A Study on the Perceived Risk of Surface Sample Collection Systems in Proposal Formulation

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1.0 Introduction

The 2003 and 2013 Decadal Surveys challenge scientists to investigate the processes that "mark the initial stages of planet and satellite formation." This question offers continued interest in missions that would prioritize sample collection and return from comets, Mars and the Lunar South Pole Aitken Basin. The purpose of the research presented in this paper is to understand the design and development of sample acquisition systems in order to gain insights that may assist in future mission formulation. Seven sample collection missions proposed from 2004-2009 are studied first to map overlapping technologies and second to identify patterns or trends in the evaluation of these missions. Simultaneously analyzing concept and proposal-related issues helps identify potential design or communication gaps that develop during the proposal process.

This project compares design and proposal elements from multiple proposals and presents conclusions and recommendations for sampling systems. Contributions from this project include a list of common evaluation themes, concept and proposal-related strengths and weaknesses and ways in which self-identified risks relate the evaluation of the mission.

2.0 Background

Sample collection methods can be categorized as either Touch-and-Go or Surface Sampling missions. The "Touch-and-Go" (TAG) collection method is used to acquire samples from bodies with a zero or negligible-gravity force such as asteroids, comets or small moons. In TAG missions, a spacecraft descends and touches the surface of the target body for a few seconds to collect the sample. A boom or robotic arm with an end-effector, or mechanism located at the end of the sampling arm, is used to acquire and verify the collection of a sample (Neal et. al.). To complete the maneuver, the sample is transferred into a return canister and the spacecraft ascends. Hayabusa, a mission developed by the Japanese Aerospace Exploration Agency, used the TAG method with a projectile end-effector to dismantle, collect and return samples from the near-earth asteroid Itokawa (see Figure 1). Other end-effectors mechanisms include Brush Wheel Samplers, penetrators, and gel-pad collectors. Figure 2 illustrates the sequence and functionality of a Brush-Wheel Sampling concept (Behar, 2003).

Surface Sampling missions are more complex than the TAG maneuvers because they require both a spacecraft and lander element. Once on the surface of another planet or moon, a robotic arm on the lander collects the sample. Surface Sampling end-effectors cover a wide range of technologies including penetrators, drills, and scoops. The Mars lander Phoenix (proposed in 2002, landed in 2008) uses a robotic arm and scoop to retrieve regolith and ice from the Martian Polar region (see Figure 1).

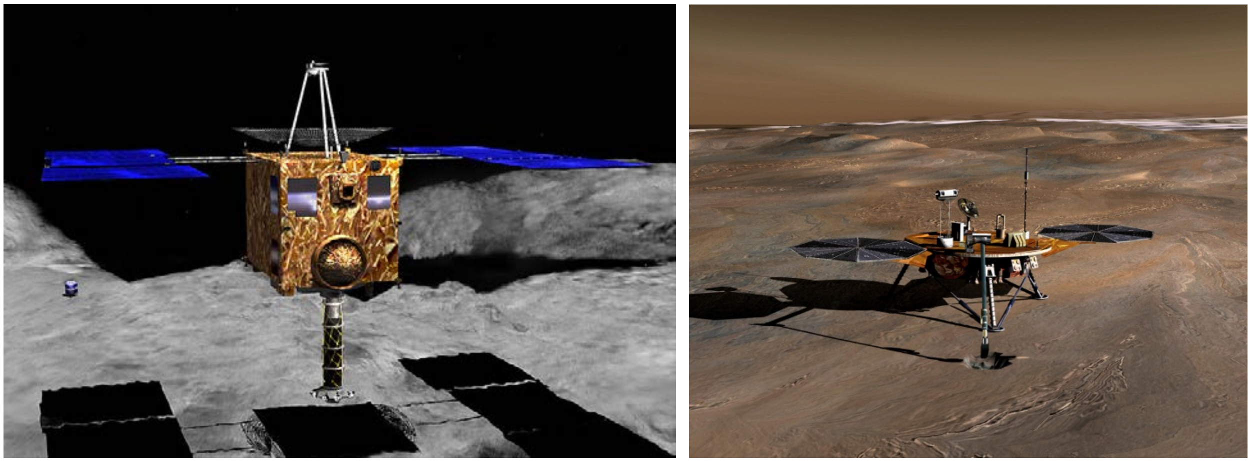

Figure 1 – Existing sample acquisition systems (Wikipedia):
Hayabusa TAG asteroid spacecraft (left), Phoenix Surface Sampling Mars lander (right)

