H.O.P.E.
Humanity's Orbital Presence Endeavour

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ABSTRACT

H.O.P.E. Humanity's Orbital Presence Endeavour

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A next generation human rated space station program to be leveraged as an interplanetary communications network is proposed, following a conceptual approach to designing the system architecture to the system level and a simulation of the orbital mechanics of interest to an extension of the system. Systems engineering studies will be conducted to propose a possible solution for such a system, comparison studies will be conducted on different viable solutions throughout the project and development of the proposed architecture. Different solutions will be investigated and contingencies for each will also be explored. This study is being conducted as a response to the impending interplanetary role human beings are striving towards and the continued emergence of distributed space systems.

Acknowledgements

The sincerest thank you to,

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Table of Contents

List of Figures

List of Tables

Symbols

Symbol	Definition	Units
a	Semi-major axis	Km
d	distance	m
E	Total energy	
e	Eccentricity	
G	Universal gravitational constant	$km^3/kg*s^2$
h	Angular momentum	km^2/s
M	Mass (Larger body)	kg
m	Mass	kg
P	Orbital Period	seconds
r	Radius	m
T	Kinetic energy	
V	Potential energy	
v	Velocity	m/s
λ	RF Wavelength	Hz
ρ	Density	Kg/m^3
Acronyms		
AMSS	Autonomous Mission Support System	
ConOps	Concept of Operations	
DSN	Deep Space Network	
FCC	Federal Communications Commission	
GMAT	General Mission Analysis Tool	
HALO	Habitation and Logistics Outpost	
HLS	Human Landing System	
HOPE	Humanity's Orbital Presence Endeavour	
ISS	International Space Station	
KPP	Key Performance Parameters	
LEO	Low Earth Orbit	
LoS	Line of Sight	
MATLAB	Matrix Laboratory	
MOE	Measures of Effectiveness	
NASA	National Aeronautics and Space Administration	
NSN	Near Space Network	
PPE	Power and Propulsion Element	

Acronyms		
RF	Radio Frequency	
SEP	Solar Electric Propulsion	
STK	Systems Tool Kit	
Subscripts		
A_{ref}	Reference area	
a_{drag}	Drag acceleration	
C_D	Coefficient of drag	
F_D	Drag force	

1. Introduction

1.1 Motivation

In the last couple decades, humankind has been pushing the envelope in space exploration consistently, continuously, and exponentially with no signs of stopping. This pattern of progression yields increased knowledge of the universe; advancements in science and engineering; the continued commercialization of the space industry; and technological innovations that have benefited those on Earth; as seen for the human race.

These benefits and advancements are the primary enablers for increasing technological capabilities with respect to space exploration as a whole. With plans for a lunar gateway, striving towards a colonized Mars, and countless opportunities for innovative ideas to establish themselves in the current space economy, organizations/companies like NASA, Lockheed Martin, SpaceX, Blue Origin, and more are now able to push even harder in the human space race.

With these increased capabilities, researchers still rely on the current communications infrastructure that has been used since the 1970s, a solution that can be improved and should be to meet the impending change in space exploration as shown in NASA's 2015 Audit of the DSN [1]. To match the technological advancements, a sustained human presence at adjacent bodies of interest to the Earth and beyond is an inevitable future that will slowly become more and more feasible as time passes. As humans begin participating in longer duration missions in space, at destinations further and further away, and with distributed space systems on the rise, a communications and gateway infrastructure throughout the universe will be an immeasurable asset to the explorers of the new frontier.

Figure 1.1 NASA Lunar Gateway illustration [2]

1.2 Literature Review

As this is a highly complex, multifaceted design problem, this review will explore the different areas of research that are considered critical or of importance to the implementation of the proposed design solution. Although they are not directly researching the proposed problem, they are highly relevant for the problem field. This literature review will attempt to cover the relevant challenges that have been identified and tackled by other researchers in their respective fields. It is important to note there are only a handful of existing systems that could be considered similar, the Lunar Gateway and the International Space Station will be considered here with the ISS as the only system that is currently in operation.

1.2.1 International Space Station as a Steppingstone

The International Space Station is just that, an international collaboration of a manned Earth based space station to carry out science and exploration that is not possible on Earth. The ISS program holds decades of knowledge and is the first steppingstone in the pursuit of an interplanetary human presence. Containing an indispensable number of lessons learned that will carry forward with the Artemis program, Mars habitation, and in extension any other interplanetary exploration efforts as discussed in Planetary Surface Operations and Utilization [3]. NASA is implementing processes to leverage lessons learned from ISS missions and operation to directly reduce risk and uncertainty for future Mars missions. Current operations and activities are deliberately aligned with enterprise level blueprint objectives as outlined by the administration. Some key considerations for a successor system to be aware of are discussed in [4]. As with any system that has been in operation for a significant amount of time, new considerations will arise that were not explicitly considered in the initial design. These uncertain characteristics are key to understanding long term reliability and robustness of a manned space station. [5] is the safety requirements document of the ISS, it is imperative to understand the key requirements that have led to the successful deployment and operation of the ISS to be able to understand how the next steps may be taken. A photo of the ISS is included in figure 1.2 for reference.

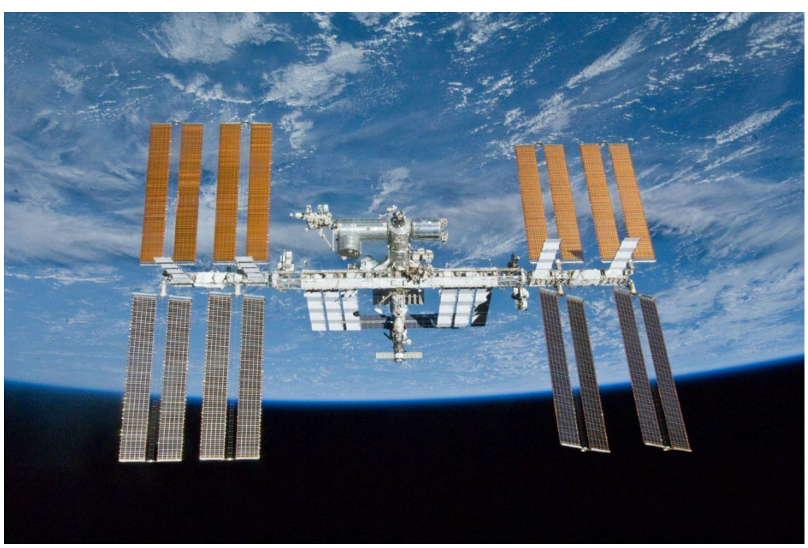

Figure 1.2 International Space Station [6]

1.2.2 Lunar Gateway as a Point of Departure

As part of the Artemis program, a lunar gateway is being developed. This gateway will act as a communications relay from the moon to Earth and will serve as a pit stop for certain missions to recollect themselves before heading to the moon and/or other bodies of interest. The gateway is not a system that is in place yet and is still undergoing development, but it will act as the exact point of departure for other interplanetary manned outposts. The gateway will function as a direct line to the moon, being able to communicate with missions taking place on or about the moon and relaying data or precious information back to the Earth [7]. The gateway will serve as the first step to an interplanetary communications network, containing communications subsystems to enable S-band, X-band, and Ka-band uplink and downlink through NASA's DSN and NSN. The communications architecture is depicted in figure 1.3 below.

