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# Evaluation of Human Space Exploration Missions Beyond Low Earth Orbit

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# Abstract

While we expect productive utilization of the International Space Station (ISS) through at least 2020, there is an international need to define a concrete strategy and plan for the initial human exploration missions that will extend beyond Low Earth Orbit (LEO). The current long term objective of global human space exploration is eventual long duration presence of people on the Martian surface. Along the pathway between current activities in LEO and eventual Mars missions are a variety of preparatory exploration missions and intermediate goals. Over the last decade several different initial steps beyond LEO have been proposed. It is important to build international consensus on such a plan soon because future missions require near-term investments for new capabilities and no single nation can achieve an ambitious program on its own. A group of academic experts from the United States and Russia are working together to address this complex multidisciplinary planning problem. The goal of this work is to provide a framework for evaluating alternatives for exploration beyond LEO.

The approach of the group will build upon the goals and objectives described by the International Space Exploration Coordination Group (ISECG). An initial evaluation of different mission options by several figures of merit includes programmatic and technical risks as well as the exploration objectives each mission satisfies for different relevant stakeholders. Moving beyond the initial evaluation, the approach will also address the questions of which actors may contribute to a cooperative program, and how specific elements can be allocated to participating nations. The paper will outline the overall analysis framework used to evaluate missions. This will include a review of mission alternatives and the metrics by which they have been evaluated. As this work is ongoing, this initial evaluation of mission alternatives will be presented, and the evaluation of specific partner contributions will be addressed in future work.

## 1. Introduction and Background

While we expect productive utilization of the International Space Station (ISS) through at least 2020, (and likely for some years thereafter), there is an international need to define a concrete strategy and plan for the initial human exploration missions that will extend beyond Low Earth Orbit (LEO). The current long term objective of global human space exploration is eventual long duration presence of people on the Martian surface [1], [2]. Along the pathway between current activities in LEO and eventual Mars missions are a variety of preparatory exploration missions and intermediate goals. Over the last decade several different initial steps beyond LEO have been proposed. It is important to build international consensus on such a plan soon because future missions require near-term investments for new capabilities. Furthermore it is unlikely that any single nation can achieve an ambitious program on its own, and cooperation must begin before development resources are allocated.

A growing body of literature on proposals for human spaceflight missions beyond LEO is available. In August 2013 the International Space Exploration Coordination Group (ISECG) updated their Global Exploration Roadmap [1]. The ISECG roadmap provides a clear vision of the goals and objectives for human space exploration. It details a number of missions that are preparatory for eventual sustained presence of humans on the Martian surface. These missions represent incremental development of human spaceflight capabilities via asteroids, cis-lunar space, and the lunar surface. Most importantly the roadmap reflects an important cooperative relationship between several agencies that must work together to achieve any ambitious future exploration program. While this roadmap provides an important reference scenario to the space exploration community, it is non-binding and is not necessarily reflected by other stakeholders involved in future exploration planning. The ISECG roadmap encompasses a variety of space exploration strategies and destinations. A major limitation of the cooperative roadmapping activity is the inability to specify particular missions with specific international contributions.

In parallel to cooperative inter-agency work, multiple industry proposals for future missions have been published. One proposal, published at the 2013 International Astronautical Congress, is the result of a collaborative effort between the large space companies currently involved with the ISS [3]. While the ISECG roadmap provides a long-term series of possible missions to multiple destinations, the industry proposal focuses on a specific mission architecture for a station at the Earth-Moon L2 Lagrange point that benefits from existing industry capabilities and elements. Industry proposals benefit from deep knowledge of available elements and programmatic expectations for cost, schedule, and risk. Alongside other mission proposals from academia and non-profit organizations, there are a variety of possible options for future human exploration beyond LEO. However proposals for entirely different mission concepts are not often evaluated alongside each other with a common set of assumptions and consistent figures of merit. While architecturally many proposals may be compatible, or even synergistic in strategic development of space exploration infrastructure, there must be a decision to pursue a given architecture with appropriate resources allocated to do so.

Although it will be several years before plans enacted now will result in missions (in the mid to late 2020s), the development timescale is not long relative to previous human spaceflight programs. While the first agreement between the United States and Russia to combine their space station efforts was signed in 1993, Expedition 1 carrying the first crew onboard the ISS was not until 2000. The developments that must occur for future exploration missions beyond LEO present a wide range of technical and programmatic challenges that must be addressed throughout the coming years. These activities must begin with general agreement from partners on what the exploration objectives will be in that time frame and the exploration missions that will fulfill those objectives.

## 2. Study Goals

Given the multiple options available for future exploration programs, it is the overall objective of this study to evaluate different mission concepts for initial missions beyond LEO with a consistent framework. The scope for analysis is intended to be limited to feasible options. It is important to understand the long-term exploration pathways towards eventual humans on the Martian surface, however specific proposals considered are more focused on near-term architectures that build from current state of the art space systems and require a limited portfolio of new capabilities.

