Design Tools for Cost-Effective Implementation of Planetary Protection Requirements

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Abstract— Since the Viking missions to Mars in the 1970s, accounting for the costs associated with planetary protection implementation has not been done systematically during early project formulation phases, leading to unanticipated costs during subsequent implementation phases of flight projects. The simultaneous development of more stringent planetary protection requirements, resulting from new knowledge about the limits of life on Earth, together with current plans to conduct life-detection experiments on a number of different solar system target bodies motivates a systematic approach to integrating planetary protection requirements and mission design. A current development effort at NASA's Jet Propulsion Laboratory is aimed at integrating planetary protection requirements more fully into the early phases of mission architecture formulation and at developing tools to more rigorously predict associated cost and schedule impacts of architecture options chosen to meet planetary protection requirements.

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1. INTRODUCTION

Stringent requirements regarding planetary protection (PP) and in-situ biological contamination control, once thought to be applicable to only a small fraction of missions to solar system targets, are now recognized as a major factor in the flight of future NASA and international space missions. A number of scientific developments in fields ranging from microbiology to planetary science have contributed to this new urgency.

First, the field of microbiology has reached an improved understanding of phenomena associated with terrestrial microbial extremophilia. This phenomenon refers to the diversity of species exhibiting tolerance or preference to environments of interest to space exploration, with metabolisms demonstrating radiation-tolerance, thermophilia, or psychrophilia (the ability to thrive in cold temperatures). These developments have led to the realization that the previously assumed limits on microbial propagation rates on extraterrestrial bodies may not be appropriate.

Furthermore, a number of scientific advances have enhanced our understanding of the potential habitability of several extraterrestrial environments. The Mars Exploration Rovers have returned new data on the hydrogeological history of the surface of Mars; these data strongly suggest that water existed on the surface at one time. In addition, data returned from the Galileo mission suggest that the surface of the Jovian moon Europa is covered by a crust consisting of a water-ice crust overlying a liquid-water ocean, raising the possibility of global contamination of the ocean via a conduit to a locally contaminated site on the surface. The potential habitability of a third body of interest, Saturn's moon Titan, has also recently been re-examined in light of the data returned from the recent Cassini-Huygens probe, and its surface, rich in organic materials, is suggestive of a prebiotic or potentially currently habitable environment.

These science discoveries have broadened our understanding of the possible habitability of other solar system bodies and have motivated a new set of planned missions with life-detection experiments or the capability to conduct an analysis of prebiotic chemistry. In concert with the planned life-detection missions of the Mars Program, NASA's Solar System Exploration roadmap identifies a number of high-priority mission concepts to these targets in the next decades. However, the astrobiological science objectives of these planned missions pose a number of challenges. Inadequately cleaned or unsterilized spacecraft have the potential of confusing or invalidating the returned science from these future planned missions; this risk is increased by the possibility that terrestrial microbes or biological materials could persist in these alien environments. As a result, planetary protection and contamination control requirements are likely to be stringent for these planned missions; anticipating these requirements and integrating them into design-phase planning therefore rise in importance.

In contrast with the process used during the Viking mission, in which PP-planning groups were an early voice in determining the mechanical layout and operation of the spacecraft, PP has more recently been practiced as a late design-phase and build-phase activity. Two consequences of this approach have included escalated cost as PP activities were fit into busy spacecraft build schedules and the generally missed opportunity to adequately plan for and track the impact of meeting PP requirements.

It has become clear that PP considerations must be understood and planned for at an earlier mission phase when choices are greatest and impacts can be anticipated to prevent later surprises; however, a science and engineering tool kit enabling PP planning does not currently exist. The development of such a tool kit is the focus of an internal effort at the Jet Propulsion Laboratory and is discussed in this document. As envisioned, the completed toolset will provide an integrated suite of estimation tools used to help identify engineering options and to more accurately assess cost and contamination risk early in the design cycle. The toolset will be designed to be applicable across a range of solar system missions and to accommodate future techniques for PP implementation including new spacecraft design materials, sterilization techniques, as well as anticipated changes in the requirements.