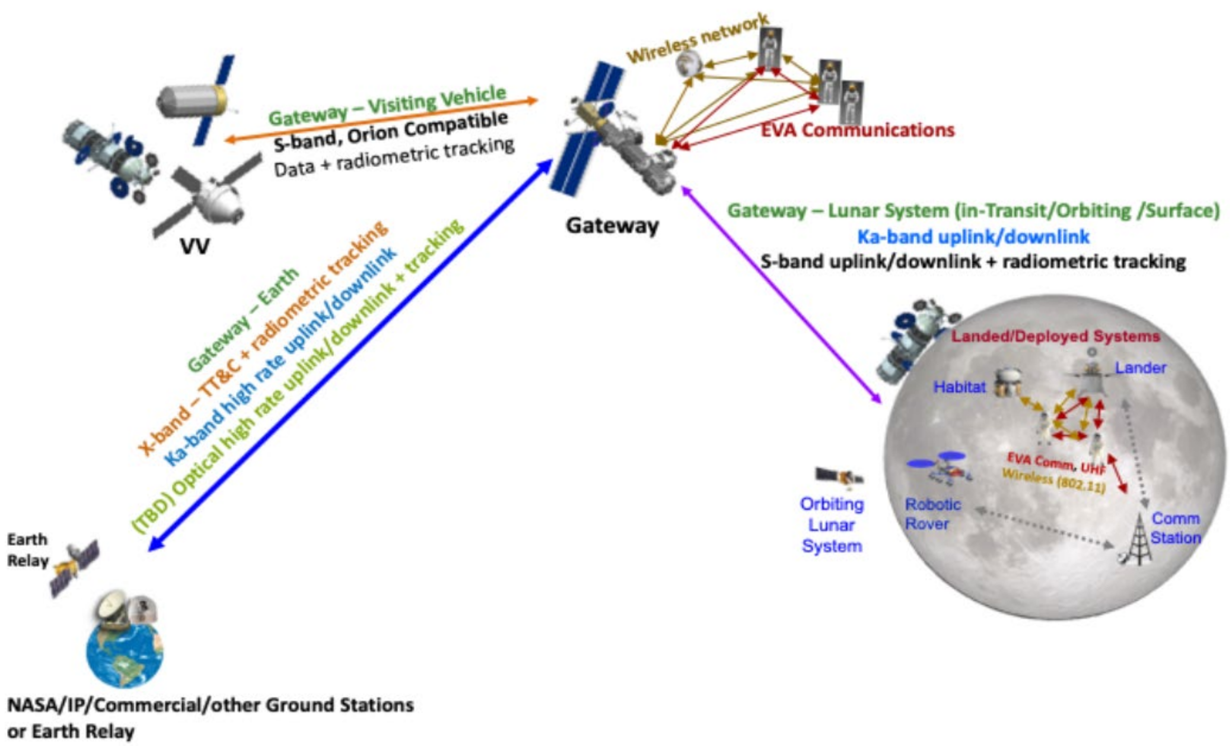

Figure 1.3 Gateway communications architecture [7]

This approach to incremental advancement of capabilities allows the gateway to serve as a building block for future space technologies. The Gateway will serve as a scientific lunar hub for missions and exploration but will be a precursor for Mars exploration and beyond [8-10]. Through the collaboration with international partners, and private industry, operation of the Gateway will foster further innovations to be applied in the future on larger scale efforts. The PPE module will house the main communications systems onboard, it will also provide power and propulsion to the Gateway. As the predecessor system, the requirements found in [11], will lend a hand to establishing the exact point of departure of the current state of the art and how that may be extended to future systems.

1.2.3 Interplanetary Mission Design Considerations

Interplanetary science and exploration have been studied since the earliest days of possibility, [12-14] are a series of references that have been chosen from three very different eras. Each reference has a focus on the possibilities of interplanetary science, manned and unmanned, starting with environmental considerations to the different possible science that could be conducted. [14] addresses the photovoltaic concerns any system in the deep space regime would need to consider, diving into what is possible and necessary for outer planetary missions in terms of power generation and radiation concerns for Jupiter. A proposed photovoltaic solution is shown in figure 1.4 for deep space applications. These considerations may be compared across all three time periods found in [12-13] to ensure a proper understanding of interplanetary mission design is established.

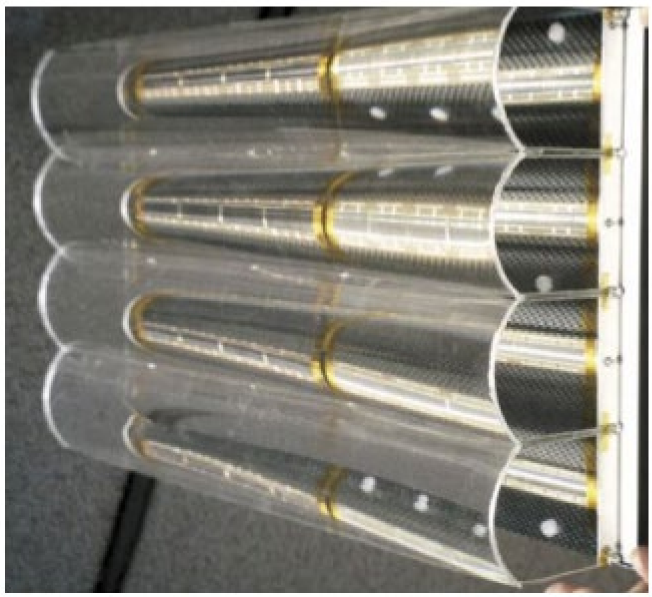

Figure 1.4 demonstration unit, stretched lens array for deep space applications [14]

1.2.4 Human Rated Space Systems

Unmanned spacecrafts have come a long way and are incredibly versatile, however there is no replacement for human intelligence and adaptability, which is why manned space stations has been a topic of research that continuously sees advancements in the limits of capability continuously. [15-19] are key areas of interest for the research conducted in this design study. [17] provides insight into the human error aspect of these manned space stations, and the analysis necessary to create a safe reliable solution, these solutions help mitigate problems at the system level rather than focusing on individuals, which is not something that can be designed for with ease. [18-19] cover some of the non-conventional forays into space structures and artificial gravity. Some key areas of research that did not seem to be as prevalent were interplanetary manned space stations, however these references have information relevant to any manned space system. As seen in figure 1.5, a project constraints box from [15] is shown and is an example of one of the higher-level balancing methodologies to consider for human rated space systems.

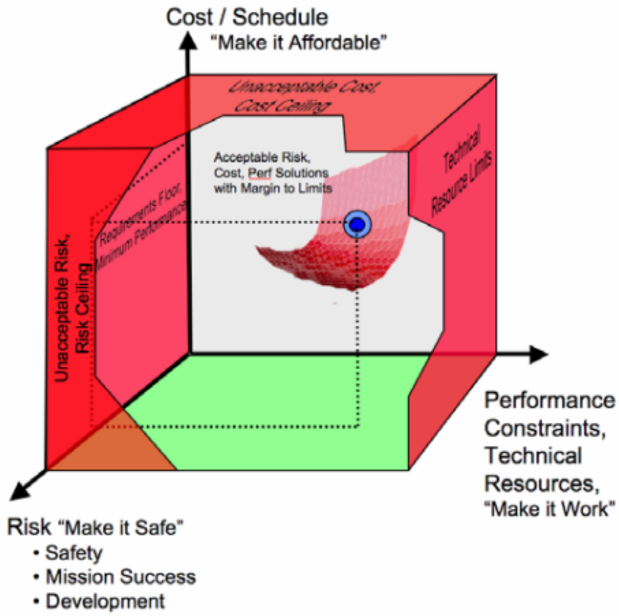

Figure 1.5 human rated system project constraint box diagram [15]

1.2.5 In-situ Resource Utilization

The references found in [20-26] delve into the research of in-situ resource utilization, spanning the ages since the early days of space flight. Although these are not the exact situations being proposed in this report, these papers lend considerable lessons to apply to any long-term deep space presence. [20,25] explores Saturn's moon Titan and the different considerations that should be taken when in-situ resource utilization is required in a deep space environment. These considerations lend their way to other bodies of interest and what may need to be investigated to leverage the environment for a sustained presence. [21-24] describe different proposed methods of large-scale manufacturing systems in space, these papers describe system concepts that are scalable and applicable to the state of the art available and how these large-scale programs may come to fruition. Figure 1.6 shows a depiction of one of the technologies proposed in [25], to be used for in-situ resource utilization, these kinds of technologies may be leveraged for other locations.

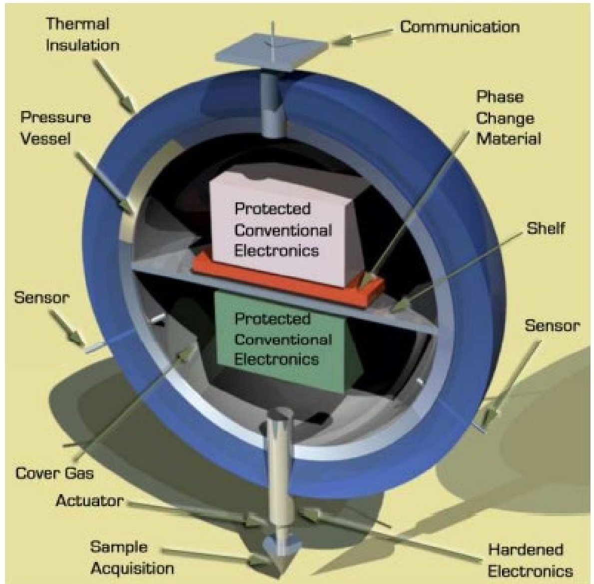

Figure 1.6 Venus in-situ mission pressure vessel [25]

1.3 Project Proposal

Design of the system architecture for a future space program for human rated space stations that will be used as a platform for galactic communications and exploration hubs at bodies of interest. This project will focus on the design and development of the generic program level distributed space system architecture, while focusing on a Jupiter centric outpost station to explore potential orbits of interest used for that implementation of the system. This system will be considered one of the steppingstones to achieving a permanent intragalactic multiplanetary human presence.

