Reducing the Risk and Improving Mission Success for NASA's Human Mission to a Near-Earth Asteroid: How Many Robotic Surveyors?

Jeffrey H. Smith[a], William P. Lincoln[b] *and* Charles R. Weisbin[c]
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, 91109-8099, U.S.A.

NASA's recent attention and interest in sending a human mission to land on a Near-Earth asteroid raises the question of need for a robotic surveyor. This paper describes a Bayesian approach for comparing the productivity and cost-risk tradeoffs of sending (versus not sending) one or more robotic surveyor missions prior to a human mission to land on an asteroid. The probability of finding an asteroid suitable for landing was derived from an analysis of more than 1200 asteroids in order to define a quantitative estimate of suitability. The low cost of the surveyors relative to the human mission underlined the multi-surveyor strategy as relatively inexpensive insurance against the risks of encountering an unsuitable asteroid for landing on arrival by a human mission.

Nomenclature

EVSI	=	expected value of sample information
X	=	value of asteroid surveyor mission
Y	=	value of human mission that lands on asteroid

I. Introduction

NASA's recent attention and interest in sending a human mission to land on a Near-Earth asteroid raises a number of issues.[1,2] A critical question was whether the asteroid would be suitable for a human landing and whether the cost-versus-risk reduction of first sending a robotic surveyor would be justified prior to the larger, more complex human mission. One alternative would send the human mission directly to an asteroid and use real-time analysis on arrival to evaluate and plan a "landing" on the surface. Alternatively, one or more surveyor missions could be sent prior to the human mission to conduct "close-up" observations to determine the feasibility of landing. This paper uses a Bayesian approach to compute the expected value of sample information (EVSI) in the form of the expected value of "suitability" information provided by a surveyor versus a direct mission without suitability information.

Orchestrating a human "landing" on an asteroid is complex because asteroids are generally not spherical in shape; have varying densities and gravity fields; different spin rates and tumbling orbits; and may have physical surface features making them unsuitable for a human landing. The term human landing used in this paper does not imply a human physically walking on the surface due to very low gravity but rather, translating over the surface on umbilical tethers or with small propulsive devices. Without initial close inspection of the asteroid, a baseline prior probability of suitability of 70% was estimated from the proportion of known asteroids with greatest scientific interest.[3] In the present study there was no intermediate condition where an asteroid might be partially suitable--it would either be suitable or unsuitable for landing. The actual prior probability would be estimated from Earth-based observations when the final target set was determined. The prior probability of suitability has been stated to be in the range of 70-75% based approximately on the proportion of carbonaceous near-Earth asteroids. However, a more accurate estimate was obtained by searching databases of known near-Earth objects. Suitability for possible landing was defined as any near-Earth asteroid with a diameter between 500 and 1500 m and a spin rate less than or equal to 0.53 revolutions per hour. The ratio of this number to the total number of objects in the catalog was used to estimate the upper bound on the probability of suitability. Two databases containing a total of 1200 asteroids reachable by

[a] Senior Member of the Technical Staff, Mission Systems Concepts Section, 4800 Oak Grove Dr., Pasadena, CA, 91109-8099, Mail Stop 301-165.
[b] Member of the Technical Staff, Instrument Software and Science Data Systems Section, 4800 Oak Grove Dr., Pasadena, CA, 91109-8099, Mail Stop 171-264.
[c] Deputy Program Manager, System Modeling and Analysis Program Office, 4800 Oak Grove Dr., Pasadena, CA, 91109-8099, Mail Stop 202-204.

the candidate missions were searched to extract those asteroids meeting the suitability definition.[4,5] The two datasets (from different studies) yielded 0.59 and 0.57 respectively and an average of 0.58 was used in this study.

II. To Survey or Not to Survey?

If a surveyor was sent, it would return a positive or negative report for suitability from visual imaging, high resolution mapping, and radar measurements. Based on the historical successes of other survey missions in the solar system, the likelihood the surveyor would report a positive suitability if the surface was actually suitable was estimated at 95 percent.[6,7] The surveyor would mistakenly report a positive suitability if the surface was not suitable with probability 5 percent (false-positive). The surveyor would correctly report a negative suitability if the surface was not suitable with likelihood 95 percent, and report negative suitability 5 percent of the time if the surface was actually suitable (false-negative).

