# NASA'S CONCEPT FOR A HUMAN MISSION TO A NEAR-EARTH ASTEROID: PREFERENCE TRADEOFFS FOR THE SURVEYOR DECISION PROBLEM

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## ABSTRACT

NASA's recent attention and interest in sending a human mission to land on a Near-Earth asteroid raised the question of whether to first send a robotic surveyor. This paper describes a Bayesian approach for comparing the value and cost-risk tradeoffs of sending (versus not sending) surveyor missions prior to a human mission. A multiattribute decision analysis approach was used to account for both mission value and cost in each of 27 hypothetical risk-attitude cases corresponding to an emphasis on mission value; equal priority between mission value and cost; and an emphasis on cost. The decisions implied by the different strategic viewpoints are described.

## INTRODUCTION

NASA's recent interest in sending a human mission to land on a near-Earth asteroid raises a number of issues [1]. 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 a larger, more complex human mission. One alternative considered sending the human mission directly to an asteroid and using real-time mapping and 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 in order to determine the feasibility of landing. Prior work by the author used 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 [2]. An objective of this study was to examine the effect of different risk attitudes by using utility functions to capture the relative differences in preference.

Orchestrating a human "landing" on an asteroid would be 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 present study had no intermediate condition where an asteroid might be partially suitable--it would either be suitable or unsuitable for landing. At this early point in pre-planning, the estimated prior probability of suitability for a human landing based on previous work was 0.58 [2].

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 [3]. The surveyor would mistakenly report a positive suitability if the surface was not suitable with probability estimated at 5 percent (false-positive). The surveyor would correctly report a negative suitability if the surface was not suitable with likelihood estimated at 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 good) are not perfect.

If the surveyor report was 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 was still believed to be significant. There was another possibility--send a second surveyor mission to another asteroid if the first surveyor report was negative. This introduced the choice of sending the two-surveyors sequentially or in parallel. Because the two surveyors would be identical the probabilities for the outcomes were assumed to be the same. If two negative reports were obtained the human mission would not be sent. 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. Note that mission and launch vehicle reliabilities were not considered in the study. Sending any surveyors that yielded positive reports followed by no human mission were inadmissible options. It was assumed that if no surveyors were sent, the option to not send the human mission would be inadmissible.

## SURVEYOR VALUATION

The specific objectives and mission success criteria for these missions had not been defined since the study was in the exploratory planning stage. Value and cost estimates for the alternatives had not been formally developed so a value of 100% mission return from a landing by the human mission was used as a benchmark for the other alternatives. Because no actual cost estimates had been developed, mass delivered to low Earth orbit (metric tons) was used as a proxy attribute for cost due to its high correlation with cost [4]. Table 1 summarizes the value and cost (mass) payoffs for the alternatives considered.

**TABLE 1. Inputs Showing Value (Percent of Goal) and Cost (tons) Estimates**

| Alternative | Value, Percent | Cost, Tons [5] |
|---|---|---|
| One Surveyor only | 30 | 0.35 |
| Two Surveyors (second weighs 0.43) | 60 | 0.78 |
| Human Mission, No Landing on Asteroid | 70 | 390 |
| Human Mission, Landing on Asteroid | 100 | 390 |
| One Surveyor + Human Mission-Lands | 130 | 390.35 |
| One Surveyor + Human Mission-No Landing | 100 | 390.35 |
| Two Surveyors + Human Mission-Lands | 160 | 390.78 |
| Two Surveyors + Human Mission-No Landing | 130 | 390.78 |

The attributes in Table 1 were used to construct nine utility function combinations. The transformations from value and cost to utility functions provided a way to examine the sensitivity of the results to differing attitudes toward risk taken by mission planners.