1.4 Methodology

Using systems engineering methodologies taught in SJSU and from outside references, a system architecture design study will be carried out to the system level of a future space station to be used as a multiplanetary human presence in the solar system. Digital engineering will be leveraged where possible, defining key features of this system and how the system will interact with its environment through the use of model-based systems engineering methodologies. Although it is important to note that a tailored approach to SysML conventions will be used in some of the diagrams, SysML convention will not be followed exactly as these graphics will be used to plainly demonstrate the concepts rather than demonstrate sysML conventions.

This project will adopt a set of tailored systems engineering methodologies to approach the system architecture development: from what is taught at SJSU, concepts from Wasson's System Engineering Process [27], Wiley's Systems Engineering Principles and Practice [28], and NASA's Systems Engineering Handbook [29] will serve as the primary resources utilized. Relevant trade studies will be conducted, and the architecture will be explored at the system level, defining key features of the system and how it will interact with its environment. The orbital mechanics and behavior will be modeled using NASA's Mission analysis tool GMAT, in conjunction with analytical hand calculations. Orbital analysis methodologies as taught in the advanced orbital mechanics course in SJSU coupled with the aid of outside references will be implemented.

The methodology can be described as a tailorable, modular approach that allows for extension and reduction in the development scope of the architecture. As shown in figure 1.7 below, a general flow of the adopted methodology has been modeled. The key to any successful architecture is translating desires and needs of the prospective system stakeholders into a solution where the system artifacts will satisfy the original needs. Architecting is an iterative and recursive process that is just one part of the development of a system.

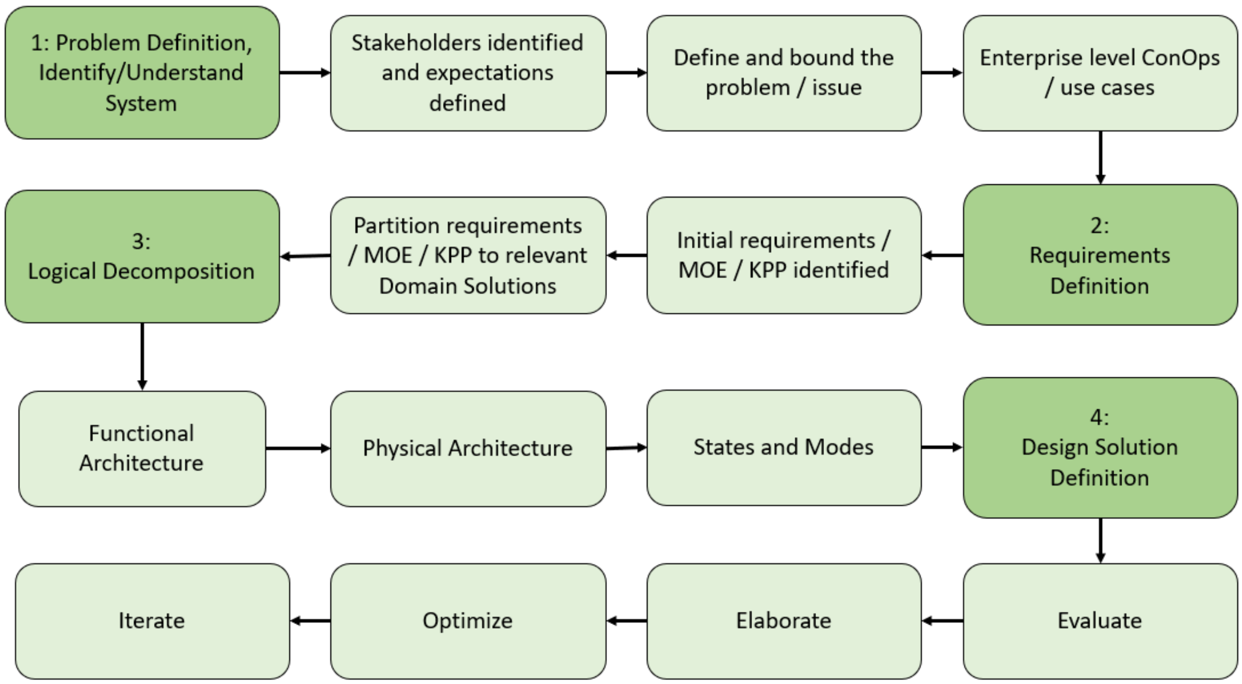

Figure 1.7 tailored methodology

2. Problem Definition

2.1 Points of Departure

2.1.1 Lunar Gateway

The Lunar Gateway reflects what will be considered a direct steppingstone for HOPE. The gateway is a lunar orbiting outpost station that will serve as a communications and explorations hub for humans in the near-Earth system and beyond. Allowing for ease of communications and enabling higher fidelity for immediate Moon and Mars science objectives. The Gateway will serve as a human rated habitat to support manned missions, science, and research objectives. These objectives include establishing a sustained human presence on the lunar surface, enabling Mars exploration, and pushing the envelope even further on what was built by the International Space Station.

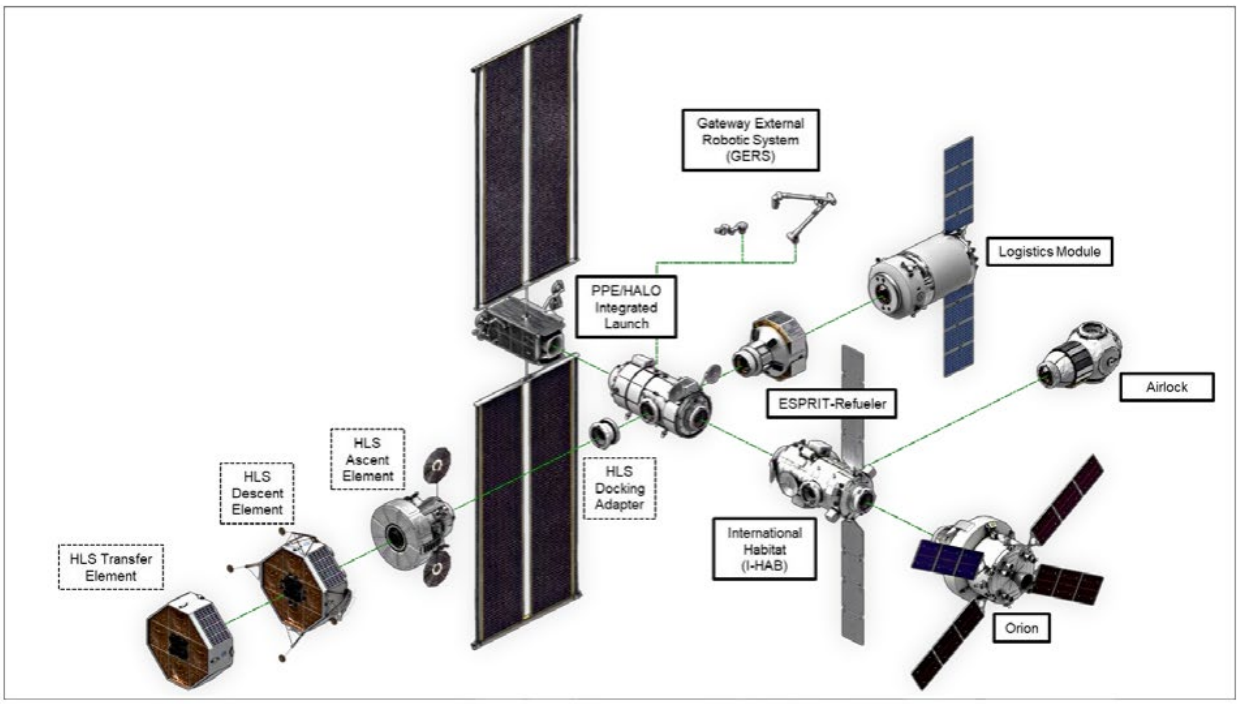

Figure 2.1 expanded view of the Lunar Gateway with optional configurations [30]

The Lunar Gateway will initially be composed of two major subsystems that in turn will be complex systems in their own right. The first element is the Power and Propulsion Element, referred to as the PPE, this can be seen in figure 2.1 above. The second element, also shown above, is the Habitation and Logistics Outpost also known as the HALO. The PPE will be responsible for housing a Solar Electric Propulsion system (SEP) for orbital maneuvers and a bi-propellant chemical propulsion system for attitude control; the primary components for Earth communications, containing multiple X-band and Ka-band links; and will handle attitude control, orbit maintenance, and transfer capabilities. The PPE spacecraft will be built by Maxar technologies of Colorado [30], contracted by NASA Glenn research Center. The HALO will handle the habitation, research, and command control aspects of the gateway. The HALO will have modular docking stations for visitor spacecraft, with NASA's Artemis program components being the first expected with a targeted launch date no earlier than November 2024. NASA's Artemis spacecraft includes the Orion spacecraft, the Human Landing System (HLS) and the logistics resupply spacecraft as shown in figure 2.1.

