Acta Astronautica 139 (2017) 545–563

Contents lists available at ScienceDirect

Acta Astronautica

journal homepage: www.elsevier.com/locate/actaastro

Advanced concept for a crewed mission to the martian moons

Davide Conte [a,*], Marilena Di Carlo [b], Dorota Budzyń [c], Hayden Burgoyne [d], Dan Fries [e], Maria Grulich [f], Sören Heizmann [g], Henna Jethani [h], Mathieu Lapôtre [i], Tobias Roos [j], Encarnación Serrano Castillo [k], Marcel Schermann [f], Rhiannon Vieceli [l], Lee Wilson [i], Christopher Wynard [m]

[a] The Pennsylvania State University, 229 Hammond Bldg, University Park, PA 16802, USA
[b] University of Strathclyde, 16 Richmond St, Glasgow G1 1XQ, UK
[c] ESA/EAC, Linder Höhe, 51147 Cologne, Germany
[d] Analytical Space, Inc., Boston, MA, USA
[e] Georgia Institute of Technology, North Ave NW, Atlanta, GA 30332, USA
[f] ESA/ESTEC, Keplerlaan 1, 2201 AZ Noordwijk, The Netherlands
[g] Universität Stuttgart, Keplerstraße 7, 70174 Stuttgart, Germany
[h] Blue Origin, 21218 76th Ave S Kent, Washington 98032, USA
[i] California Institute of Technology, 1200 E California Blvd, Pasadena, CA 91125, USA
[j] Luleå University of Technology, Space Campus, 981 28 Kiruna, Sweden
[k] Università di Bologna, Via Fontanelle 40, 47121 Forlì (FC), Italy
[l] New Mexico Institute of Mining and Technology, 801 Leroy Pl, Socorro, NM 87801, USA
[m] NASA Johnson Space Center, 2101 E NASA Pkwy, Houston, TX 77058, USA

ARTICLE INFO

Keywords:
Mars
Phobos
Deimos
Human exploration
Martian moons
Mars mission

ABSTRACT

This paper presents the conceptual design of the IMaGInE (Innovative Mars Global International Exploration) Mission. The mission's objectives are to deliver a crew of four astronauts to the surface of Deimos and perform a robotic exploration mission to Phobos. Over the course of the 343 day mission during the years 2031 and 2032, the crew will perform surface excursions, technology demonstrations, In Situ Resource Utilization (ISRU) of the Martian moons, as well as site reconnaissance for future human exploration of Mars. This mission design makes use of an innovative hybrid propulsion concept (chemical and electric) to deliver a relatively low-mass reusable crewed spacecraft (approximately 100 mt) to *cis*-martian space. The crew makes use of torpor which minimizes launch payload mass. Green technologies are proposed as a stepping stone towards minimum environmental impact space access. The usage of beamed energy to power a grid of decentralized science stations is introduced, allowing for large scale characterization of the Martian environment. The low-thrust outbound and inbound trajectories are computed through the use of a direct method and a multiple shooting algorithm that considers various thrust and coast sequences to arrive at the final body with zero relative velocity. It is shown that the entire mission is rooted within the current NASA technology roadmap, ongoing scientific investments and feasible with an extrapolated NASA Budget. The presented mission won the 2016 Revolutionary Aerospace Systems Concepts - Academic Linkage (RASC-AL) competition.

1. Introduction

Space exploration enriches and strengthens humanity's future by bringing nations together for a common cause; it reveals knowledge, inspires and educates people, creates a global partnership, establishes a sustained human presence in the Solar System, and stimulates technical and commercial innovation on Earth. Sustainable space exploration is a challenge that no single nation can do on its own. To this aim, the Global Exploration Strategy, which was agreed on and published in May 2007 by fourteen space agencies, reflects a determination to explore our nearest neighbors: the Moon, asteroids, and Mars. In this framework, the Dream Team has been created with young engineering and applied science students from all over the world with a common goal, the IMaGInE Mission.

* Corresponding author.
E-mail address: davide.conte90@gmail.com (D. Conte).

http://dx.doi.org/10.1016/j.actaastro.2017.07.044
Received 21 February 2017; Received in revised form 12 June 2017; Accepted 28 July 2017
Available online 3 August 2017
0094-5765/