If the report was positive after the surveyor rendezvous, a decision to go forward with the launch of the human mission would be taken. However, if the human mission was launched, there would remain uncertainty whether the surface was actually suitable or not suitable for the landing since the suitability detection capabilities (although very good) are not perfect. If the decision was not to launch the human mission, only the payoff associated with the surveyor would be incurred.

If the surveyor report were negative, the choice could be made to proceed with the human mission anyway since the quantity of science data gathered from a close encounter without landing is still believed to be significant. If the human mission launch proceeded, the outcome suitability would still be uncertain.

There is another possibility--send a second surveyor mission to another asteroid if the report from the first surveyor was negative. This also introduces the choice of sending the two-surveyors sequentially or in parallel. Because the two surveyors would likely be identical for economic reasons, the estimated likelihoods for the various outcomes described for the first surveyor were assumed to be the same. After the second surveyor report, the decision to launch or not launch the human mission would be reviewed. Note that the second surveyor would go to a different asteroid since the first asteroid was declared as unsuitable for landing. This distinction affects some of the probability calculations described below.

Note also that sending any surveyors that yielded positive reports followed by no human mission were inadmissible options. It was also assumed that if no surveyors were sent, the option to not send the human mission would also be inadmissible.

III. Surveyor Valuation

The productivity of each alternative in the study was computed from a measure of value divided by a measure of cost. Because the study was in the exploratory planning stages, cost estimates for the alternatives had not formally been developed. However, there were estimates of total mass delivered to orbit in metric tons, t, which historically have correlated with cost.[8] In addition, the specific objectives and mission success criteria for these missions had also not been formally defined. As a result, 100% mission return from a landing by the human mission was used as a benchmark for the other alternatives. An estimate had been made by decision makers that a survey mission would contribute 30% of the value of a human mission while a human mission that could not land would only obtain 70% of the value of a human mission that landed. It was further assumed that combinations of options would be additive in value. Table 1 summarizes the cost (mass), value (relative to the human landed mission), and productivity payoffs for the alternatives. Note that only the uncertainties associated with suitability for a human landing were addressed in this study—it was assumed that all of the missions in whatever combinations were enumerated would reach their destination and conduct the requisite activities successfully.

Table 1. Inputs Showing Cost (tons), Value (Percent of Goal), and Productivity Estimates

Alternative	Cost, Tons	Value, Percent	Productivity (Value/Ton)
Surveyor only	0.5	30	60.0
Human Mission, No Landing on Asteroid	390	70	0.18
Human Mission, Landing on Asteroid	390	100	0.26

IV. Approach

The question that propelled this study was whether the risk-reducing strategy of sending a surveyor before a human mission could be demonstrated quantitatively. The elements of this problem suggested a classic Bayesian value of information approach since the benefits of sending a surveyor could be quantified using the expected value of sample (suitability) information, EVSI.[9,10] After a number of discussions with mission planners, a decision tree for this problem was developed with branches for the outcomes of each surveyor and four decision strategies:

1. Send one surveyor before the human mission
2. Send one surveyor with an option for a second if the first was unsuitable
3. Send two surveyors at the same time
4. Send no surveyors—send the human mission directly (see Fig. 1)

Additional options considered up to 6 surveyors however, the additional benefits beyond two were found to be of diminishing value and not considered here. The branches of the tree were populated by the probabilities described above and by the posterior probabilities for the surveyor branches using Bayes theorem.[10] The optimal decision strategy was determined using backward induction to compute the expected value of each choice. The EVSI's were computed and compared to the human mission without surveyors to determine whether (and how many) surveyors should be employed to lower the risk of sending the human mission. The EVSI was computed from the following expression:

$$\text{EVSI} = \text{Expected Value with Surveyor Information} - \text{Expected Value without Surveyor Information} \quad (1)$$

If the EVSI was found to be positive then sending the surveyor(s) would be beneficial since the combined value, cost, and lower risks of the surveyor(s) and subsequent human mission would be greater than the combined value, cost, and risk of sending the human mission alone. A negative EVSI would indicate that the surveyors cost and risk-reducing benefits were insufficient to exceed the expected value of the human mission. Negative EVSI's are typically reported as zero to indicate a survey is not worthwhile.