The Gateway will leverage key lessons learned from the ISS, major lessons include acceptable risk and human rated safety concerns. Another key lesson learned from previous space endeavors has led to the evolution of how humankind conducts state of the art space program developments, from international competition to now international cooperation. The gateway, just like the ISS will be an international effort, with partners, contractors, and subcontractors from all over the world contributing to the development of and execution of the Artemis program. This evolution comes from the benefits seen from collaboration, as was done during the earliest days of the ISS to the present-day logistics and activities concerning the ISS. Figure 2.2 below shows a size comparison between the Lunar Gateway and the ISS. The positioning of the gateway and size constraints will lead to different safety concerns for humans aboard for sustained periods of time, invaluable experience onboard the ISS will serve as a baseline for the gateway in terms of the technology required and where advancements must be pushed.

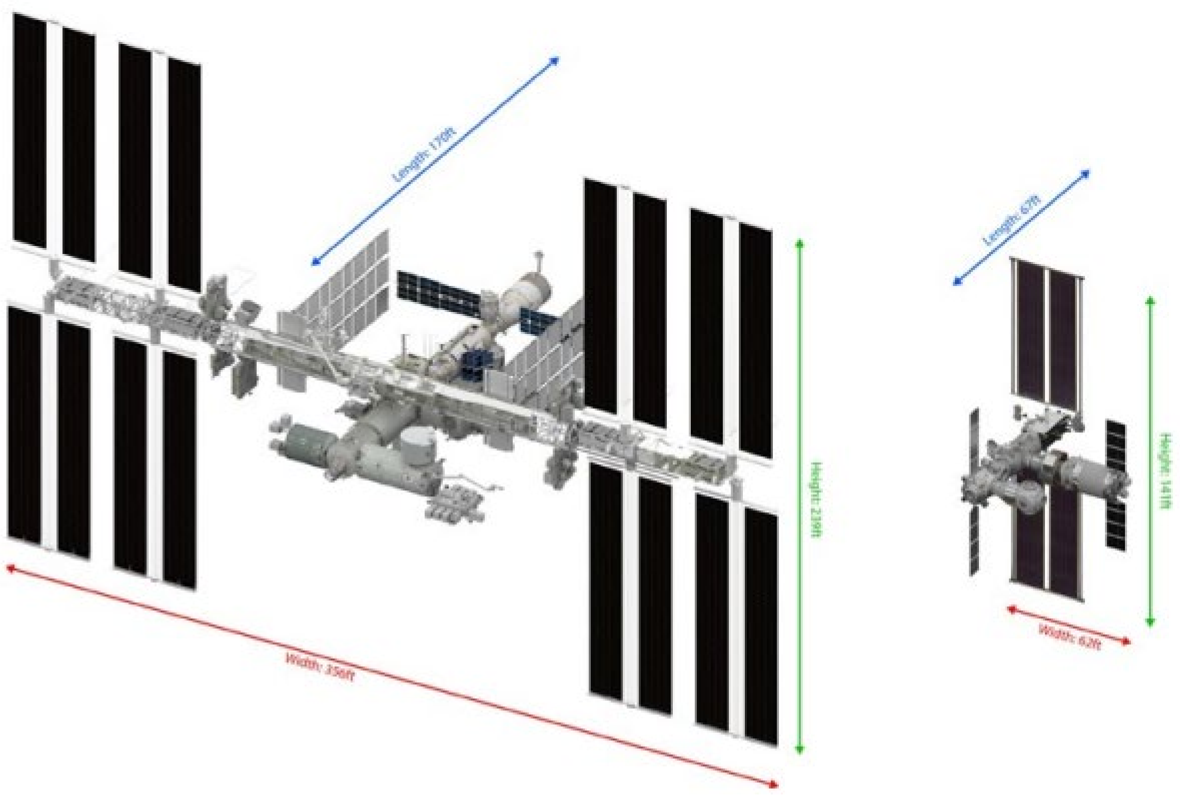

Figure 2.2 ISS (Left), Gateway (Right), size comparison [30]

It is important to note that a major intention of the Lunar Gateway is to enable technologies that will serve to raise the baseline of what is possible and expand upon the maturation of the state of the art available. NASA plans to leverage the gateway for unique research concerned with lunar and heliophysics, space biology, life sciences including human health, and materials to name a few. This will enable and pave the way for Mars centric manned and unmanned missions, ultimately pushing towards a manned intragalactic presence.

2.1.2 International Space Station

The International Space Station represents the first international human effort for a long term, manned presence onboard a spacecraft. Starting with a presidential directive in 1984 from Reagan, the ISS has maintained a manned crew for over 20 years. The ISS is a space station that resides in low Earth orbit (LEO) supporting international government research and in recent years has supported many private industry experiments, research, and technology. The ISS was built over the course of a decade before becoming fully functional through international efforts and utilization of NASA's Space Transportation System (STS). The ISS was intended to be an in space laboratory platform for microgravity experiments, a deployment hub for in space LEO missions such as CubeSats, and was thought to serve as an outpost for lunar and earth based missions. For these reasons it can be considered as the major system in service that HOPE can be traced to.

Over the course of its service life, the ISS has seen its share of human related challenges and solutions that come about to address these challenges. Some of these challenges include extravehicular activity (EVA), resource management, resource recycling, radiation, and more. These experiences are essential for the development of any future human rated space station, the Lunar gateway, and HOPE. The development of life support systems will be essential not just for HOP, but for the Artemis program that is set to operate within the decade. Systems such as the Air String and Water String, which will be tested by the ISS are examples of the kinds of systems that will be leveraged for future space outpost missions [31]. An operational concept diagram is shown in figure 2.3 below.

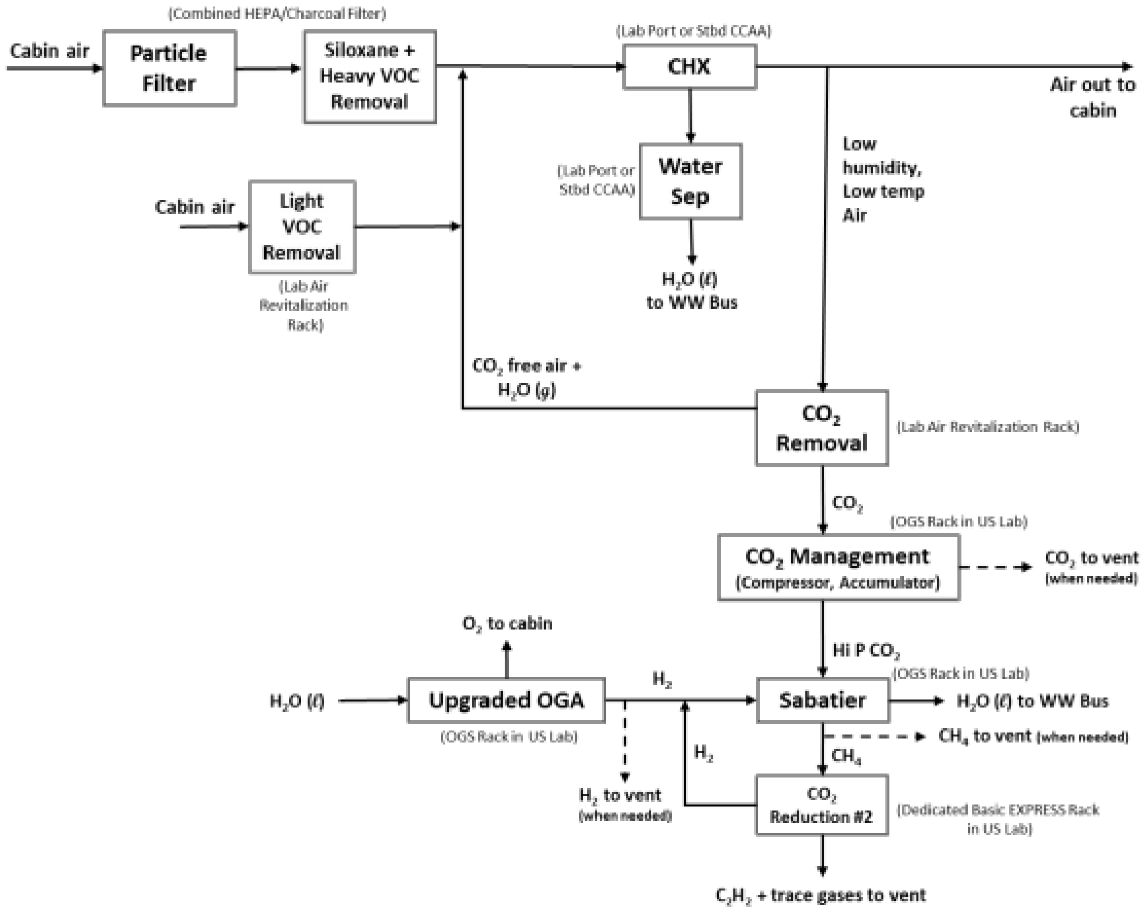

Figure 2.3 ISS Air String operational concept [31]

Risk reduction and acceptance by the ISS will be a critical component of lessons learned to incorporate and build on for future systems. Over the decades, the ISS has seen many things impossible to predict in the design phase and could only be addressed through experience in operation. Initially many design requirements were deemed adequate and through its service life has seen revisions due to unforeseen circumstances causing these requirements to become inadequate. Many areas where risks were underestimated have since been reassessed and mitigated with understanding only found through operational use [4]. New processes have been put in place by NASA to leverage these lessons learned from the ISS, mature them through the Artemis program and extend them to Mars and beyond. These activities and the process to achieve them are outlined at a high level in figure 2.4, the deliberate coordination between NASA programs have been designed to gain a closer understanding of maintaining a human presence in space.

