum balance among small, medium, and large missions and supporting activities, informed by the Board's study on this topic ("mission-enabling activities") currently in progress;
- An assessment of NSF-supported infrastructure;
- A discussion of strategic technology development needs and opportunities;
- A prioritized list of major flight investigations in the New Frontiers and larger classes recommended for initiation over the decade 2013–2022;
- Recommendations for supporting research required to maximize the science return from the flight investigations; and,
- A discussion of the opportunities for conducting science investigations involving humans *in situ* and the relative value of human-tended investigations to those performed solely robotically.

Table 1. Schedule of Activity

	2008	2009	2010	2011
1st Quarter		• Funding received, chair identified, chair and vice chair appointed	• Mission studies continue	• Report approved, NASA briefed, and report released (pre-publication format)
2nd Quarter		• Steering group appointed, panels appointed	• Final panel meetings, panel reports finalized • Prioritization and drafting of survey report	
3rd Quarter		• Meetings of steering group and panels begin	• Prioritization and drafting of survey report (continued)	• Printed report released
4th Quarter	• Informal request received, NRC approves initiation • Formal request received, proposal to NASA	• Panels' period of peak activity, mission studies begin, proposal to NSF, contract with Aerospace Corporation for independent cost estimates (ICEs).	• Draft survey report to reviewers, report revised	

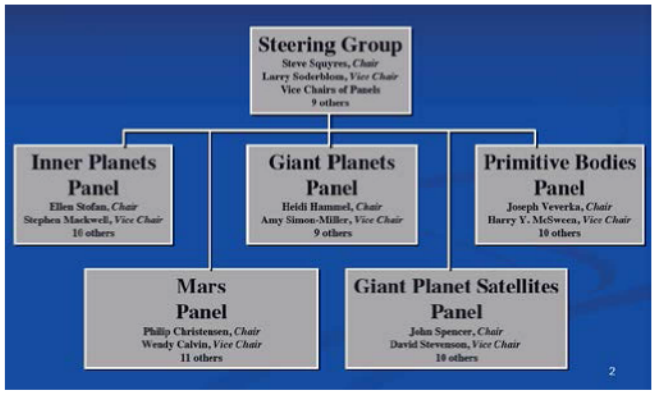

Figure 1. Planetary Science Decadal Survey panels

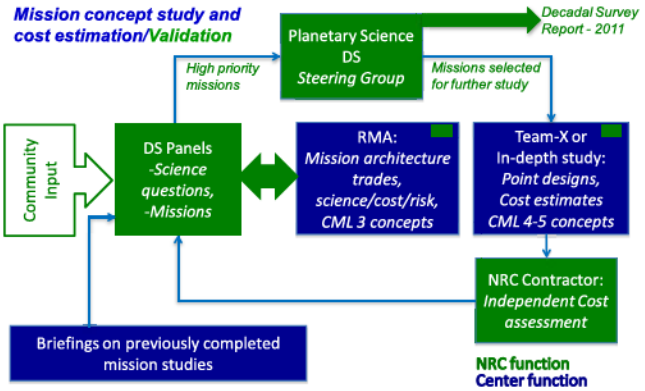

Figure 2. Funded studies were part of the PSDS approach to achieve cost realism

This new decadal survey, like its predecessor, has been conducted by a steering committee supported by topical panels as shown in Figure 1. The schedule of activity is shown in Table 1.

Results of the survey are planned to be released in the second quarter of 2011 as shown in the schedule above.

2. Overview of Study Approach

In contrast to the 2003 decadal survey, this survey places a much stronger emphasis on cost realism. To achieve this, funded studies were conducted by JPL, APL, and GSFC, in accordance with ground rules agreed to by NASA and the PSDS steering group, and estimated mission costs were independently assessed by the Aerospace Corporation (Figure 2). Study results were used as the basis for the survey panel recommendations. This section describes the approach used to conduct the funded studies.

As shown in Figure 2, the funded studies included the following methods, which span a scale of concept maturity levels (CMLs) from 2–5 (CML is described later in this section):

- **Rapid Mission Architecture (RMA):** Architectural trade study at CML 2–3 to determine the most promising mission architectures for further study and point design.
- **Team X:** Point-design concept study and cost estimates at CML 4.
- **In-depth studies:** Higher fidelity extension of Team X point-design concept studies approaching CML 5.
- **Other studies:** Focused science target and technology assessment studies ranging from CML 2–4. These studies utilized their own process tailored to the required output and are not described in this paper.

Concept Maturity Level

A key challenge facing the PSDS was to translate an inventory of the top-level scientific questions into (1) the

optimum balance among small, medium, and large missions, (2) a prioritized list of major flight investigations in the New Frontiers and larger classes, and (3) a list of important science goals that could be achieved by small spacecraft (Discovery and Scout class) missions. To achieve objectives (1), (2), and (3), members of the PSDS had to create and sort through scores of mission concepts. A successful outcome *required* that the concepts be at similar levels of maturity because cost uncertainty scales directly with concept maturity. Hence, the survey needed a tool for assessing the CML of every decadal survey study.

As can be seen from the Werner-Gruhl plot (Figure 3), which was developed in 1991 based on NASA's historical costs, an investment of 10–15% of total mission cost is required to reach 10–30% cost-estimate uncertainty. It is clear that there is *no way* the PSDS or NASA could support such a level of investment for scores of mission concepts. Hence, NASA and the PSDS tempered their expectations for what the survey would produce. The approach taken was to focus instead on achieving a similar level of concept maturity, and therefore cost uncertainty, for *all* concepts to be considered.

Why CML? As shown in Figure 4, absent a common language and yardstick, one person's concept could be interpreted to be at the same level of maturity as another's doodle.

What is CML? CML is a quantified measure of maturity conceived of by JPL's Mark Adler and inspired by NASA's technology readiness level (TRL) scale.

As shown in Figure 5, CML covers the mission concept formulation phase from "cocktail napkin" ideas to NASA Preliminary Design Review (PDR). Figure 6 shows a mapping of CML relative to NASA project phases and indicates the CML for rapid mission architecture (RMA), RMA, Team X, and in-depth study products.