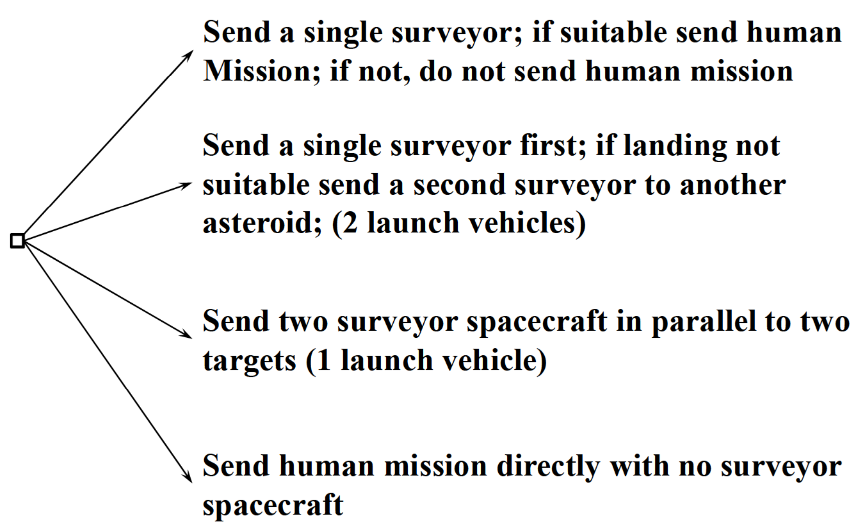

Figure 1. Decision Strategies for the Surveyor Problem.

V. Results

A. Comparing Mission Strategies: Gain vs. Risk

The optimal decision strategy was to send two surveyors simultaneously to two asteroids. This was influenced primarily by the probability of suitability and the higher compound probability of at least one asteroid being suitable. The single surveyor case had a baseline probability of 0.58. The two mission case had a probability at least one would be suitable of 0.82. The three mission case would be the first point where the probability would exceed 90% (92%).

The EVSI results are summarized in Table 2.

Table 2. Expected Value of Surveyor Information (EVSI) Showing Maximum for Two Surveyors Launched Simultaneously; Prior Probability of Suitability = 0.58.

Alternative	EVSI, (Value/Cost)
Single Surveyor	0
Single Surveyor with Potential Second Surveyor	36
Two Surveyors Sent At The Same Time	54
No Surveyors—Direct Human Mission	0

The low cost of the surveyors relative to the human mission made them inexpensive insurance against the risks of an unsuitable outcome. In probabilistic terms, the single surveyor case was analogous to tossing a single die to determine the suitability outcome; the two surveyor case with one surveyor followed by an optional second surveyor had a higher probability since tossing a single die once followed by the chance of tossing a second die if the outcome of the first was unsuitable provides a "second chance" for obtaining suitability. Sending two surveyors simultaneously was analogous to tossing two dice at the same time with the highest probability of at least one "success" since there would always be two chances with each toss versus an optional second chance in the sequential case.

While it was initially assumed that each mission would achieve 100% success (no technical failures), the same probabilistic results would apply if the term "suitability" was replaced by "mission success." That is, the ranking of surveyor strategies would be the same except the probabilities would be higher (e.g. the prior probability of mission success might be 0.99).

Because the prior probabilities were subject to debate, they were varied parametrically over a range of values. The value of the surveyor missions was also a point of contention because the argument was made that the surveyors had little inherent value (science or otherwise) to the human mission other than risk reduction. The EVSI's were recomputed over a range of surveyor science values from the baseline of 30% down to 10% of the human mission. One parametric space for different prior probabilities and a surveyor value of 30% is illustrated in Fig. 2. As the surveyor value was decreased toward 10%, the curves moved downward retaining the same conclusion in each case—send two surveyors at the same time. The figure also shows that the single surveyor case does not become feasible until the prior probability of suitability reaches approximately 60%.

The results of the study thus far showed that sending at least two surveyors was more beneficial than zero or one surveyor and that sending multiple surveyors in parallel had a higher expected payoff than sending them sequentially. However, a strong argument could be made that uncertainties in the estimates or even the definitions of cost, value, and productivity used here could yield misleading results. This issue was addressed by defining the general cases for any figure of merit.