2. Historic and Current Implementation

While NASA requires that all missions be assigned to a planetary protection category to determine the appropriate requirements, to date, only the missions to Mars have been subject to the more stringent (COSPAR Category IV) biological controls designed to minimize the risk of accidental biological contamination of the planet. Because of the dearth of missions requiring this level of planetary protection, the requirements did not change substantially for approximately twenty years and little work was done on creating independent cost estimation tools.

In the late 1960's and early 1970's, the Viking project took planetary protection (then called "planetary quarantine") into account from the project inception and supported the necessary research, as well as the implementation[1]. This included ensuring compliance of the scientific instrumentation with strict cleanliness levels designed to maintain the integrity of the returned science as well as compliance with planetary protection policy. After performing subsystem dry heat sterilization, the Viking landers were sterilized on a system level and upon assembly, a bioshield encapsulated the entire descent module to prevent recontamination. Ultimately, the Viking results established the low habitability of the Mars surface[2], leading to a long hiatus in landed and orbital missions to Mars.

However, the 1996 discovery of mineral deposits interpreted by some to be evidence of past life on the Allan Hills meteorite ALH84001[3], stimulated new interest in Mars. As Buxbaum[4] describes, it reignited interest in life-detection research and experiments, starting with the contemporaneous Mars Pathfinder (MPF) mission. MPF's design and assembly processes included some techniques to reduce contamination of the landed elements, as well as at the landing site. Planetary protection implementation for the subsequent Mars Exploration Rover (MER) missions expanded on the MPF design, although changes in the backshell design called for a revised planetary protection approach [5]. The MPF/MER systems included use of dry heat microbial reduction on components or subsystems, as much as possible. While MPF included one High Efficiency Particulate Arrestor (HEPA) filter to isolate some components and prevent contamination of the landing site, by comparison the larger MER rovers used multiple HEPA filters.

As an orbiter, the Mars Reconnaissance Orbiter (MRO), launched in 2005, was subject to COSPAR Category III requirements. The eccentric orbit meant that orbital lifetime requirements could not be met. However, surface cleaning was considered an inappropriate approach for sterilizing the entire exposed surface. A study was conducted to understand the method of reducing bioburden by taking advantage of heating during atmospheric entry[6] upon the mission's termination. This study led to the conclusion that, in the event of failure maintain orbit, surface heating would be sufficient to sterilize all the external surfaces. Although analytically intensive, this analysis led to considerable cost savings in the final assembly process because it obviated the need for surface cleaning and recontamination prevention of the orbiter.

The upcoming (2007) Phoenix Scout mission to Mars has addressed planetary protection compliance by enclosing the sterilized sample acquisition arm in a biobarrier, meeting the requirements by ensuring that only the sample acquisition arm reaches into the subsurface "Special Region" (defined as a region where there has been or is liquid water); the rest of the lander is not subject to this tighter requirement.

On the other hand, the Mars Science Laboratory (MSL), scheduled for launch in 2009, has an architecture with additional challenges. One concern is that the use of radioisotope power sources (RPS) for power poses the possibility of inadvertently creating a local "Special Region" by melting the ice in the mineral matrix. An additional challenge faced by the MSL mission is the use of a number of novel materials, such as in the electronics; the tolerance to dry heat needs to be understood prior to implementation.

Table 1: Examples of key drivers for missions to Mars and Europa to be examined in coupled contamination and cost assessments.

Trade space parameter	Motivation	Mars orbiter	Mars lander	Europa orbiter	Europa lander
Duration of exposure UV environment	Use of radiation for terminal surface sterilization	✓	✓		
Exposure to heat flux during atmospheric entry	Use of heat for terminal sterilization of exposed and mated surfaces	✓			
Duration of exposure to Jovian particle environment	Use of radiation for terminal surface sterilization			✓	✓
Radiation shielding architecture (thickness, spatical distribution)	Use of radiation for terminal surface sterilization			✓	✓
Power source architecture (flux, spatial distribution)	Possibility of melting ice trapped in mineral matrix and produce "special region"		✓		
Power source architecture (flux, spatial distribution)	Possibility of melting surface ice to produce conduit to ocean			✓	✓
Heat and chemical tolerance of radiation-hard electronics	Development of compatible sterilization technique			✓	✓

