Reconciling Scientific Aspirations and Engineering Constraints for a Lunar Mission via Hyperdimensional Interpolation. Charles R. Weisbin[1], Pamela Clark[2], Alberto Elfes[1], Jeffrey H. Smith[1], Joseph Mrozinski[1], Virgil Adumitroaie[1], Hook Hua[1], Kacie Shelton[1], William Lincoln[1], Robert Silberg[1]; [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109; [2]Goddard Space Flight Center, 8800 Greenbelt Road, Greenbelt, Maryland 20771. E-mail: Charles.R.Weisbin@jpl.nasa.gov

Virtually every NASA space-exploration mission represents a compromise between the interests of two expert, dedicated, but very different communities: scientists, who want to go quickly to the places that interest them most and spend as much time there as possible conducting sophisticated experiments, and the engineers and designers charged with maximizing the probability that a given mission will be successful and cost-effective. Recent work at NASA's Jet Propulsion Laboratory (JPL) seeks to enhance communication between these two groups, and to help them reconcile their interests, by developing advanced modeling capabilities with which they can analyze the achievement of science goals and objectives against engineering design and operational constraints.

The analyses conducted prior to this study have been point-design driven. Each analysis has been of one hypothetical case which addresses the question: Given a set of constraints, how much science can be done? But the constraints imposed by the architecture team—e.g., rover speed, time allowed for extravehicular activity (EVA), number of sites at which science experiments are to be conducted— are all in early development and carry a great deal of uncertainty. Variations can be incorporated into the analysis, and indeed that has been done in sensitivity studies designed to see which constraint variations have the greatest impact on results.

But if a very large number of variations can be analyzed all at once, producing a table that includes virtually the entire trade space under consideration, then we have a tool that enables scientists and mission architects to ask the inverse question: For a given desired level of science (or any other objective), what is the range of constraints that would be needed? With this tool, mission architects could determine, for example, what combinations of rover speed, EVA duration, and other constraints produce the desired results. Further, this tool would help them identify which technology-improvement investments would be likely to produce the largest or most important return.

However, the number of variations that need to be considered for such analysis quickly balloons to an unwieldy size. If three variations are considered for each of six constraints—a very modest example—there are a total of 243 variations to consider. If it takes 40 minutes to compute each variation, as it does with HURON, our automated optimization system, then it would take 162 hours or nearly 7 days of round-the-clock computing to calculate the results. Adding further constraints or variations exponentially increases the amount of time that is needed.

In this study, we explore three methods—radial basis functions (RBF), kriging, and regression—for interpolating about 90% of the trade space based on actual computations of about 10%, which dramatically reduces the time needed to compute results. RBF is found to carry a higher error rate than the other two and to be the least suitable for our purposes. Choosing between kriging and regression, however, is more complicated and depends on how the tool is to be used.