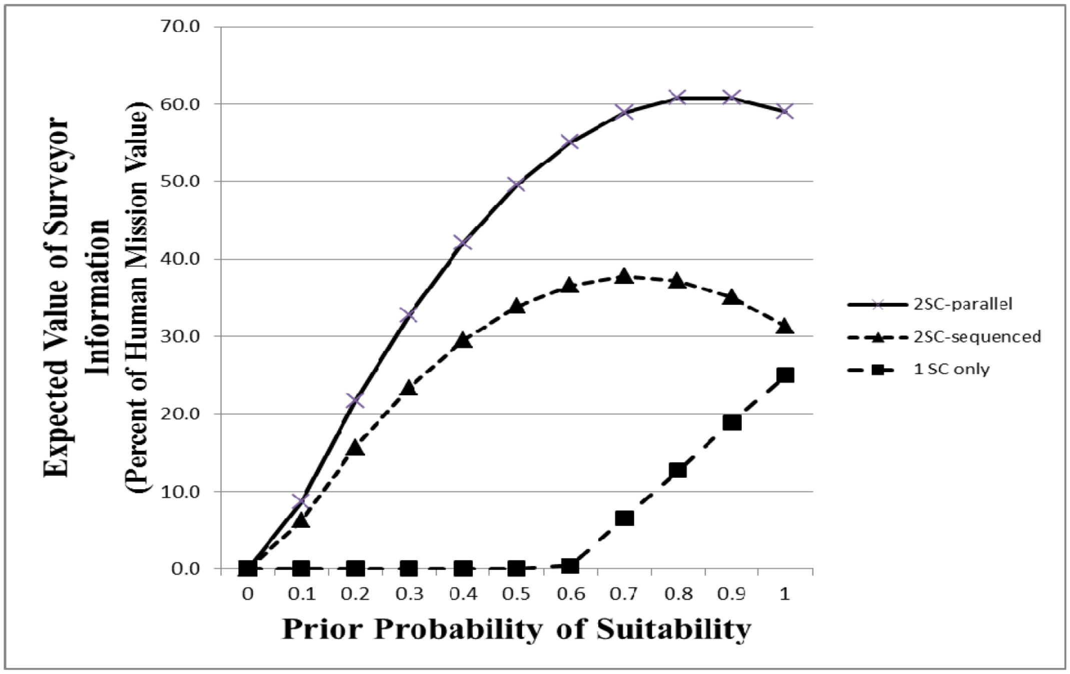

Figure 2. Prior Probability Asteroid Suitable for Landing versus EVSI Showing Expected Value for Single, Two Sequential, and Two Parallel Surveyors

B. The General Cases

Let X = a measure of value for the surveyor; let Y = the value of the human mission that can land; and let p = the prior probability of a suitable asteroid = 0.58. Finally, let the value of the human mission without landing be defined as 0.7Y (70% of the value of the human mission).

1. The Single Surveyor Case

The single surveyor decision tree is shown in Fig. 3. The branch probabilities in the tree were computed using Bayes Theorem described earlier. The expected value for sending only one surveyor was computed by backward induction yielding an expected value for the decision to send one surveyor = X + 0.56Y.

2. Two Surveyors Sent Sequentially

The two surveyor case adds the option to send a second surveyor if the first asteroid is found unsuitable for human landing (Fig. 4). The expected value of this strategy was 1.43X + 0.81Y. The coefficients of both X and Y for the two surveyor case dominated those of the single surveyor case for *any* monotonically increasing value measure (e.g., "more is better than less" such as science value, productivity, and samples returned). Note the result would not be true for monotonically decreasing value measures such as cost ("less is better than more"). The next step was to evaluate the parallel option.

3. Two Surveyors Sent in Parallel

The two-surveyor parallel case would send both surveyors at the same time resulting in four possible suitability outcomes:

1. Surveyor one finds asteroid one suitable for landing and surveyor two finds asteroid two suitable
2. Surveyor one finds asteroid one suitable for landing and surveyor two finds asteroid two unsuitable
3. Surveyor one finds asteroid one unsuitable for landing and surveyor two finds asteroid two suitable
4. Surveyor one finds asteroid one unsuitable for landing and surveyor two finds asteroid two unsuitable

