Are Robotic Surveyors to an Asteroid Before a Human Mission Justified?

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Source: Smith, Jeffrey H., W. Lincoln, and Charles Weisbin, "Reducing the Risk and Improving Mission Success for 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.

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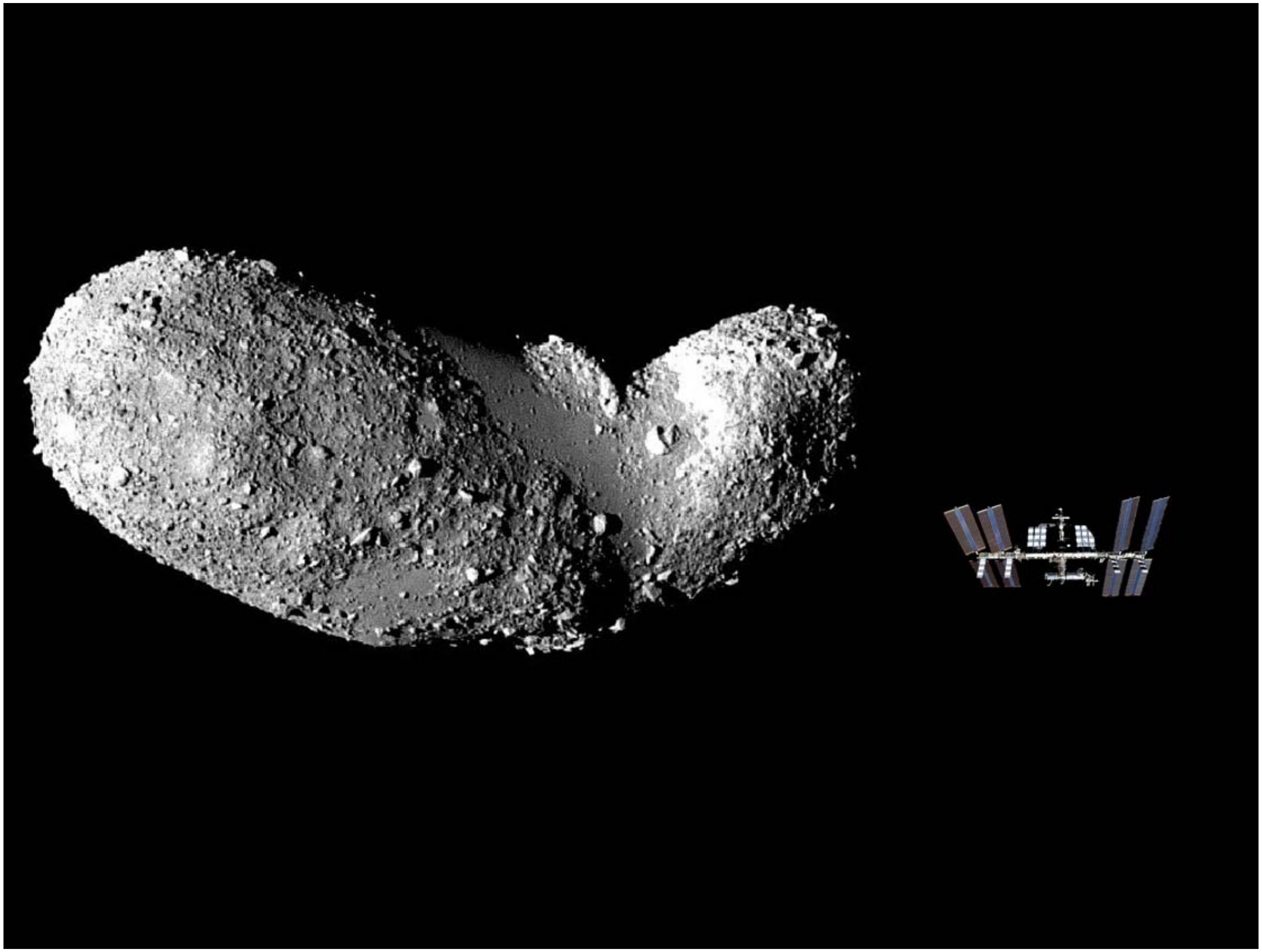
- NASA's human exploration program working to develop a mission to land humans on a Near-Earth asteroid (NEO) in 2025-2030.
- Planning such a mission raised some basic questions for this study
    1. If candidate asteroids are to be surveyed by a precursor spacecraft, how many should be sent?
    2. Is it worthwhile to send a surveyor spacecraft before the human mission to determine suitability for landing?
    3. If more than one asteroid is to be surveyed, is it better to survey sequentially or in parallel?