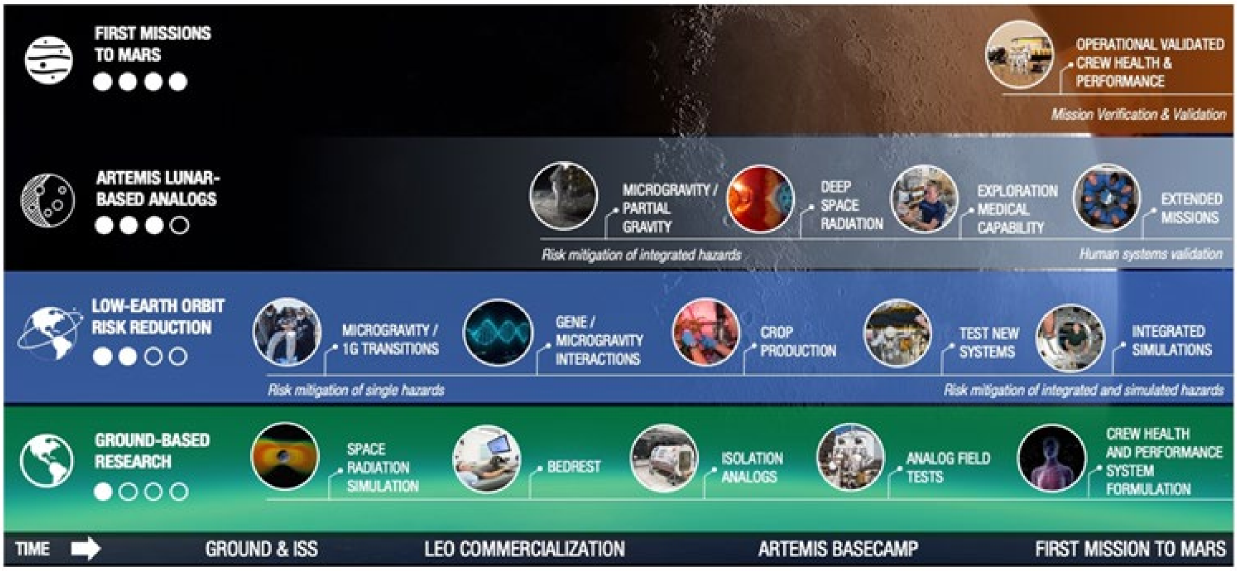

Figure 2.4 notional human spaceflight strategy to achieve Mars mission readiness [32]

The active and deliberate usage of the ISS to extend to future missions has established this space station as the ground zero steppingstone for all future manned space outposts. The gateway will leverage all lessons learned and mature the solutions that rise from them, while these solutions will in turn lend a hand to future outpost systems like HOPE.

2.2 Stakeholders

The HOPE program will leverage existing systems as a point of departure and potential stakeholders will be derived as such. The stakeholder definition process from NASA's Systems Engineering Handbook [29] will be tailored and leveraged as the methodology applied to the HOPE program.

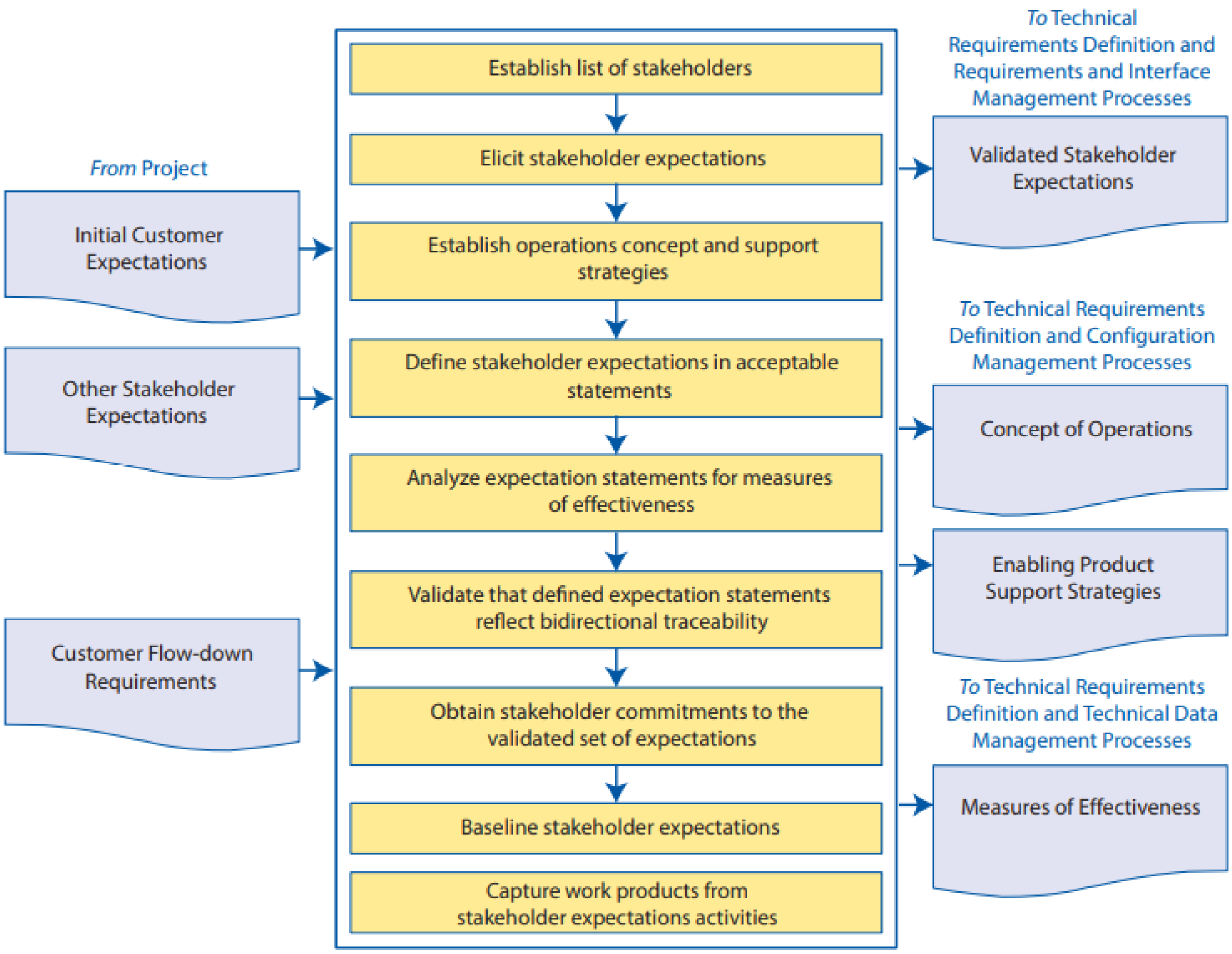

Figure 2.5 stakeholder expectations definitions process [29]

2.2.1 Stakeholder Definition

Active stakeholders for the HOPE system shall be defined as stakeholders that play an active role with the system when it is operational and in use. Passive stakeholders for the HOPE system shall be defined as stakeholders that do not play an active role with the system when it is in operation, rather these stakeholders will influence the system. It is important to note that the list of stakeholders may change for a given system depending on the phase of the program lifecycle, this notional list will be considering stakeholders during the time of operation. A preliminary list of stakeholders for the HOPE program is shown below in table 2.1.