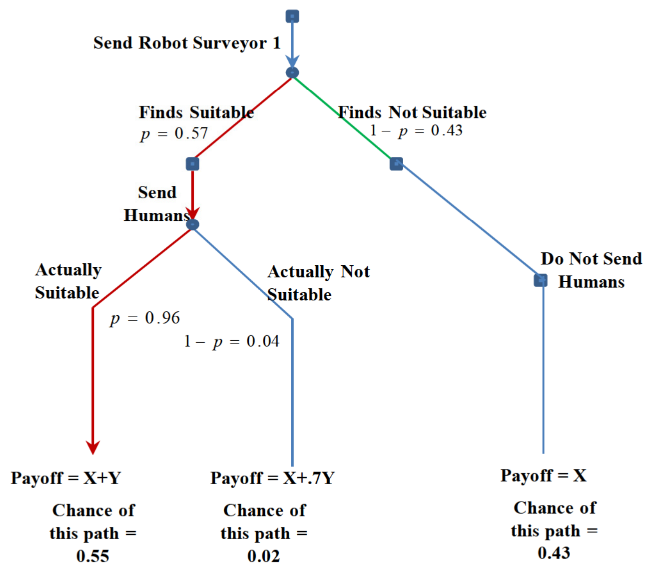

Figure 3. General Case for Sending One Surveyor Only; Expected Value = X+0.56Y

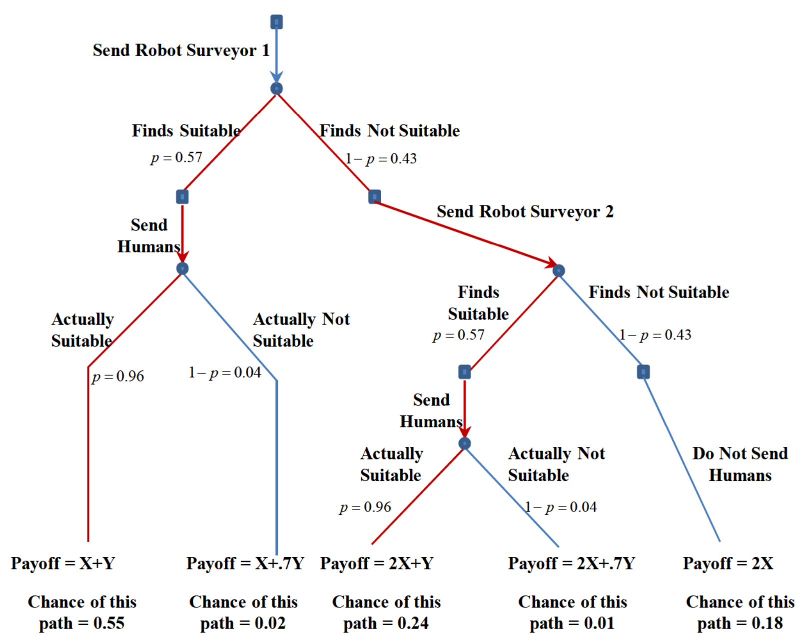

Figure 4. General Case for Sending Two Surveyors Sequentially; Expected Value = 1.43X + 0.81Y

Figure 5 displays the decision tree for the parallel case which yielded an expected value of 3.47X + 1.78Y. As before, the coefficients of the parallel case dominate the single and sequential strategies due to the additive value of each surveyor combined with the reduction in risk from the "learning" that is gained by previewing the asteroids prior to risking the human mission.

Additional insight may be gained by invoking the earlier assumption that the value of a surveyor mission would only yield 30% of the value of the human landing. That is, let X = 0.3Y and substitute in the three expected value equations:

Expected Value of Single Surveyor Strategy	= X + 0.56Y	= (0.30Y) + 0.56Y	= 0.86Y
Expected Value of Two Sequential Surveyors	= 1.43X + 0.81Y	= 1.43(0.30Y) + 0.81Y	= 1.24Y
Expected Value of Two Parallel Surveyors	= 3.47X + 1.78Y	= 3.47(0.30Y) + 1.78Y	= 2.82Y

The intriguing aspect of these results is that even though the relative "value" of the surveyor was assumed to be only 30% of the human mission, the expected value discounts the human mission value, Y, by 14% due to the low chance of finding suitability (0.58 is getting close to 50-50). When two surveyors are sent, the chance at least one is suitable increases to 82% so there is almost a three-fold increase over the human mission value. There is an added benefit when the two are sent in parallel because the added value of the second surveyor is always obtained whereas the sequential case would not send the second surveyor 43% of the time (1—0.57). There is a tradeoff between the prior probabilities of suitability vs. the high value of the human mission. At low probabilities of finding a suitable asteroid (p < 0.60), the high value of the human mission is sufficient to rule out a single surveyor approach. At higher probabilities of finding a suitable asteroid (> 0.60), the payoffs of the surveyors combined with the increased chance of finding suitability yield positive benefit for all three strategies.

