Temporal Investment Strategy to Enable JPL Future Space Missions

William P. Lincoln, Hook Hua, and Charles R. Weisbin
California Institute of Technology, Jet Propulsion Laboratory
William.Lincoln@jpl.nasa.gov

Abstract

The Jet Propulsion Laboratory (JPL) formulates and conducts deep space missions for NASA (the National Aeronautics and Space Administration). The Chief Technologist of JPL has the responsibility for strategic planning of the laboratory's advanced technology program to assure that the required technological capabilities to enable future JPL deep space missions are ready as needed; as such he is responsible for the development of a Strategic Plan. As part of the planning effort, he has supported the development of a structured approach to technology prioritization based upon the work of the START (Strategic Assessment of Risk and Technology) team.

A major innovation reported here is the addition of a temporal model that supports scheduling of technology development as a function of time.

The JPL Strategic Technology Plan divides the required capabilities into 13 strategic themes. The results reported here represent the analysis of an initial seven.

1. Introduction

The JPL Strategic Technology Plan divides the required capabilities into 13 strategic themes [1]. The results reported here represent the analysis of an initial seven (In-situ Planetary Exploration Systems, Survivable Systems for Extreme Environments, Precision Flying Systems, and Deep Space Communication, Planetary Protection Systems, Utilization of High Capability Computing, and Engineering Systems).

A capability hierarchy is created for each technology theme. Performance metrics are defined. Information is gathered on a mission-by-mission basis, and includes projected metric performance levels, their importance, estimated cost and development schedule, and likelihood of success if fully funded. A mission technology development timeline is used to constrain the timing of the developments. The temporal portfolio must not exceed annual budget levels available for investment. Each capability has a cost profile consisting of duration and annual costs needed for development. This information is input to an optimization method that recommends a temporal investment portfolio. Capabilities are given credit if, and only if, all capabilities needed to enable a particular mission of interest are selected for funding. By including temporal information into the optimization, our results suggest not only which set of capabilities to fund, but also when to fund them.

START is a tool to optimize research and development primarily for NASA missions [3]. 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 paper, START is used to analyze the capability needs using data from JPL's Strategic Technology Plan and a mission technology database we have assembled. It's important to note, however, that analysis isn't a onetime 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.

2. Input data

A capability hierarchy is created for each technology theme. Performance metrics are defined for each theme. The number of levels in a capability hierarchy can vary with the fidelity of the subdivisions. The structure allows weighting within each branch, with weights normalized to sum to one within each sub-branch.

Figure 1 shows a partial view of the capability hierarchy for Mars Sample Return.

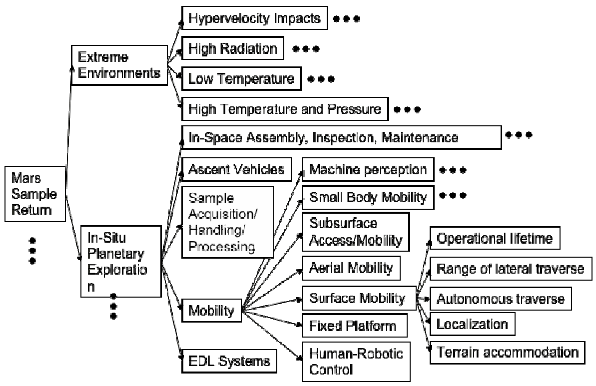

Figure 1. Partial view of the capability hierarchy for Mars Sample Return. Two themes are shown, Extreme Environments and In-Situ Planetary Exploration. Both themes are subdivided further. Metrics are placed at the lowest level. Metrics are shown for Surface Mobility.

Metrics are organized under the lowest level of the capability hierarchy. Each metric in the database has a name, a physical unit, polarity, State-Of-the-Art (SOA) performance, and current maturity. Each mission has its own set of projected metric values, their importance to the mission, and probability of development success given the development cost and schedule. Recall that these are advanced research areas and not every effort is assured to succeed. Development costs are to technology readiness level (TRL) 6.

This study used the mission set of interest to JPL at the time this work was performed. This set is shown in Table 1.

TABLE 1. MISSION SET.

