Technology Assessment in Support of the Presidential Vision for Space Exploration

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Abstract

This paper discusses the process and results of technology assessment in support of the United States Vision for Space Exploration of the Moon, Mars and Beyond. The paper begins by reviewing the Presidential Vision: a major endeavor in building systems of systems. It discusses why we wish to return to the Moon, and the exploration architecture for getting there safely, sustaining a presence, and safely returning. Next, a methodology for optimal technology investment is proposed with discussion of inputs including a capability hierarchy, mission importance weightings, available resource profiles as a function of time, likelihoods of development success, and an objective function. A temporal optimization formulation is offered, and the investment recommendations presented along with sensitivity analyses. Key questions addressed are sensitivity of budget allocations to cost uncertainties, reduction in available budget levels, and shifting funding within constraints imposed by mission timeline.

I. Presidential Vision for Space Exploration: A Major Endeavor in Building Systems of Systems (1)

On January 14, 2004, some 31 years after a human being last set foot on the lunar surface, President Bush announced a new Vision for Space Exploration which will pick up where Apollo left off on the Moon and propel us onward to Mars. It forms the foundation of NASA's plans for its next era.

The Vision calls for the existing fleet of space shuttles to be used to complete the International Space Station (ISS), and then retired in 2010. The shuttle's replacement, the Crew Exploration Vehicle (CEV), will be deployed by 2012 (target 2011), and will carry astronauts to the Moon by 2020 (target 2018) in preparation for human missions to Mars. The CEV architecture is also compatible with missions to the ISS and ultimately to Mars.

II. Why Do We Return to the Moon

The Moon will help us learn how to live and work for extended periods of time on a cold, dusty world without a breathable atmosphere, without Earth's atmospheric pressure or protective magnetic field, with much less than Earth's gravity, and with regolith up to ten meters deep. As a test-bed analog for Mars, the Moon will enable us to develop and demonstrate technologies for coping with such a world.

It will allow us to determine the integrated effects on human biology of radiation and low gravity, and to develop countermeasures. It will provide an opportunity for meeting such challenges as planetary protection (avoiding contamination of other worlds with organisms transported from Earth) and mitigating electrostatically charged dust. All of these issues are key to missions to Mars.

Studying lunar regolith, rocks, and craters will not only reveal the character and history of the Moon, but also provide insights into the history of Earth, the meteoric bombardment of the inner solar system and its effect on the development of life on Earth, and the evolution of the sun (Apollo data hint at nuclear processes not predicted by current models). And on a practical level, geological research forms the basis for assessing lunar resources.

Astronomers will be able to take advantage of the very stable viewing along the Moon's spin axis to conduct ultra deep surveys of the very early universe with long-baseline interferometers, and also with liquid-mirror telescopes for which lunar gravity is uniquely enabling.

III. System of Systems Architecture for Travel to the Moon and Return to Earth

The architecture is one in which the crew is launched separately from the lunar lander, Earth-departure stage, and other cargo. This enables the crew to ride a smaller, safer rocket.

First, the Lunar Heavy Cargo Launch Vehicle (CaLV) lifts the Earth-Departure Stage (EDS), with the Lunar Surface-Access Module (LSAM) attached, to low-Earth orbit (LEO), where they are capable of remaining for up to 30 days until the crew is launched. The CaLV launch system is largely derived from the shuttle. It consists of a large external tank with five shuttle main engines on its back.

The Crew Launch Vehicle (CLV) carries the Crew Exploration Vehicle (CEV) to LEO. The CEV rides atop the CLV; if foam or other debris breaks off of the CLV during launch, it will not be able to hit the CEV. Additionally, a Launch Escape System (LES) enables the crew to escape at any time during the launch. The CLV is also derived from the shuttle, and employs a resuable shuttle solid rocket booster (SRB) first stage and a new second stage powered by a single shuttle main engine.

The CEV circularizes its orbit and then docks with the LSAM, which is attached to the EDS and whatever other cargo is going to the Moon. The EDS engine burns, propels the CEV/LSAM to their lunar-transfer trajectory, and separates from the lunar-bound spacecraft.