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

Example: Asteroid Itokawa (540m) to scale with International Space Station



- Meteor Crater, Arizona (40m diameter; 50,000 years ago; weighed 300,000 tons and entered atmosphere at 28,500 mph)

FIGURE 2.1 Meteor Crater (also known as Barringer Crater) in Arizona, with the Great Pyramids of Giza and the Sphinx inserted for size comparison. One of the most familiar impact features on the planet, this crater is about 1,200 meters in diameter and 170 meters deep; the interior of the crater contains about 220 meters of rubble overlying bedrock. The crater was formed about 50,000 years ago through the impact of an approximately 40-meter iron-nickel meteorite moving at about 13 kilometers per second (Melosh and Collins, 2005). SOURCE: Crater image courtesy of U.S. Geological Survey; composite created by Tim Warchocki.

- There are a lot of NEO's out there with Earth-crossing orbits.

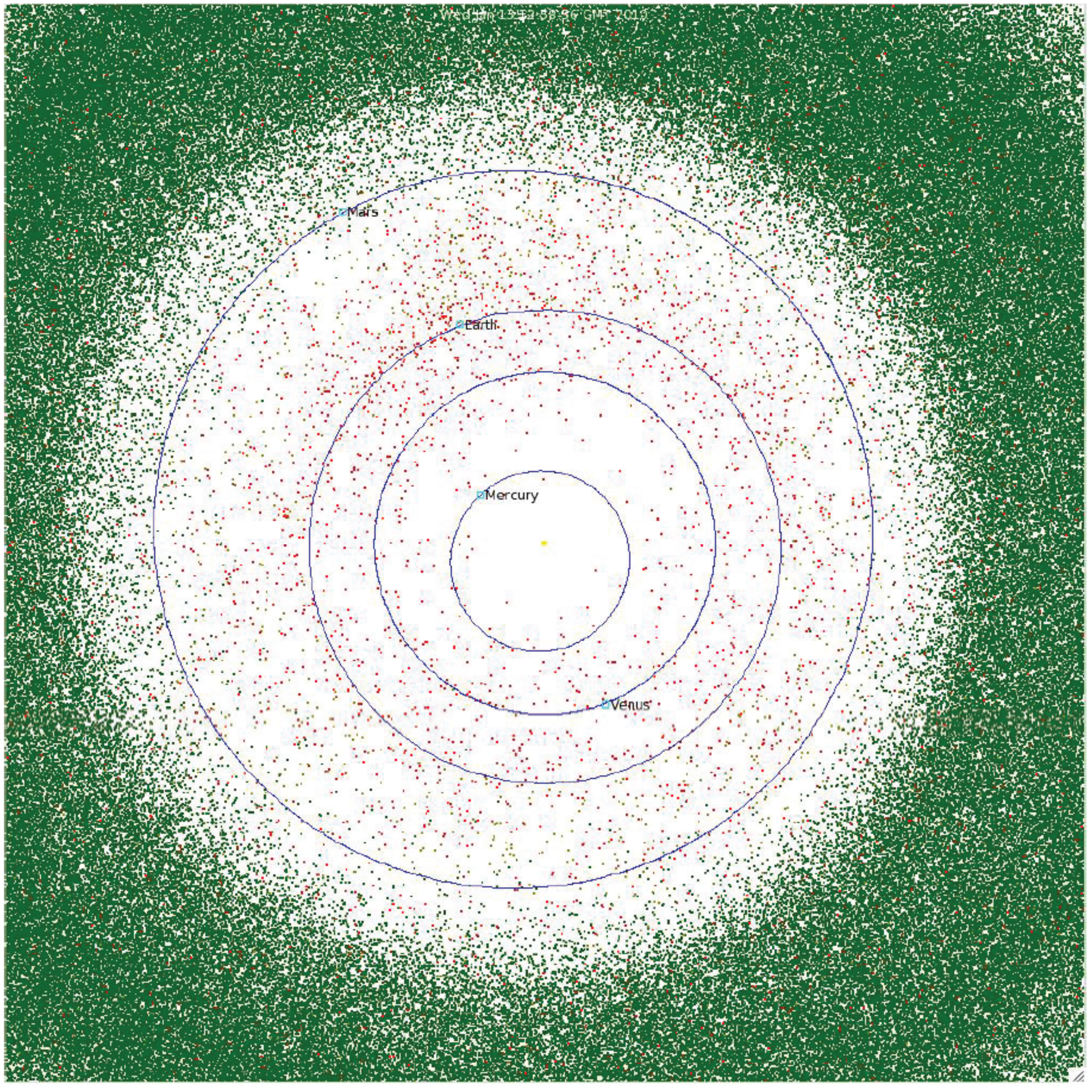


FIGURE 2.3 The distribution of currently known asteroids (in January 2010). The green dots represent asteroids that do not currently approach Earth. The yellow dots are Earth-approaching asteroids, ones having orbits that come close to Earth but that do not cross Earth's orbit. The red boxes mark the locations of asteroids that cross Earth's orbit, although they may not necessarily closely approach Earth. Contrary to the impression given by this illustration, the space represented by this figure is predominantly empty. SOURCE: Courtesy of Scott Manley, Armagh Observatory.

- Need to identify a ***suitable*** NEO for a human landing.
- Surface of asteroid could be unsuitable
  - "Rubble pile" of loose aggregate of dust, gravel, or rocks held together by minimal gravity. Force of landing will blow asteroid apart.
  - Surface composition of fine dust—appears to be solid soil but is actually floating and cannot support landing or will disperse to block visibility during landing
  - Sharp features, deep trenches and overhangs, pointed rocks with sharp edges capable of damaging spacecraft

- *So what might be the prior probability an asteroid might be suitable?*