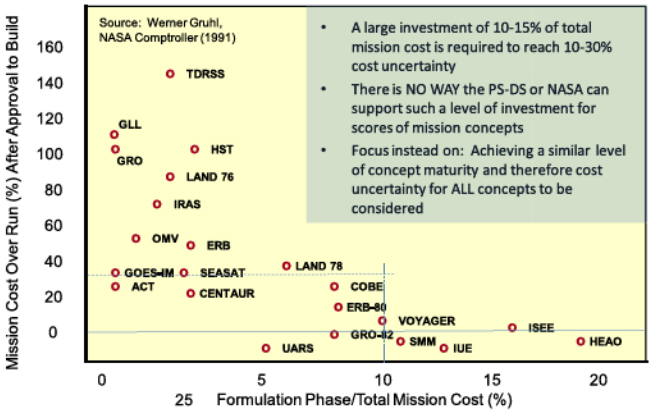

Figure 3. Mission concept maturity at "Approval" vs. subsequent mission implementation cost over-run

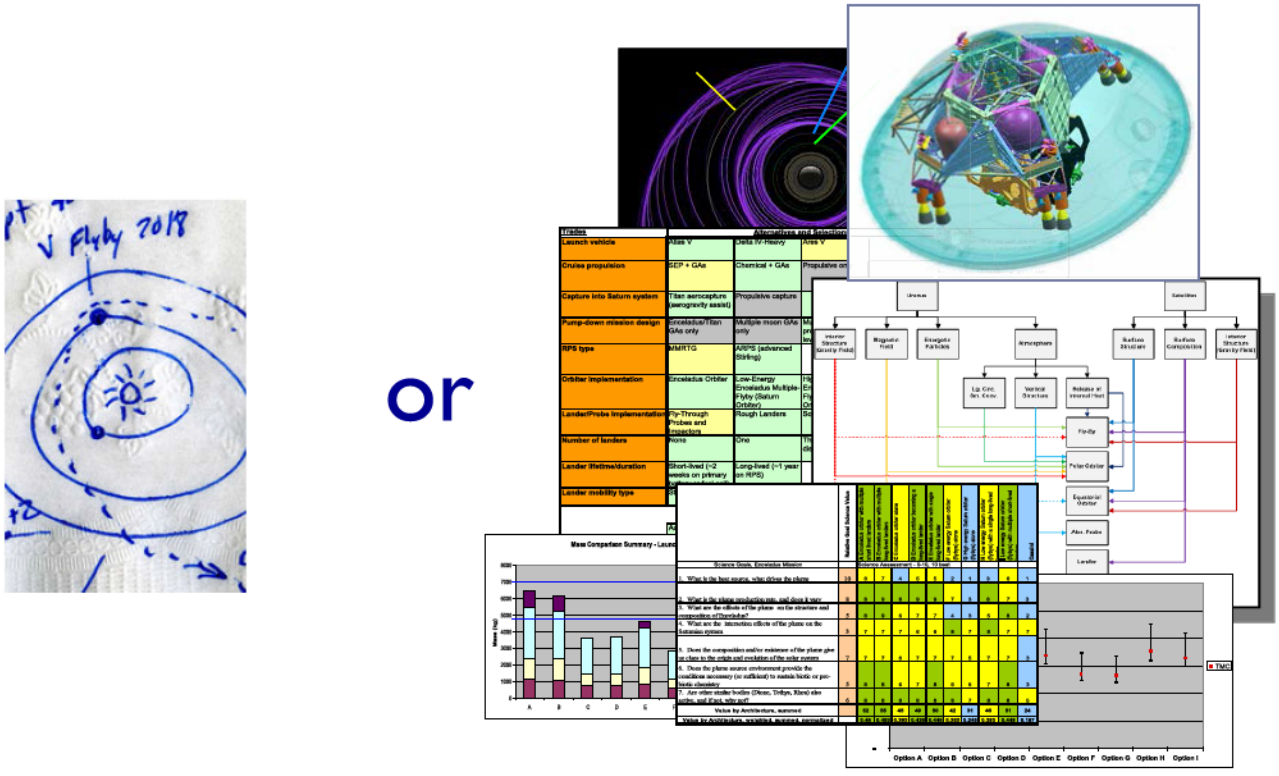

Figure 4. In the absence of a concept maturity metric, one person's detailed concept could be considered equivalent to as another's doodle

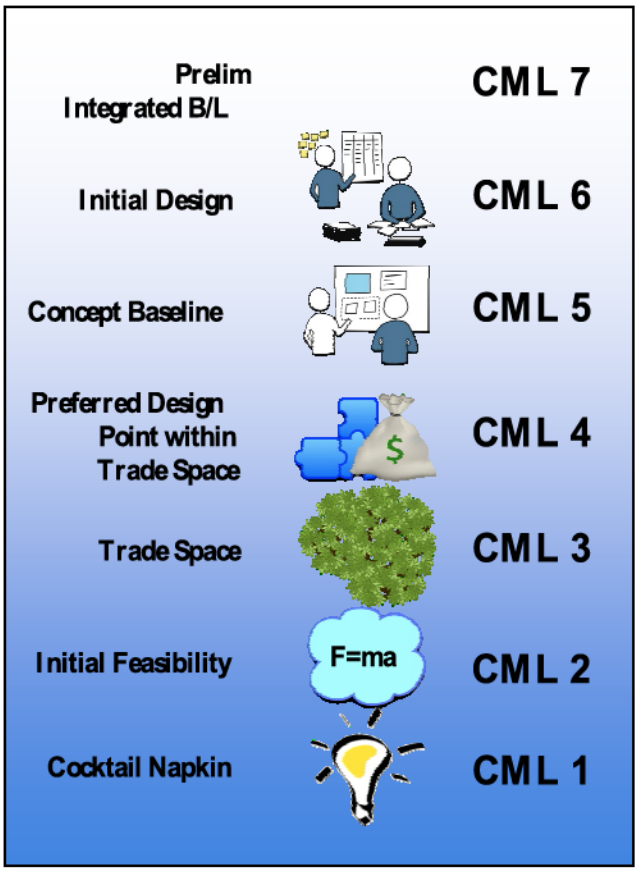

Figure 5. Concept maturity level yardstick

Cost estimation methods for studies of various CMLs must be appropriate for the information that is available for the basis of such estimates. Figure 7 indicates the various costing methods that are appropriate for such studies.

In summary,

- Cost uncertainty scales with mission concept maturity (and mission complexity)
- Use of CML *alone* does not *directly* decrease cost uncertainty
- It *does* enable a much more confident comparison and ranking of concepts within a given mission cost bin, by establishing that each concept is at a similar level of maturity, including the level of understanding of the mission complexity
- Use of CML indirectly will decrease cost uncertainty by leading to more mature, better-understood mission concepts and markedly reduce the risk of prioritizing one immature, high-cost-uncertainty concept over another that is more mature and therefore has lower cost uncertainty

CML is an important aspect of gauging cost uncertainty and has been an integral part of the formulation approach and study methodology used for the PSDS.

