# SYSTEMS ANALYSIS APPROACH FOR NASA AND ITS PROJECTS, PROGRAMS AND ENTERPRISES

C. R. Weisbin, G. Rodriguez, A. Elfes
S. Prusha, R. Easter, R. Pomphrey and D. Stetson
Jet Propulsion Laboratory
4800 Oak Grove Drive
Pasadena, CA 91109

add California Institute of Technology

## Abstract

The current transformation from a NASA of loosely coupled enterprises to "one NASA" which embodies cross-enterprise Agency Missions and an Integrated Space Plan, has created an important need for an overall integrated Agency wide approach to systems analysis. One NASA will only work if the Agency assigns high priority to the development and deployment of a consistent methodological foundation supporting the selection and monitoring of R&D tasks that support new system concepts that enable future missions. This capability should be applicable at various degrees of abstraction depending upon whether one is interested in formulation, development or operations. It should also be applicable to a single project, a program comprised of a group of projects, an enterprise typically including multiple programs, and the NASA agency itself. Emphasis here is on technology selection and new initiatives, but the same approach can be employed to deal with new system architectures, risk reduction, task allocation among humans and machines, etc. The purpose of this paper is to describe one such approach to achieving this capability.

This overall approach has been, and is being applied at JPL to a number of projects and programs, illustrative examples of which will be reported herein.

## I. Introduction

The current transformation from a NASA of loosely coupled enterprises to "One NASA," which embodies cross-enterprise Agency Missions and an Integrated Space Plan, has created an important n
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analysis. One NASA will work only if the agency assigns high priority to the development and deployment of a consistent methodological foundation for selecting and monitoring R&D tasks that support new system concepts to enable or enhance future missions.

This capability should be applicable at various degrees of abstraction, depending upon whether one is interested in formulation, development, or operations. It should also be applicable to a single project, a program comprised of a group of projects, an enterprise typically including multiple programs, and NASA itself.

START (STrategic Assessment of Risk and Technology) offers one approach to achieving this capability. Developed within the Strategic Systems Technology Program Office, a division of the Office of the Chief Technologist at NASA's Jet Propulsion Laboratory, START offers systems for quantifying the features of each development candidate, assessing its risk, and calculating its probable return-on-investment.

Emphasis here is on technology selection and new initiatives, but the same approach can be employed to deal with new system architectures, risk reduction, task allocation among humans and machines, etc.

## II. Methodology

The following describes the general procedure that the START team follows. It represents a significant departure from the process by which many important decisions about funding and technology selection have been made until now.

Though expert decision-makers may be guided by extensive experience and good judgment, they have human limitations. Usually, a decision-maker will consider only a few attributes when comparing competing technologies. Our system's usefulness, as much as anything, is that it induces decision-makers to consider all of the pertinent attributes, and provides a sound method for using them in the decision-making process.

Even when a decision-maker is confident about a selection based solely on his or her experience and judgment, the START process can provide a valuable, objective foundation to support that decision.

Please note, however, that not all studies begin at Step 1 and continue through to Step 8. A sponsor may have determined the answers to early-stage questions before initiating a study. Or a study may focus on, for example, identifying and evaluating possible system architectures for a given mission (Step 3).

In some cases, we may be called upon to assess the usefulness of a particular technology that was funded as basic research. To take a hypothetical example, the developer of a particular nanotechnology might want to know how it could be put to use in NASA's various programs. In such a case, we would employ a "bottom-up" approach, beginning at Step 5 and working upward to Step 2.

Frequently, we are called upon to split the difference: Working top-down until we've derived the capability requirements for a particular mission, then switching to bottom-up to identify the capabilities of a particular set of technologies that were funded as basic research. The case study, "Rover Autonomy #2," described below, is a good example of this approach. The action lies in matching capabilities with capability requirements.

Here, then, are the Methodology steps:

**1. Develop a clear, complete statement of the problem to be studied.**

State the problem unambiguously, specifying what is to be maximized or minimized, with all pertinent policy, schedule, and budget constraints. Probe to uncover any unstated assumptions that need to be taken into account. Unarticulated assumptions can undermine a study.

In a study of competing technologies, for example, the decision-maker might want to fund only as many technologies as can be brought to completion, or might prefer to fund all of the competing technologies at some level. If that preference is not stated at the beginning, the study may not provide the information that the decision-maker seeks.

Most often, we are asked to address the problem of maximizing science return subject to a given resource. However, our studies are capable of pursuing any number of other objectives, such as minimizing cost for variable range in performance, maximizing continuity of tasks, maximizing public interest, etc.

**2. Identify top-level goal.**

Identify top-level goals and quantify what would constitute satisfying those goals. For example, a mission to detect possible life one kilometer below the Martian surface would be one way to meet NASA's goal of searching for life on other worlds. For NASA work, we draw goals, investigations, and experiments from NASA strategic plans and science working group meeting reports.