Mission
Mars Science Laboratory
Large Observatory Platform
Comet Sample Return
Venus Surface Sample Return
Mars Scout Line
Mars Sample Return
Europa Surface/Subsurface
Terrestrial Planet Finder – Interferometer
Titan Explorer

3. Optimization

3.1. Defining value

The benefit function described here emphasizes performance improvement for metrics required for a mission. The metric's polarity indicates whether improvement is measured by reduction or increase; it is equal to -1 for metrics where a reduction in the metric's value is improvement; otherwise it is equal to 1. A total gain value of 1 means the projected level is 100% improvement of state of art. The metric gain, which measures the projected improvement of a metric over state of art is computed using equation 1.

$$\text{gain}_{metric} = \text{polarity}_{metric} * \log_2 \frac{\text{projected level}_{metric}}{\text{state of art}_{metric}} \quad (1)$$

Alternate benefit functions are possible. For example, the benefit may be more directly related to the impact of the technology on the mission.

Each metric gain has a probability of development success to reach the projected performance level based on cost and schedule. The calculation of the expected gain is given by equation 2.

$$\text{expected gain}_{metric} = \text{probability of development success}_{metric} * \text{gain}_{metric} \quad (2)$$

Mission gain is the weighted sum over all the required metrics' gains in the capability hierarchy for the mission.

$$\text{mission gain} = \sum_{themes} w_{theme} \sum_{areas} w_{area} \sum_{technologies} w_{technology} \sum_{metrics} w_{metric} * \text{expected gain}_{metric} \quad (3)$$

Where w_{theme}, w_{area}, $w_{technology}$ and w_{metric} are weights at the different levels of the capability hierarchy.

The total cost for the technology development of the mission is the sum of the cost for each of the required gains.

$$\text{mission technology development cost} = \sum_{themes}\sum_{areas}\sum_{technologies}\sum_{metrics} \text{cost for gain}_{metric} \quad (4)$$

The optimization algorithm selects missions to enable by maximizing the benefit function subject to a budget constraint.

Selection variables, Xi = {0,1}, are associated with each mission. A selection variable, Xi, equals 1 when all the required metric improvements are funded for the mission. If Xi equals 0 then none of the metric improvements are funded for that mission. Note that a technology development in a capability area is selected for funding only if all technologies needed to enable a particular mission of interest are selected for funding.

Projected metric levels for a mission have an importance weight. Higher weights correspond to metrics more important to the mission. At the extreme high end of the scale are the required metrics.

3.2. Development timeline

A 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.

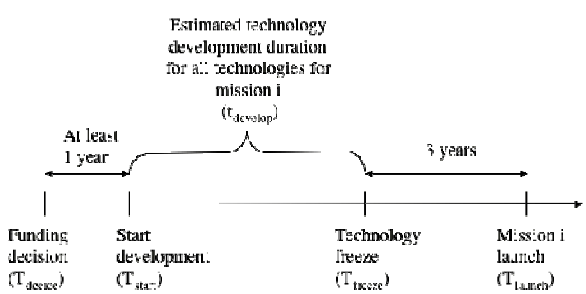

Figure 2. Mission capability development timeline.

All capability development of a mission occurs between T_{start}, and T_{freeze}. Figure 3 shows the temporal alignment of the developments.

The temporal optimization assumes that the portfolio investment is of independent capabilities (no dependencies), that the funding profile for individual capability development is constrained within the mission timeline, and that capabilities must be either fully funded or not funded at all for each mission.

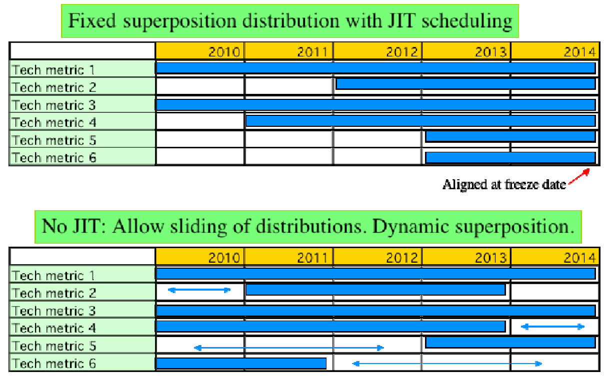

Fig. 3. Cost distribution profiles for each capability. With the just-in-time (JIT) model, all capabilities' funding is constrained so their last year of funding ends at the freeze date. Relaxing this constraint allows the funding profiles of each capability to be moved in time (blue arrows) to find the best total portfolio funding profile.