Table 2.1 notional stakeholders

Name	Role	Description
	Active Stakeholders	
NASA	Owner / Maintainer	Government Space Agency
International Collaborators	Owner / Maintainer	Federal Government
Private Industry / Technology Development	User / Maintainer	N/A
Science / Research and Exploration	User	N/A
Public	User	N/A
	Passive Stakeholders	
United States Government	N/A	Federal Government
Internal / External Program Advisory Board	N/A	Advisory Team
Public	Beneficiaries	N/A

2.2.2 Expectations

Leveraging legacy systems, and the stakeholders outlined in table 2.1, preliminary stakeholder expectations may be derived for HOPE. These expectations may be derived using the methodology laid out in [29]. This thought process is shown in the figure below.

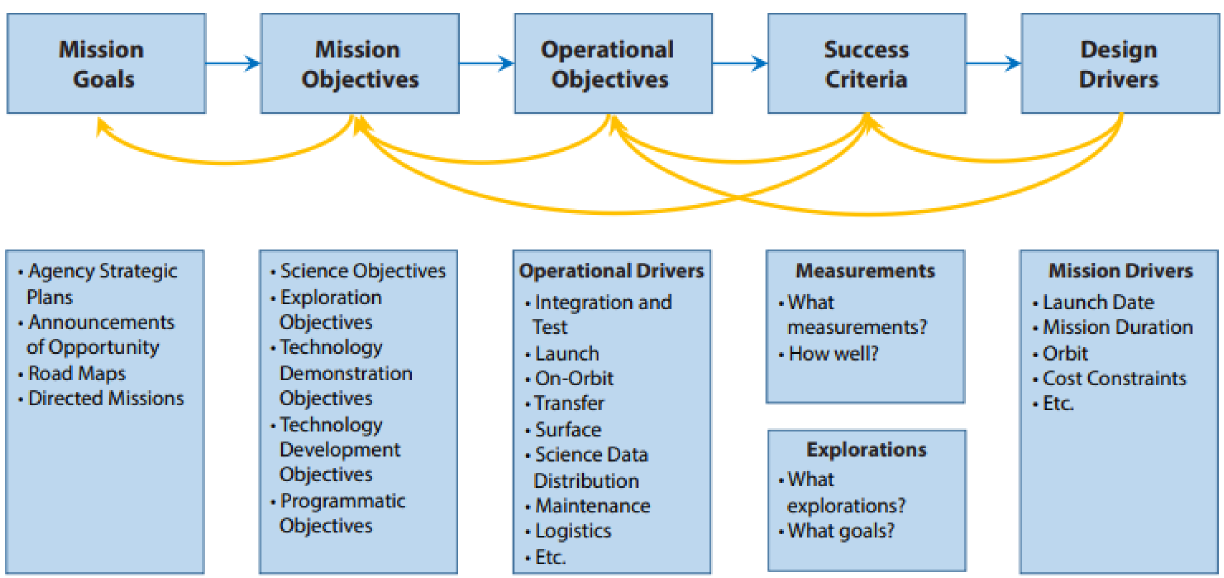

Figure 2.6 information flow for stakeholder expectations [29]

These stakeholder expectations will be captured in the following sections, as we follow through on the flowchart shown in figure 2.6, a tailored methodology will be adopted to define the elements within stakeholder expectations.

2.2.3 Constraints

As with any highly complex system with key stakeholders, constraints will be driven into the system and will influence the overall design approach and requirements. These constraints will flow into the system from both active and passive stakeholders of the system.

2.3 Mission Definition

2.3.1 Needs

This is the single statement that will drive everything else, a singular statement that does not relate at all to the solution but is fully addressing the problem at hand [29]. In other words, the need to be addressed exists regardless of the solution. The HOPE program will be developed to create a means for having manned outpost stations throughout the galaxy at different bodies or locations of interest. There is no current system that achieves this, and the legacy systems chosen will take the first steps to reach the point of departure that HOPE is addressing. This singular statement encompasses the ultimate problem being addressed by the proposed program designed in this study.

2.3.2 Goals

The goals will be defined as an extension of our program's need statement. These goals will constitute a specific set of expectations for the system to be developed and will address critical issues identified in the initial problem assessment. It is imperative that goals do not need to be a measurable metric, rather they should allow for the assessment of if these metrics can be achieved.

2.3.3 Objectives

The objectives of the HOPE system will, while ignoring any potential solutions, specify levels of different targets or parameters HOPE must achieve to be considered a successful system. These objectives will be traced to various relevant goals as outlined in the section above.

2.3.4 Constraints

Constraints will be imposed on the system, from external interfaces and entities. These constraints will assist in establishing the design boundaries of the system.

The two major constraints that will be considered for this design study will be the natural space environment and the induced environment expected to be experienced by the system. The natural space environment will place constraints on the system and influence system requirements at a functional and physical level. The induced load environments expected for the system capture any self-imposed loading conditions and load conditions that may occur from non-space environments experienced throughout the lifecycle of the system.

2.3.5 Mission Defined

The high-level mission definition is achieved through the methodologies and definitions laid out in the sections above. The stakeholder assessment has resulted in the following table.

Table 2.2 mission definition

Mission Need: To establish an intragalactic, interplanetary human presence.	
Goals	**Objectives**
1. Provide sustainable human presence onboard outpost stations in deep space.	1.1 Enable deep space crew habitation for a minimum of 8 months.
	1.2 Develop a system that can be extended to multiple bodies of interest in deep space.
2. Provide an intragalactic communications network.	2.1 Provide a means of communication between bodies of interest.
	2.2 Reduce the average time of communications between major deep space locations and Earth by 40% as compared to conventional deep space communications methods of 2023.
3. Provide a research and exploration hub for locations of interest.	3.1 Provide a platform to enable deep space science missions
	3.2 Provide a platform to enable deep space exploration missions
	3.3 Provide a platform to enable technology maturation missions
	3.4 Provide these capabilities at multiple bodies of interest
4. Reduce the risk of sustained human presence in deep space.	4.1 Reduce the risk of environmental effects on crew by 50%
	4.2 Provide life support for deep space missions with adverse conditions
	4.3 Provide life support for deep space missions with off nominal conditions

2.3.6 Concept of Operations

Now that the stakeholder expectation study has come to an initial conclusion, notional high-level concepts of operation will be proposed. These concepts of operation will tie to various program level scenarios of the completed system. These scenarios may be referred to as design reference missions and will encompass all known operational uses including off nominal events. These events will be considered a walkthrough of the lifecycle of the program at the highest level and are intended to be very broad at the current state of development.

Table 2.3 operational concepts

Program Level Operational Concepts		
Scenario Name	**Pre-condition / post condition**	**Description** This operational concept describes all the activities or scenarios that…
System Deployment	End of manufacturing / Orbit emplacement	Encompass the system and its interactions immediately after manufacturing all the way up to orbit emplacement by the launch vehicle.
Nominal Operations	System deployed / End of mission	Describe the system activities once it is deployed at the location of interest, all the way up to the nominal end of mission.
Off Nominal Operations	Off nominal event / Reset and recover	Captures all the off nominal or unintended events that may occur and the operations that take the system from the off-nominal event to a reset and recover protocol.
System Disposal	End of mission / System disposed	Will handle the responsible disposal of the system, starting with the end of mission nominal or off-nominal to the disposal.

2.4 System Level Requirements

2.4.1 Initial Requirements

NASA's Systems Engineering Handbook leads the previously defined stakeholder expectations and transforms them into a set of technical requirements. These requirements will encompass the system's inputs, outputs, relationships, constraints, performance, etc. Figure 2.7 below outlines this process.