- Searched two independent data sets to count "suitable asteroids" between 100 and 1500m, near-Earth, and with spin rates < 0.53 revolutions/hour
  - Data Set 1: TALCS data set of 828 NEO asteroids[1].
  - Data Set 2: JPL NEO Study dataset of 372 objects used for NEO target set analysis[2].
- Estimates for prior probability of suitability:
  - TALCS data yielded p = 0.593
  - JPL data set yielded p = 0.571
- Used 0.58 in this study for prior probability of suitability (Likely to be higher when actual candidates selected for more detailed observations)

[1]The Thousand Asteroid Light Curve Survey, Joseph Masiero, Robert Jedicke, Josef Durech, Stephen Gwyn, Larry Denneau, Jeff Larsen, e-Print: arXiv:0906.3339 [astro-ph.EP], June 2009.
[2]Landau, D., JPL NEO Search_9-17-10r2.xls, Jet Propulsion Laboratory, Pasadena, CA, October 1, 2010.

1. If candidate asteroids are to be surveyed by a surveyor spacecraft, how many should be sent?
   – NEO surveyor can visit up to six potential NEO targets (up to three spacecraft can visit two targets each)
   – One of the NEO objectives is to find a target suitable for human landing
   – The probability of finding a suitable target before the mission launches is imprecise or unknown

Stated another way:

How many targets should be surveyed to achieve ≥90% probability at least one is suitable for a landing?

Let event A = target A suitable for landing

Let event B = target B suitable for landing

Definition: Two events are mutually exclusive when P(A and B)=0 (the two events cannot occur together)

- Since any two targets selected could both be suitable, P(A and B)≠0 so we cannot assume A and B are mutually exclusive.

Definition: Two events are independent if P(A|B)=P(A)

- Since the chance that target A is suitable doesn't depend on whether target B is suitable—they can be assumed independent (no evidence at this time that suitability for a human landing on different targets would be related
- Therefore, P(A or B suitable) = P(A) + P(B) – P(A)P(B)
- For more than two targets use the binomial distribution

- ≥ 90% landing suitability achievable with two targets if target prob ≥ 70%
- Need to visit at least three targets if suitability = 0.58
- Need to visit at least four targets if suitability 50-50.