3.3. Temporal optimization formulation

The optimization has multiple cost profiles for each capability. Constraints force the restriction of only funding a capability at most once. If Xi equals one then mission i is enabled; if it equals zero then it is not enabled. The portfolio is optimized by finding the set of Xi and Yi,j,q that maximizes equation 5 subject to constraints 6, 7, and 8.

$$\sum_{i=1,N_{missions}} X_i * w_i * mission\ gain_i \quad (5)$$

If Yi,j,q equals one then the qth cost profile is used for funding capability j for mission i. The annual cost constraints are given by:

$$\sum_{i=1,N_{missions}}\sum_{j=1,M_{capabilities}}\sum_{q=1,Q_{cost\ profiles}} Y_{i,j,q} * C^{(t)}_{i,j,q} \le B^{(t)} \quad (6)$$

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

The development constraints for each mission i are given by:

$$Y_{i,\ j,\ q} = X_i \quad \text{for all enabling capabilities j}$$

$$q=1,Q_{\cos t\ profiiles}$$

(7)

and

$$Y_{i,\ j,\ q} \leq X_i \quad \text{for all enhancing capabilities j}$$

$$q=1,Q_{\cos t\ profiiles}$$

(8)

Each cost profile Ci,j,q is checked that it ends by the freeze date of the capability for the mission. Equations 5 and 6 enforce the constraint that only one cost profile is used to fund a capability for a mission. The optimization problem is solved using a variant of the Branch and Bound algorithm [1]. Figure 4 shows an example showing two capabilities and representative cost profiles.

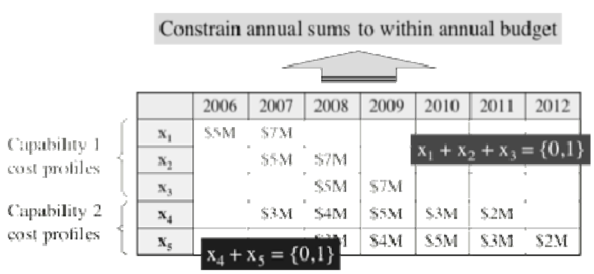

Figure 4. Constraints restrict only one cost profile per capability development. The annual cost constraints restrict the annual costs below the annual budget cap.

4. Results

4.1. Assumptions and caveats

The results reported here represent the initial analysis of seven out of thirteen themes. Data from the additional six missing themes will affect the results.

Furthermore the results are based on the validity of the input data. The input data needs to be independently reviewed by technologists and mission architects, before the process outlined in this paper is used to aid decision makers.

In particular, the designation of a metric level as required for a mission is critical since enabling metrics have priority over other metrics. By definition, if it were clear which metrics were necessary to mission success, the problem of selecting capabilities would already be solved. But in order to compare metric gains, the requirements must be known; for many future missions the system architecture is not completely defined and thus the requirements are not firm.

Changes in the mission set used for the analysis will also result in different recommended portfolios. For example, additional missions beyond TPF that use capabilities in Precision Formation Flying will raise the forecasted investments in that theme. The current data is for a single mission, TPF.

It is important to perform post-optimality analysis to qualify the recommendation obtained from the optimal solution and offers the decision-maker an array of viable alternatives.

We assume a capability needs to be fully funded each year to achieve its mission impact. Therefore, partial funding does not provide any benefit and therefore partial funding of a capability is not allowed.

Capability dependencies are not included in the input data. 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 results may be inconsistent where dependencies actually exist. The analysis can be updated when dependency data becomes available.

4.2. Illustrative results

With these caveats firmly in mind, illustrative results in figures 5-8 are presently at two annual budget levels, $180M and $150M annual budget levels.

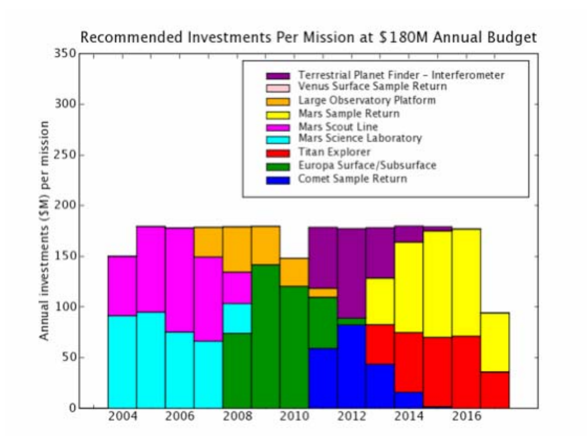

Figure 5. Annual recommended investments per mission at the $180M annual budget level. For seven of the thirteen themes there is enabling development for all missions except Venus Surface Sample Return.