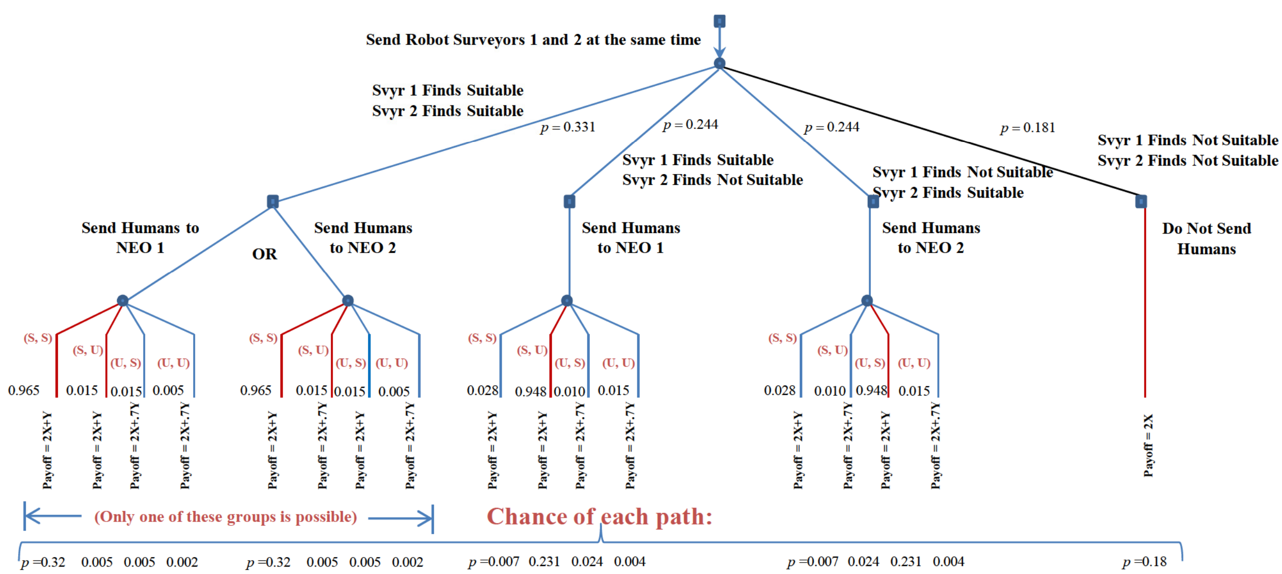

Figure 5. General Case for Sending Two Surveyors at the Same Time; Expected Value = 3.47X + 1.78Y

VI. Discussion and Conclusions

The probability of suitability was a central input to this study and the review of 1200 asteroids to estimate its value should be viewed as preliminary and as an upper bound. As progress is made toward identifying and selecting candidate targets, additional Earth and space-based observations will certainly enhance the knowledge of landing suitability. However, at this early stage of exploration it is useful to consider how the variability in such estimates might impact decisions to send humans to an asteroid.

The issue of whether value, productivity, or other measures of effectiveness would lead to different conclusions was shown not to affect the ranking of decision options. The single surveyor option appears not to be viable until the probability of suitability exceeds approximately 60%. The two surveyor cases are superior to the single or no-surveyor cases because they reduce the high risk of 42% that the asteroid would turn out to be unsuitable for landing. This is further boosted by the dramatically lower cost of the surveyor as "insurance" compared to the much higher cost of the human mission and the gap between those costs.

The substitution of mass for cost was not believed to be a significant influence on the results since mass has been shown to correlate with mission cost in other studies.[8,9] The large gap between the masses of the surveyors versus the human mission (0.5 t vs. 390t) was believed to be more reflective of a similar gap in dollar costs than uncertainties in cost estimates. If costs were available, there would still be a very large gap between the payoffs resulting in a similar conclusion. Questions regarding the value figure of merit were addressed analytically showing the conclusions to be invariant to both differences and definitions of value when the figure of merit is monotonically increasing (more value better than less value). Nonetheless, previous work has developed and applied an improved measure of value based on science sampling and measurements that should be useful to an asteroid exploration program as the science objectives are refined.[11]

During this study a number of conclusions were drawn:

1. This analysis supports the value of surveyor missions to asteroids in order to reduce risk and maximize value. It was shown two spacecraft going simultaneously to two independent asteroids appears optimal. The likelihood of finding a suitable asteroid was substantially greater for two surveyors (82%) than with just a single surveyor.