Number of	Probability of Suitable Target for Human Landing, P(Xi)								
Survey Targets	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
One Target	0.10	0.20	0.30	0.40	0.50	0.60	0.70	0.80	0.90
Two Targets	0.19	0.36	0.51	0.64	0.75	0.84	**0.91**	**0.96**	**0.99**
Three Targets	0.27	0.49	0.66	0.78	0.88	**0.94**	**0.97**	**0.99**	**0.99**
Four Targets	0.34	0.59	0.76	0.87	**0.94**	**0.97**	**0.99**	**0.99**	**0.99**
Five Targets	0.41	0.67	0.83	**0.92**	**0.97**	**0.99**	**0.99**	**0.99**	**0.99**
Six Targets	0.47	0.74	0.88	**0.95**	**0.98**	**0.99**	**0.99**	**0.99**	**0.99**

2. Is it worthwhile to send a surveyor spacecraft before the human mission to determine suitability for landing?

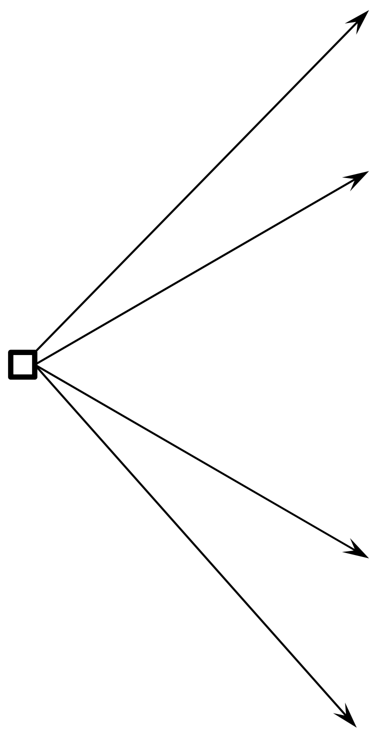
"Sending a surveyor [before a human mission] is a risk-reduction strategy –the question is, can this benefit be demonstrated?" J. Baker, 10/19/2010

Stated another way:

Is the expected value with the surveyor greater than just sending the human mission directly (no surveyor)?

- Classic problem in Bayesian Decision Theory
  - Value of information gained by surveyor vs. chance that Earth-based observations might not detect that object is unsuitable
  - The uncertainty? Whether the NEO is actually suitable or unsuitable for a human landing
- Consider two decision options
  - Send the human mission directly to best target identified using Earth-based observations (no surveyor)
  - Or, first send a surveyor mission to gather “close-up” information to determine suitability for a safe human mission

Surveyor Decision Strategies



Send a single surveyor, if suitable send human mission; if not, do not send human mission

Send a single surveyor first; if not suitable send a second surveyor to another asteroid; (2 launch vehicles)

Send two surveyor spacecraft in parallel to two targets (1 launch vehicle)

Send human mission directly with no surveyor spacecraft

- Use Bayes theorem to compute the posterior probabilities of suitability depending on whether the precursor returns a positive or negative report

Positive report

State of Nature	Prior Chance	Chance Suitable, Unsuitable if Positive Survey	Posterior Chance
Suitable	0.58	0.95	0.96
Unsuitable	0.42	0.05	0.04

Negative report

State of Nature	Prior Chance	Chance Suitable, Unsuitable if Negative Survey	Posterior Chance
Suitable	0.58	0.05	0.07
Unsuitable	0.42	0.95	0.93

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How to Value Payoffs?

- Value function assigned 100% value to human mission that lands on the asteroid; other options relative to this goal.
- "Cost" based on mass delivered to low Earth orbit (proxy for cost) in tons.
- Productivity = benefit ÷ cost

Alternative	Relative Value (percent of total)	Mass to Low Earth Orbit, mt	Productivity (Value/Mass) @ 30%
Surveyor only	30, 20, 10%	0.5	60
Human mission—no surface contact	70	390*	0.18
Human mission—contact with surface	100	390*	0.26

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

Expected Value of Surveyor Information (EVSI)