**3. Develop or select one or more architectures for accomplishing the goal.**

Design or select architectures (precise scenarios) for conducting specific subsets of the desired experiment. A study may address mission architectures, system architectures, or both. For example, for the goal described above, a mission architecture might include launching a spacecraft, landing it safely in a certain location on Mars, having a rover disembark and travel to where scientists suspect a pool of underground water, drilling to a depth of 1 km, retrieving a sample, analyzing the sample for signs of life, and reporting the results to Earth. A system architecture may be limited to the design and functions of the rover.

The START team can also help sponsors identify the time horizon they wish to target for development of their technologies. For example, estimated mission science return can be based on projected Code S and Code Y missions as depicted in their respective roadmaps from 2009 through 2025.

**4. Identify the capabilities needed for the architecture.**

Decompose the mission or system concepts into specific quantitative capability requirements whose importance is based on their estimated contribution to the objective stated in Step 1 (such as maximizing science return). Our models are capable of capturing interdependencies between capabilities. For example, a Mars rover's sample acquisition capability depends on coordination of its sensing and manipulation capabilities.

**5. Identify technologies that could provide the needed capabilities.**

Assess technology candidates that purport to fulfill or partially fulfill the required capabilities. Capture uncertainties in their capabilities, using performance attributes and their probability distributions. Define each technology development task by at least four critical metrics:

a. performance requirement attributes
b. budget estimate
c. scheduled delivery date
d. risk level

**6. Evaluate and rank the technology candidates to identify which to use or fund for development.**

Rank technologies by calculating their contributions to all relevant capabilities and missions. Generate uniform unitless values to compare attributes with dissimilar metrics (for example, mass in kg, volume in $cm^3$, cost in dollars, etc.).

Risk may be calculated and considered, both in terms of an individual technology's risk of failure (useful in comparison with competing technologies), and in terms of the impact a technology's failure would have on the entire mission.

Construct optimal portfolios (sets of technologies for the desired purpose) for the objective stated in Step 1 (such as maximizing the total science return within allowable cost limits and other programmatic constraints).

**7. Validate results.**

Though it is impossible to compare a study's outcome with "truth," we consider our results validated if they are consistent with all known information (experiments, models, expert opinion, uncertainties). If not, we reexamine the inputs and model assumptions that led to the study's result.

**8. Track and reconstitute the technology portfolio as needed.**

Maintain an optimal portfolio as technologies mature and customer requirements change.

## IIa. Validation

Validation is the process of comparing a model's output with a real system or, lacking one, with an expert's judgment. If the result is consistent with all known information and the expert's opinion, we consider it validated. A positive validation confirms that the model's output represents the most reasonable result, within the limits of uncertainty.

If a result is invalidated, we examine the model's assumptions, revisit the inputs to see whether they were estimated accurately, and/or adjust for any new constraints that were not previously expressed.

It's important to note that some degree of uncertainty surrounds every input, and some inputs -- such as the relative importance of a particular attribute -- can only be estimated by experts, and are likely to have relatively high uncertainty levels. For technologies that do not yet exist, virtually all inputs may have to be estimated amid considerable uncertainty.

If the experts involved in a study's validation process reaffirm the values for each attribute, the

decision-maker may reconsider a conflicting opinion and bring it into accord with the study's results. Alternatively, the experts and decision-maker may revise some of the input values, leading to a different outcome.

### Sensitivity and Uncertainty

We can calculate which attributes (such as mass, volume, cost, or an aspect of performance) were most influential in producing the study's outcome, versus some other particular outcome. In practice, this is most useful when a study's outcome differs from the outcome preferred or expected by a decision-maker.

If a small change in the value assigned a particular attribute would produce a large difference in the result, that attribute is said to have high sensitivity. Conversely, low sensitivity indicates that even a big change in the value assigned a given attribute would have little impact on the study's results.

Relative uncertainty in a result is deduced from the product of sensitivity and uncertainty in the data that led to the result. If an attribute's uncertainty is much higher than that of the other attributes, it may be worthwhile to try to reduce that level of uncertainty. If all attributes have about the same level of uncertainty, we focus on sensitivity.

We can use sensitivity information in two ways. First, with the dominant influences on the study's output brought to light, a decision-maker can decide whether these particular influences make sense. If, for example, the cost of testing has high sensitivity in a study of competing technologies, but the decision- maker doesn't think that the cost of testing should be much of a determining factor, that's a signal that we need to reconsider the factors that produced such a high sensitivity for that attribute.

Second, if our results don't agree with the decision-maker's judgment, sensitivity tells us which attributes to target for re-evaluation of the input values. Minor revisions to a few highly sensitive attributes values may bring the study's results into conformity with the expert's opinion. The goal of this process, however, is not simply to make the study agree with an expert's preconceived ideas. It is to examine the underlying reasons for the difference in outcomes, and to determine whether any of the initial values should be changed on their own merits.