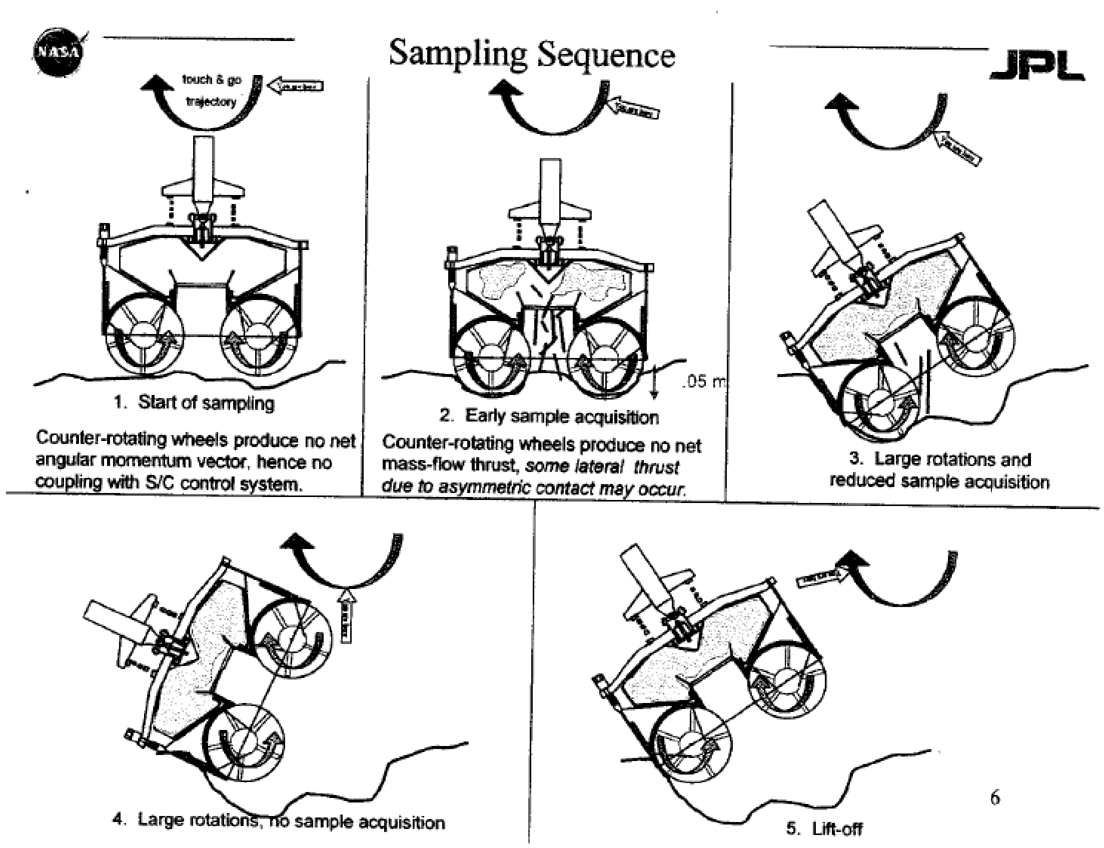

Figure 2 – TAG Brush Wheel concept sampling sequence (Behar, 2003)

3.0 Objectives

1. Characterize different surface sample collection methods
2. Identify the strengths and weaknesses associated with both the technology and proposal communication of acquisition concepts
3. Create guidelines for developing and communicating surface sample acquisition approaches in future proposals

4.0 Approach

A four-step analysis approach was used to complete this study (see Figure 3). First, the scope of the sample was narrowed to focus only on missions proposing surface sample acquisition systems within a given time frame. Next, information related to technical design and proposal-based feedback was gathered from the mission proposals and post-submission debrief reports. Finally, descriptive tables were generated to help draw connections between the information found in the proposals and debriefs. Conclusions and recommendations were generated based on the descriptive tables and a detailed analysis of select proposal pairs.