When the CEV/LSAM pair reaches the Moon, the CEV service module's engine injects the spacecraft into low-lunar orbit (LLO), using LOX/liquid methane fuel (as will the lunar ascent stage) in preparation for future missions expected to use in situ methane on Mars. All four crew members transfer to the LSAM, which descends to the lunar surface, using LOX/liquid hydrogen propellant. The CEV continues orbiting autonomously. The LSAM is able to access any location on the lunar surface, and the system is designed to enable anytime return to Earth.

When the crew's surface activities have been completed, they board the ascent stage, which returns them to LLO using the same LOX/methane fuel as the CEV's service module. The remainder of the LSAM remains on the lunar surface, to be used in constructing a lunar habitat.

Once in orbit, the ascent stage docks with the CEV, and the crew transfers back into the command module. The ascent stage separates from the CEV and is disposed of via impact on the lunar surface. The service module engine injects the CEV into its Earthbound trajectory. Before entering Earth's atmosphere, the CEV's command module separates from its service module. The service module splashes down in the Pacific Ocean, while the command module touches down on dry land, probably in western California, by means of a combination of parachutes, airbags, retro-rockets, stroking seats, etc.

IV. Determining A Technology Investment Portfolio to Enable the Vision (2)

IV- 1. Introduction

START (3,4) is a tool to optimize research and development primarily for NASA missions. It was developed within the Strategic Systems Technology Program Office, a division of the Office of the Chief Technologist at NASA's Jet Propulsion Laboratory. START is capable of quantifying and comparing the risks, costs, and potential returns of technologies that are candidates for funding. START can be enormously helpful both in selecting technologies for development -- within the constraints of budget, schedule, and other resources -- and in monitoring their progress. In this report, START is used to analyze the capability needs using data from NASA's Exploration Systems Architecture Study (ESAS). It's important to note, however, that analysis isn't a one-time event, and changes occur. Assessment is a continuous process throughout a project lifecycle and, commensurately, data such as cost estimates should be frequently updated to provide the best information for management decisions.

IV-2. Input Database

Our sponsor at NASA Headquarters provided a database of inputs to our analysis. This section describes the organization of the data.

- Capability Hierarchy

The capabilities are organized into twelve capability areas shown in Table 1.

1	Structures
2	Protection
3	Propulsion
4	Power
5	Thermal Control
6	Avionics & Software
7	Environmental Control & Life Support
8	Crew Support & Accommodations
9	Mechanisms
10	In-Situ Resource Utilization (ISRU)
11	Analysis & Integration
12	Operations

Table 1: Top-Level Capability Areas

- Mission Set

There were four missions of interest having different relative importance, as shown by their given weight in Table 2:

Mission	Importance weight
CEV to ISS	9
CEV to moon	6
Lunar outpost base	1
Mars outpost base	0.1

Table 2: Mission Importance Weights

Although the Mars mission was included structurally in the analysis, a complete dataset was not available; thus incorporation of R&D for human-robotic Mars missions was deferred to a subsequent study.

- Figures of Merit

Six figures of merit (FOM) defined by the sponsor are associated with each capability for each mission). The FOMs are defined in Table 3. Each FOM is assigned a High/Medium/Low label corresponding to weights 9, 3 and 1 respectively.

Figure of Merit	Definition
Overall criticality	Impact of the need on the architecture
Safety and mission success	Probability of loss of crew, Probability of loss of mission
Extensibility / flexibility	Lunar, Mars, other destinations, Commercial activities, National security
Programmatic risk reduction	Technology development risk, Cost risk, Schedule risk, Political risk
Affordability	Technology development cost, Facilities cost, Ops cost, Cost of failure
Technical performance	How the technical performance affects the architecture

Table 3: Figures of Merit Defined

Note that quantitative performance metrics (goals) were not available at the time of the study; they will be included as part of the next revision in FY '06.

- Cost Profiles

Each capability has a cost profile outlining its cost requirements per year to bring it to technology readiness level (TRL) 6. The database also contains absolute start and end years for each cost profile. The base case does not allow time shifting of the funding profiles, thus fixing the cost profiles in time. We subsequently performed a temporal analysis which relaxed this assumption such that profiles are only constrained to fit within the missions' capability development timelines.

- Probability of Successfully Developing a Capability

Success in fulfilling a capability for a mission is defined for this study as the capability development reaching a TRL of 6 within the specified budget and schedule. TRL 6 requires a system/subsystem model or prototype demonstration in a relevant environment.