## APPROACH

The elements of this problem suggested a classic Bayesian decision analysis since the benefits of sending a surveyor could be quantified using the expected value of sample (suitability) information, EVSI [4] [6]. A decision tree was developed with branches for the outcomes of each surveyor and four decision strategies:

1. Send a single surveyor. If suitable send the human mission; if not don't send the human mission.
2. Send a single surveyor first; if suitable send the human mission; if not send a second surveyor to another asteroid; if it reports suitability send the human mission; if not do not send.
3. Send two surveyors in parallel (at the same time) to two different asteroids. If one or more suitable send human mission; if neither suitable do not send.
4. Send human mission directly to asteroid with no surveyor and decide on arrival.

The branches of the tree were populated by the probabilities described earlier and the posterior probabilities for the surveyor branches using Bayes theorem [6]. The expected utilities for each surveyor strategy were computed using differing risk attitude assumptions to identify the conditions under which each strategy might prevail. All possible risk attitudes for value and cost were enumerated. The utility functions were defined from an approach by Kirkwood [7]. Each of the utility functions was used to compute the multiattribute utility of each terminal branch in the decision tree using an additive multiattribute utility function [8]. The additive model assumption for the two attribute case implies perfect substitution in attribute preference ($k_{value} = 1 - k_{cost}$ ), which allowed a range of attribute tradeoff scaling constants to be examined for the value attribute, *v*, (which automatically determined the cost attribute, *c*, tradeoff scaling constant).

An investigation of how the relative priorities of value versus cost might affect the decision was also performed for three preference ordering scenarios. The first preference ordering was termed "value-dominant preference" used to represent the prioritization of value over cost typical of space exploration missions. This scenario set the attribute tradeoff scaling constant for value higher than cost (value >> cost, e.g., $k_v = 0.9$, $k_c = 0.1$). The second preference ordering was termed "value-equivalent preference." This scenario set the scaling constant for value ≈ cost (e.g., $k_v = 0.5$, $k_c = 0.5$). The third preference ordering was termed "budget-dominant preference" used to represent the prioritization of cost over value. This scenario placed the highest priority on the cost attribute with cost >> value (e.g., $k_v = 0.9$, $k_c = 0.1$). As each of the three preference orderings was varied, the multiattribute expected utilities were computed for each of the four strategies for the 9 combinations of risk attitude. The 108 values were converted from ordinal utilities to rankings and the results analyzed and compared to assumptions likely to be held by mission decision makers.

## RESULTS

The optimal decision strategy depended primarily on the risk attitudes toward value versus cost attributes and the relative priorities of value versus cost (the attribute tradeoff scaling constants). Table 2a displays the value-dominant case ($k_v >> k_c$) rankings for the four surveyor strategies. This case most reflects the traditional priorities of NASA which place a high priority on taking risks (albeit calculated) to obtain science value from exploration activities. The risk attitudes for value and cost are presented across the columns of the table. When the utility function for value was risk-averse, the optimal strategy was to send the human mission directly (no surveyors) because the prior uncertainty in suitability (0.58) coupled with the high value of the human mission exceeded the smaller benefit of sending a surveyor. The effect of the large cost of the human mission was minimized by the low importance of cost ($k_c = 0.1$). In addition, the low cost priority made this result insensitive to the risk attitude for cost. However, when the risk attitude for value became risk-neutral or risk-seeking, the optimal strategy was to send 2 surveyors in parallel. Because the sequential case would only send 2 surveyors 57% of the time and not realize their value 43% of the time, the expected value of the sequential case would always be lower than the parallel case (which sends both all the time).