This procedure exposes the implications and ramifications of any given result, whether it is the study's initial output or the expert's preference. Result "A" means that all the values, preferences, and weightings that led to "A" are the best choices. Result "B" means that all the parameters that led to an output of "B" are the best choices. Going through this process leads a decision maker to examine those values, preferences, and weightings, and to make sure that they are as accurate as they can be.

In doing so, we build a solid foundation for whatever result the study ultimately produces. If, after this re-examination process, the study confirms the decision-maker's original preference, it provides a comprehensive explanation for why that is the best prediction that can be made. On the other hand, if it leads to a change of mind, the decision-maker will know exactly why such a change was warranted.

## III. Case Studies

Following is a group of case studies that involve technology tasks applied to exploration of the surface of Mars. The techniques employed, however, are applicable to a wide variety of mission types inside and outside of NASA.

The common thread in these studies is the development of models that enable us to calculate the impact technologies would have on the science return of their missions. This enables us to assign values to the projected return-on-investment for each technology, a very useful tool in ranking the technologies for funding and development.

### Autonomy for Mars Rovers

Whenever the Mars Pathfinder rover experienced a failure, it had to stop, wait for the next scheduled opportunity to communicate its

problem to Earth (relatively brief periods each day, due to limitations of the rover's solar batteries), and wait for new commands attempting to resolve the problem. After each command, the Earthbound controllers would await Pathfinder's progress report before issuing a follow-up command.

The process, guided by extreme caution, was tedious and time-consuming. The twin MERs (Mars Explorer Rovers), on their way to Mars as of this writing, will follow a similar procedure. Technology that would increase a rover's autonomy -- that is, improve its ability to conduct science while reducing its need to phone home for help -- would save a great deal of time and therefore enable the rover to accomplish much more.

Following are two case studies that represent efforts to determine the relative benefits of investing in various software technologies that purport to help Mars rovers do science more efficiently, avoid most failures, and diagnose and correct their own problems when failures occur.

The first study (Rover Autonomy #1) focuses on technologies that were proposed specifically to reduce fault rates observed during extensive field-testing in Mars-like terrain here on Earth.

The second study (Rover Autonomy #2) analyzes technologies that were funded as basic research, only loosely coupled to a mission.Hence, we needed to determine technology-derived capabilities and match those capabilities with mission requirements. These technologies are more advanced than those studied in Rover Autonomy #1, capable of automating entire sequential operations.

## Case Study 1: Rover Autonomy #1

We conducted this study to determine the relative benefits of developing various autonomy software technologies for a surface rover in the proposed Mars Science Laboratory (MSL) mission scheduled for 2009. Since the rover prototypes had been extensively field-tested in Mars-like terrain on Earth, we had access to an extensive body of real-world information.

We decomposed the mission into functional steps (acquire panorama, develop range map, plan path, etc.) covering long-range traverse, short-range approach to target, and sample acquisition and handling. For each of these steps in each mission element, we noted the kinds and frequencies of failure, and the time that was lost while the controllers developed a strategy to mitigate the failure.

For each of the science operations (moving samples to the rover's onboard analytic lab, conducting contact experiments, moving to a new site, etc.), we developed a utility function, based on interviewing an expert, which captured the relative importance of each activity. For example, the first sample collected in a bag may be worth 40% of the total mission value. In general, intrusive experiments, such as grinding up a rock sample and analyzing it with a mass spectrometer, merited the highest values.

We calculated the abilities of the autonomy software technologies under study to mitigate potential failures, as well as the difficulty in developing each of them. Subsequent work transformed the difficulty estimation into dollars. Since the cost of each technology cannot be predicted with certainty, we established uncertainty estimates in return-on-investment with regard to performance and, through modeling, to science return.

Each autonomy software technology was judged by two attributes: ability to save time (measured in Martian days, or "sols"), and cost.

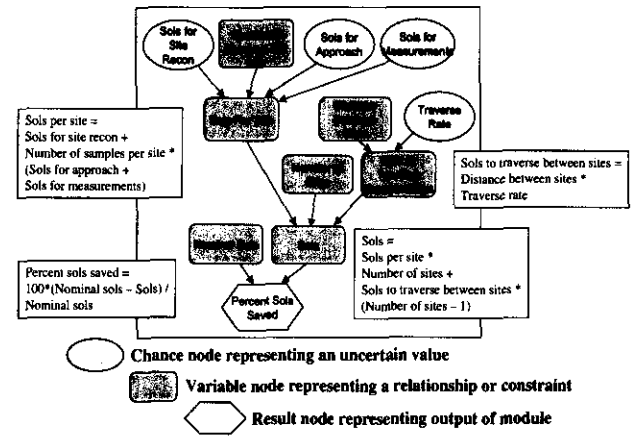
The relative contributions of the autonomy technologies appear in following graphs:

| Area | Technology Group |
|---|---|
| 1 and 2 | Onboard Fault Identification for Planetary Rovers |
| 1 and 2 | System-Level Verification Technology |
| 1 and 2 | Autonomy Infusion Simulation Environment |
| 3 | Distributed Control Testbed for Autonomy |
| 3 | Rover Autonomy Architecture |
| 4 | Single-Cycle Instrument Placement |
| 4 | Rover-Based Manipulation |
| 5 | Multimedia Human Computer Interfaces |
| 5 | Human-Centered Computing for MER |
| 6 | Onboard Science Analysis |
| 7 | MER Rover Sequence Generation |
| 7 | Contingency Planning for Concurrent Activities |
| 7 | Accelerated Long-Range Traverse |
| 7 | System for Mobility and Access to Rough Terrain |
| 7 | Super-Resolved 3-D Surface Models from Rover Images |

**Key to Areas**:
1. Fault Management
2. Validation/Verification
3. Software Architecture
4. Approach/Instrument Placement
5. Human-Computer Interaction
6. Sample Handling
7. Mobility

For example, we determined the impact that "System for Mobility and Access to Rough Terrain" would have on the rover's traverse rate. Then we plugged that information into the Mission Model to calculate its impact on the number of sols (Martian days) this technology would save over the current state-of-the-art, as a percentage of the total mission duration.

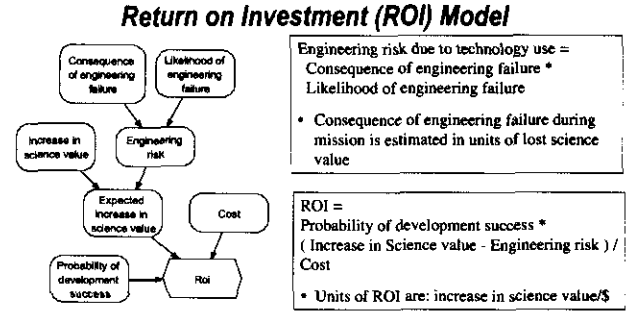
***Mission Model***




This template illustrates the procedure for calculating how many sols each technology group would save, as a percentage of the total mission. Each technology would impact (and presumably improve) one or more of the bubbles that lead to determining a number for "sols." "Nominal sols" refers to the number of sols that would be spent using state-of-the-art technology as represented by the MER rovers.

Saving sols means enabling the rover to spend time doing science instead of -- in this case -- traveling. So saved sols are presumed to correlate to an increase in science value. We used the number of saved sols in the ROI Model to determine each technology's return on investment, and the resulting numbers were used to rank the technologies.

***Return on Investment (ROI) Model***




- Increase in science value is estimated by percent sols saved when using technology.
- Assume mission will use the extra sols engaged in additional activities based on their relative utility.

This template illustrates the procedure for determining ROI for each technology group. "Increase in science value" uses the "percent sols saved" number calculated in the Mission Model.

The table below shows the results of the initial prioritization. The task names have been replaced by the letters A-O because the data is still preliminary and under review. We provide the results table, with the data and supporting models, to all parties involved to begin a dialogue on the perceived impact and rationale.

| Initial Results | | | |
|---|---|---|---|
| Task | MSL ROI | Polar ROI | Combined ROI |
| Technology A | 4 | 6 | 5 |
| Technology B | 7 | 9 | 8 |
| Technology C | 15 | 17 | 15 |
| Technology D | 14 | 17 | 15 |
| Technology E | 10 | 11 | 10 |
| Technology F | 13 | 10 | 12 |
| Technology G | 31 | 32 | 31 |
| Technology H | 3 | 3 | 3 |
| Technology I | 4 | 8 | 5 |
| Technology J | 4 | 0 | 3 |
| Technology K | 23 | 46 | 31 |
| Technology L | 7 | 15 | 10 |
| Technology M | 14 | 14 | 14 |
| Technology N | 5 | 23 | 11 |
| Technology O | 2 | 2 | 2 |
| Combined ROI used illustrative weighting with relative ratio 2:1 for MSL and Polar missions. | | | |

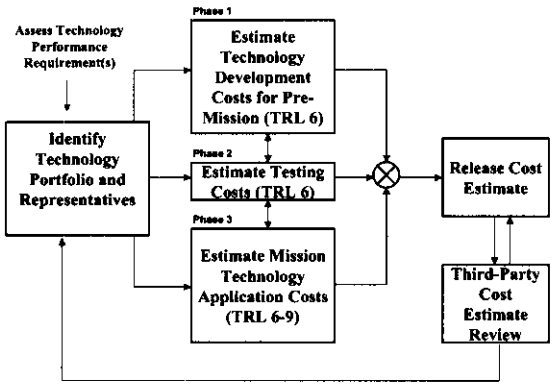
ROI represents increase in science value (as measured by the number of sols saved over state-of-the-art, or "SOA") divided by cost. When calculating the *combined* ROI for each technology task, we gave the MSL value twice as much weight as the polar value. This weighting is somewhat arbitrary and could be changed if desired. But it was intended to reflect the fact that these technologies are more likely to be used in the more-imminent MSL mission, and to be precursors to the technologies that will enable and enhance the polar mission. Though these technologies are innovative, far exceed SOA for the most part, and are intended for long-term impact, they will have as much as a decade for further improvement between the two missions.