It is the intent of the authors to provide a comprehensive framework for the evaluation of mission alternatives in support of the formation of concrete plans for human exploration beyond LEO. While the authors attempt to evaluate the most relevant concepts in literature, it is intended that the framework itself will be useful in the coming years even if new concepts are published. The scope of the paper presented is limited to technical evaluation of mission concepts, however ongoing work is evaluating potential contributions from different international partners.

## 3. Evaluation Framework and Scope

In order to obtain quantifiable metrics for comparison of various exploration options, an analysis framework has been developed that allows for technical assessment as well as policy assessment in relation to potential contributing partners. Once these metrics are obtained an informed, objective assessment of disparate and similar exploration alternatives can be performed. The overall analysis framework is shown in Figure 1.

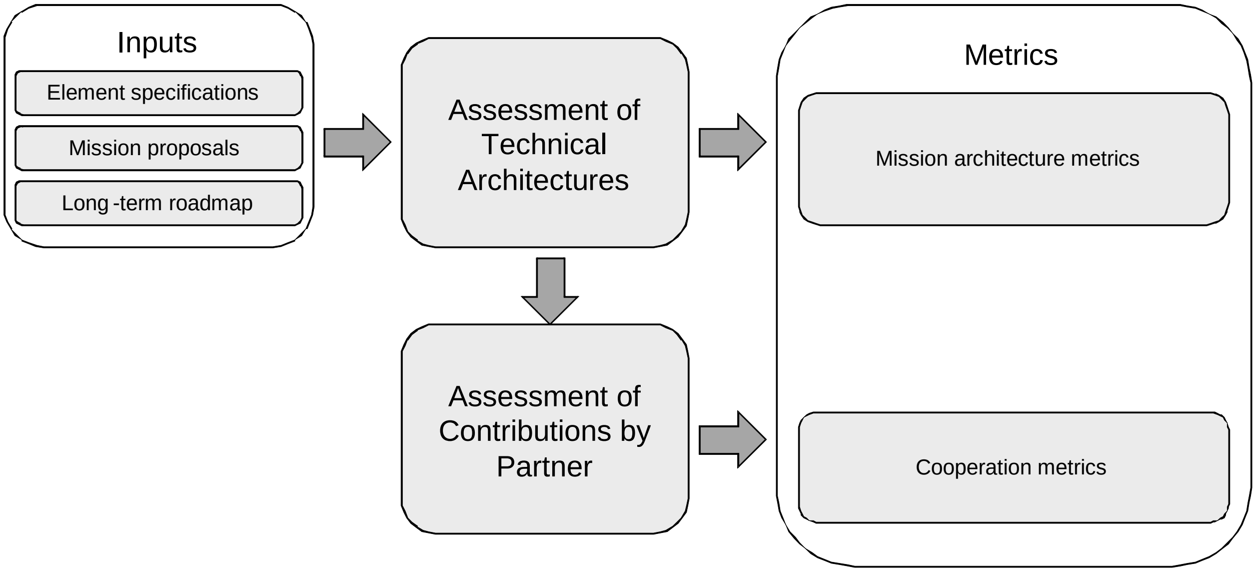

**Figure 1 Analysis framework for comparison of exploration options**

The analysis framework has been structured to provide evaluation of an extensive set of realistic, viable mission alternatives beyond LEO. The first step in the framework is to provide a set of mission characteristics that define the mission elements. In the analysis presented, these elements are obtained with deference to recent mission studies, mission proposals, and the ISECG roadmap for each of the exploration options. The ISECG roadmap also provides a common end-goal for the exploration options: long-term presence on the Martian surface. While the mission rationales and architecture are to be preserved as close as possible to their published forms, the presented analysis is based on independently developed models for habitats and propulsion systems. The goal of the modeling activity is to capture the strategic aspects of each proposed mission, while evaluating them with a consistent set of assumptions about technology performance and system requirements. These models are based in part on physical analyses as well as historical regressions. Models were developed for each of the following elements that could be used in any of the potential mission alternatives: crew vehicle, in-space habitats, cargo and logistics, chemical and electric propulsion stages, and exploration payloads.

After reviewing literature produced by agencies, industry, and academia over the last several years there are a finite number of well-defined concepts for human missions. Furthermore there is consensus that human spaceflight activities beyond LEO are generally seen as incremental developments towards eventual human Mars surface missions. Beginning with current capabilities and ending with sustainable

Mars surface missions we narrow strategic options to those that are realistically feasible as the next steps beyond the ISS and beyond LEO shown in Table 1.