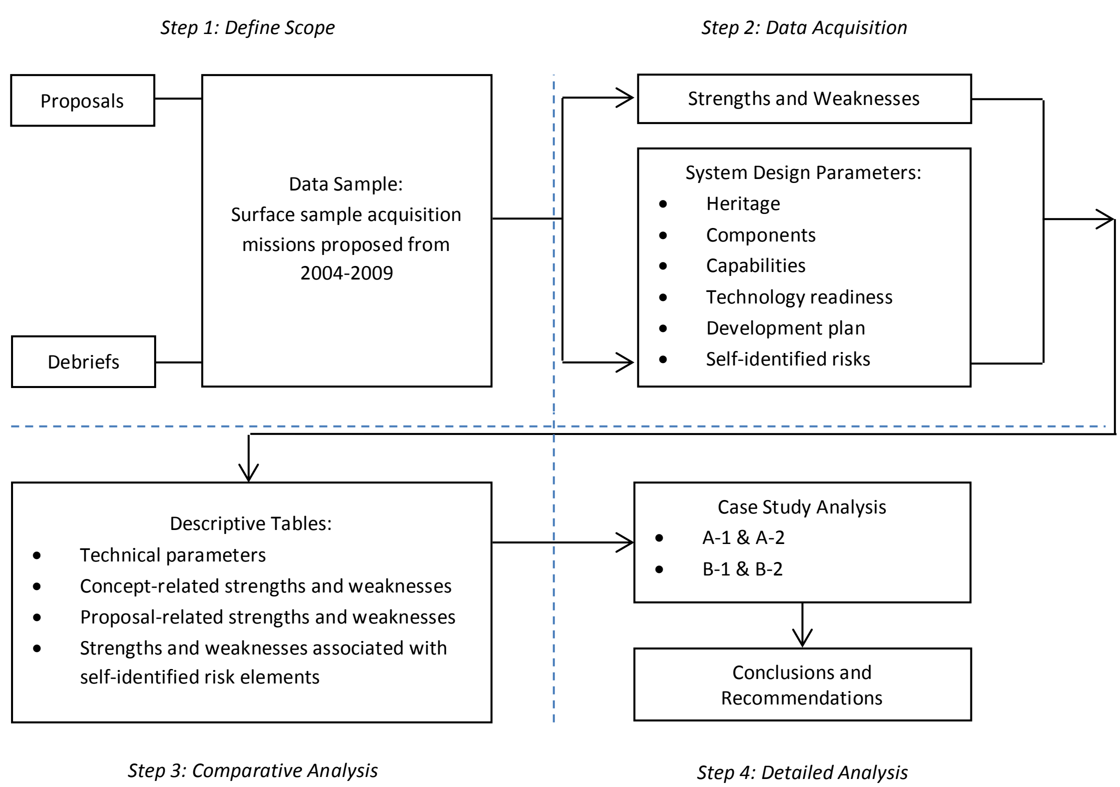

Figure 3 – Method of analysis for sample acquisition systems

4.1 Description of Data Sample

The sample chosen for this study is the seven surface sample collection missions proposed for Discovery, New Frontiers, and Mars Scout opportunities between 2004 and 2009 (see Table 1). The data consists of the step-one proposals and debrief comments for the missions in the sample.

Surface Sampling System

Year		Brush Wheel Sampler (BWS)	Brush Wheel Sampler (BWS) + Rock Chipper	Touch and Go Impregnable Pad (TGIP)	Scoop
Year	2004	A-1		B-1	
Year	2006	A-2		B-2	
Year	2009	C	D		E

Location 1	Location 2	Location 3	Location 4

Table 1 - Surface sample acquisition missions proposed from 2004-2009

By looking at missions proposed over multiple years and three different types of opportunities, the chosen sample covers a broad range of environmental conditions, as identified below:

1. Proposal structures and requirements that have evolved over time
2. The structure of debrief comments differ from year to year due to method of acquisition
3. Focus and cost constraints vary across announcement of opportunity
4. State of practice, such as what technologies have been shown to work, change over time

Table 1 illustrates how the different proposals in the data sample relate to one another in terms of sampling method, target body, and proposal year. The A-1/A-2 and B-1/B-2 comparison pairs were selected for further analysis because they differ only by proposed year, thereby minimizing environmental differences and allowing a more direct comparison between successive iterations of the same mission.