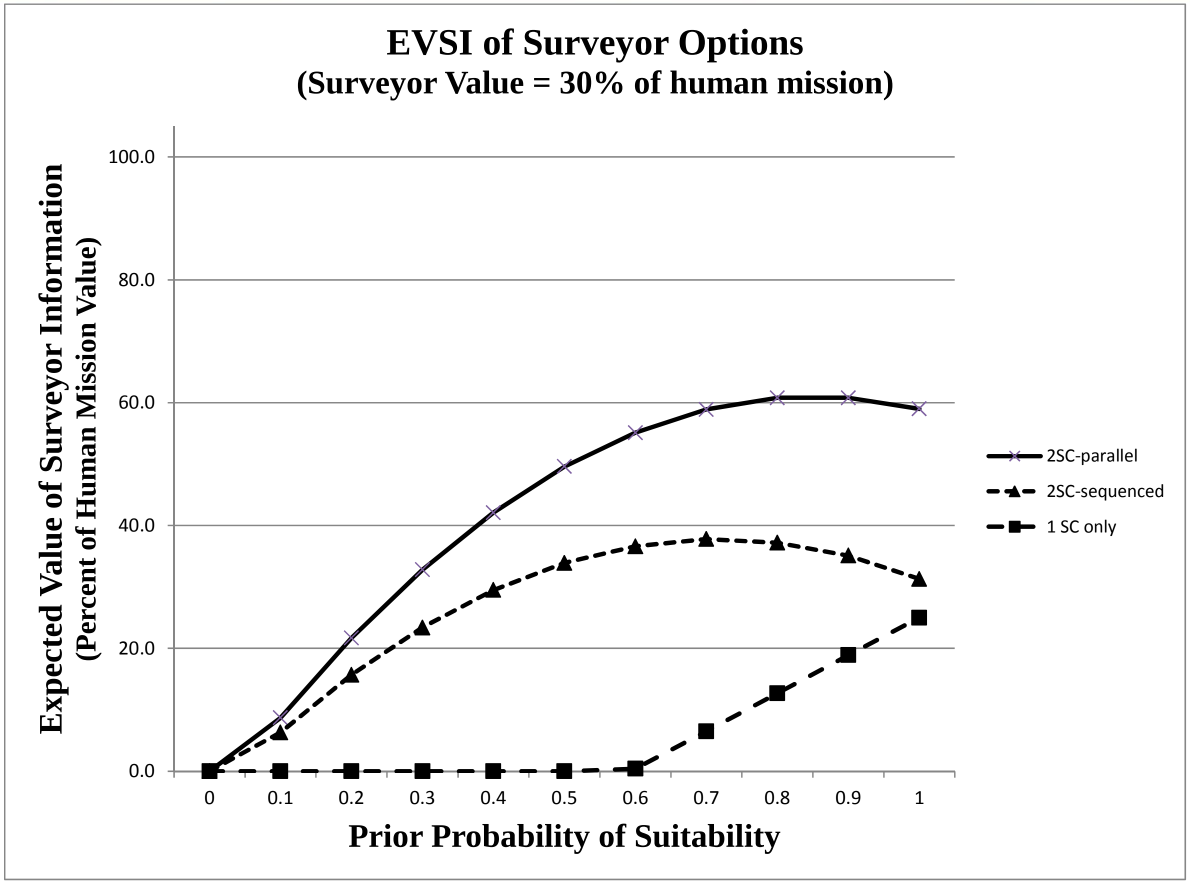
$$EVSI = EV_{\text{With Surveyor Information}} - EV_{\text{Without Surveyor Information}}$$

Three cases for obtaining surveyor information:

1. Send one surveyor only:
   - If suitable send human mission, if not, do not send human mission.
2. Sequential option for 2 targets: send first surveyor to target
   - If suitable send human mission
   - If not suitable, send 2nd surveyor to a new target; if suitable send human mission, if not, do not send human mission.
3. Parallel option for 2 targets: send both surveyors at the same time
   - If one or more found to be suitable, send human mission; if none, do not send human mission.

If EVSI positive, worthwhile to send surveyor, if negative, do not.

Question 2 Results



- It is worthwhile to send 2 surveyors
- Must be confident of suitability (>~60%) if only one surveyor to be sent

3. If more than one asteroid is to be surveyed, is it better to survey sequentially or in parallel?

Or, stated another way:

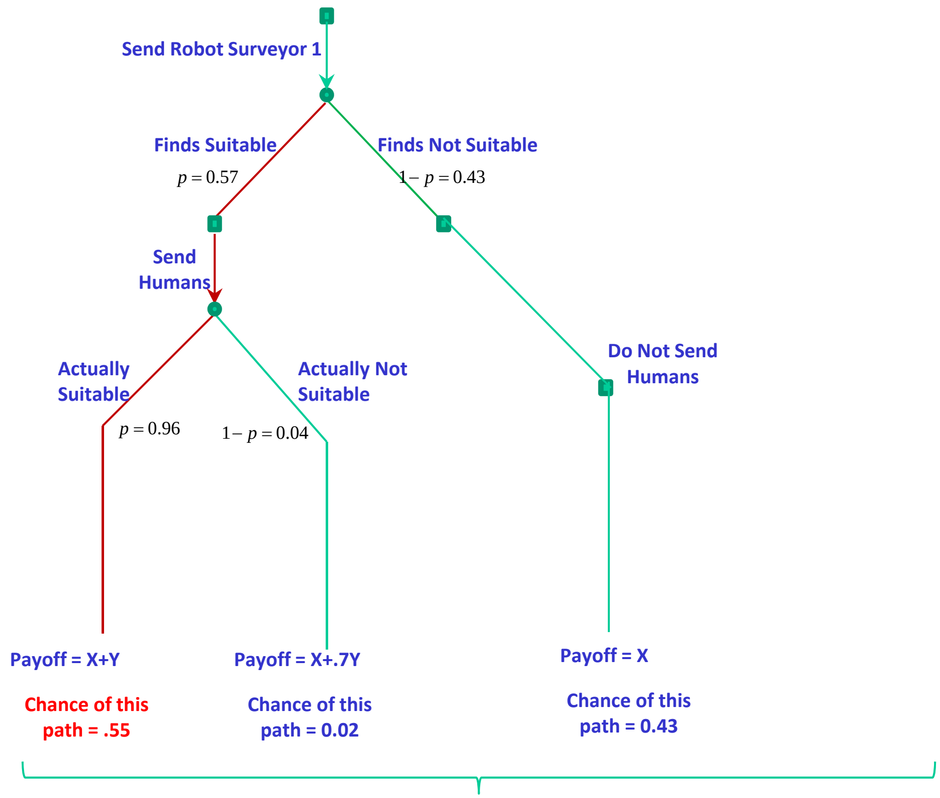
Which surveyor strategy has the highest EVSI?

Note on Figure of Merit

- One of the issues facing this analysis was a debate over which figure of merit should be used and its effect on the conclusions
  - Value percent of human mission?
  - Productivity?
  - LEO mass?
  - Others?.
- Suppose the analysis were performed using a placeholder for *any* figure of merit—what conclusions, if any, could be drawn?

- Let
  - X = the figure of merit for worth of surveyor
  - Y = the figure of merit for worth of human mission that lands
  - The prior probability of finding a suitable asteroid for landing = 0.58
- If the figure of merit for the human mission without landing is 70% of the human mission with landing, then its worth is 0.7Y
- The sequential and parallel cases can be obtained from the decision trees as follows…