Note also that these ROI numbers are not intended to represent final, definitive evaluations, but rather a solid basis for further investigation and discussion. They indicate the potential performance of each technology under certain conditions and for specific purposes. A given technology might benefit additional operations that, if factored into the study, would improve the technology's ROI. Similarly, we could amplify the study by factoring in additional metrics -- such as development and operations cost, heritage value, innovation, and public inspiration -- and potentially arrive at different results.

However, the study does demonstrate that it is possible to estimate mission-level science return impacts of diverse autonomy technologies, that the results can be very useful in assisting decision-makers in the selection of technology groups for funding and development, and that these methods are applicable to a wider class of technologies and mission classes.

## Case Study 3: Predicting the Cost of New Technologies

People seeking technology development funding tend to put the best light on their estimates of how much time and money they will require. Add to this trait the fact that technologists and mission designers often have conflicting, unexpressed assumptions about what is required, and you have the makings of costly misunderstandings and cost overruns.




This particular task subset dealt only with technologies up to TRL 6, and so did not include the action described in the lower middle box.

This task concept was to develop a process to generate plausible cost estimates grounded on clear assumptions.

We developed a process for estimating the cost of new technology that included uncertainty and an independent peer review of the estimate. It is based on interviews with technology representatives that focus on cost and performance relationships for each technology:

1) What are the important relationships that influence the cost?
2) What are the development issues?
3) What happens to performance if the cost is higher or lower?
4) What happens to cost if performance is higher or lower?
5) What assumptions underlie the cost estimate?
6) What is the probability of successfully developing the technology?

As a test case, we applied the process to a set of autonomy software technologies for Mars rovers that were the focus of the "Rover Autonomy #1" study.

The interviews in this case revealed important and subtle factors such as technology interdependencies, resource dependencies, and areas of common problems for the technologies studied.

The third-party review was critical in helping to (1) validate the original prediction, (2) identify missing or redundant cost issues affecting the initial prediction, and (3) determine any adjustments that might need to be made to the original cost estimate.

While the task was to model the relationships between performance, cost, and schedule for autonomy software, the general approach should be extensible to other technologies, including hardware systems.

### Stopping Rule

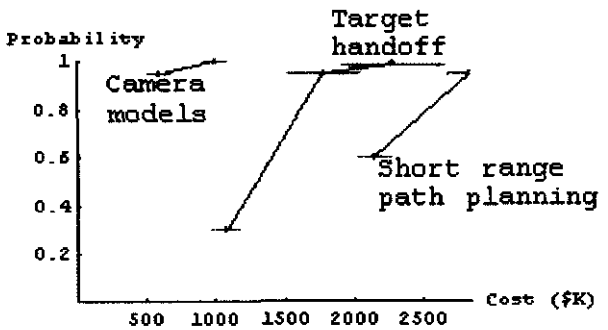
Part of the task was to develop and validate a "stopping rule," a formula that determines at what point diminishing returns make it inadvisable to invest in improving a technology to reduce its failure rate.

We developed an algorithm to improve the cost-effectiveness of the cost estimation process by focusing attention on the technologies with lowest performance and greatest potential benefit. Further study would likely yield a better understanding of the requirements and feasibility of finding the optimal stopping rule.

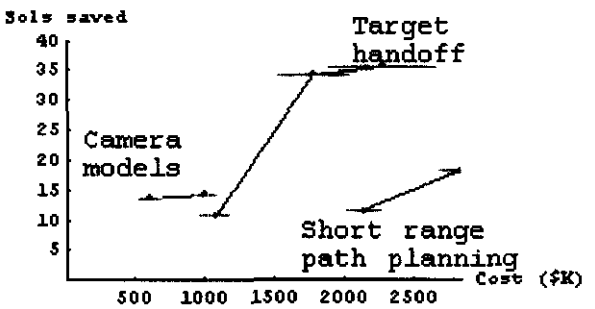
### Optimizing Technology Portfolios

An optimal $50 million portfolio does not necessarily simply add new technologies to those of a $40 million portfolio. Expanding the budget may make an entirely different set of technologies possible and preferable.

By more reliably predicting the costs of component technologies and considering the interrelationships of their science return, we can help decision-makers to determine the best place to set the cutoff points for their technology budgets.




The above graph shows the probability of completing three tasks to their specified level of performance, at a range of budgets. For example, the probability of completing target handoff rises from about 0.3 at roughly $1.1 million to about 0.95 at a cost of about $1.75 million. The green shading around each budget point indicates the amount of uncertainty in the figure.