A measure of the probability of this success can be taken from the parameter for quantifying the difficulty of maturing a particular capability, the "Research and Development Degree of Difficulty" ($R\&D^3$)(5). The sponsor provided the $R\&D^3$ levels for each capability for each mission, and each level was then linked to a corresponding probability of success for fulfilling the capability for each mission using table 4.

$R\&D^3$	Probability of Success
1	99%
2	90%
3	80%
4	50%
5	20%

Table 4: Probability of success of "Normal" R&D effort for different $R\&D^3$ levels.

- Center Splits

Multiple centers can contribute to a capability. Individual center contributions associated with each capability have been provided as a percentages of the cost. Validation of the center splits is needed since the capabilities were not broken down into individual tasks, where center splits can be easily identified.

- Assumptions and Caveats re: Data

We assume a capability needs to be fully funded each year to achieve its mission impact, and the funding profile is contiguous (no abrupt starts and stops). The analysis assumes independent capabilities, i.e., the decision on whether or not to fund a capability is independent of the decision of whether or not any of the other capabilities are selected. The analysis can be updated if dependency data becomes available. Large cost capabilities without correspondingly large FOMs should be reviewed. An example of such a capability is 8e, Crew Healthcare Systems.

IV-3. Optimization Formulation

The optimization algorithm builds portfolios with the highest possible total benefit, subject to budget and schedule constraints. Using the definitions in the following table:

$N_{missions}$	Number of missions under consideration
W_i	Weight of the i^{th} mission
$M_{capabilities}$	Number of capabilities under consideration
$P_{i,j}$	Probability of fulfilling the j^{th} capability for the i^{th} mission
R	Number of Figures of Merit
$FOM_{i,j,k}$	k^{th} Figure of Merit, of the j^{th} need, with respect to the i^{th} mission
$X_{i,j}$	Binary control variables indicating if capability j for mission i is selected for funding. $X_{i,j} = \{0,1\}$.

Table 5: Benefit Function Parameter Definitions

The benefit function (BF) is a weighted sum of expected Figures of Merit (summed per capability, per weighted missions).

If $X_{i,j}$ equals 1, the capability is selected for funding; if it equals 0 then it is not funded. The portfolio is optimized by finding the set of $X_{i,j}$ that maximizes:

$$\sum_{i=1,N_{missions}} W_i \sum_{j=1,M_{capabilities}} X_{i,j} * P_{i,j} \sum_{k=1,R} FOM_{i,j,k} \quad (1)$$

Subject to annual cost constraints:

$$\sum_{i=1,N_{missions}} \sum_{j=1,M_{capabilities}} X_{i,j} * C^{(t)}_{i,j} \le B^{(t)} \quad (2)$$

$$for\ all\ years\ \ t$$

Where t = 2006, 2006+T (T number of years in portfolio).

The optimization problem is solved using the Branch and Bound algorithm (6).

IV-4. Sensitivity Analysis

Sensitivity analysis involves adjusting model input values to determine the impact on the recommended portfolio. Our sensitivity analysis estimates robustness of the funding to each capability. A number of cases using various budget scenarios were examined. A representative example is reported here.

1) Case 1: The baseline – the full capability set at the full budget
2) Case 2: \$100M/year budget reduction

- Assumed Beta Density Function and Cost Uncertainties

Ideally, cost distributions should be based on engineering estimates, with the costs and probabilities for various contingencies provided by engineers and cost analysts. If details of this type are unavailable, the beta distribution is commonly used to model cost uncertainty.

This study fits a beta density function distribution based on three costs: minimum, mean, and maximum values. It is a rounded version of a triangular distribution. The random value from the beta distribution is the percent cost variation from nominal. The beta function parameters are $\alpha = 1.5$, $\beta = 3$, minimum = 98 %, maximum = 300 %.

- Monte Carlo Simulation

The Monte Carlo simulation repeatedly generates random values used to model the cost uncertainties. An iteration of the Monte Carlo simulation starts by multiplying a random number drawn from the Beta distribution by each cost for each year for each capability. The optimization algorithm is then run on this modified data. The optimum portfolio is found. Each capability's status as in or out of the portfolio is recorded.