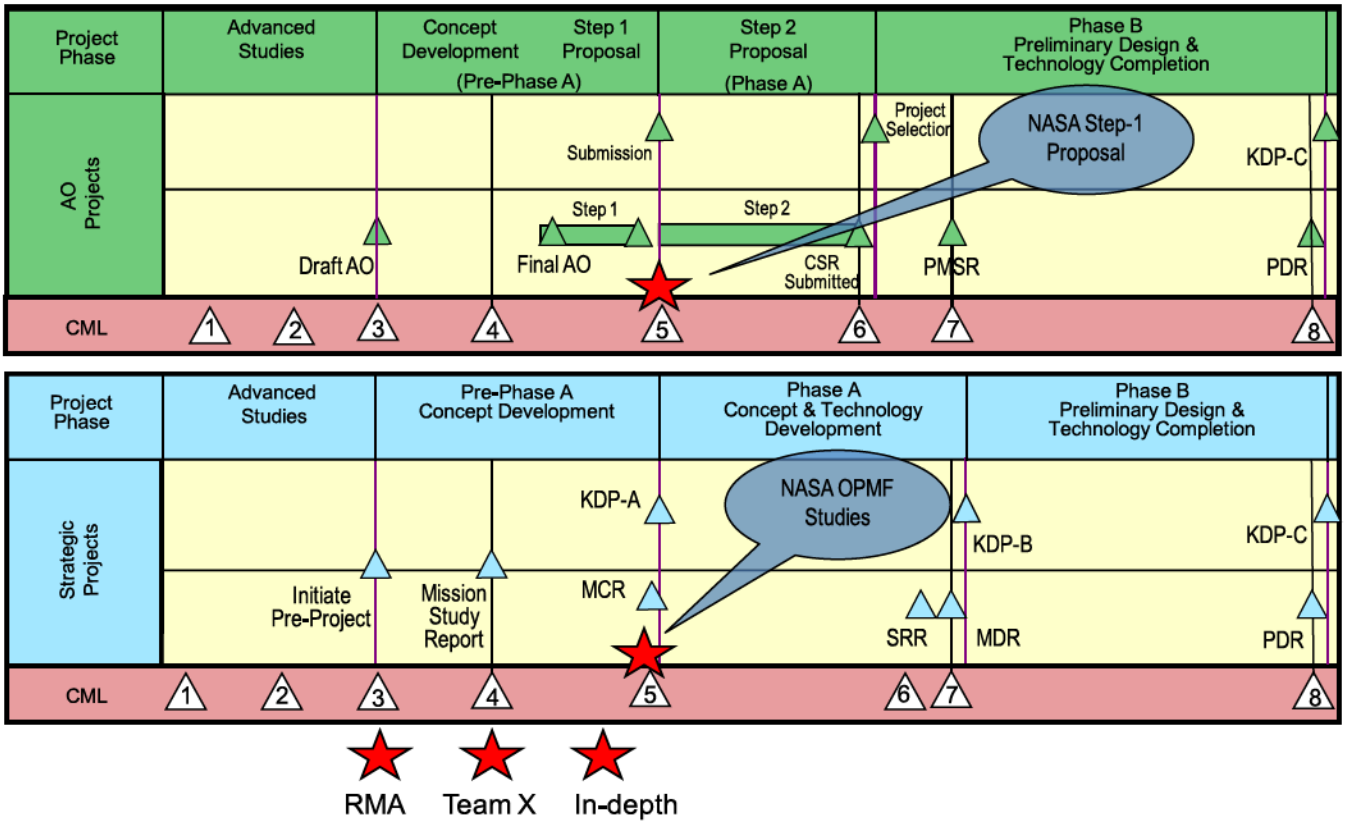

Figure 6. Relationship of CML to NASA project phases

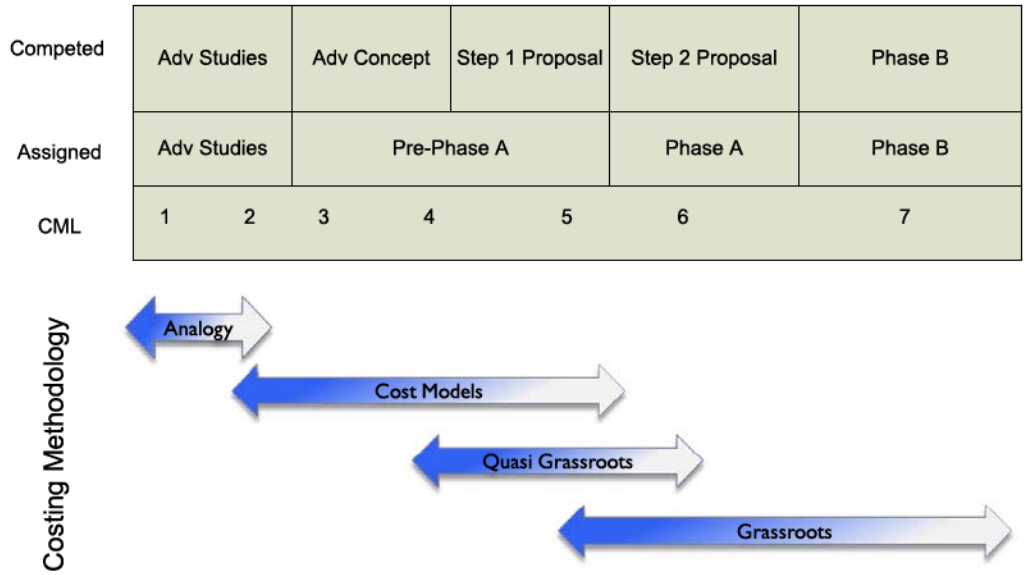

Figure 7. Appropriate costing methods for each CML

3. Study Methodology

As mentioned in Section 2, funded studies were conducted by several organizations and estimated mission costs were independently assessed by the Aerospace Corporation to provide the information needed by the PSDS as the basis for their recommendations. Figure 8 shows how the CML 2–3 (RMA), CML 4 (point design, a.k.a. Team X), and CML 5 (in-depth studies) integrated into the PSDS process. This section describes the specific methodologies used for each.

Rapid Mission Architecture Method

JPL's RMA capability includes a collaborative team and a set of methods used to generate new mission architectures, explore broad trade space options, and conduct architecture-level analyses. RMA studies address feasibility and identify the most promising candidates to proceed with for detailed design studies.