This graph illustrates the performance level (measured in the number of Martian days, or sols, that would be saved) one can expect at the budget levels plotted in the previous graph. For target handoff, the number of sols saved increases from about 10 at roughly $1.1 million to about 35 at about $1.75 million. The data for both graphs was derived from interviews with experts.

Together, these two graphs can help a decision maker to optimize a portfolio.

Suppose he or she has about $2 million to spend on autonomy software technology. Considering the three technologies represented on these graphs, the decision maker can fund one of three possible portfolios:

1. Camera models and target handoff. But there will only be enough money to fund target handoff to the point where the top graph indicates less than a 0.4 probability of being completed.
2. Target handoff alone, but to the level where the top graph indicates near certainty that it will be completed.
3. Short range path planning, but only to the level where it has around a 0.5 probability of being completed.

The bottom graph tells us that Portfolio #1 will save about 15 sols for the camera models plus about 10 sols for the target handoff, for a total of 25 sols saved. Portfolio #2 would save about 35 sols. Portfolio #3 would save about 11 sols.

All other things being equal, the best return-on-investment would come from portfolio #2, which would save 35 sols with a near-certainty of completion.

## Case Study 4: Optimizing Technology Portfolios for Mars Missions

This study illustrates a more extensive approach to developing optimal technology portfolios for specific budgets.

Mars program goals include discovering whether life ever arose there, determining the planet's climate history and the evolution of its surface and interior, and preparing for human missions. We began our study by developing concepts for missions to accomplish these goals during the timeframe of 2009-2020. They are summarized in the table on the next page.

Next, we developed quantitative capability requirements to enable the potential missions, and identified the technology development efforts required to enable those capabilities, taking note of their funding levels, probabilities of success, and the alternate technologies available for use if the new technology cannot be successfully developed.

| Mission Name | Description |
|---|---|
| Polar Layer Deposit | Rover mission to characterize polar regions with in-situ sampling |
| Volcanology Rover | Rover mission to characterize volcanic region with in-situ sampling |
| Rover/Lander (MSL) | Rover to characterize landing site with in-situ sampling |
| Wildcat Lander | Lander with 30mm depth drilling system |
| Sabertooth Lander | Lander with 1000m depth drilling system |
| Synthetic Aperture Radar Orbiter | Orbiter sounding for surface science experiments and mapping |
| Magnetometer Orbiter | Orbiter for magnetometer and gravity instrument science |
| Imaging/Atmospheric Sounding Orbiter | Next generation remote sensing orbiter (imaging and atmospheric sounding) |
| Surface Science Orbiter | Orbiter for large-scale (area) surface science |
| MSR Sample Lander | Sample return with a Mars ascent vehicle |
| Scout Mission | Low-cost opportunity mission |

We picked three levels of technology investment for a 12-year period: $25 million per year, $50 million per year, and $75 million per year, and used an optimization program to determine which sets of technology would yield the best science return at each funding level. The results appear in the following table.

The table presents two alternate choices at the $50 million per year level. For that budget, one can either develop three missions (Mars Smart Lander, Mars Sample Return, and Scout Mission) expected to result in the maximum amount of science, or a greater number of missions that would provide more diverse technology development but have less potential for science return. Note that for this study, budgets were not permitted to exceed the budget cap in any given year, even if the cumulative budget over the course of 12 years would have been maintained.

| Technology Investment | Technology Portfolio | Missions Enabled |
|---|---|---|
| **$25M Per Year** | • On-orbit science<br>• Telcom network & navigation<br>• Multi-mission survivability, orbiters | • Magnetometer orbiter<br>• Synthetic Aperture Radar orbiter<br>• Imaging/Atmospheric Sounding orbiter<br>• Surface Science orbiter |
| **$50M Per Year** | • Precision landing<br>• Impact attenuation<br>• Hazard avoidance<br>• On-orbit science<br>• Forward planetary protection<br>• Sample characterization, surface<br>• Sub-surface access<br>• Mobility<br>• Sample handling, contamination<br>• Back planetary protection<br>• Telecom network, navigation<br>• Mars Orbit Rendezvous<br>• Multimission survivability<br>• Scout technology | Minimum number of missions:<br>• Precision landing<br>• Impact attenuation<br>• Hazard avoidance<br>• On-orbit science<br>• Forward planetary protection<br>• Sample characterization, surface<br>• Sub-surface access<br>• Mobility<br><br>Maximum number of missions[a]:<br>• Mars Smart Lander<br>• Mars Sample Return<br>• Scout mission<br><br>[a] Excludes on-orbit science, back planetary protection, Mars orbit rendezvous, and multi-mission survivability. |
| **$75M Per Year** | • Precision landing<br>• Impact attenuation<br>• Hazard avoidance<br>• On-orbit science<br>• Forward planetary protection<br>• Sample characterization, surface<br>• Sub-surface access<br>• Mobility<br>• Sample handling, contamination<br>• Back planetary protection<br>• Telecom network, navigation<br>• Mars Orbit Rendezvous<br>• Multimission survivability<br>• Scouts | • Volcanology Rover<br>• Mars Smart Lander<br>• Magnetometer orbiter<br>• Synthetic Aperture Radar orbiter<br>• Imaging/Atmospheric Sounding orbiter<br>• Surface Science orbiter<br>• Polar Layer Deposit Lander/Rover<br>• Mars Sample Return<br>• Wildcat Lander<br>• Sabertooth Lander<br>• Scout mission |