Once 1000 iterations have been completed, the percentage of time each capability was chosen in the optimization is tabulated and is used as the measure of robustness for the given capability. The accuracy of the Monte Carlo estimate is based on the number of iterations; with 1000 iterations the 95% confidence interval for true percentage is +/- 1.5%.

- Case 1: The Baseline

The initial optimization with no cost uncertainties resulted in each capability being funded as shown in Figure 1. However, for the first 6 years, the cost of the capabilities met the budget line exactly as shown in figure 1 below. In this case, the slightest cost overrun by a capability during any of these years would cause a cost overrun in the portfolio. A sensitivity analysis was run on the baseline to see which capabilities would be recommended for a budget cut if an overrun occurred.

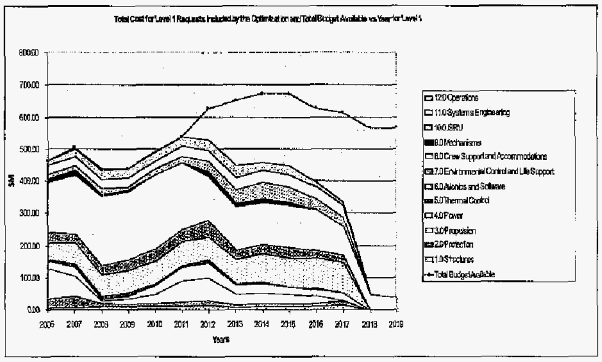

Figure 1: The total capability costs for the first 6 years all meet the budget exactly, threatening budget overruns if a capability cost is underestimated. *The results are illustrative rather than normative; they are based on preliminary data still undergoing revision, and the final results are subject to change.*

The results are shown in table 6. Nine of the 52 capabilities from the baseline set enter the portfolio less than 90% of the time, and four enter less than 50% of the time. Capability 8e never enters the portfolio.

8e	Crew healthcare systems (medical tools and techniques, countermeasures, exposure limits)	0.0%
8f	Habitability systems (waste management, hygiene)	10.1%
8b	EVA Suite (surface including portable life support system)	23.8%
3a	Human-rated, ~20 K lbf class in space engine and propulsion system	47.2%
5b	Surface heat rejection	52.7%
6l	Low temperature electronics and systems (permanent shadow region ops)	57.2%
3h	Long-term, cryogenic, storage, management and transfer (for lunar surface module)	76.2%
6j	Autonomous precision landing and GN&C (Lunar & Mars)	84.6%
10c	Demonstration of polar volatile collection and separation	88.4%

Table 6: Capabilities selected for full funding less than 90% in the Baseline Monte Carlo case. *The results are illustrative rather than normative; they are based on preliminary data still undergoing revision, and the final results are subject to change.*

Data such as this indicates a preliminary order for consideration of deletion of capabilities due to insufficient availability of funding, provided that the given figures of merit, costs, and probabilities etc. were accurate, and there were no other extenuating circumstances. Review of this table is an excellent starting point for contingency mitigation; it is not meant as a final recommendation.

- Case 2 – Baseline Minus $100M/year

Case 2 is a repeat of case 1, but with the budget cap decreased by $100 M/year.

The results are shown in Table 7. In Case 2 there are 12 capabilities below the 90th percentile.

Compared to case 1, there are some changes in the rankings of the capabilities. The bottom 5 capabilities keep their rankings, but 10f, which was in the 90th percentile before reducing the budget by $100 M/year, is now the 6th least robust capability. For non-robust capabilities competing to enter a portfolio, the change in rankings at different budget levels is a result of the changing "competition border" (7)]. For a given budget level, the first capabilities entering the portfolio are the highest scoring capabilities that can enter without putting the portfolio over budget. As the budget cap is approached, a weaker scoring capability can become more competitive by simply fitting into the portfolio better when other remaining, better scoring capabilities are too large cost-wise to fit. This dynamic drives the changing of the order of robustness rankings seen here and in the results that follow as well. From this it can be concluded that while a capability might be one of the most robust at one budget level, it can be eliminated from the optimum portfolio by lesser capabilities as a large budget change shifts the location of the competition border.