Single Surveyor Decision Tree



Probability at surveyor finds suitable asteroid

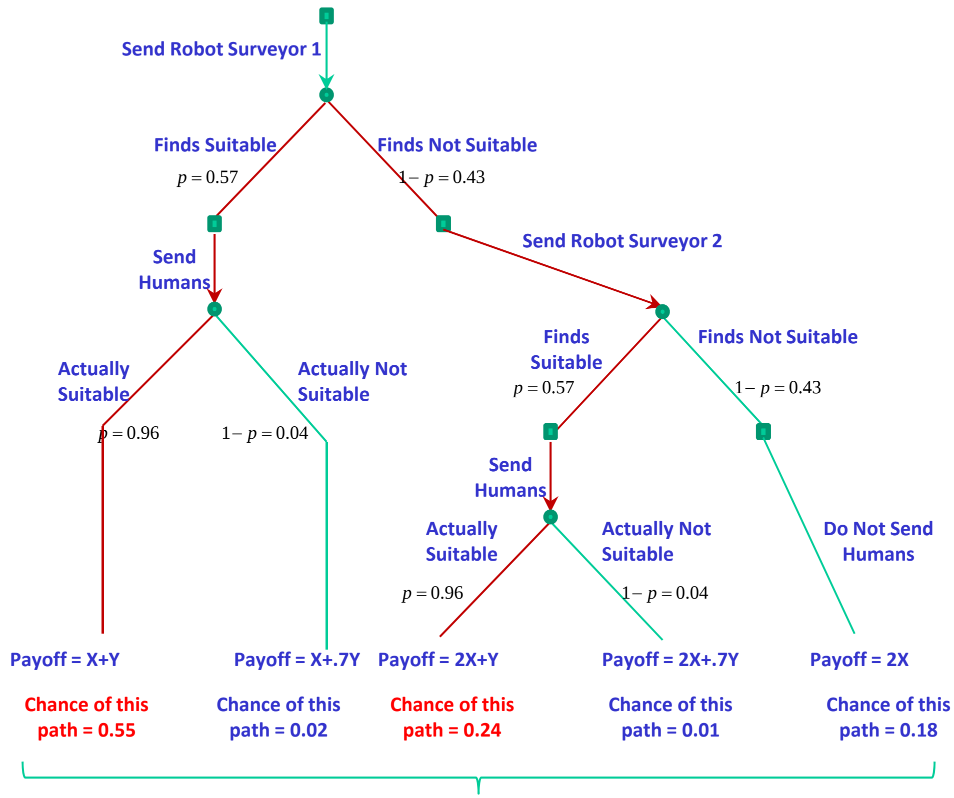
= 0.55

Expected value of sequential survey approach

= .57 (.96 (X+Y) + .04 (X+.7Y)) + .43 X

= 1.0X + 0.56Y

Two Surveyors Sequentially Decision Tree

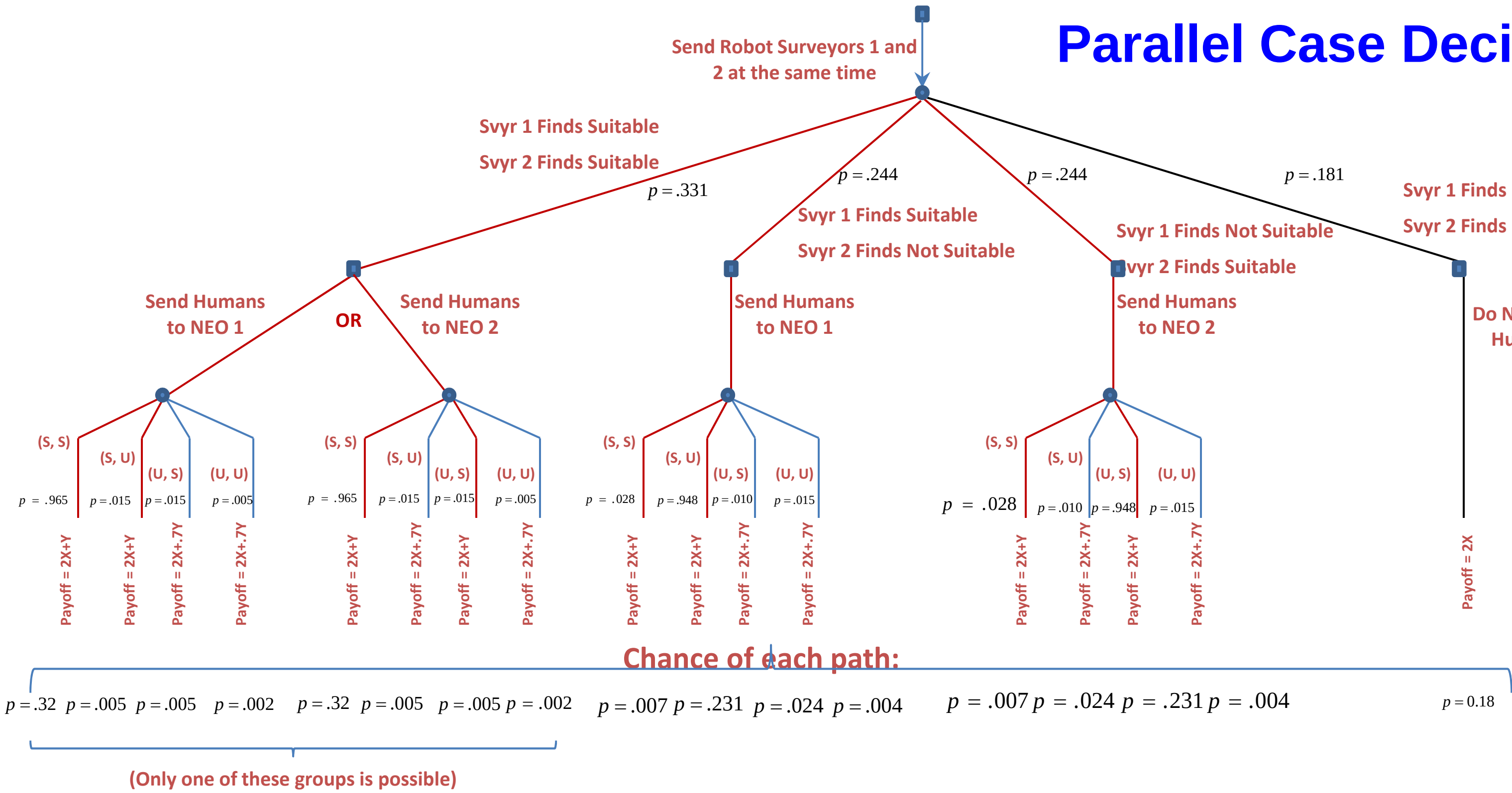


Probability at least one surveyor finds suitable asteroid = 0.55 + 0.24 = 0.79

Expected value of sequential survey approach = .57(.96(X+Y) + .04 (X+.7Y)) + .43 (.57 (.96 (2X+Y) + .04 (2X+.7Y)) + .43 (2X)

= 1.43X + 0.81Y

Parallel Case Decision Tree



Probability at least one surveyor finds suitable asteroid = (.32+.005) + (.007+.231) + (.007+.231) = 0.80

Expected value of this approach = .331(.965 (2X+Y)+ .015 (2X+Y) + .015 (2X+.7Y) + .005(2X+.7Y)) + .244(.028(2X+Y) + .948(2X+Y) + .01(2X+.7Y) + .015(2X+.7Y)) + .244(.028(2X+Y) + .01(2X+.7Y) + .948(2X+Y) + .015(2X+.7Y)) + .181(2X)

= 2X + 0.81Y which is > 1.43X + 0.81Y

⇒ parallel survey approach is better than the sequential approach.

Now assume the value of surveyor = 30% of the value of the human mission then X = 0.3Y

- Single surveyor case:
  - EV = X + .56Y = (.3Y) + .56Y = **0.86 Y**
  - The single surveyor case does not add benefit if P(suit.) = 0.58.
- Sequential case:
  - EV = 1.43X + 0.805Y = 1.43 (.3Y) + 0.805Y = **1.24 Y**
  - Which indicates the two-surveyor sequential case is 24% better than the no-surveyor case.
- Parallel case:
  - EV = 2X + 0.814Y = 2(.3Y) + 0.814Y = **1.41 Y**
  - Which indicates the parallel case is 41% better than the no-surveyor case and 14% better than the sequential approach (1.41/1.24)