4.2 Analysis Method

In Step 2 of the analysis approach, technical information was collected based on design parameters commonly addressed in debrief reports while debrief information was condensed to include only strengths and weaknesses that directly related to the sampling systems. The proposals selected for the detailed analysis in Step 4 were chosen to control for sources of variance i.e., they have the same principle investigator, same science goals, same target body, and same sampling system.

5.0 Results

After identifying and analyzing the commonalities between different sample acquisition systems, results can be provided in the following three areas:

1. Common debrief discussion themes
2. Proposal versus concept-related strengths and weaknesses
3. Relationship between debrief comments and self-identified risks

5.1 Common debrief discussion themes

A closer look at proposal debrief comments reveals a number of discussion themes that are common to all surface sample collection missions. These themes consistently result in major or minor strengths when they have been thoroughly considered but cause weaknesses when presented in an incomplete or unclear manner. Table 2 provides a list of the four most common sample acquisition discussion themes as well as general rules for how they relate to debrief comments.

Table 2 – Common surface sample acquisition debrief discussion themes

1	Redundancy	If the sampling system is not fully or partially redundant, the proposal must address how the mission can still achieve its science objectives in the case that the sample collection system fails
2	Descopes	Proposals must discuss all risks associated with a descope plan, including how the collection capabilities of the sampling system are compromised
3	Advanced Development	Development plans are recognized as well thought-out when they include the following three components: 1. Results from previous and in-progress activities, 2. A description of available testing facilities, and 3. A complete schedule including back-up options
4	Contamination	Contamination issues (e.g. from digging operations, loose regolith, use of thrusters, jettisoning the BWS, and inadequate cleaning between measurements) must be considered at all stages of the sampling operation including descent, collection, transfer, and return

5.2 Comparison of proposal to concept related strengths and weaknesses

By distinguishing between concept and proposal-related strengths and weaknesses, debrief comments can provide insight into both design and communication-related aspects of a proposed sample collection system. Concept-related debrief comments address design, development, overall system capabilities and performance dynamics in connection to spacecraft and target body interactions. Proposal-related comments highlight the proposal's success or failure in communicating the concept and convincing the evaluation committee. Figure 4 displays the percentage of proposal-related comments for each set. This data shows that for all missions in our sample, over half of the weaknesses received were proposal-related, meaning that these weaknesses were due to issues in communicating the sampling system design rather than inherent flaws in the system itself. Table 3 provides a list of the most common proposal and concept-related strengths and weaknesses.