While the competition border can lead to drastic drops in robustness for some capabilities, it can also boost the robustness for other capabilities. The budget reduction of $100 M/year raised 8b's robustness from 23.8% to 30.5%, and bumped 10c into the 90th percentile. The number of capabilities who see their robustness increase by budget cuts, however, is only a few.

8e	Crew healthcare systems (medical tools and techniques, counter measures, exposure limits)	0.0%
8f	Habitability systems (waste management, hygiene)	9.8%
8b	EVA Suit (surface including portable life support system)	30.5%
3a	Human-rated, 5-20K lbf class in space engine and propulsion system	40.7%
5b	Surface heat rejection	47.5%
10f	Extraction of water/hydrogen from lunar polar craters	64.0%
6l	Low temperature electronics and systems (permanent shadow region ops)	64.6%
3h	Long-term, cryogenic, storage, management and transfer (for lunar surface module)	73.1%
4i	Surface power management and distribution (e.g., efficient, low mass, autonomous)	75.1%
6j	Autonomous precision landing and GN&C (Lunar & Mars)	84.2%
12c	Surface handling, transportation, and operations equipment (Lunar or Mars)	85.1%
4f	Surface solar power (high efficiency arrays, and deployment strategy)	88.7%

Table 7: Capabilities selected for full funding less than 90% for case with reduced budget of $100M/year. *The results are illustrative rather than normative; they are based on preliminary data still undergoing revision, and the final results are subject to change.*

IV-5. Temporal Optimization

As seen earlier, Figure 1 had the feature that funding every capability resulted in total costs meeting the budget cap in the early years, but lying far below the budget cap in later years. Due to this, another optimization was run in parallel to the sensitivity analysis to try to take advantage of this untapped budget in the later years of development. This temporal optimization calculates not only which capabilities to fund, but also when to fund them, by moving the cost distribution profiles for each capability against the development timeline. The capability portfolio is optimized while taking advantage of budget surpluses by allowing capabilities costs to move to different years.

Our temporal optimization searches all possible combinations of capability funding schedules across all capabilities and all missions. In essence, the optimization explores the total development costs of each configuration by "sliding" each capability cost distribution along a timeline.

The temporal model, shown in Figure 2, takes into account a capability development time range where all development for a given mission would occur. Before this development time, one year of delay is allocated for the time between the funding decision and the start of development.

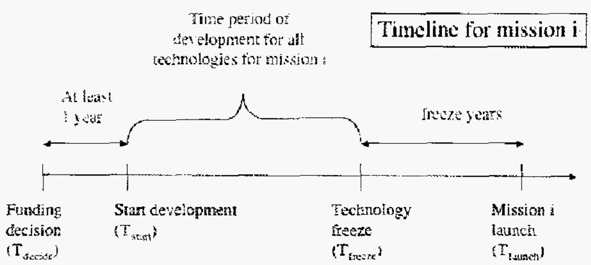

Figure 2: Mission Capability Development Timeline

- **Temporal optimization formulation**

The optimization in equations 1 and 2 is generalized by adding multiple cost profiles for each capability. Additional constraints force the restriction of only funding a capability at most once. If $X_{i,j}$ equals one then capability *j* for mission *i* is selected for funding; if it equals zero then it is not funded. The portfolio is optimized by finding the set of $X_{i,j}$ and $Y_{i,j,q}$ that maximizes equation 3 subject to constraints 4 and 5.

$$\sum_{i=1,N_{missions}} W_i \sum_{j=1,M_{capabilities}} X_{i,j} * P_{i,j} \sum_{k=1,R} FOM_{i,j,k} \quad (3)$$

If $Y_{i,j,q}$ equals one then the q^{th} cost profile is used for funding capability *j* for mission *i*. The cost constraints are given by equations 4 and 5:

$$\sum_{i=1,N_{missions}} \sum_{j=1,M_{capabilities}} \sum_{q=1,Q_{cost\ profiles}} Y_{i,j,q} * C^{(t)}_{i,j,q} \leq B^{(t)} \quad (4)$$

for all years t

$$\sum_{i=1,N_{missions}} \sum_{j=1,M_{capabilities}} \sum_{q=1,Q_{cost\ profiles}} Y_{i,j,q} = X_{i,j} \quad (5)$$

for all i and j

- **Temporal Optimization Results**

We ran several temporal optimizations based on different scenarios from the ESAS dataset. The given annual budget curve was adjusted by adding and subtracting funds (from -\$250M to \$200M) uniformly across all years. We computed the percentage of times each capability was selected by the optimization. The following shows which capabilities were selected the least amount of times.