3. Historic and Current PP Costing

A wide range of items contributes to the overall costs associated with meeting the planetary protection requirements for a given mission concept. The obvious cost elements include tasks associated with cleaning, sterilization, and assaying. Additionally, many components and/or materials on the spacecraft may require testing for compatibility with the cleaning and sterilization methods planned. In some situations, certain components or materials may require re-design or alternates used, in order to achieve compatibility with the planetary protection protocols. Costs for a spacecraft's propulsion system might be influenced by required trajectory changes in order to reduce the probability of a non-nominal impact or by requiring an end-of-mission maneuver, such as one causing atmospheric reentry and burnup or reaching a defined orbit with particular sterilization properties (known as a "quarantine orbit"). These are just a few of the myriad costs that are associated with meeting planetary protection requirements.

For the Mars missions to date, the far reaching influences of planetary protection requirements result in the associated costs being bookkept in many different segments of a mission's cost. Most of the mitigation hardware (i.e. HEPA filters) were rolled into the overall mechanical subsystem cost. In contrast, the costs for surface cleaning and testing were bookkept in an area readily identified as planetary protection cost items.

This distributed nature of planetary protection compliance costs tends to hide the overall impact of planetary protection and makes it difficult for design engineers to consider such costs in early design trades. Often, the planetary protection costs are not fully realized until quite late in the development schedule and can lead to cost overruns.

Historically, the costs for planetary protection have been estimated by a variety of methods. During pre-formulation design studies, these costs have been coarsely estimated using table lookups or even using a simple percentage of the overall mission cost. To a crude measure, this method is often reasonable; however, it lacks the detail required for comparing different planetary protection architectures for a given mission. Simple estimates also lack sufficient detail to be adequately defended in a cost review.

During phase A/B, planetary protection costs have been estimated using simple spreadsheet models and, more often, by grass-roots estimates generated by planetary protection engineering staff. In order for engineers to conduct design trades that consider the many costs of planetary protection options during pre-formulation studies, those costs must be estimated in a manner that yields understandable and defensible values. This is one of the objectives of the development work described in this paper. The design engineers need the ability to consider different sterilization options, different trajectory options, and different system reliability options, as they all contribute to satisfying the planetary protection requirements.

4. PP-Sensitive Mission Concepts

The roadmaps of both the Mars Program and the Solar System Exploration Office call for a number of missions supporting astrobiological investigations, and thus more likely to have stringent planetary protection or contamination control requirements. Although the Mars Phoenix mission is not scheduled to launch until 2007, its planetary protection plan is sufficiently mature that it will provide useful validation data on the cost models. Similarly, as discussed above, the mission architecture for the Mars Science Laboratory (MSL) is reasonably well understood and will provide more useful benchmarks.

On a longer time scale, the Mars Sample Return mission is envisioned to be the first robotic sample return mission facing substantial back contamination requirements. While back contamination is not a focus of this effort, the entire mission, and particularly the sample handling and containment system, would be subject to stringent forward contamination control. Because the technologies and techniques for returned sample containment are still under development, it is conceivable that a sample return mission concept, such as Mars Sample Return, could potentially benefit from a cost and design tool such as that developed here. Later missions to Mars with life-detection experiments would similarly benefit from such a tool.

The Solar System Exploration roadmap describes a number of missions pursuing science objectives related to astrobiology. Two missions to the Jovian moon Europa are in the planning stages: Europa Geophysical Observer (EGO) and Europa Astrobiological Lander (EAL). EGO, with a launch date as early as 2013, is envisioned to conduct the majority of its science remotely; however, there is a strong desire from the science community to include a small landed package to conduct preliminary in situ science. A complete in situ analysis is planned for the EAL, with a launch date late in the second decade.