**Table 1 Mission Alternatives**

| Current | Near-Term | Mid-Term | Goal |
|---|---|---|---|
| ISS | Technology Development (no crew) | Permanent Lagrange Infrastructure | Long Duration Presence on Mars |
|  | LEO Activities | Moon Surface |  |
|  | GEO Servicing | High delta-V Asteroid Rendezvous |  |
|  | Cis-Lunar Lagrange Station | Mars Orbit |  |
|  | Asteroid Retrieval | Mars Phobos/Deimos Mission |  |
|  | Low delta-V Asteroid Rendezvous |  |  |
|  | Mars Flyby |  |  |

The current ISECG roadmap's preferred path is also identified within the potential mission alternatives shown in Table 1: ISS → Asteroid Retrieval → Cis-Lunar Lagrange Station → Moon Surface → Long Duration Presence on Mars.

While the study considers the entire roadmap to Mars important, analysis emphasis is placed on the near-term options. While many metrics can be defined in evaluation of missions, there are three primary categories of metrics to consider related to the mission benefits, programmatic considerations, and robustness or flexibility to program uncertainties. Although not presented in this paper, an evaluation of policy implications is ongoing. This analysis includes three metrics that must be evaluated for each potential partner once specific contribution scenarios are enumerated. Metrics evaluated for each partner will relate to evaluation of individual affordability, development risk, and stakeholder satisfaction in the context of different actor contributions.

The technical metrics are evaluated for each mission using a multidisciplinary system analysis approach. The benefits category measures the return to science, exploration, and other stakeholder communities as enumerated by the ISECG Exploration Objectives [1]. Note that there is not a one-to-one mapping of ISECG objectives to the enumerated benefits proxy metrics, however some of the related objectives are provided in Table 2. The programmatics category relates to aspects such as the overall cost, schedule, and evaluation of risk. The third technical area evaluates robustness or flexibility, which is related to the program's ability to provide value in the face of uncertain and changing objectives or cost and schedule scenarios. Proxy metrics must be distinguishing and measureable at the high level of abstraction considered. All proxy metrics for the technical mission evaluation are provided in Table 2.

**Table 2 Proxy metrics for architecture evaluation**

| Categories | Proxy Metrics |
|---|---|
| **Benefits**<br>***(ISECG Objectives in italics)*** | Number of new technologies<br>*(Develop exploration technology, stimulate economic expansion)* |
| | Frequency of mission opportunities<br>*(Engage the public)* |
| | Demonstration of exploration firsts<br>*(Engage the public)* |
| | Operation in new orbital environments<br>*(Extend Human Presence, Perform science to enable human exploration)* |
| | Operation at a rocky body<br>*(Enhance Earth Safety, Extend Human Presence)* |
| | Development of capabilities for Mars missions<br>*(Develop exploration technology)* |
| **Programmatics** | Initial Mass in Low Earth Orbit (IMLEO) |
| | Number of development projects |
| | Number of elements to operate |
| | Expected required spending profile |
| | System readiness level |
| | Hazard enumeration and mitigation |
| **Robustness/ Flexibility** | Number of elements common to other missions<br>(in case the mission objective changes) |
| | Frequency of mission opportunities |

## 4. Overview of Evaluated Concepts

For each of the exploration options an overall mission concept description is provided as taken from the referenced materials. Each mission has been re-evaluated with a consistent set of assumptions related to propulsion and habitat sizing while specific required payloads are taken from the reference missions. Major assumption changes are noted where departures from the reference materials are significant. All missions are assumed to begin in LEO for this initial analysis. The reason for this assumption is to separate this evaluation from issues related to specific launch vehicles. The common assumptions used to evaluate each mission are provided in Table 3.

**Table 3 Assumptions for mission evaluation (Isp indicates specific impulse)**

| Assumption | Value |
|---|---|
| **Initial departure orbit** | 370 km circular orbit |
| **Crew vehicle mass** | 9000 kg |
| **Storable hypergol performance** | $I_{sp}$: 325 s |

| | |
|---|---|
| **(for the service module)** | structure mass ratio: 0.24 |
| **Liquid oxygen/liquid hydrogen performance (no improvement in storage capability)** | $I_{sp}$: 460 s<br>structure mass ratio: 0.11 |
| **Electric propulsion performance** | $I_{sp}$: 3000 s<br>tank mass ratio: 0.05 |

Reference architectures for a given mission concept were selected with preference for near-term initial operating capability. For example, several references describe trades between existing chemical and more advanced solar electric propulsion technologies. For such a propulsion tradeoff, selected reference missions favor chemical propulsion if the mission architecture does not require the more advanced solar electric capability in initial operations.

## 4.1. Technology Development (No Crew)

The technology development option would indicate an intentional end of human spaceflight activities until some predetermined criteria are met for advances in human exploration technology. This strategy would reallocate funds currently spent on spaceflight operations and drastically accelerate technology development projects related to deep space habitation such as low-mass radiation shielding and high efficiency propulsion such as nuclear thermal rockets or long duration cryogenic propellant storage. It is unlikely that pure technology development would provide a sustainable strategy as the lack of exploration firsts, scientific achievements, or general media that foster support for human spaceflight would all cease. It is difficult for the authors to imagine sustained funding for human spaceflight technology developments that do not return incremental human spaceflight achievements. Furthermore, once a human spaceflight program was pursued again there would be drastic loss of institutional knowledge in the required operations.