As shown in Figure 9, RMA was developed to address the perceived need for rapid, effective early mission architectural development and trade space exploration as a precursor to the traditional point-design development stage (e.g., dedicated mission proposal teams and the well-established "Team X" point design team). RMA provides concept creation, feasibility assessment, and preliminary analyses at the earliest CMLs (CML 2–3). Key figures of merit such as science value, cost, risk, and performance/resource estimates are evaluated across multiple mission architectures to identify the most promising options for further consideration. RMA studies have been used to support the various JPL and NASA program offices and external customers such as the National Research Council (NRC) PSDS studies. RMA studies include broad mission trade space assessments, focused architecture-specific analyses, and technology benefit/impact analyses.

The RMA approach integrates a small team of architecture-level experts (typically 6–10 people) to generate and explore a broad trade space driven by the science objectives. RMA particularly emphasizes a small collaborative team approach to enhance team agility and creativity and is not just a set of tools. Key roles often include the customer/science team representative(s), study lead/mission architect, team facilitator, science and instruments lead, systems engineer(s), mission design lead, and technologists/specialists (Figure 10). Specific roles are tailored depending on the needs of a particular study. Because the science objectives and priorities are so important in guiding the study process, concurrent participation by the customer science team is essential for real-time decision-making.

By examining a large number of varied mission options early, the RMA approach avoids a classical design team's tendency to drive to a baseline architecture prematurely and seeks to avoid getting constrained early on by a mission that does not significantly address the science objectives or has unacceptable cost or risk. The team instead strives to identify innovative, unforeseen paths in the trade space and rapidly analyze multiple high-level architectures before recommending best candidates for further study. Diverse architectures are generated spanning both conventional and novel platforms, approaches, and technologies. A range of options, including flybys, orbiters, landers, probes, and other architectural platforms, may be considered and evaluated against the science objectives (Figure 11).

RMA operates on a rapid time scale to respond to short-turnaround customer needs. Collaborative sessions normally span one to three weeks, depending on the scope of a study's