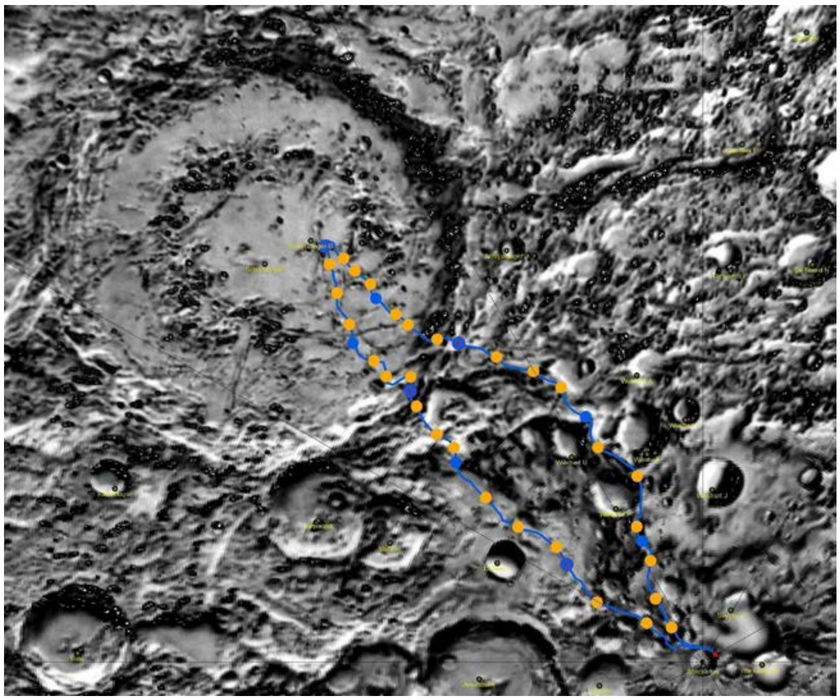

Figure 1: Geometry of a hypothetical 90-day excursion from an outpost at Shackleton crater (lower right) to Schrödinger crater and back.

Baseline study

The subject of our study is a hypothetical mission to Schrödinger crater, which is thought to expose underlying stratigraphic material from South Pole Aitken Basin, the oldest, largest basin on the Moon. The allotted round-trip time from an assumed base camp at Shackleton crater to Schrödinger and back is 90 days.

Figure 1 lays out the geometry of the mission. Blue dots indicate primary localities for science experiments, while orange dots indicate secondary localities where scientific experiments would enhance mission results. Each of these localities comprises 6 sites where scientific activities are to be performed. The mission is conducted with two 2-astronaut teams, each of which drives a pressurized rover that is periodically recharged by a separate, slower vehicle operated remotely from Earth. A target list of experiments and other activities is derived from the scientific goals expressed by NASA's Lunar Exploration Analysis Group (LEAG), and a set of constraints is provided by a mission-architecture team. Each experiment and activity is assigned a relative science value.

A baseline solution of the Schrödinger excursion problem is computed, using HURON. It is found that the desired activities can be conducted at all primary sites and many secondary sites in a mission totaling 89.5 Earth days. Given these conditions, the constraint on EVA time, during which all scientific activities are conducted, is found to be the primary driver of results. A significant amount of IVA time (i.e., intravehicular activity time, when the astronauts are inside the pressurized cabins of their rovers) is included in the mission profile, during which further science activities could potentially be conducted if that were permitted and enabled.

Response surface analysis

In the next phase of the study, the objective is to determine the ranges for a variety of architecture parameters that achieve equivalent levels of science return. With 3 variables for each of 6 constraints (EVA time, time per locality, rover speed, number of primary localities included, number of secondary localities included, and time needed for egress from and ingress into the rover's pressurized cabin), the trade space is an irregular, multidimensional (aka hyperdimensional) grid. Twenty-two cases are run on HURON, and the remaining 90% of cases are interpolated using each of the three methods stated above.

The analysis produces results for 5 parameters: science value, productivity, cost, mission duration, and kilometers traversed. We choose to sort the results by science value, but the sorting could just as easily be done by any or all of the other parameters. Results are validated and an error rate is computed for each interpolation method (Figure 2).