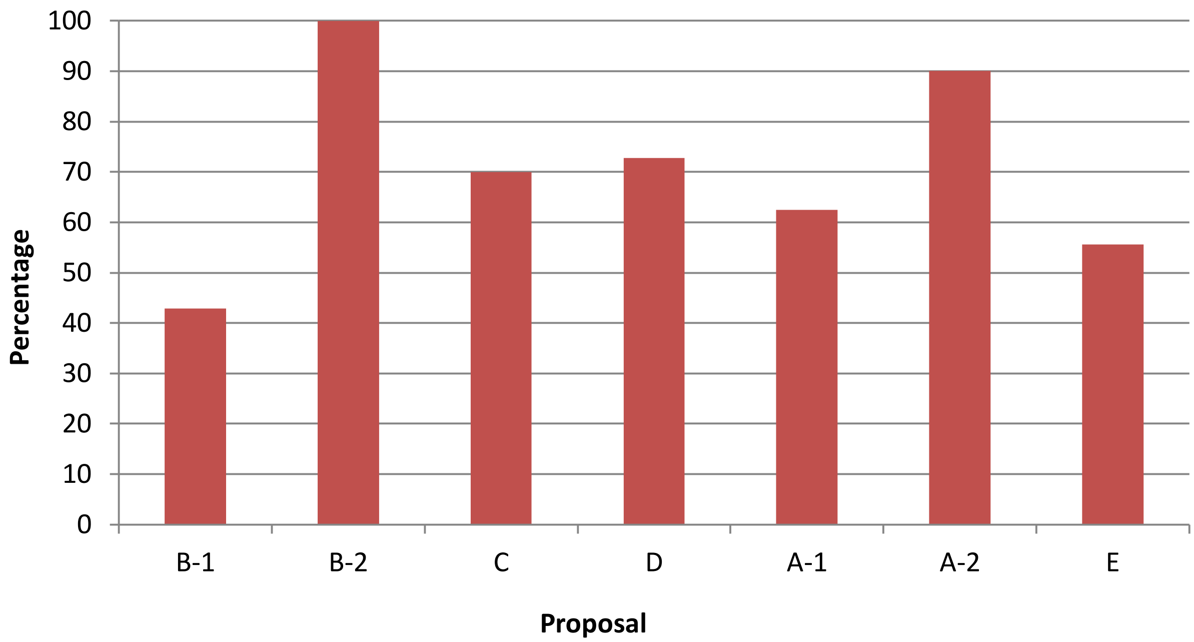

Figure 4 – Percentage of debrief comments that are proposal related vs. concept related

Table 3 – Common proposal and concept-related strengths and weaknesses

Concept-related Strengths	Reliability, simplicity and robustness of sampling system
Concept-related Weaknesses	Design does not consider: 1. Contamination issues 2. Jamming due to loose debris or unexpected sample size 3. Robotic arm precision during the sample transfer process 4. Lack of flight based heritage
Proposal-related Strength	Well documented testing and risk reduction plans
Proposal-related Weaknesses	Proposal inadequately demonstrates or describes: 1. Design changes from heritage basis 2. Sample verification process 3. System capabilities 4. What happens if a non-redundant sampling component fails 5. End-to-end sample acquisition operations

5.3 Relationship between debrief comments and self-identified risks

Each proposal is required to identify the significant risks faced by the project and/or mission. These self-identified risk elements fall into four broad categories based on content and distinguishing key words. For example, phrases like "failure of key mechanism," "development in time for ATLO," "environmental uncertainties," and "TAG contact dynamics" can be used to categorize risk elements into the four categories listed in Table 4. While risk elements range in content, overarching statements can be made about how the debrief comments relate to these items.

In general, self-identified risks result in strengths when the topics under consideration are addressed in detail elsewhere in the proposal. In contrast, a self-identified risk is associated with a proposal-related weakness when a potential area of concern is presented only in the risk management section.

Table 4 – Debrief connections to self-identified risks

Self-identified Risk (by element category)	Reason for Strengths	Reason for Weaknesses
Failure related to inadequate system performance	Risk mitigation strategies reference a detailed development plans that is discussed in more detail outside of the risk management section	A component or process is identified as a potential risk but is not discussed elsewhere in more detail
Failure to complete development plan	Proposal provides ample information on the testing that is already planned or underway	No detailed backup plan is described in the case that more development is deemed necessary
Failure related to unknown environmental conditions	Testing has verified the system's ability to collect an adequate sample amount on different terrain roughness and slopes	Proposal does not address the possibilities of dust, jamming and contamination
Failure related to TAG maneuver	Contact dynamics are considered in both the sampling system design and sampling operation plan	The end-to-end TAG maneuver is not adequately described

6.0 Discussion

To verify and better understand the results presented in Section 5.0, a case-study analysis was performed on two sets of proposal pairs: The first is a Touch-and-Go (TAG) Impregnable Pad system proposed to collect regolith from Location 2 (B-1 2004 and B-2 2006) and the second is a TAG Brush Wheel Sampling method used to collect regolith from Location 3 (A-1 2004 and A-2 2006). Each pair contains a re-proposed mission and so that the focus of the analysis can be to observe how technology maturity influences proposal debrief comments.

The main weaknesses associated with the A-1 2004 and B-1 2004 missions are that both use new, complex technologies with no flight heritage. The TAG maneuvers are also deemed poorly described leading to technology concerns for how the system will behave under variable approach and surface conditions. By the time the systems are re-proposed in 2006 however, they have demonstrated reliability through “fly as you test” validation programs on microgravity test beds. In addition to making design changes that accommodate uncertain surface conditions, B-2 2006 uses lessons from Hayabusa to mitigate risk while the boom used in A-2 2006 gains credibility through flight heritage. Table 5 provides a more complete list of design, risk, and debrief-related changes that each proposal pair experienced from 2004 to 2006.