A preliminary analysis of the planetary protection requirements associated with a mission to Europa was conducted in conjunction with the Jupiter Icy Moons Orbiter (JIMO) project[7]. Although this mission study has terminated, the methodology highlighted some of the differences in contamination prevention for a mission to Mars and one to Europa. Some of the techniques used for missions to Mars, such as HEPA filtered enclosures, are not suitable for contamination prevention on Europa; other entry/descent/landing-based approaches useful for orbiters, such as atmospheric burn-and-breakup, are also not relevant. Although current plans for missions to Europa no longer include a fission reactor, the JIMO experience illustrated a number of key architectural differences between a generic mission to Mars and one to Europa, as summarized in Table 1.

Although Mars and Europa are the primary targets of interest for this effort, it is natural to consider extensions to other targets that may face planetary protection concerns. For instance, the Solar System Exploration roadmap also calls for a mission to Titan early in the second decade. The architecture of the Titan Explorer would likely include an aerial platform to conduct in situ investigations; this aerobot may have the capability to collect samples for analysis. The integration of a sample acquisition system with an aerial vehicle potentially leads to a number of further challenges for planetary protection.

Finally, the Solar System Exploration roadmap also describes returned sample mission concepts in the form of the Comet Surface Sample Return (CSSR), with a planned launch date of 2013, and the Comet Cryogenic Sample Return (CCSR) mission, with a launch date in the second decade. These missions are envisioned to sample the surface and the subsurface, respectively, of comets potentially rich in organic materials. While these missions are not anticipated to have forward contamination requirements that are as strong as those for Mars, Europa, and Titan, containment measures for the returned sample are still envisioned to be strict and will therefore interact with the sample acquisition system [8].

5. CONTAMINATION REDUCTION COST TOOL

For maximum cost-effectiveness, the development of an architecture for a specific mission should be coupled early in the formulation phase to the planetary protection architecture selected to meet the appropriate requirements. (For purposes of discussion, a planetary protection architecture is defined herein as a combination of processes, analyses, and mission architecture choices intended to achieve a specified low probability of contaminating a body of interest). A simplistic example of a planetary protection architecture might be to completely clean and sterilize all parts of a spacecraft, and enclose it in a biobarrier until after launch.

A more practical approach to achieving the planetary protection requirements for a given body would ideally comprise an "optimized" combination of cleaning/sterilization, trajectory/orbit design, and flight system design. As an example, if it can be demonstrated that the probability of an orbiter coming into contact with a body of interest is sufficiently low, it may be unnecessary to sterilize and/or clean the entire orbiter. However, achieving that low probability may entail modifications to the orbiter trajectory or orbit, and/or modifications to reliabilities or redundancy of selected hardware elements in the flight system, with associated mass and cost penalties.

This philosophy has been implemented gradually for the Mars Program; the MRO experience demonstrates that the analysis of the heat fluxes experienced during atmospheric entry made it possible to limit the surface cleaning activities. The Mars Phoenix mission has also met the planetary protection requirements in a cost-effective way by limiting the stringent cleaning requirements to the sterilized, isolated sample acquisition system.

To make the best choices for planetary protection, the end-to-end mission architecture must be assessed in terms of the planetary protection requirements and architectures applicable to each flight system element (orbiter, lander, probe, etc.). Ideally, cost impacts could be evaluated for the selected implementation options for each element. This assessment would include mission design elements, such as the likelihood of each element impacting a target or region with stringent planetary protection requirements, as well as probabilistic assessments of the expected bioburdens on each element at the time of contact and the probabilities of any viable organisms surviving to reproduce. This suggests the need for an analysis tool coupling conventional mission architecture elements with planetary protection procedures and analyses. Mission architecture elements would include factors such as trajectory and orbit design parameters and statistics, spacecraft hardware reliabilities, fault-tree analyses, and entry and breakup analyses, while planetary protection analyses would include pre- and post-launch bioburden reduction and models of microbial survivability in relevant envrionments.