## 4.2. LEO Activities

There are several references to LEO missions beyond planned ISS activities. This concept could encompass re-use or reconfiguration of ISS modules [4], extending the lifetime of assets already in orbit, or using new elements in similar LEO orbits. These activities would support a variety of customers. Government platforms could be used to further support development of commercial activities. Another option would be to advance the envelope on human health research analog missions in duration and stress testing of life support systems and crew health procedures. Analog missions could also be used to develop and test operations related to logistics and communications protocols as they would relate to isolated deep space missions. Many of these applications are described by Raftery and Hoffman [5]. While this option represents a range of possible activities for future LEO operations, minimal initial operating capability requires little more than a habitable volume in LEO either physically taken from the ISS or based on a derivative design of existing capability.

## 4.3. GEO Servicing

Various types of geostationary orbit servicing missions have been proposed for a long time. The repeated servicing missions of the Hubble Space Telescope demonstrated the effective use of astronauts in fixing, servicing, and upgrading a large space satellite. The reference mission used is from a NASA architecture analysis team [6]. Geostationary satellites are primarily used as Earth-centered communications and observation platforms. While the rationale for sending humans to service spacecraft in geostationary orbit may be technically sound, this type of mission would not align well with the vision, goals, and objectives described by space agencies in the last several years. In particular it is important to note that since the 1986 Challenger accident, the US human spaceflight community has had a particular aversion to commercial space activities and explicitly reduced the application of human spaceflight capabilities to commercial needs [7].

**Table 4 GEO servicing mission concept**

| **Concept Overview** | |
|---|---|
| **Destination** | Geostationary Orbit |
| **Crew** | 3 |
| **Duration (days)** | 11 days |
| **Elements** | **Function** |
| **Crew vehicle** | Habitation for mission duration |
| **EVA equipment** | Servicing payload |
| **LH2 propulsion stage** | LEO departure, GEO arrival (4.4 km/s) |
| **Crew vehicle service module** | GEO departure (1.4 km/s) |

## 4.4. Cis-Lunar Lagrange Station

The concept for a cis-Lunar station at either the Earth-Moon Lagrange 1 or 2 points has many benefits. The Lagrange infrastructure would most likely be stationed in a semi-stable halo orbit about one of these points, offering a location to operate beyond LEO with moderate delta-v required for access and station keeping. The reasons for pursuing a Lagrange point station include the flexibility in mission opportunities and durations. It offers a location outside of the Earth’s Van Allen belts to develop all the preparatory biological research and engineering related to the microgravity, radiation, and life support systems required for long duration human spaceflight. The Lagrange points also offer a location for a logistics platform that provides relatively low delta-v access to and from the entire lunar surface. Finally, the station could provide a location to stage further deep space missions or a place for convenient telerobotic operation on the lunar surface.

Multiple Lagrange point mission concepts have been proposed ranging from short duration 11 day missions, to 6 month or full year mission profiles [8], [3]. The concept of the station would most likely maintain a semi-autonomous predeployed habitat that has periodic crew visits. A typical reference mission used has a crew of four for a 30 day stay, however capability could be scaled down or up as necessary due to program cost and schedule constraints. Deployment of the habitat is considered part of the mission analysis as it is required for initial operating capability.

**Table 5 Cis-Lunar Lagrange station mission concept**

| **Concept Overview** | |
|---|---|
| **Destination** | EML1 or EML2 |
| **Crew** | 4 |
| **Duration (days)** | 30 days |
| **Elements** | **Function** |
| **Crew vehicle** | Crew launch, outbound, inbound, re-entry |

| | |
|---|---|
| **Habitat** | Semi-autonomous deep-space hab (multiple mission use) |
| **EVA equipment** | Exploration payload |
| **LH2 propulsion stage** | LEO departure (4 km/s) |
| **Crew vehicle service module** | Lagrange arrival, trans-Earth injection (1 km/s) |

## 4.5. Asteroid Retrieval

The Asteroid Retrieval Mission (ARM) was recently made popular by a Keck Institute study on the feasibility of such a mission [9]. The overall concept is for an initial robotic retrieval mission that enables future human exploration. A solar-electric spacecraft will capture a small asteroid (or piece of one) and returns it to cis-lunar space (a lunar distant retrograde orbit). Once there, it will be provide a planetary surface that can be regularly visited by people with lower delta-v penalty than any other rocky body. Recently NASA has engaged in a concerted architecture design effort to reduce some of the uncertainties of the mission implementation [10], [11]. While the initial operations of this mission are entirely robotic, they are motivated by human exploration needs. There may be some science and planetary defense rationale for the concept, but the architecture decisions are primarily driven by human space exploration concerns. Compared to the other proposed concepts, it will take at least 5 to 10 years from launch of the robotic mission before any human missions would take place. It is also worth noting that the propulsion sizing of the robotic mission is very sensitive to asteroid trajectories and masses both of which have an extremely large uncertainty. As described in the reference materials, it is assumed that the retrieval spacecraft payload has a mass of approximately five metric tons. Pursuing this concept will require a concerted search effort to characterize small asteroids to find good target candidates. Since the goal of this study is to evaluate concepts for operational human spaceflight capability, the scope of the reference considered here includes both the robotic retrieval mission and an initial human flight to explore the asteroid in a Lunar distant retrograde orbit.