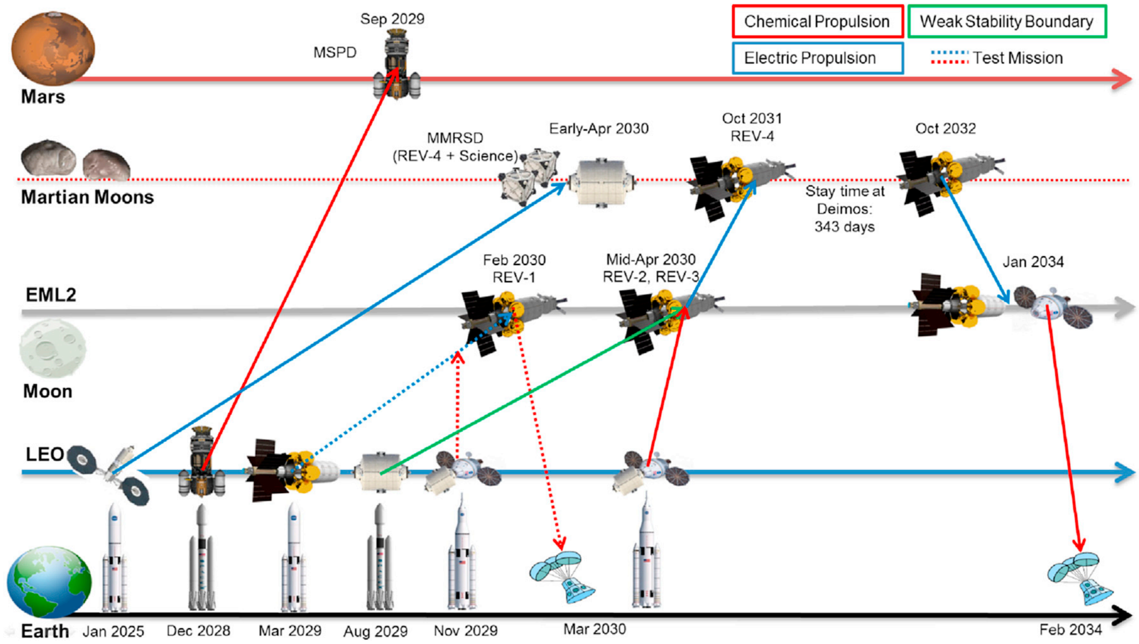

Fig. 1. IMaGInE's mission architecture.

Previous missions to any body outside of the Earth-Moon sphere of influence have been limited to robotic missions. While such systems are superior to humans in certain areas, they cannot yet compete with human adaptability and intuition. Moreover, human presence is required to initiate an outpost and lay the foundation for human settlement and utilization of other planetary bodies. Nonetheless, human-robot cooperation will most likely maximize chances of success of this endeavor and, thus, the overarching requirements of the mission as stated by RASC-AL are: "Given a 20 year timespan starting in 2015, and a flat total NASA budget of $16 Billion a year, derive an architecture that delivers a crew of four to the surface of either Phobos or Deimos (or both) for a minimum of 300 days total. Lay out a series of Mars moons surface excursions driven by science, technology demonstration, ISRU and possible future human exploration site reconnaissance on Mars. The architecture will convey a series of missions, both robotic and crewed, that will capture the exploration of one or both of the Martian moons, and must include tele-operating Mars surface assets (i.e., rovers, ISRU production plants, infrastructure cameras, small Mars flyers, deployment of power and support systems, etc.) while the astronauts are not conducting Extravehicular Activities (EVAs). All existing NASA programs will continue with some reduction in annual funding allowed (maintain at least 80% of their current budget), but the total NASA budget will remain flat, adjusting for inflation."

To fulfill these requirements the Dream Team started with a rigorous analysis of technology options, existing technology roadmaps, as well as astrodynamics, time and financial constraints. The result is a reusable architecture designed to ferry astronauts between planetary bodies, utilizing a chemical-electric hybrid propulsion concept and re-supply missions from Earth. During the entire mission duration a total mass of 340 mt is launched into Low-Earth-Orbit (LEO) with 6 launches including crewed, test, and resupply missions. Maximizing the synergies with existing programs, the total cost is well within the projected NASA budget, at B$32 (FY2016) over 20 years. While some of the proposed technologies do not exist yet at a sufficient Technology Readiness Level (TRL), it was made sure that they are realistic options with regard to funding, current interest and scheduling. A preliminary risk analysis shows that the presented architecture minimizes the risk of loss of crew and loss of mission.

Key aspects to minimize the overall launch mass, number of launches, and impact of the Earth-Mars transit on the crew are highly optimized trajectories, artificially induced torpor [1] of the crew and a development schedule accounting for sufficient tests of the life support system and the spacecraft as a whole. During the mission robotic exploration of Deimos, Phobos and Mars itself are conducted. Moreover, ISRU is tested, which is a key enabling technology for future deep space missions and anything resembling an interplanetary economy [2]. The science mission introduces a satellite based beamed power concept [3] which powers a grid of 54 decentralized science stations on Mars. This will allow for an unprecedented amount of detail in charting large parts of the Martian geography and environment over long periods of time. Thus, progressing our understanding of a different world as well as our efforts for colonization and extraction of resources.

2. Mission architecture and test mission

The IMaGInE mission will deliver a crew of four astronauts to the surface of Deimos and a robotic exploration mission to Phobos for approximately 343 days during the years 2031 and 2032. The crew will perform surface excursions, technology demonstrations, and In Situ Resource Utilization (ISRU) of the Martian moons as well as site reconnaissance for future human exploration of Mars. The IMaGInE Mission is divided into two main segments: the test mission and the main mission. The test mission first provides the opportunity to test all of the major subsystems combined together in space, thus raising the overall system's Technology Readiness Level (TRL). Additionally, the test mission substantially lowers the risk the main mission crew incurs and leaves the science portion of the mission untouched. A summary of IMaGInE's mission architecture is depicted in Fig. 1. This diagram also shows when and where supplies are replenished (REV-1, REV-2, REV-3, REV-4). The mission architecture is explained in detail in the following paragraph. Deimos was chosen over Phobos for the crewed portion of the mission primarily because of the moon's accessibility (lower ΔV requirements and better access to the subsurface), better illumination conditions, and longer communication passes to sites on Mars. The Phobos vs. Deimos trade study is shown in Table A.9.

The first launch takes the Martian Moons Resupply and Science Deployment (MMRSD) vehicle into Low Earth Orbit (LEO) in January 2025. This launch is performed using a NASA Space Launch System (SLS) Block 1B from the Kennedy Space Center (KSC) and consists of a Resupply Expendable Vehicle (REV) that is pre-deployed at Deimos to