One major challenge is to develop design tools to estimate the cost impact of these mission architecture and planetary protection architecture choices in real-time, although contemporary mission design tools address some of the relevant factors. Cost estimation tools exist that give coarse estimates of flight system costs based on design parameters. Probabilistic tools are used to quantify the likelihood of a flight system component inadvertently contacting a specific target, and can yield guidance on required hardware reliabilities or mission (trajectory) design parameters. Furthermore, current analytical models predict surface temperatures during atmospheric entry or the dynamics of the breakup and scatter of flight system elements at impact. Existing models also assess the cost of implementing existing microbial reduction techniques such as Dry Heat Microbial Reduction (DHMR) for conventional spacecraft hardware to specified cleanliness levels. In addition, planetary protection analysis capabilities predict pre-launch bioburden reduction and some models of microbial surviability in relevant environments.

Prior to this effort, no design system existed to link these capabilities to enable real-time, concurrent assessment of both cost and effectiveness of various mission and planetary protection architectures during the concept formulation phase of a project. In an effort to improve the consideration of planetary protection factors during early mission design activities, a model is currently under development at JPL.

The focus of the Contamination Reduction Cost Estimation Tool (CoRCET) is to aid a design team in characterizing the impacts associated with different PP architectures and implementation choices, thereby allowing the designers to improve their understanding of both the cost impacts of meeting PP requirements and the various options available to them while still in the early mission concept phase. The specific objectives are two-fold: 1) By integrating PP requirements early during mission concept formulation, mission designers are given maximum flexibility in effectively addressing those requirements with minimal downstream impacts on the design; and 2) useful early cost estimates are established for this non-insignificant cost element. The primary input to CoRCET will be a set of mission architecture and PP architecture choices, and its primary output will be coarse PP-related cost estimates and cost sensitivities. The delivered cost estimates will include the spread of those costs over the project's lifecycle as well as estimated schedule impacts and associated technology risks. Once a cost and schedule impact is known for an initial set of choices, a mission designer or design team will be able to iterate the mission architecture many times, exploring the optimal combination of mission elements that meet PP requirements with the least total impact and risk.

CoRCET will directly address mission and flight system design choices that influence PP requirements and compliance and will provide cost sensitivities in these areas. Examples of relevant design choices include flyby events, trajectory biasing, system configuration, and hardware selection. CoRCET will also support the assessment of PP factors unique to mission environments, such as the UV radiation of Mars landers and the exposure to the Jovian radiation environment for missions to or near Europa. CoRCET is intended to support a broad mission set, with particular focus on the contemporary targets of interest (Mars, Europa, and Titan).

A major objective of the CoRCET implementation is that it will be compatible with a dynamic concurrent engineering environment, such as JPL's Team X, as well as with other PP tools. An adjunct model, named the Contamination Likelihood Assessment (CoLA) tool, will estimate the efficacy of selected PP methods for a given architecture. Once choices about mission architecture and PP approach are investigated in CoRCET, they will be introduced into CoLA, where an assessment will be generated of the probable bioburden levels on the space hardware delivered to the target. Together, CoRCET and CoLA will be used to provide the design team with information needed when choosing a PP architecture. The anticipated interface between CoRCET and CoLA is illustrated in Figure 1. Key design parameters from a given mission architecture will be used by CoRCET to estimate probabilities of relevant events occurring (such as inadvertent contact with a target of concern). These probabilities, as well as other relevant design parameters (such as numbers of hardware assemblies, surface areas, etc.) will be passed to COLA for use in assessment of the effectiveness of the PP architecture. Simultaneously, cost estimates will be generated for the mission. Ultimately, costs of PP-specific activities and the associated assessment of the PP effectiveness of the overall mission architecture will be generated. The resulting costs and efficacies can be compared for different mission