**Table 6 Asteroid retrieval mission concept**

| **Concept Overview** | |
|---|---|
| **Destination** | Retrieved Asteroid |
| **Crew** | Retrieval: 0<br>Crew: 2 |
| **Duration (days)** | Retrieval: 5-10 years<br>Crew: 21 days |
| **Elements** | **Function** |
| **Robotic retrieval payload** | Characterization and capture of a 1300 mt asteroid |
| **Solar electric propulsion** | Earth departure and rendezvous with asteroid, return to lunar distant retrograde orbit (9.4 km/s) |
| **Crew vehicle** | Crew launch, EVA egress, sample storage, re-entry |
| **EVA equipment** | Asteroid exploration payload |
| **LH2 propulsion stage** | LEO departure (4 km/s) |
| **Crew vehicle service module** | Retrograde orbit arrival, trans-Earth injection (1.5 km/s) |

## 4.6. Low Delta-V Asteroid Rendezvous

There are a variety of concepts for an asteroid rendezvous mission. The performance of the mission is particularly sensitive to mission opportunities and associated delta-v. Finding an architecture that will allow for multiple mission opportunities but does not rely on extremely large delta-v is difficult. As a result non-traditional propulsion methods may be necessary. For the presented analysis only liquid hydrogen (without advanced boil-off control) is considered. Sample architectures are based on the ISECG International Architecture Working Group (IAWG) [12], an independent study conducted by SpaceWorks Enterprises [13], and a third study conducted by Lockheed-Martin [14]. All these references identify targets with C3 in the range of 1-5 $km^2/s^2$ however there is a larger range of delta-v requirements for arrival and departure maneuvers to and from the asteroid. While the IAWG reference is more optimistic the other references specify in the range of 2km/s for asteroid arrival and departure maneuvers.

**Table 7 Low delta-V asteroid rendezvous mission concept**

| Concept Overview | |
|---|---|
| **Destination** | Asteroid Rendezvous |
| **Crew** | 4 |
| **Duration (days)** | 370 days |
| **Elements** | **Function** |
| **Crew vehicle** | Crew launch, re-entry |
| **Habitat** | Long duration deep-space habitat |
| **EVA equipment** | Asteroid exploration payload |
| **LH2 propulsion stage** | LEO departure (3.3 km/s) |
| **Crew vehicle service module** | trans-Earth injection (1.5 km/s) |

## 4.7. Mars Flyby

The Mars Flyby reference mission is based on the architecture described by the Inspiration Mars Foundation [15], [16]. This mission provides two astronauts with 10 hours observation time within 100,000 km of Mars. This is expected to be achieved for a particularly optimal mission opportunity in 2018 that only occurs every 15 years. The overall concept of this mission is a demonstration of advanced capability as the returns are purely in incremental system development (as opposed to scientific return). The proposal accepts extremely high development risk for the benefit of actually putting humans in the Mars vicinity.

While the long-duration habitat sizing parametric used for the presented analysis [17] suggests a larger specific volume per crew is required for this mission, the Inspiration Mars reference assumes a reduced habitable volume per person, with the expectation that this increases mission risk and relaxes current standards for crew comfort. In terms of overall launch mass assessment, the Inspiration Mars study assumes the capability for the dual-use upper stage of the NASA Space Launch System. This indicates the upper stage rocket is then re-used for Earth departure. However in this analysis all missions are analyzed with reference to an initial starting orbit in LEO so as to remain independent of launch vehicle analysis.

Table 8 Mars flyby mission concept

| Concept Overview | |
|---|---|
| **Destination** | Mars (flyby) |
| **Crew** | 2 |
| **Duration (days)** | 500 days |
| **Elements** | **Function** |
| **Crew vehicle** | Launch and re-entry |
| **Habitat** | Long duration deep-space habitat |
| **LH2 propulsion stage** | Earth departure (4.9 km/s) |

## 4.8. Compiled Mission Evaluations

One output of the mission evaluations is the metric of initial mass in low-Earth orbit (IMLEO). Given the early state of mission architecture definition for all the options, and the fact that some concepts may not stage in LEO, this metric does not provide a precise discriminating criteria. However it provides a rough comparison of mass required to execute each of the concepts. Figure 2 provides the relative calculated values.