**TABLE 2a. Expected Utility Rankings for Value-Dominant Preference ($k_v >> k_c$) Showing Transition to Sending Two Surveyors in Parallel When Risk Attitude for Value is Neutral or Seeking.**

| Value Risk Attitude | Averse | Averse | Averse | Neutral | Neutral | Neutral | Seeking | Seeking | Seeking |
|---|---|---|---|---|---|---|---|---|---|
| Cost Risk Attitude | Averse | Neutral | Seeking | Averse | Neutral | Seeking | Averse | Neutral | Seeking |
| No Surveyor | 1 | 1 | 1 | 4 | 4 | 4 | 4 | 4 | 4 |
| Single Surveyor | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
| Two Surveyors, Sequenced | 3 | 3 | 3 | 2 | 2 | 2 | 2 | 2 | 2 |
| Two Surveyors, Parallel | 2 | 2 | 2 | 1 | 1 | 1 | 1 | 1 | 1 |

Next, the priority for value was equated to the priority for cost. Table 2b presents the value-equivalent case rankings. This case reflects a transition toward cost-constrained mission planning where value and cost play an equal role in decision making. When the utility function for value was risk-averse or neutral, the optimal strategy was to send a single surveyor because the cost of a single surveyor yielded a high utility for cost in the event a negative report was returned. This result held until the risk attitude for value became risk-seeking which caused a switch to two surveyors in parallel strategy.

**TABLE 2b. Expected Utility Rankings for Value-Equivalent Preference ($k_v = k_c$) Showing Transition to Sending One or Two Surveyors in Parallel When Cost Priority Increases.**

| Value Risk Attitude | Averse | Averse | Averse | Neutral | Neutral | Neutral | Seeking | Seeking | Seeking |
|---|---|---|---|---|---|---|---|---|---|
| Cost Risk Attitude | Averse | Neutral | Seeking | Averse | Neutral | Seeking | Averse | Neutral | Seeking |
| No Surveyor | 2 | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 4 |
| Single Surveyor | 1 | 1 | 1 | 1 | 1 | 1 | 2 | 2 | 2 |
| Two Surveyors, Sequenced | 4 | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 |
| Two Surveyors, Parallel | 3 | 3 | 3 | 2 | 2 | 2 | 1 | 1 | 1 |

The budget-dominant case is shown in Table 2c reflecting more recent budget and cost realities where value would be outweighed by cost. When cost begins to dominate value, ($k_c >> k_v$) and the attributes take on *any* risk attitude, the optimal strategy was to send a single surveyor due to the cost aversion. Even though the value of the two surveyor case increased, the low priority of value compared with the high priority for low cost limited the strategy to a single surveyor. It was also noted that once the risk attitude for value moved away from risk aversion (to neutral or seeking), the two parallel surveyor case moved into second place even though cost was increased.

**TABLE 2c. Expected Utility Rankings for Budget-Dominant Preference ($k_c >> k_v$) Showing Lowest Bound of Sending One Surveyors Independent of Risk Attitude.**

| Value Risk Attitude | Averse | Averse | Averse | Neutral | Neutral | Neutral | Seeking | Seeking | Seeking |
|---|---|---|---|---|---|---|---|---|---|
| Cost Risk Attitude | Averse | Neutral | Seeking | Averse | Neutral | Seeking | Averse | Neutral | Seeking |
| No Surveyor | 2 | 2 | 2 | 4 | 4 | 4 | 4 | 4 | 4 |
| Single Surveyor | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |
| Two Surveyors, Sequenced | 4 | 4 | 3 | 3 | 3 | 3 | 3 | 3 | 3 |
| Two Surveyors, Parallel | 3 | 3 | 4 | 2 | 2 | 2 | 2 | 2 | 2 |

Since the prior probabilities anchored the Bayesian and subsequent expected values, the cases were repeated with prior probabilities of 0.20 and 0.80 to examine the sensitivities. At the lower chance of suitability (0.2), the only change observed was in Table 2b where the single surveyor case was extended

to all risk attitudes. At the higher chance of suitability (0.8), the two-parallel surveyor case was ranked first across all risk attitudes for the value-dominant case, and the single surveyor option was ranked first for the budget-dominant case. In the value-equivalent case the single surveyor case was dominant for all cases except the risk-seeking value case where the two parallel surveyors were preferred.