Observations and Conclusions

- If the prior chance of asteroid suitability is around 58%, two asteroids should be surveyed to provide at least an 80% chance one will be suitable for landing.
- For >90%, three asteroids should be surveyed.
- Surveyors provide low cost insurance against sending a human mission only to find the asteroid unsuitable for landing.
  - Difference in “costs” between surveyors and human mission so large that, “Why not send surveyors?” Cost of 2 surveyors = 1/390th of human mission cost.
  - EVSI is positive for 2 or more surveyors; if the prior chance of suitability is low (<~60%), EV of direct human mission exceeds benefit of sending only one surveyor.
- Send 2 surveyors in parallel rather than sequentially
  - Due to benefit added by 2nd surveyor over possibility that 2nd surveyor may not be sent in the sequential case.

Backup Slide: Bayes Rule Sample Calculation

- Use Bayes theorem to compute the posterior probabilities of suitability depending on whether the precursor returns a positive or negative report

Numerator of Bayes Theorem

Positive report

State of Nature	Prior Chance	Chance Suitable, Unsuitable if Positive Survey	P(Suit. | Positive Report) x P(Suit.)	Posterior Chance of Suitability given Positive Report
Suitable	0.58	0.95	0.551	0.551/0.572 = **0.96**
Unsuitable	0.42	0.05	0.021	0.021/0.572 = **0.04**

Probability of a Positive Report (denominator of Bayes Theorem)

Sum = 0.572

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