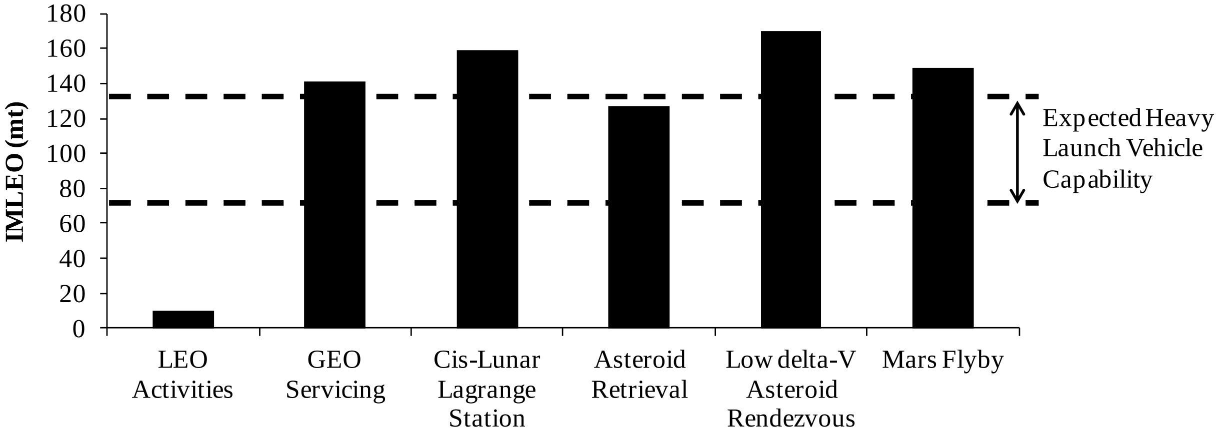

Figure 2 IMLEO for the mission concepts

Aside from pursuing possible activities in LEO, all of the mission concepts are likely to require more than one single heavy launch vehicle, at minimum providing a separate launch of crew. Whether any of the missions requires two or three separate launches, is as much a function of heavy launch vehicle development in the coming years as it is related to the required refining of mission concepts. Given these uncertainties, the IMLEO or number of launches required for initial operating capability is not a primary distinguishing factor between the missions at this point in time.

There are too many proxy metrics to practically visualize the multi-dimensional attributes of all the proposed options. However one visualization capturing the aggregated benefits of the mission, the system readiness, and the relative levels of operational risk is provided in Figure 3. Aggregated benefits are measured by relative comparison to current ISS activities as provided in Appendix A. The system readiness is a relative measure of development risk based on the Technology Readiness Levels (TRL) of each required mission element (provided in Appendix C). The operational risk measures are adapted from the approach provided by Leveson [18] where hazardous situations are enumerated through all mission segments and a hierarchy of loss severity and mitigability parameters are used to compare the relative operational risk (Appendix B). Figure 3 demonstrates a tradeoff between system readiness and risk metrics and the benefits of pursuing the different mission concepts.