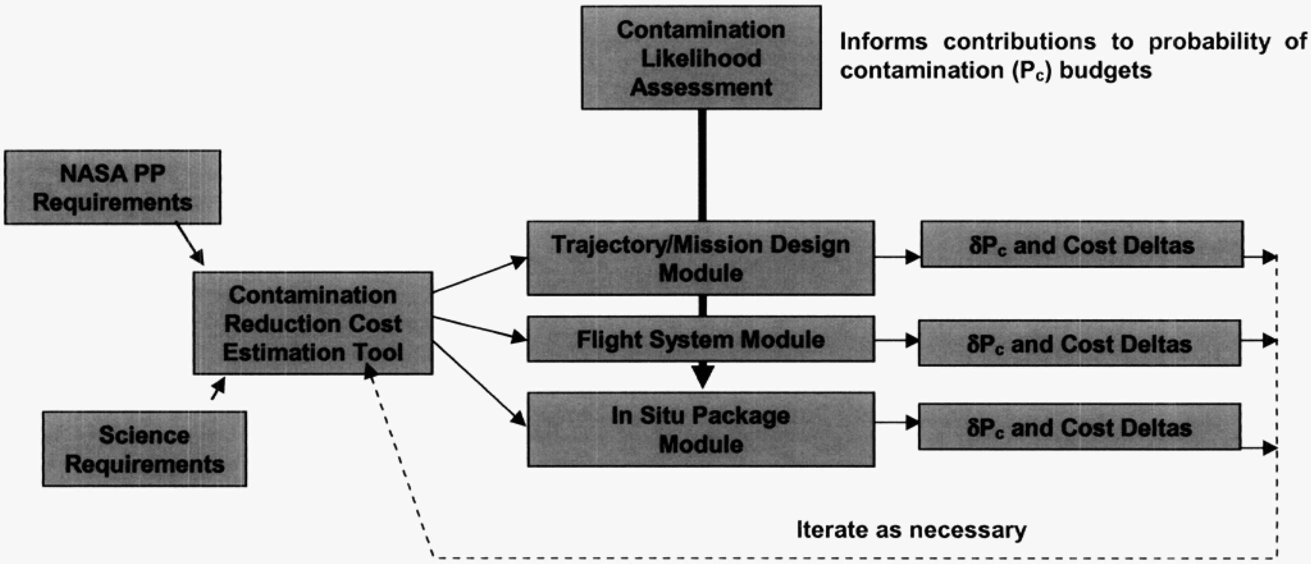

Figure 1: CoRCET connection to CoLA.

architecture choices.

In order to improve its lifecycle utility, CoRCET's architecture will be modular, allowing integration of new PP techniques and coverage of new mission elements, such as deep ice penetrators or airship ballonet materials sterilization. CoRCET capability will be developed incrementally, starting with integration of existing tools and models, and with simplified models as "placeholders" for additional needed capabilities identified along the way. This modular design will also allow incremental improvements in the cost modeling relationships, as well as accommodating unique cost relationships for special case mission scenarios. As CoRCET is developed, gaps will be identified where additional experiments, modeling and validation activities, or new analysis tools may be needed. The intent is for the CoRCET architecture to be flexible enough to adapt to new concepts, technologies, and requirements in the future. CoRCET is envisioned to be an ongoing effort, staffed by JPL mission architects working jointly with planetary protection engineers, with each community learning from the other and working together to achieve cost-effective planetary protection for future missions.

6. Conclusions

Designing missions to be compliant with planetary protection requirements while at the lowest cost and risk is a challenge to all parts of the flight system. This challenge will rise to the forefront as missions are launched to a greater number of biologically-interesting solar system targets over the next decades. To be effective, planning for PP must begin during the early phase of mission definition, when the greatest number of options are available to mission designers. This integration of PP engineering into top-level architectural design represents a shift in paradigm from that employed on contemporary missions.

The authors have described a current tool development at the Jet Propulsion Laboratory which will enable mission architects to explore the design space available to them for optimal combinations of mission design, spacecraft design and bioburden mitigation procedures. The product of such a tool capability will be estimates of both the cost and effectiveness of each planetary protection architecture assessed. This will allow iterative design cycles concurrent with the rest of the mission design. An additional benefit of this capability is that it will allow for a quantitative cost-benefit analysis of the development of items such as alternative materials, fabrication techniques, and bioburden reduction methods, as well as for broader system-level options such as the use of alternate flight system technologies or mission architectures. This development effort will transform the paradigm of planetary protection from an implementation-phase mitigation effort to a mission design activity.

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