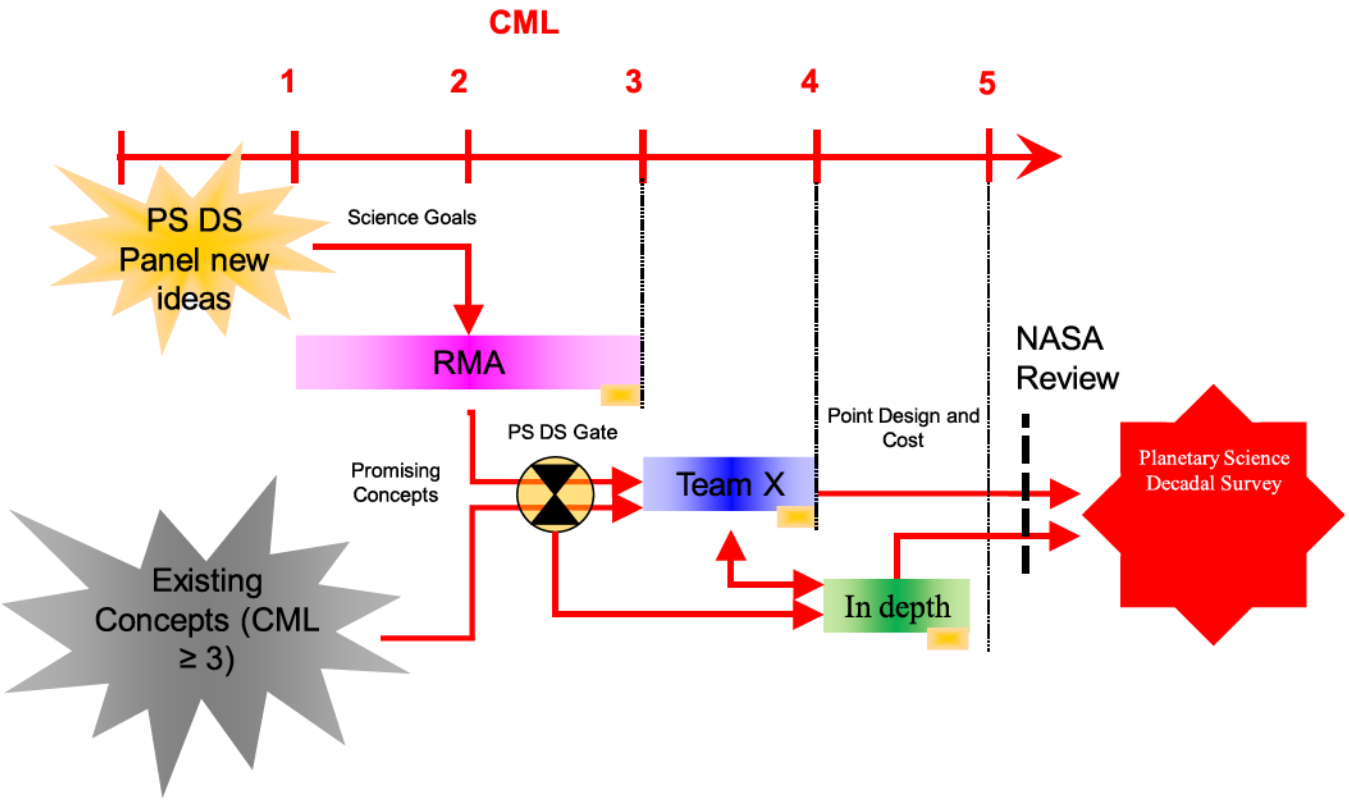

Figure 8. Study approach used for PSDS

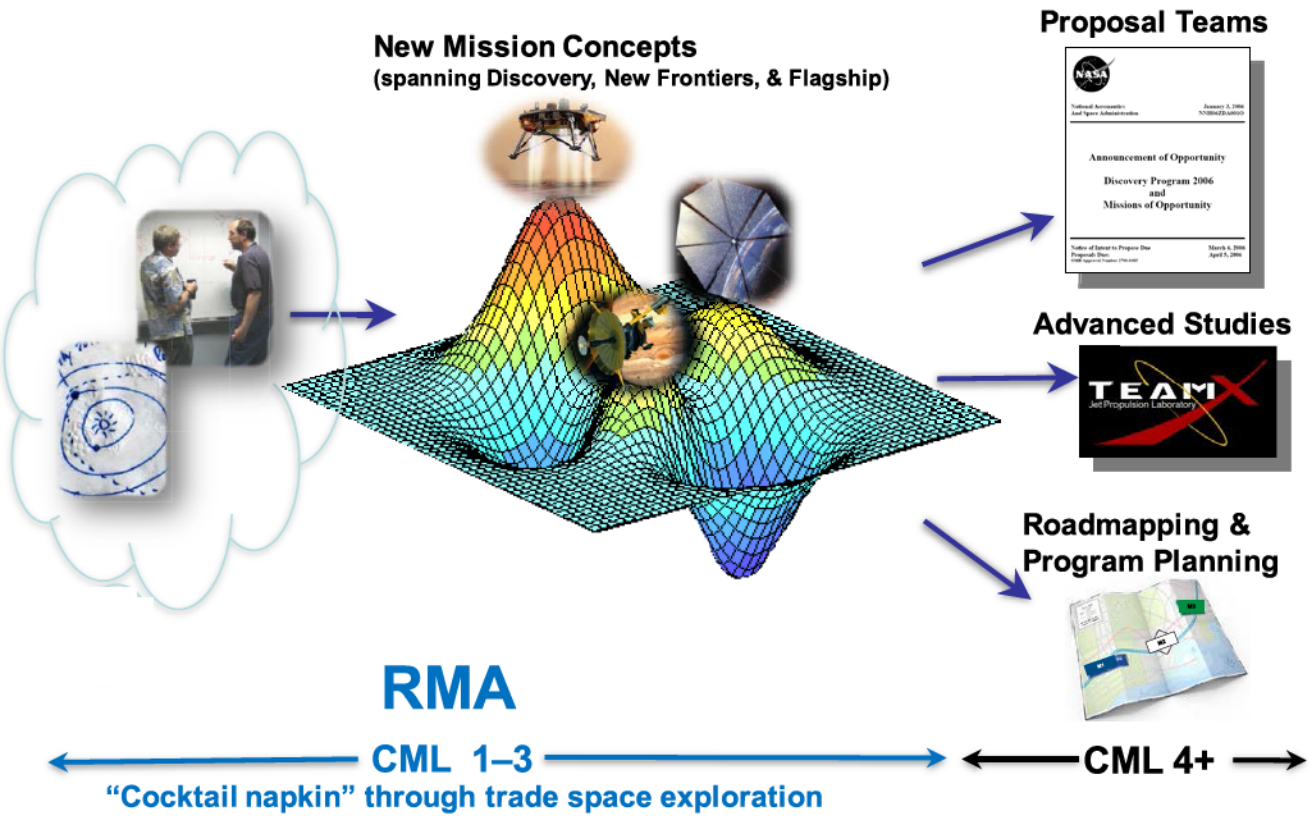

Figure 9. RMA is used to evaluate a broad trade space in early mission formulation

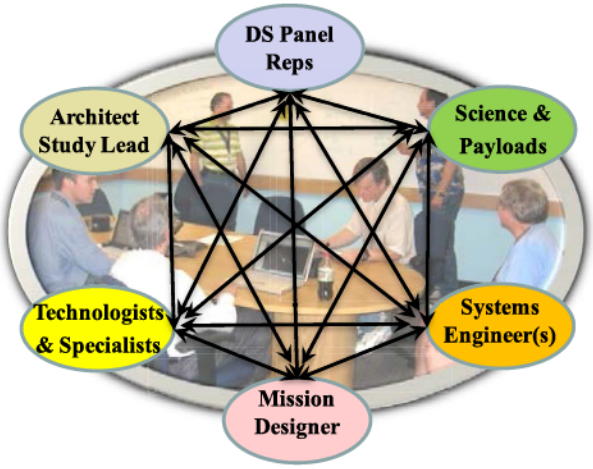

Figure 10. RMA is a small team-based approach for exploring diverse mission concepts

trade space to be considered. Much of the work is done concurrently, but time is also allocated "offline" outside of sessions for research or certain analyses better suited for independent work. As shown in Figure 12, the RMA process begins with scoping of the specific study needs with the customer, followed by RMA team sessions to assess and prioritize the science and technical objectives, open the trade space (brainstorming and identifying linkages between objectives and architectural options), filter and prioritize the trade space, analyze and evaluate the mission architectures, and generate final products. Early brainstorming often yields dozens of architectural concepts and combinations. Typically, 10 or more mission architectures are selected to proceed to the integrated assessment stage of the RMA process. Key figures of merit, including science value, cost, and risk, are evaluated consistently across these multiple architectures and compared in an integrated view. Analyses are kept at a broader architectural or system level of assessment rather than detailed point design. Parametric models, rapid first-order analysis techniques, and flight system analogies are used. This approach enables a quick preliminary assessment across a broad range of candidate architectures. From these mission concepts, the team identifies the most promising candidates for further study.

Application of RMA methodology to the PSDS required direct participation from science panel members, which included the science champion. Typical RMA studies operated in the following fashion:

Planning and "Pre-Session"

- PSDS panel representatives interacted "offline" to identify study scope and mission objectives
- RMA lead helped to identify any additional preparation work needed before study

RMA Concurrent Sessions

- Panel representatives joined the team (in person or via videoconference/teleconference) to affect key decisions in real-time