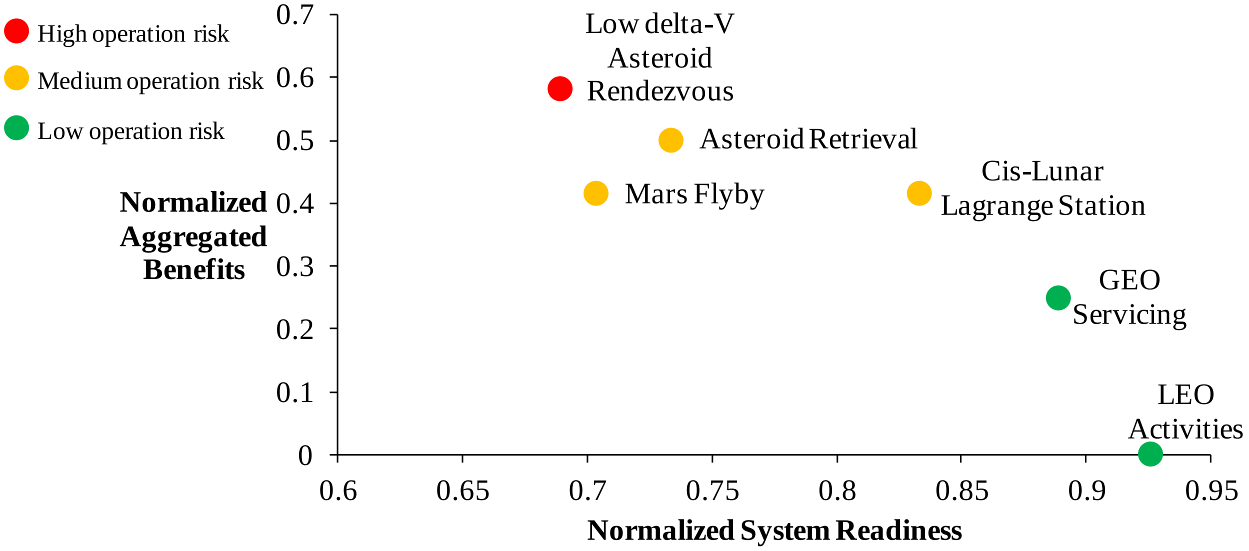

**Figure 3 Visualization of benefits, system readiness, and operational risk of the concepts**

The concepts presented in this analysis all provide a variety of benefits and challenges. Pursuing a successful human exploration program will require balancing these issues while implementing a program that returns value to all the participating actors. In preparation for future analysis on the potential contributions of each partner, a brief summary of the particular benefits and challenges associated with each option are presented.

*Technology Development (no crew)*

A technology development program that allocates human spaceflight operations funds towards exploration technology is far more likely to bring about a revolutionary game-changing increase in exploration capability. However with no incremental development to engage the public and government stakeholders, it is unlikely that a technology program on its own will foster enough support to remain a sustainable enterprise. Astronaut flights are seen as an essential part of the value proposition of human space exploration.

*LEO Activities*

Continued activities in LEO represent the bare minimum for continuing a human spaceflight program, without development of increased capabilities. Exploration preparation activities in LEO allow for some analog testing of deep-space operations but will be limited and may not be perceived to fulfill the "exploration firsts" that foster program support.

*GEO Servicing*

Pursuing GEO servicing capability may provide significant commercial benefits, however accepting human spaceflight risk for commercial services is out of alignment with ongoing national policies. GEO missions represent a small increment in capabilities, although it is not necessarily on a path towards future exploration activities in deep-space.

### *Cis-Lunar Lagrange Station*

A Lagrange station provides a flexible platform for missions of increasing duration and scope. It is a unique location that provides the ability to develop deep-space operations to the Moon, Asteroids, and Mars with minimum development required for initial operating capability. It is uncertain if a Lagrange station will be seen by the public as an exploration first.

### *Asteroid Retrieval*

The asteroid retrieval mission will provide lasting value in the development of advanced technology, and the creation of an otherwise inaccessible asset in the cis-lunar region. Implementing this mission will not provide a human spaceflight milestone for five to ten years from launch and the feasibility of the mission is sensitive to parameters of asteroid characterization that may not be refined for some time.

### *Low delta-V Asteroid Rendezvous*

The asteroid rendezvous mission provides the experience of humans operating in deep space, and the extra-vehicular activity of going to a rocky-destination. Compared to the other missions considered, the complexity of the asteroid rendezvous mission requires significant development effort before initial operations. As with the asteroid retrieval mission, the rendezvous has significant uncertainty of the target's parameters and may have infrequent mission opportunities.

### *Mars Flyby*

The motivation behind the Mars Flyby mission is an inspirational demonstration of capability by satisfying the exploration milestone of "humans in the vicinity of Mars." However the concept is reliant on a very specific near-term mission opportunity with little flexibility if the opportunity is missed. The mission will require accelerated development and likely increased budgets due to the hard schedule constraint.

## 5. Ongoing Analysis

The purpose of this paper is to explain the scope and procedure for the ongoing study. Mission concepts continue to be refined and validated against current industry assumptions on capabilities and requirements. Separate analysis is ongoing on two major technical aspects that have been left out of this paper. Assessment of ISS transition activities and the interface between missions and required launch vehicle capabilities are both critical to understanding specific contributions from different international actors.

Towards the goal of identifying practical scenarios for exploration beyond LEO, the next major phase of analysis will focus on evaluating international contributions to different reference missions. This exercise begins with enumeration of participating nations' competencies and national goals. The analysis will focus on identifying mission contributions that provide robust technical architecture while providing value to the non-space advocate political decision makers in those nations.

The policy metrics will be evaluated for each collaboration required by the specific actors to complete a mission. The first of these metrics is affordability, which is a matching of the partners' available budget to the expect budget required by the partner to complete the mission. Development risk is the aggregated readiness of each actor's contributions and their preparedness to accomplish what is expected of them. Finally, stakeholder satisfaction is the satisfaction of the national government and the industrial goals set forth by each participating actor.