2. The conclusion of this paper is that the greatest value and lowest risk for a human mission to a near-Earth asteroid can be obtained by:
    a. Sending (at least) two surveyor spacecraft to different asteroids prior to a human mission
    b. If affordability, budgets, or timing is an issue, sending two surveyors sequentially is the next viable option
    c. If only one surveyor can be sent, the estimated probability of finding a suitable landing area on the asteroid should exceed 60%. If not, sending the human mission directly will still be risky but the expected value of a human mission that finds it cannot land will be greater than sending a single surveyor.

3. The primary determinant of the optimal decision was the probabilistic structure of the sampling approach. The higher the overall probability of suitability along a decision tree branch, the larger the expected value of that branch and the resulting EVSI.

4. Demonstrating the risk reducing benefit of sending surveyors has been shown in this paper. There is value in sending the relatively inexpensive surveyors to confirm suitability for the human landing and it has been shown quantitatively for a range of possible prior probabilities and surveyor values.

5. The same ranking of surveyor strategies would follow if the surveyor problem were redefined to address mission success. The event "suitability" would be replaced by the event "mission success" and the prior probabilities of success would be estimated from reliability and historical estimates.

Acknowledgments

The authors are indebted to John Baker of JPL for his help in defining the parameters of this study and answering our numerous questions in many interesting discussions. This research was carried out by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

References

[1]Committee to Review Near-Earth Object Surveys and Hazard Mitigation Strategies; National Research Council, "Defending Planet Earth: Near-Earth Object Surveys and Hazard Mitigation Strategies: Final Report," National Research Council, available at http://www.nap.edu/catalog/12842.html.

[2]Sanders, L., "Finding the Right Asteroid for Astronauts to Land On," Science News.[d]

[3]The Planetary Society, "Space Topics: Asteroids and Comets."[e]

[4]Masiero, Joseph, Robert Jedicke, Josef Durech, Stephen Gwyn, Larry Denneau, Jeff Larsen, "The Thousand Asteroid Light Curve Survey," June 2009. e-Print: arXiv:0906.3339 [astro-ph.EP].

[5]Landau, D., JPL NEO Search_9-17-10r2.xls, Jet Propulsion Laboratory, Pasadena, CA, October 1, 2010.

[6]Paschall, S.C.; Brady, T.; Cohanim, B.E.; Sostaric, R., "A Self Contained Method for Safe & Precise Lunar Landing," IEEE Aerospace Conference, 2008 IEEE (1095-323X) (978-1-4244-1487-1) 2008. p.12-12.

[7]Silverman, S., and P. Christensen, "Successful Mars Remote Sensors, MO THEMIS and MER Mini-TES," Acta Astronautica (0094-5765), October/December 2006, Vol. 59 Iss. 8-11; p. 1039-1047.

[8]Borden, Chester, Diane L. Schwartz, and Jeffrey H. Smith, "A Space-Based Scientific Remote Sensing Instrument Cost Model With Application to Earth Observing System Instruments," JPL Document D-3771, Jet Propulsion Laboratory, Pasadena, California, October, 1986.

[9]Smith, J.H., "In-Situ Resource Utilization for the Human Exploration of Mars: A Bayesian Approach to Valuation of Surveyor Missions," *Proceedings of the 35th Annual Meeting of the Western Decision Sciences Institute*, meeting papers on disc [CD-ROM], Waikoloa, HI, April 11-15, 2006.

[10]Winkler, R., *Introduction to Bayesian Inference and Decision*, 2nd Ed., Probabilistic Publishing, Gainesville, FL, 2003.

[11]Weisbin, C.R., J.H. Smith, T. Van Houten, R. Moeller, W. Zimmerman, W. Smythe, W. Lincoln, A. Elfes, V. Adumitroaie, and R. Silberg, "Technical Feasibility and Relative Productivity of Alternate NASA Robotic Missions to a Lunar Dark Crater," *IEEE Systems Journal*, Vol. 2, No. 1, March 2008, pp. 120-128.

[d] http://www.wired.com/wiredscience/2010/05/asteroids-to-land-on/, May 7, 2010.

[e] http://www.planetary.org/explore/topics/near_earth_objects/asteroids_and_comets/facts.html, January 2011.