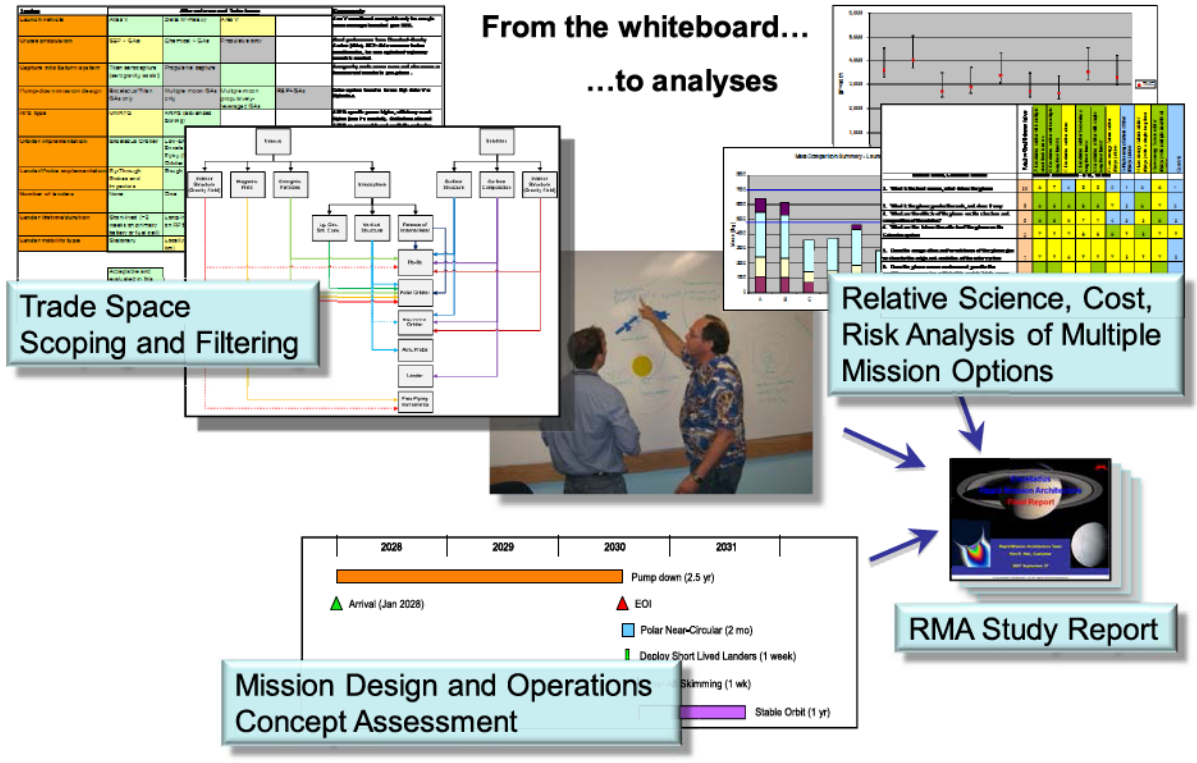

Figure 11. Products are tailored to the needs of mission architecture-level analyses

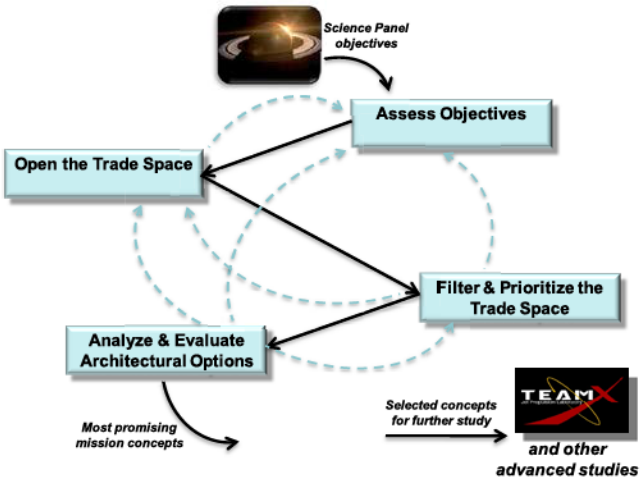

Figure 12. RMA approach promotes assessment

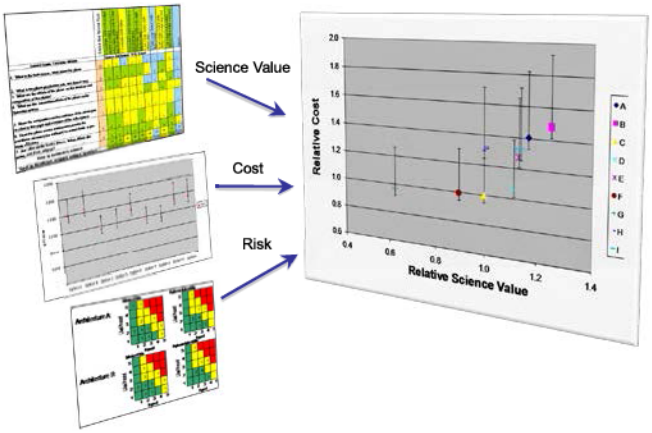

Figure 13. RMA reveals the "sweet spots" for further study through integrated assessment of multiple Figures of Merit

- Typically, ~5–8 concurrent sessions were conducted, ~2–3 hrs each, spanning 2–3 weeks
- Interim results were made available to panels at the time of completion of concurrent sessions

Product Generation

- Panel representatives contributed directly and **co-owned** the study products (e.g., science objectives, science value, assessment of architectures)
- Final report was generated to capture results

For the PSDS, the RMA methodology provided an effective and consistent approach to generate and assess low CML concepts in a broad trade space driven by science objectives. As shown in the example in Figure 13, the integrated assessment of science value, risk, and relative cost was used to determine preliminary cost class bins (e.g., Flagship, New Frontiers, Discovery) for the set of evaluated science mission architectures.

RMA results provided the PSDS panels with the necessary information to identify most promising mission options for further consideration in a point-design or in-depth study.

Point-Design Study Method

The point-design concept study methodology is based on the JPL Team X process, which produces the science, technical, management, and cost results at CML 4. For the PSDS studies, the final report was subsequently used by the Aerospace Corporation to complete an independent cost estimate (ICE).

JPL's Team X is best characterized as a concurrent engineering (CE) team for rapid design of space mission concepts. It was developed in 1995 as the first aerospace CE team to reduce study time and cost. More than 900 studies had been completed prior to the PSDS and that list has now grown well beyond 1,000.

The process is institutionally endorsed and is staffed with functional chair positions "owned" by the technical divisions (a.k.a. doing organizations). Team members are discipline experts with significant flight project experience. The study starts with a pre-session meeting to integrate customer input and get organized. This is followed by one week of pre-session technical work and then three intense concurrent design sessions over a period of one week that involve approximately 20 engineers. Results are then synthesized and documented in a final report. The entire process usually takes a total of five weeks from start to delivery of preliminary report to the customer. The study process also incorporates routine objective review. Typical Team X study products are shown in Figure 14 and are documented in a written final report.

Detailed mass estimates are produced by accumulating subsystem-level mass estimates. Subsystem estimates are mostly created from summing assembly-level masses taken from extensive experience-based databases. Resource contingencies and margins are applied according to organizational design principles. These values are also translated into NASA contingencies and margins as defined in the study ground rules.

Power estimates are developed from initial high-level operations modes set by systems engineers. Those estimates are compiled in the same manner as the mass estimates as shown in Figure 15.