The next step was to consider the most likely scenario in the present budget climate—the budget-dominant case. It could be argued that past NASA missions were historically funded with value as a higher priority than cost. As budgets have become increasingly constrained, the importance of cost constraints has certainly tempered the emphasis on mission value. It has been stated publicly and many would agree that the exploration focus of NASA has been a risk-seeking attitude toward mission value. Under the budget-dominant scenario a risk-averse attitude toward cost showed that sending a single surveyor prior to the human mission was the most budget sensitive solution. Should the budget focus yield to greater emphasis on science value, it would be more beneficial to send two surveyors in parallel since the cost of the surveyors was a fraction of the human mission cost.

## DISCUSSION AND CONCLUSIONS

This study had a number of limitations. The probability of suitability was a central input to this study and should be viewed as preliminary. There were no decision maker inputs to the value models described—the decision models and their potential inputs were hypothetical. Although the attributes of value and cost would clearly not be the only criteria for a decision of this magnitude, there could be others that might displace them.

During this study a number of conclusions were drawn:

1. This analysis supports the value of sending surveyor missions to asteroids prior to a human mission in order to reduce risk and maximize value. It was shown that sending at least one and sometimes two spacecraft simultaneously appeared optimal.

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 any of the following scenarios:
   - Value-Dominant Preference: If the mission planners were risk-averse for value even though it was much more important than cost, the risk aversion was sufficient to exclude sending any surveyors until the attitude toward value was neutral or risk-seeking (more likely) which pointed to sending two surveyors in parallel.
   - Value-Equivalent Preference: If the mission planners had any risk attitude except risk-seeking for value, the equivalency of cost was sufficient to send a single surveyor. When the attitude toward value was risk-seeking (more likely) the decision jumped to sending two surveyors in parallel.
   - Budget-Dominant Preference: If the mission planners viewed cost as the primary attribute that (likely in the current budget environment), then under any assumption about risk attitude for value or cost, the governing choice was to send one surveyor.

3. Demonstrating the effects of risk attitude on the preference for different information gathering strategies 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, surveyor values and costs, and programmatic priorities for value and cost.

4. The use of multiattribute utility to quantify preferences between value and cost provided a way to quantify and view the tradeoffs between priorities of the attributes, the values of the options, and the potential risk attitudes decision makers might express.

5. While it is acknowledged that space exploration is inherently risky, it is unlikely that planners would consider the costs and value of a space mission to be equally important. Rather, in an era of tightening budgets, risk aversion to high budgets and risk-neutrality or risk-seeking attitudes toward value would be more likely.

Based on these conclusions, the option that minimized risk and maximized value and cost under the most likely scenario would be to send a single surveyor. If the science value of these missions were elevated to a more equal standing with cost, the two surveyors in parallel option should be selected.

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## REFERENCES

[1] Sanders, L., "Finding the Right Asteroid for Astronauts to Land On," Science News, http://www.wired.com/wiredscience/2010/05/asteroids-to-land-on/, May 7, 2010.

[2] Smith, J.H., W. Lincoln, and C. Weisbin, "Reducing the Risk and Improving Mission Success of NASA's Human Mission to a Near-Earth Asteroid: How Many Robotic Surveyors?", *Proceedings of the AIAA SPACE 2011 Conference & Exposition*, Long Beach, CA, September 27-29, 2011.

[3] 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.

[4] 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, Waikoloa, HI, April 11-15, 2006.

[5] Svitak, Amy, http://www.spacenews.com/civil/101119-extra-flights-needed-hedge-cots-delays.html, 11/19/2010.

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

[7] Kirkwood, C., "Notes on Attitude Toward Risk Taking and the Exponential Utility Function," online publication http://www.public.asu.edu/~kirkwood/DAStuff/refs/risk.htm, January 1997.

[8] Keeney, R., and H. Raiffa, *Decision With Multiple Objectives: Preferences and Value Tradeoffs*, John Wiley, New York, 1976.