Both 2006 debriefs recognize that the systems have evolved and matured and consequently the review panel awarded them a number of major and minor concept-related strengths. Consistent with the results presented in Section 5.0, redundancy, descope, advanced development, and contamination are continued themes of discussion in the 2006 debriefs even though many of the issues from 2004 have been resolved. The percentage of concept-related weaknesses decreases from 2004 to 2006 for both proposals, and a closer look at the proposal debriefs reveal that many of the comments are related to either the four main discussion themes or inadequate descriptions of design changes.

It is clear that the TRL for both systems increased from 4 to 5 from 2004 to 2006, but it is still ambiguous as to why the overall Risk Rating changed from *high* to *low* for the A-1/A-2 set but not B-1/B-2 In addition, the Technical Merit and Feasibility rating changed from *below average* to *good* from A-1/A-2 but remained constant at *below average* for B-1/B-2.

Table 5 – Detailed comparison of select mission pairs

Comparison Element	Changes from B-1 2004 to B-2 2006	Changes from A-1 2004 to A-2 2006
System Overview	• TGIP TRL increased from 4 to 5 • Hayabusa mission provided B-2 2006 with a successful flight reference • The robotic arm decreased in complexity by changing from 5 degrees of freedom to 3 degrees of freedom • The pad design evolved to include a movable back plate and different material • The amount of contact force between the sampling arm and asteroid increased from 10 N to 25-30 N and collection capabilities improved from .1kg of regolith to .028-.15 kg of regolith	• Overall risk rating dropped from *high* to *low* and the Technical Merit and Feasibility rating improved from *below average* to *good* • BWS TRL increased from 4 to 5 • BWS testing proposed in 2004 was demonstrated to a higher readiness level by 2006 • Boom gained flight heritage • The 2006 design incorporates a remote sensor pivot (RCP) to address the "flush contact" requirement • System mass and power changed between 2004 and 2006 with no explanation
Self-identified Risks	• To address TAG contact dynamics, the 2006 mitigation strategy proposed that early TAG-B efforts focus on [sampling system]/surface interaction in Vertical Test facility • The planned TGIP sample collection validation tests presented in 2004 were in progress by 2006	• Risks and mitigation plans in 2004 focus on mechanical or maneuver-related failures • 2006 risks are related to failures from unfavorable surface conditions. They do not include any mitigation strategies related to technology development
Concept-related Comments	• The system proposed in 2004 was noted as complex with no flight heritage but the mission reduced risk in 2006 by proposing simple operations without tight requirements (W → S) • There were no concept related weaknesses 2006	• 2004 mission lacks heritage and descope details (W) • 2006 system has clearly evolved from 2004 and sufficiently demonstrated that it is simple and robust (S) • Fewer concept related weaknesses in 2006
Proposal-related Comments	• 2006 mission organization should help ease the integration of advanced technology (S) • No field simulation test was proposed in 2006 (W)	• TAG dynamics are not addressed in detail in 2004 but are well developed by 2006 (W → S) • 2006 lacks detail related to contamination control, dust, and jamming (W)

*(S) = debrief strength, (W) = debrief weakness

7.0 Conclusions

Based on this analysis, the following recommendations can be used to help improve concept and proposal development during the early stages of future mission formulation:

1. All sample acquisition designs and proposals should provide clear explanations regarding redundancy, descopes, advanced development, and contamination control, even if the discussion is to defend why one of these areas lacks development.
2. The majority of weaknesses are proposal-related but can be corrected by addressing the four common debrief themes identified above in recommendation 1.
3. Self-identified risks can strengthen a proposal, but only if they are re-addressed in more detail outside of the risk management section.

Given these results, it can be hypothesized that a mature design will only lead to lower Risk Ratings or higher Technical Merit and Feasibility ratings if the design development is clearly documented and if previously identified proposal-related weaknesses have been addressed. The detailed analysis of the A-1/A-2 and B-1/B-2 proposal pairs demonstrate how technological development positively reflects in debrief comments. However, it is still ambiguous how the written-form of the proposals has progressed from one year to the next. I recommend studying the A-1, A-2, B-1, B-2 proposals more closely to see what proposal-related factors contributed to the change in Risk and Technical Merit and Feasibility ratings from A-1 to A-2 but not B-1 to B-2.

8.0 Acknowledgements

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