Team X cost estimates are developed using various methodologies. Engineering subsystem models are primarily quasi-grass root estimates based on procurements and labor. Instruments are often estimated with the NASA Instrument Cost Model. Estimates capture recurring and non-recurring costs which enable multiple unit estimates. The work breakdown structure (WBS) follows JPL's standard WBS, which is compliant with the NASA standard. Cost reserves typically use the organization's design principles; however, for the PSDS studies, a 50% reserve on cost was required. Technology development is not typically included as part of

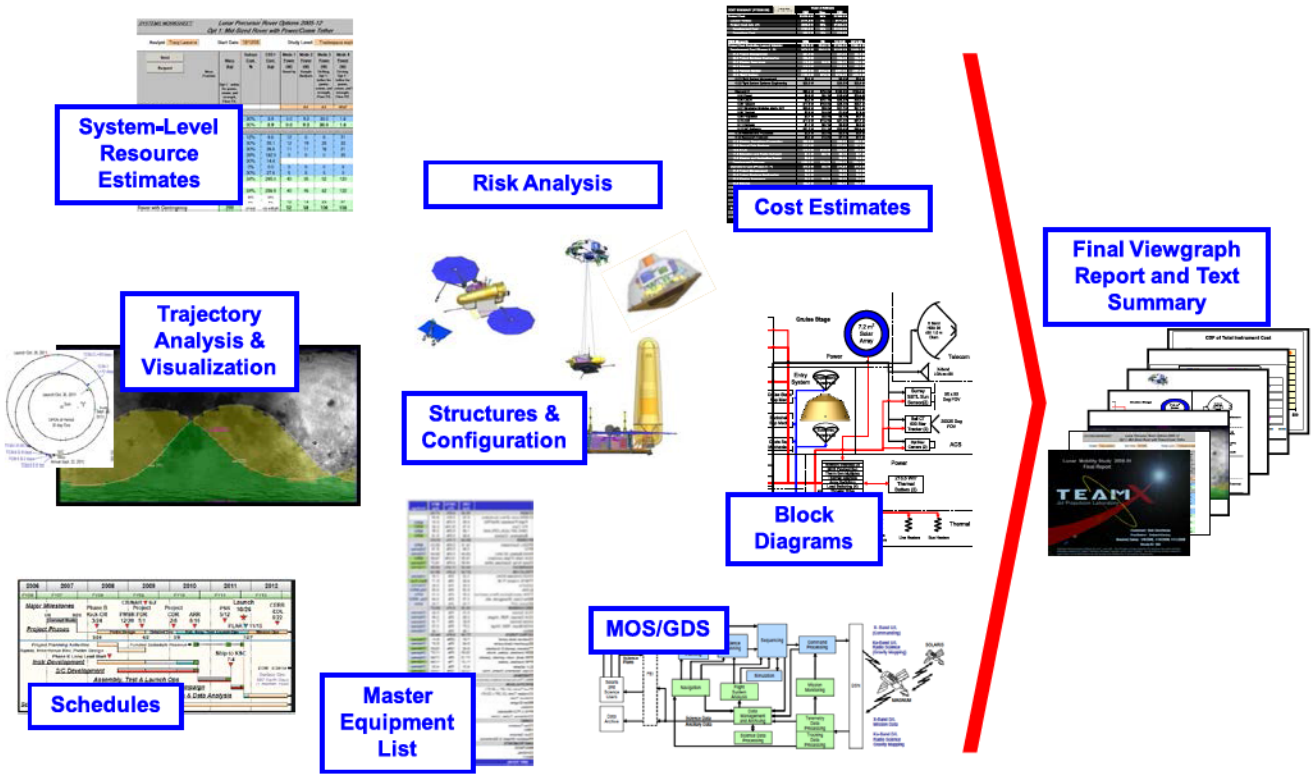

Figure 14. Typical Team X study products for CML 4

the basic Team X model estimate but can be addressed in an offline session and inserted into the report.

Team X produces a risk assessment for the concept. Functional chairs identify and rank mission and implementation risks from their point of view as well as related mitigations. The risk chair arbitrates ratings of similar risks from different chairs and compiles the final risk list. The final product is a written report that includes the risk list and a 5×5 "fever" chart as shown in Figure 16.

The Team X study methodology produces two documentation products: a basic Team X viewgraph report and a formal word report. The viewgraph report contains approximately 200 viewgraphs and is organized by subsystem. This bulletized format captures requirements and assumptions, design description, key trades, schedule, costs, and risks. The formal word report contains anywhere from 30 to 200 pages of written text and figures. This report captures all of what is in the viewgraph report as well as design basis and rationale for clear interpretation long after the study's completion. All of the input needed for an ICE is captured, including the following:

- Science overview
- Concept maturity level
- Technical implementation
- Enabling technology

SYSTEMS WORKSHEET: *Lunar Precursor Rover Options 2005-12*
Opt 1: Mid-Sized Rover with Power/Comm Tether

Analyst: Tracy Leavens Start Date: 12/12/05 Study Level: Tradespace expl

Send / Request	Mass Fraction	Mass (kg) Opt 1 - tether for power, comm, and strength, Floor P/L	Subsys Cont. %	CBE+ Cont. (kg)	Mode 1 Power (W) Stand-by	Mode 2 Power (W) Sample Analysis	Mode 3 Power (W) Drilling, Opt 1 - tether for power, comm, and strength, Floor P/L	Mode 4 Power (W) Driving, Opt 1 - tether for power, comm, and strength, Floor P/L
Power Mode Duration (hours/cycle)						*0.5*	*3.5*	*18.5?*
Rover Payload								
Instruments	1%	3.0	30%	3.9	0.0	9.3	30.0	1.8
Payload Total	1%	3.0	30%	3.9	0.0	9.3	30.0	1.8
Rover Bus								
Attitude Control	3%	7.7	12%	8.6	12	0	6	31
Command & Data	12%	27.0	30%	35.1	12	19	25	33
Power	9%	20.5	30%	26.6	11	11	16	21
Structures & Mechanisms	59%	131.7	39%	182.5	0	0	0	35
Cabling	5%	11.1	30%	14.4				
Telecomm	0%	0.0	0%	0.0	0	0	0	0
Thermal	10%	21.4	30%	27.8	5	5	5	0
Bus Total		219.4	34%	295.0	40	35	52	120
Rover Total (Dry)		222.4	34%	298.9	40	45	82	122
Subsystem Heritage Contingency		76.5	34%	34%				
System Contingency		0.0	0%	0%	12	13	25	37
Rover with Contingency		299	of total	w/o addl pld	52	58	106	158

Figure 15. Team X mass and power estimates are developed and compiled in a mode-based format

- Mission operations development
- Programmatics and schedule
- Cost
- Risk

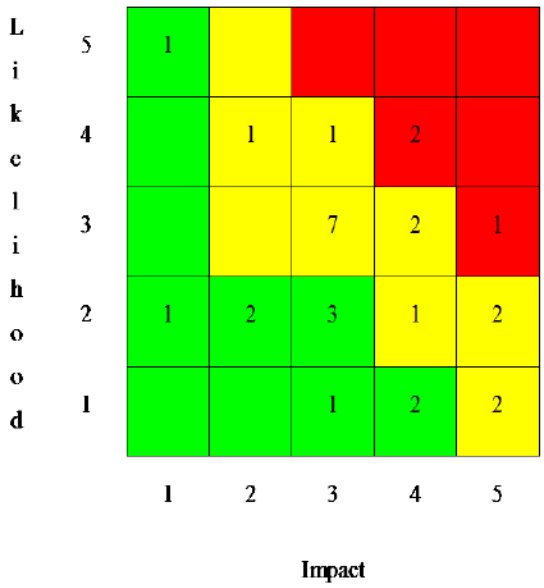

Figure 16. Risk assessment matrix

The JPL Team X process is now being emulated by many institutions and, as such, has been applied to the PSDS point-design studies conducted by JPL, APL, and GSFC.