## Appendix A – Benefits Metrics

The benefits metrics are evaluated with a simple grading scheme in comparison to ISS activities.

| Score | Comparison to ISS |
|---:|---|
| -2 | Significant loss of benefit in comparison to ISS |
| -1 | Moderate loss of benefit in comparison to ISS |
| 0 | No change from ISS |
| 1 | Moderate increase in benefit compared to ISS |
| 2 | Significant increase in benefit compared to ISS |

**Table A . 1 Benefits scoring criteria**

| | Tech | LEO | GEO | Lagrange | Aster. | Aster. | Mars |
|---|---:|---:|---:|---:|---:|---:|---:|
| **Measurable Metrics** | **Dev** | **Station** | **Service** | **Station** | **Retr.** | **Rend.** | **Flyby** |
| # new technologies | 2 | 0 | 1 | 1 | 2 | 2 | 1 |
| mission frequency | -2 | 0 | 0 | 0 | -2 | -2 | -2 |
| demonstrate firsts | -2 | 0 | 1 | 1 | 2 | 2 | 2 |
| pursue an asteroid/rocky surface | -2 | 0 | 0 | 0 | 2 | 2 | 0 |
| operate in new space environment | -2 | 0 | 1 | 1 | 1 | 2 | 2 |
| Mars exploration prep activities | 0 | 0 | 0 | 2 | 1 | 1 | 2 |

**Table A . 2 Benefits evaluation**

## Appendix B – Evaluation of Operational Risk

Hazard anaylsis is adapted from [18]. Hazards represent a system state that can result in loss. Losses represent exponentially increasing categories of severity and so are graded as such. Mitigability is based on a hierarchy of hazard avoidance. The scores are linearly increasing with the less desirable solutions. Final relative operational risk scores are taken as the sum of the product of each hazards severity and mitigability scores.

| Score | Severity of Loss |
|:---:|---|
| 0 | Not applicable |
| 1 | Loss of data |
| 2 | Damage or reduced capability |
| 4 | loss of mission or loss of infrastructure |
| 8 | Injury or loss of life |

**Table B . 1 Severity of loss criteria scores (exponentially increasing)**

| **Hazard Severity Scores** | **Tech** | **LEO** | **GEO** | **Lagrange** | **Aster.** | **Aster.** | **Mars** |
|---|---|---|---|---|---|---|---|
| **Hazards** | **Dev** | **Station** | **Service** | **Station** | **Retr.** | **Rend.** | **Flyby** |
| inability to communicate | 0 | 2 | 4 | 4 | 4 | 8 | 8 |
| unable to sustain life | 0 | 8 | 8 | 8 | 8 | 8 | 8 |
| contamination of samples | 0 | 0 | 0 | 0 | 1 | 1 | 0 |
| inability to dock components | 0 | 2 | 2 | 2 | 2 | 4 | 4 |
| inability to rendezvous with target | 0 | 0 | 4 | 4 | 4 | 4 | 4 |
| incorrect propulsive maneuver | 0 | 2 | 4 | 4 | 4 | 8 | 8 |
| unable to return from EVA | 0 | 8 | 8 | 8 | 8 | 8 | 0 |

**Table B . 2 Hazard severity evaluated scores**

| **Score** | **Mitigability** |
|---|---|
| 1 | Not applicable, eliminated by architectural design |
| 2 | Reduction/prevention of hazard via alternative operations, increased control authority |
| 3 | Control of hazard or accident through redundancy, safety margins, abort options |
| 4 | Recovery- hazard occurs, loss is minimized |

**Table B . 3 Mitigability criteria scores**

| **Hazard Mitigation Scores** | **Tech** | **LEO** | **GEO** | **Lagrange** | **Aster.** | **Aster.** | **Mars** |
|---|---|---|---|---|---|---|---|
| **Hazards** | **Dev** | **Station** | **Service** | **Station** | **Retr.** | **Rend.** | **Flyby** |
| inability to communicate | 1 | 1 | 2 | 3 | 3 | 4 | 4 |
| unable to sustain life | 1 | 2 | 3 | 3 | 3 | 4 | 4 |
| contamination of samples | 1 | 1 | 1 | 1 | 3 | 3 | 1 |
| inability to dock components | 1 | 2 | 3 | 3 | 3 | 3 | 3 |
| inability to rendezvous with target | 1 | 1 | 3 | 3 | 3 | 3 | 1 |
| incorrect propulsive maneuver | 1 | 1 | 2 | 2 | 2 | 4 | 4 |
| unable to return from EVA | 1 | 2 | 3 | 3 | 3 | 4 | 1 |

**Table B . 4 Hazard mitigability evaluated scores**

## Appendix C – Technology readiness of all capabilities

Following are the Technology Readiness Levels used to evaluate overall system readiness of each concept.

| | | **TRL** |
|---|---|---|
| **Crew Vehicle** | | |
| | 8 km/s | 9 |
| | 12 km/s | 7 |
| | 14 km/s | 6 |
| **In-Space habitat** | | |
| | <100 days | 8 |
| | >100 days | 6 |
| **Asteroid EVA/robotic payload** | | 4 |

| | | |
|---|---|---|
| **Solar Electric Propulsion** | | |
| | 50 kW | 7 |
| | 300 kW | 5 |
| **In-Space Chemical Propulsion** | | |
| | Hypergol (Service Module) | 8 |
| | LOX-LH2 | 7 |
| | LOX-LH2 Stored | 4 |

**Table C . 1 Technology Readiness Levels for required capabilities**

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