Also, only the costs of developing technology were considered, not the costs of the missions. In a subsequent study, still being completed, the expenditure schedule is more flexible and mission costs are included.

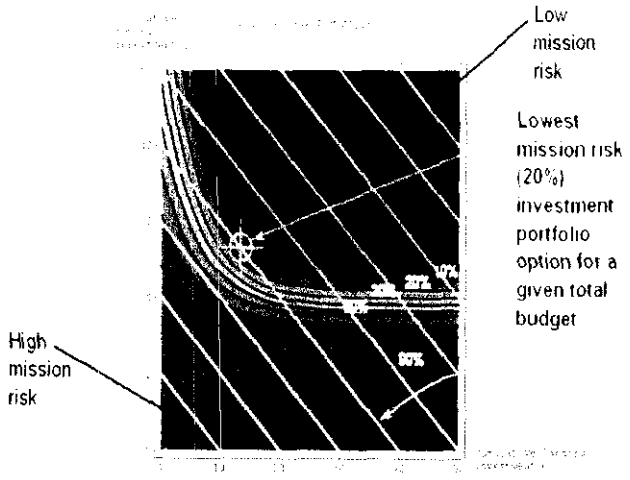
## Case Study 5: Lander vs. Rover

This case study compares the impact of investments in precision landing and long-range roving technologies on a hypothetical mission to Mars. We show how to develop an optimal investment strategy that minimizes mission risk, given a fixed total technology investment budget.

The baseline mission scenario for this study is a Mars 2009-class mission with precision landing

capability and a long-range rover. There are three preselected science sites, including the target-landing site, with a total traversal distance of six kilometers. Total mission time is 90 sols (Martian days), with 50 sols allocated to traversal.

The results are shown below.




In this graph, investment in lander technology is shown on the horizontal axis, and investment in rover technology is shown on the vertical axis. The dollar amounts on the two axes are connected by diagonal "isobudget" lines. Every point along the straight line that connects $40M on the lander axis with $40M on the rover axis, for example, indicates a combined investment of $40M.

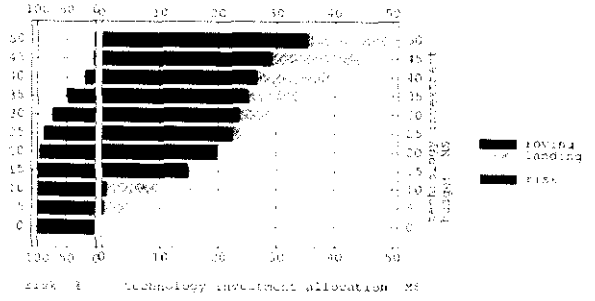
The curved lines represent levels of risk of mission failure. The top curved line, for instance, represents a 10% chance that the mission will fail (or, to put it more optimistically, a 90% probability of success).

The uppermost "risk" curve that is intersected by any given "budget" line indicates the lowest risk level that budget can buy. The point of intersection reveals what combination of investments in lander and rover technology will achieve that lowest possible risk.

For example, if you have $40M to spend, you look along the $40M diagonal line until you see where it intersects the highest risk curve. $40M doesn't intersect the very top curve, which indicates a 10% risk of failure, but it does intersect the 20% curve. So the least amount of risk you can have for a $40M budget is 20%. And by seeing where that intersection point falls on the two axes, you can determine how that $40M budget should be divided between lander and rover technology. In this case, you'd spend about $13M on lander technology and about $27M on rover technology to achieve the lowest possible risk for that budget: 20%.

If risk level is more important to you than dollar amount, you can use this graph to see how much you have to spend -- and where you should spend it -- to achieve that level of risk. For example, if nothing greater than a 10% risk (that is, nothing less than a 90% probability of success) is acceptable, you can see that the least amount you can budget is $50M. And $26M of that should be spent on lander technology, while $24M should be spent on rover technology.

Another method of visualizing the results from this study is shown below.



On this graph, total budget levels vary vertically. The minimum mission risk achievable at each budget level is shown on the left, while the corresponding technology portfolio appears on the right.