Percentage Selected	Mission	Capability	Capability Name
25%	Lunar Outpost	8e	Crew healthcare systems (medical tools and techniques, countermeasures, exposure limits)
58%	Lunar Sortie	8f	Habitability systems (waste management, hygiene)
58%	Lunar Outpost	2a	Detachable, human-rated, ablative environmentally compliant TPS
58%	Lunar Outpost	5b	Surface heat rejection
58%	Lunar Outpost	6d	Integrated System Health Management - ISHM
58%	Lunar Outpost	7c	Advanced air and water recovery system
58%	Lunar Outpost	8f	Habitability systems (waste management, hygiene)
67%	Lunar Sortie	8b	EVA Suit (surface including portable life support system)
67%	Lunar Sortie	8e	Crew healthcare systems (medical tools and techniques, countermeasures, exposure limits)
67%	Lunar Outpost	1a	Lightweight structures – pressure vessel, insulation (vehicle)

Figure 3: Temporal optimization results showing least robust capability needs. *The results are illustrative rather than normative; they are based on preliminary data still undergoing revision, and the final results are subject to change.*

The results show that capability 8e, "Crew healthcare systems (medical tools and techniques, countermeasures, exposure limits)" is least robust and highly likely to be flagged for funding cuts, even with increased funding to the annual budget.

The classification of capability 8e as one large conglomerate makes it highly volatile in the temporal optimization. There is also no room for temporal displacement as the cost distribution covers the full 14-year timeline. By breaking up capability 8e up into smaller parts on the order of magnitude of those capabilities it is competing with, a more optimal scenario may be achieved.

- **Finding a Better Annual Budget Curve**

The given annual budget had a maximum annual cost of $527.9M at year 2012. We asked the question of whether or not there is any other annual budget distribution profile that would fund all capabilities while requiring a smaller maximum annual budget. By applying the constraint that the budget in any year may not exceed $527.9M but letting the shape float as a function of year, we were able to determine another investment profile with lower annual investments and a seemingly flatter shape.

The results indicate that the smallest annual budget that can be used and still fund all capabilities is $459.5M per year. This explores all time displacements at multiple annual budget caps to find the best annual budget curve.

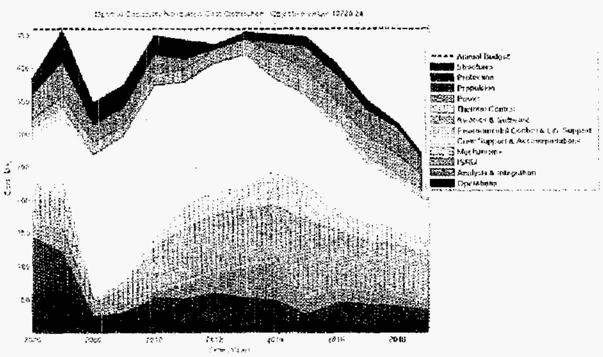

Figure 4: Optimal Annual Curve by Areas for Flat Budget of $459.6M. Given annual budget curve has peak of $528M. *The results are illustrative rather than normative; they are based on preliminary data still undergoing revision, and the final results are subject to change.*

V. Conclusions

This paper reports on the deployment of the START system to determine technology resource allocations for a variety of capabilities in support of the Presidential vision for space exploration. The vision inherently involves a large number of complex systems and a program of missions as a function of time. An extensive database of cost, performance, schedule and associated uncertainties is required to effectively allocate finite resources among multiple competing candidates. Key questions addressed are sensitivity of budget allocations to cost uncertainties, reduction in available budget levels, and shifting funding within constraints imposed by mission timeline.

The capability now exists to optimize portfolio investment including annual as well as total cost constraints. The process is transparent and auditable, and would benefit by continuous update and data validation. A methodology is demonstrated for systematically dealing with uncertainties in costs and in available budgets. The methodology allows one to include non-technical constraints if such is desired. Temporal optimization gives the decision maker the ability to analyze scheduling capability developments in time.

VI. Acknowledgements

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