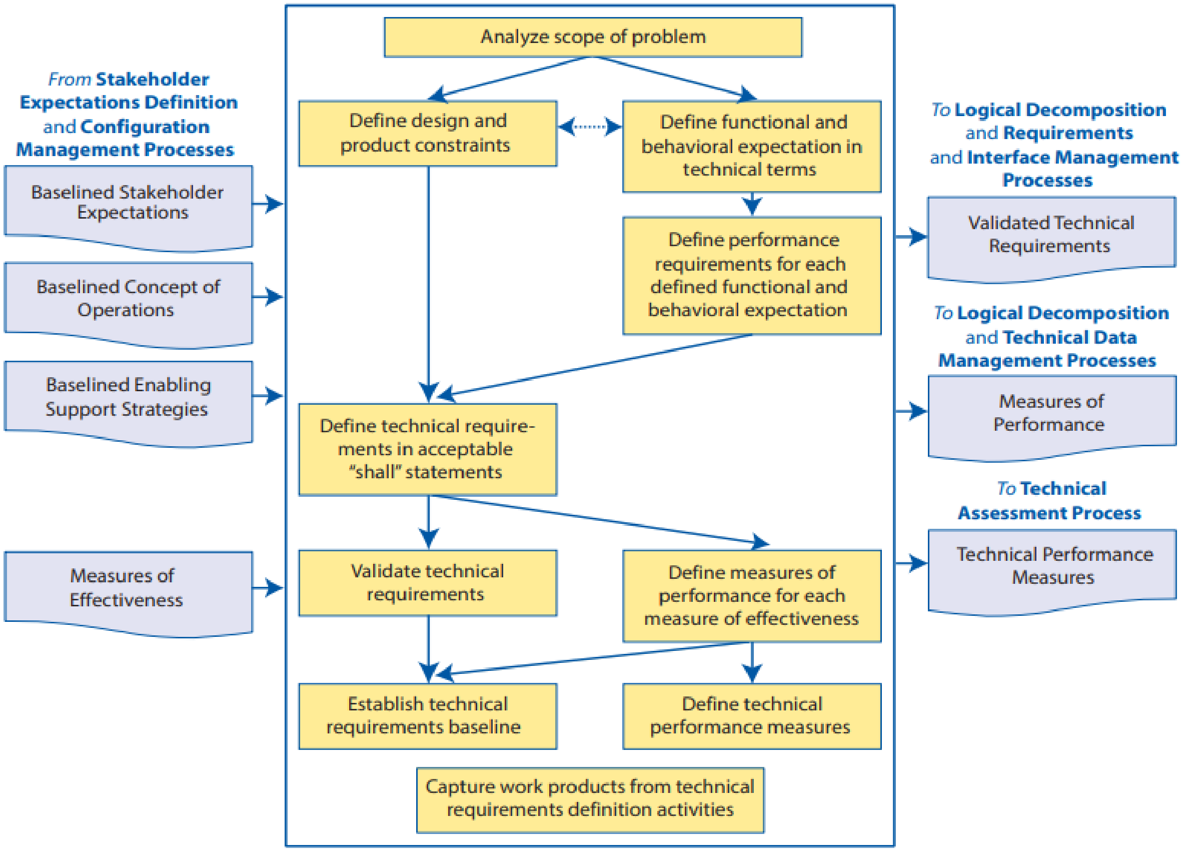

Figure 2.7 requirements definition process [29]

System level requirements at the highest level will be derived from the initial stakeholder expectations defined in section 2.3. These system level requirements will be revisited throughout the course of this design study and will capture only what is necessary for the scope of the study. The vernacular used within the requirements will follow standard NASA verb implementations as seen below [11].

- "Shall" statements will be used to denote requirements that are non-negotiable contractually obligated for the system.
- "Should" statements will be used to denote requirements that are considered best practices that are desired, but not necessary for the success of the system.

Table 2.4 system level requirements

Requirement ID	Description
SYS-01-001	The HOPE system shall support a crew of 6 for a minimum of 8 months.
SYS-01-002	The HOPE system shall have a presence at each major planet or nearby body of interest adjacent to major planet within the galaxy.
SYS-01-003	The HOPE system should support a crew of 6 for a maximum of 13 months.
SYS-01-004	The HOPE system shall support crew sizes of 1 – 6.
SYS-02-001	The HOPE system shall provide a communications network between at least 6 locations of interest within the galaxy.
SYS-02-002	The HOPE system should reduce the link budget losses as seen in current DSN communications by 50%.
SYS-02-003	The HOPE system shall comply with all FCC regulations and guidance.
SYS-02-004	The HOPE system should support encrypted and unencrypted communication pathways.
SYS-03-001	The HOPE system shall utilize a modular docking interface.
SYS-03-002	The HOPE System shall provide federal and private entities with testbed capabilities at various locations in the galaxy.
SYS-04-001	The HOPE system shall mitigate radiation exposure to crew.
SYS-04-002	The HOPE system shall contain mitigation procedures in the event of an off-nominal radiation event.
SYS-04-003	The HOPE system shall provide necessary life support for crew for a minimum of 6 months without resupply.
SYS-04-004	The HOPE system should reduce radiation exposure to crew by 50% as compared to heritage systems in similar environments.
SYS-05-001	The HOPE system shall have modular replaceable units in the event of corrective maintenance.
SYS-05-002	The HOPE system should have a minimum operational service life of 30 years in orbit.
SYS-05-003	The HOPE system shall support a minimum of 3 significant orbit transfers per mission duration.
SYS-05-004	The HOPE system shall maintain sufficient functionality for end of mission disposal.
SYS-06-001	The HOPE outposts shall have accommodations for autonomous logistics resupply
SYS-06-002	The HOPE outposts shall have accommodations for autonomous docking and undocking
SYS-06-003	The HOPE outposts shall have accommodations for in orbit refueling

2.4.2 Key Performance Parameters

Table 2.5 key performance parameters

System Level KPP		
ID	Description	Justification
SYS-01-001	The HOPE system shall support a crew of 6 for a minimum of 8 months.	N/A
SYS-02-001	The HOPE system shall provide a communications network between at least 6 locations of interest within the galaxy.	Violation of program needs if this requirement cannot be achieved.
SYS-03-001	The HOPE system shall utilize a modular docking interface.	Violation of crucial system level goals and objectives if this requirement cannot be achieved.
SYS-04-003	The HOPE system shall provide necessary life support for crew for a minimum of 6 months without resupply.	Violation of human safety is a zero-tolerance approach. In the event of an off-nominal event, this is the maximum allotted time for a mitigation solution or rescue.
SYS-05-002	The HOPE System should have a minimum operational service life of 30 years in orbit.	N/A

2.5 Solution Domains

The various solution domains shall be defined and explored for the HOPE system as relevant. These domain solution definitions and processes are derived from Wasson's systems engineering approach [27], in which the various problem spaces are allocated individual solutions to methodically approach the total solution in a manner that decouples highly complex systems. Wasson's definition of the process is as follows [27],

- Precept #1 – Stakeholder needs provide the basis for deriving a Requirements Domain Solution that bounds and specifies the system operational outcomes, environmental operating conditions, and constraints.
- Precept #2 – The Requirements Domain Solution provides the basis for deriving an Operations Domain Solution that defines how the system is envisioned to be deployed, operated, sustained, and disposed.
- Precept #3 – The Operations Domain Solution provides the basis to derive the Behavioral Domain Solution that characterizes how the system responds to operating environment stimuli, excitations, or cues.
- Precept #4 – The Behavioral Domain Solution provides the basis to derive the Physical Domain Solution that includes selection of physical components and configurations to implement behavioral capabilities.

The various solution domains as defined above will present themselves as we move along through this design study. The beginning of the formulation of the system requirements solution domain is seen in section 2.4 above.

2.6 Conclusion

With the problem defined, a stakeholder analysis was conducted allowing for the derivation of notional system level requirements. The development of these requirements lends the way for top level operational concepts to be explored and KPP to be defined. With the stakeholder analysis done, the process and resulting products are reflective of what is considered the requirements solution domain for HOPE.

3. Logical Decomposition

3.1 Functional Architecture

The functional architecture of the system is designed as follows to fulfill the top-level requirements and stipulations found in chapter 2's stakeholder analysis exercise. NASA's logical decomposition process will be utilized to decompose from the high-level requirements into technical and functional requirements for each element of the system. This decomposition process will also allow for the formulation of the various solution domains. The illustration in figure 3.1 is a representation of the general flow of activities.

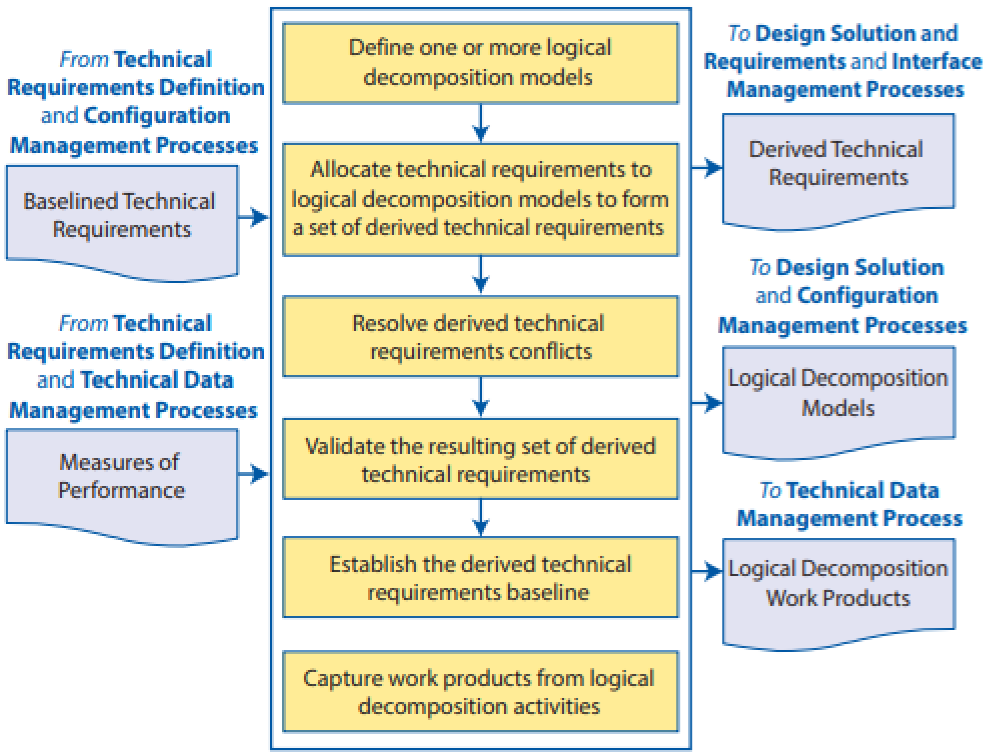

Figure 3.1 logical decomposition process [29]

The requirements seen in table 2.4 establish what is desired to fulfill the basic needs of the stakeholders. Using these baselined requirements, functionality will be assigned to subsystems from the functional perspective and lower-level requirements will emerge from these allocations. This will allow for a purely functional view of the HOPE architecture and will allow for clear traceability of the functional decomposition. The table below shows the traceability from top level requirements to functions of the system.