## IV. Conclusions

NASA, as well as many other organizations, can benefit enormously from a consistent methodology for selecting and monitoring R&D tasks. We have proposed a flexible system that assists decision-makers in evaluating all pertinent attributes of development candidates, including risk and uncertainty, and identifying the main drivers of a result. The system provides a sound foundation for the decision-making process, based on the candidates' predicted contribution to

science return or other goals. We have shown that it is quite possible to estimate mission-level science return impacts of diverse technologies, even when those technologies were conceived primarily as basic research.

We have demonstrated a system for making plausible predictions of the cost of new technologies, of determining when diminishing returns make further development inadvisable, and of optimizing technology portfolios at various budget levels.

The case studies cited here illustrate our methodology and the results it can produce. We have emphasized, however, that a study's outcome is generally not intended to be a definitive conclusion, but rather a basis for further investigation and discussion. Ultimately, the process provides solid support for a decision-maker's judgement.

## V. Acknowledgements

This work would not have been possible without the financial support and encouragement of a number of outstanding and technically knowledgeable sponsors. These include, in alphabetical order:

*Robert T. Caffrey*
(Deputy Program Manager for Structure and Evolution of the Universe), National Aeronautics and Space Administration (NASA) Goddard Space Flight Center (GSFC)

*Yuri O. Gawdiak*
(Program Manager for the Engineering of Complex Systems (Engineering Complex Systems [ECS] Program), NASA Headquarters (HQ)

*Christopher Moore*
(Manager of the Code R Enabling Concepts and Technology Program, as well as the Revolutionary Aerospace Systems Concepts (Revolutionary Aerospace Systems Concepts [RASC] Program), NASA HQ

*Robert A. Pearce*
(Manager of Division of Strategic Planning for NASA Code R), NASA HQ

*Julie A. Pollitt*
(Staff Member, Division of Strategic Planning for NASA Code R), NASA HQ

*John F. Stocky*
(Technology Manager, New Millennium Program (New Millennium Program [NMP]) of NASA Code S), JPL

*Harley A. Thronson*
(Director of Technology for NASA Code S), NASA HQ

*William R. van Dalsem*
(Computing, Communications and Information Technology [CICT]), NASA Ames Research Center

*Charles W. Whetsel*
(Mars Program Chief Engineer), JPL

For their essential contributions to the case studies, we wish to acknowledge and thank our esteemed colleagues, William P. Lincoln, Ram Manvi, Jeffrey H. Smith and Ayanna M. Howard.

We would also like to express our deep appreciation to Bob Silberg for his work on the text for this paper and the START web site, and to Sherry Lagé for her invaluable efforts in preparing this document and the ongoing smooth functioning of the entire START operation.

## VI. Web Site

The START web site offers many more case studies, and describes how our methodology is applied to other areas besides Mars. Please visit http://start1.jpl.nasa.gov.

## VII. Publications

**Rover Autonomy #1**

"Relative Benefits of Potential Autonomy Technology Investments," Bill Lincoln, Alberto Elfes, Guillermo Rodriguez, and Charles Weisbin; International Conference on Space Mission Challenges for Information Technology (SMC-IT), Pasadena, California, July 13-16, 2003.

**Predicting the Cost of New Technologies**

"Predicting the Cost of New Technology, An Approach and Case Study for Autonomy Technologies," Jeffrey H. Smith, Julie Wertz, Charles Weisbin; Engineering for Complex Systems, JPL Doc. No. D-26750, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, October 2003.

**Optimizing Technology Portfolios for Mars Missions**

"Reaching Mars: Multi-Criteria R&D Portfolio Selection for Mars Exploration Technology Planning," J.H. Smith, B. Dolgin, and Charles Weisbin; Proceedings of the 32nd Annual meeting of the Western Decision Sciences Institute, Marriott Resort and Beach Club, Lihue, Hawaii, April 15-19, 2003.

"Building a Pathway to Mars: Mars Technology Program Analysis and Case Study," with B. Dolgin and C. Weisbin, presented at the 2003 Portland International Conference on Management of Engineering and Technology (PICMET): Technology Management for Reshaping the World, Portland, OR, July 20-24, 2003.

"Building a Pathway to Mars: Technology Investment for Science Return," J.H. Smith, J. Wertz, and C. Weisbin, forthcoming, *Journal of Space Mission Architecture* (JSMA), JPL Publication No. 03-15, Jet Propulsion Laboratory, Pasadena, CA, Issue 3, Fall 2003.

"Identifiying Technology Investments for Future Space Missions," J. P. Chase, A. Elfes et al. AIAA Space 2003 Conference, Long Beach, September 2003.

**Lander vs. Rover**

"A Risk-Based Framework for Optimization of Technology Portfolio Investment Choices for Early Space Mission Design," Alberto Elfes, William P. Lincoln, Guillermo Rodriguez, Charles Weisbin, and Julie A. Wertz; submitted to IEEE Transactions on Aerospace Engineering.