In-Depth Studies Method

In some cases, special in-depth studies (approaching CML 5) were requested in order to produce a more comprehensive understanding of a mission or specific elements and to further reduce the risk and/or cost uncertainty. Such a study is structured around a dedicated study team to produce a higher fidelity technical baseline and cost estimate. These studies were typically applied to areas of high complexity, challenging implementations including environments and architectures, significant technology requirements, elements with high cost impact (e.g., Flagship), and missions or elements that are "out-of-family" with past experience.

The methodology was based on forming a dedicated in-depth study team with deep technical experience in the required areas. The dedicated study team is assembled using a full complement of experienced science, technical, management, and cost experts and is led by an experienced study lead. As was done in the RMA and Team X studies, the responsible PSDS panel member was identified as the science champion. These studies typically operate for 2–4 months depending upon unique challenges and complexity.

The output from an in-depth study approaches CML 5 and can be viewed as an extension and enhancement of Team X products and/or a more detailed penetration of specific significant technical challenges (e.g., entry, descent, and landing [EDL], extreme environments, surface operations, aerocapture). Typical product extensions beyond Team X include:

- Full science and requirements traceability
- Technology identification
- More detailed mission planning and costing for science operations scenario

Typical product enhancements beyond Team X include:

- Refined cost (further, selected use of grass roots)
- Comprehensive risk identification/mitigation
- Schedule developed to lower levels of WBS
- Higher fidelity mission trajectory/navigation design
- Refined mission technical baseline
- Technology assessment

A final written report is prepared that captures all study results and rationale for key decisions and is suitable as input for an independent cost estimate.

4. Study Results

RMA, Team X point-design, and in-depth study methodologies described in Section 3 were applied to many of the candidate concepts and technologies selected by the PSDS panels and approved by the steering group (Table 2). RMA studies were used to systematically sort through a broad mission trade space to identify the most promising approach to meet a set of high priority science requirements (balance between science, cost, and risk). In some cases, a single mission architecture resulting from an RMA study was selected for a follow-on Team X point-design or in-depth study. Team X point-design and in-depth studies were used to develop the baseline science, technical, management, and cost input needed by the Aerospace Corporation in generating the ICE for PSDS planning. Because of the broad base of previous work, many mission concepts were selected for a Team X point-design or in-depth study without having to go through an RMA. In other cases, previous studies or proposals were already available and therefore did not require a PSDS funded study. Examples are the current New Frontiers (NF) Step 2 competing mission concepts and Outer Planet Flagship Mission (OPFM) concepts.

Table 2. Studies Included in the PSDS.

Study	Type
Mercury Lander	RMA
Venus Mobile Explorer	RMA
Venus Tessera Lander	Point design
Venus *In Situ* Explorer	NF—SAGE
Venus Climate Mission	Point design
Lunar South Pole/Aitken Basin SR	NF—MoonRise
Lunar Network	Other
Lunar Polar Volatiles Mission	Point design

Study	Type
Mars Trace Gas Orbiter	Point design
Mars 2018 Skycrane Capabilities	RMA
Mars Geophysical Network Concepts	RMA
Mars Geophysical Network Mission	Point design
Mars Polar Climate Mission Concepts	RMA
Mars Astrobiology Explorer-Cacher	Point design
Mars Ascent Vehicle	Point design
Mars Sample Return Orbiter	Point design
Asteroid Sample Return	NF—OSIRIS REX
Main Belt Asteroid Lander	Point design
NEO Target Assessment	Other
Comet Surface Sample Return (SR)	Point design
Comet Cryogenic SR Technology	Other
Europa Jupiter System Mission	OPFM in-depth
Io Observer	Point design
Ganymede Observer	Point design
Trojan Asteroid Tour	Point design
Saturn Probe Mission	Point design
Saturn Probe Mission	RMA
Saturn Ring Observer Technology	Other
Titan Lake Lander	In-depth
Titan Saturn System Mission	OPFM in-depth
Enceladus Flyby/Sample Return	RMA
Enceladus Orbiter	Point design
Chiron Orbiter	Point design
Uranus System Mission	RMA
Neptune/Triton Mission	RMA
Nuclear Thermoelectric Generator Technology	Other

Although details of these studies go beyond the scope of this paper and cannot be included here, a publically releasable final report has been generated for each. The reports are available from NASA or the NRC Space Studies Board via their Web site or on Compact Disk.

5. Conclusions

In 2009, the NRC Space Studies Board established a decadal survey committee to develop a comprehensive science, mission, and technology strategy for planetary science in the next decade. In contrast to the 2003 decadal survey, this survey placed a much stronger emphasis on cost realism. To achieve this, funded studies were conducted in 2010 by JPL, APL, and GSFC in accordance with ground rules agreed to by NASA and the PSDS steering group and consistent with CML metrics. RMA, Team X point-design, and in-depth studies represent the primary methodologies used to produce consistent results across a range of CMLs. Principal results of this work include the following:

(1) An unprecedented set of high-fidelity studies and cost estimates were completed for all high priority science missions considered by the PSDS. This directly addressed their goal of cost realism

(2) The NRC and NASA have embraced CML

(3) Mission studies aligned with the CML produced consistent cost estimates commensurate with concept maturity and mission complexity

(4) Decadal chairs, science panels, and NASA POCs were extremely pleased with RMA, Team X, and in-depth study methodologies and products

Results of the studies identified here were used as the basis for the PSDS recommendations. Final results of the decadal survey, including studies that were completed and the specific science, programmatic, and technology recommendations, will be disclosed publically in March of 2011. Those results will drive NASA Planetary Program science, mission, research and technology efforts for the next decade.

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Biography

Kim R. Reh *has a broad base of program, project and line organization experience that spans project formulation through implementation. His experience includes significant interaction with the science community, working with international partners and implementing projects according to NASA requirements for flight projects.*

Kim is currently Deputy Program Manager at JPL responsible for business development, mission formulation, pre-Phase A concept studies and strategic technology investments for solar system exploration missions.

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