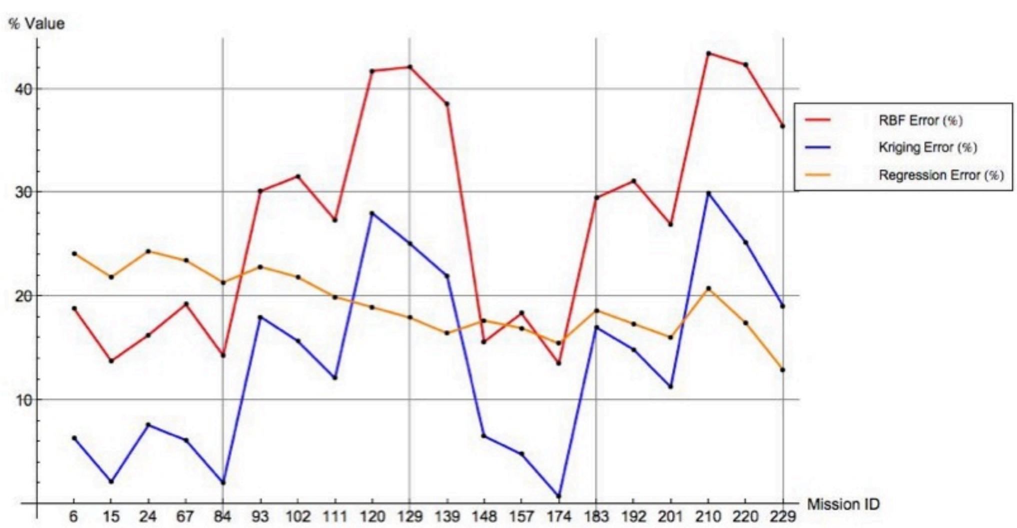

Figure 2: Comparison of the error rates of 3 interpolation methods

Kriging (the purple curve) is found to have the lowest average error rate and is used to compute a table in which the 243 cases are ranked by science value (Figure 3). The rows near the top of the table section containing a green column thus represent the cases that would likely be selected by mission architects who wish to maximize science value. Given this information, they would be able to further winnow the choices according to other constraints that are not included in this analysis—e.g., public outreach considerations or participation by other countries.

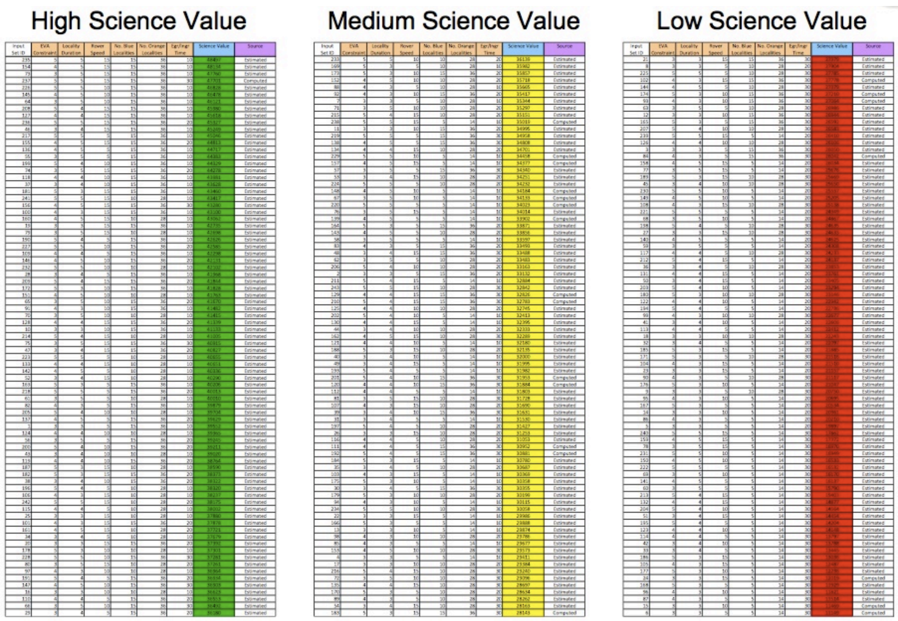

Figure 3: The product of the response surface analysis. In each section of the table, the first column gives an identification number to each case, the 6 orange-headed columns are the 6 constraints discussed above, the blue-headed column gives the total science value of each case, and the purple-headed column indicates whether each case was computed or interpolated.

Conclusions

We have shown that we can survey a very broad range of combinations of architect parameters through a combination of computer optimization runs and interpolation, and that we can provide an estimate of the quality of the results by a number of different methods. Increasing the number of computer runs decreases the interpolation error rate. Of the three interpolation methods employed in this study, kriging (which had the lowest average error rate) was found to be best for our purposes, but the more consistent results of the regression method (the yellow curve in Table 2) may be preferable in certain circumstances.