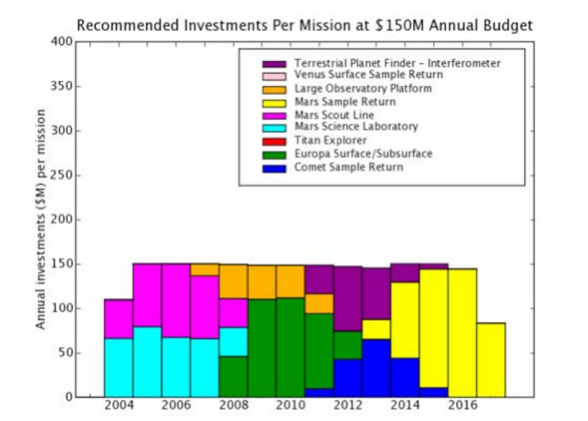

Figure 6. Annual recommended investments per mission at the $150M annual budget level. For seven of the thirteen themes there is enabling development for all missions except Venus Surface Sample Return and Titan Explorer.

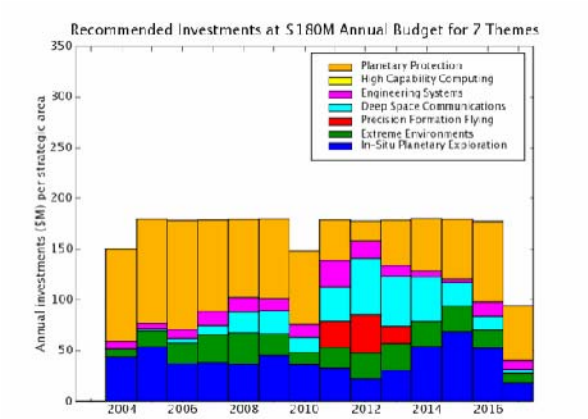

Figure 7. Annual recommended investments for seven of the thirteen themes at the $180M annual budget level.

The initial data is incomplete and not validated. The results reported here can only be taken as illustrative of the methodology.

Illustrative conclusions can be drawn from the plotted results. Technology for Venus Surface Sample Return is relatively expensive and should not be developed at either $150M or $180M annual budgets. Technology for Titan Explorer should not be developed at $150M annual budget. All others in the mission set can be enabled at $150M and $180M annual budget levels.

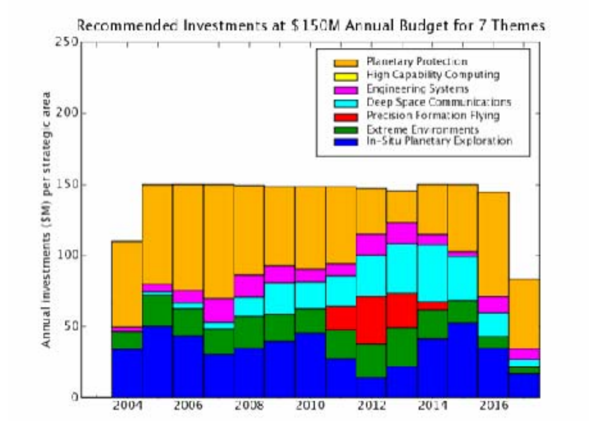

Figure 8. Annual recommended investments for seven of the thirteen themes at the $150M annual budget level.

Development might begin earlier than recommended for low TRL or high-risk technology development. Designation of technology as enabling versus enhancing is critical in funding recommendations. Results are dependant on complete and correct input data. Data from other strategic themes may change recommendations. Changes in mission set, launch dates, and mission weights may change results.

5. Conclusion

The START team developed a structured approach to technology prioritization. Our approach and its current status relative to the JPL technology investment strategy have been demonstrated.

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. 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.

Future work includes establishing mission value, adding the remaining themes to the analysis, and determining importance of metric levels for missions.

6. Acknowledgment

Work reported here was performed at California Institute of Technology, Jet Propulsion Laboratory under contract to the National Aeronautics and Space Administration.

We acknowledge the support of the Erik Antonsson, Loren Lemmerman, and Steve Prusha for encouraging and guiding this work; to Jeff Smith who created Fig 2; to colleagues Virgil Adumitroaie, Alberto Elfes, Jason Derleth, Joe Mrozinski and Kacie Shelton for their review, critique and suggestions; to Sherry Lage for administrative support.

7. References

[1] Antonsson, E. and L.A. Lemmerman, "Strategic Technology Plan for Jet Propulsion Laboratory", 2005.

[2] Martello, S. and P. Roth, Knapsack Problems -- Algorithms and Computer Implementations, John Wiley and Sons, 1990.

[3] Weisbin, C.R., G. Rodriguez, and A. Elfes, "Technology Resource Allocation for NASA and Its Enterprises," Systems Engineering Journal, vol. 7, no. 4, pp. 285-302, July 2004