Table 3.1 functional allocation

Functional Allocations	
Function	Requirement ID
Sustain Crew	SYS-01-001
	SYS-01-003
	SYS-01-004
	SYS-04-003
Protect Crew	SYS-04-001
	SYS-04-002
	SYS-04-004
Sustainment	SYS-05-002
	SYS-05-004
Provide Intragalactic Communications	SYS-01-002
	SYS-02-001
	SYS-02-002
	SYS-02-003
	SYS-02-004
Provide Science / Exploration Hub	SYS-03-002
	SYS-05-003
In-space Maintenance Activities	SYS-03-001
	SYS-05-001
	SYS-06-001
	SYS-06-002
	SYS-06-003

These traces are then used to identify key functions desired from the HOPE system. Once these functions are identified, the common grouping allows for functional group allocations to begin. These groupings can be used to begin the process of interface definition and physical decomposition. This notional grouping of requirements also helps to begin defining the operations solution domain of our system as described in section 2.5. Once the operations domain begins to present itself, the behavioral domain can begin development. The high-level behavior of the HOPE system can be seen in figure 3.2 below.

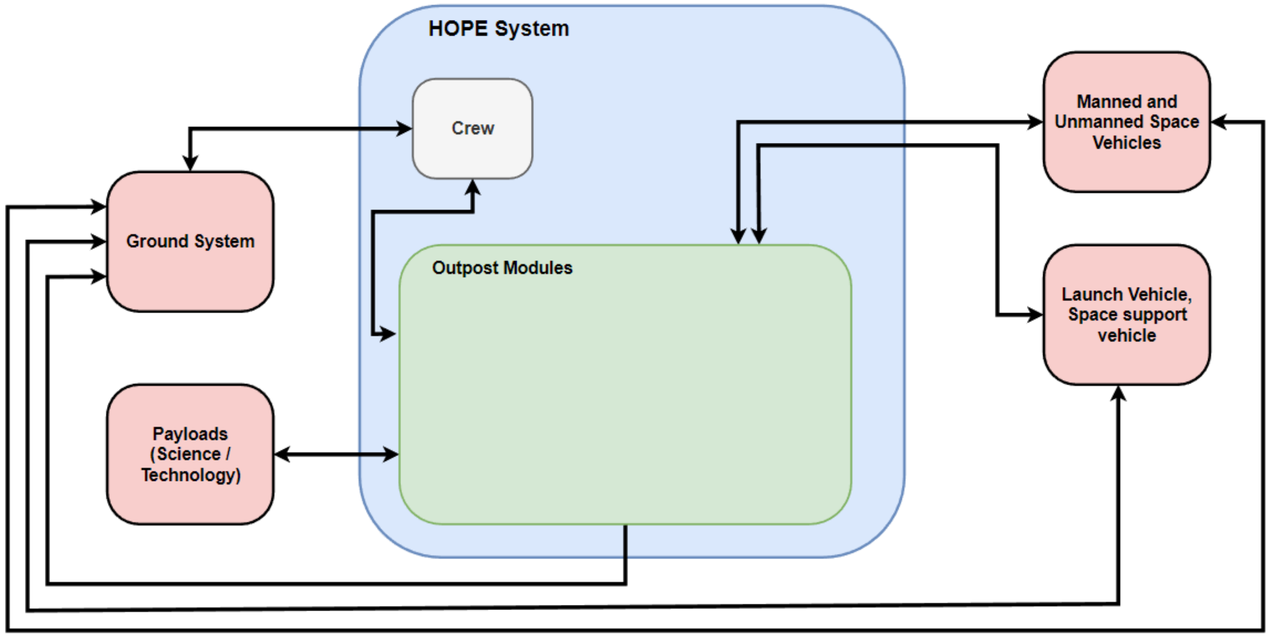

Figure 3.2 HOPE functional diagram

This notional functional diagram depicts the HOPE system and how it interacts with its environment. This notional behavioral depiction coupled with the previously defined solution domains allow for the physical solution domain to begin formulating as discussed in section 3.2. The derivation of the various solution domains as presented in preceding sub sections follows the logical decomposition process laid out in NASA's systems engineering handbook and methods from Wasson's systems engineering method. These steps set the system definition up for the physical architecture to be defined.

3.2 Physical Architecture

The proposed physical architecture is derived from the various points of departure discussed in previous sections and from the various solution domains as defined in section 3.1. The notional physical architecture can be seen in figure 3.3 below, this is a notional architecture and is subject to trade studies of each proposed element.

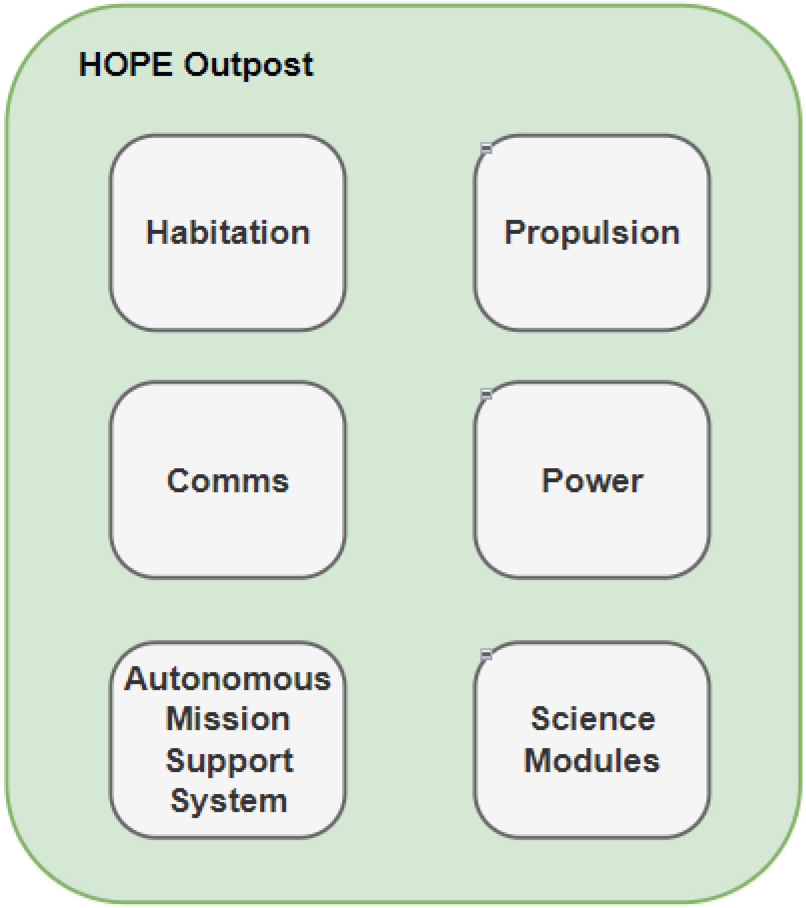

Figure 3.3 HOPE outpost physical architecture

3.3 Outpost Elements

The various proposed elements from figure 3.3 above will be discussed in the following sections. The outpost elements will place an emphasis on leveraging state of the art technologies that either currently exist in a premature fashion to some degree or technologies that are on the cusp of a breakthrough. These elements will also place human and system safety as a top priority, although establishing an intragalactic communications network is a key theme of the system, safely advancing human exploration capabilities will be imperative for creating a sustainable approach to interplanetary travel.

3.3.1 Habitation

The habitation module will house the onboard crew during the various missions possible for each outpost, the associated functional allocations can be seen in table 3.1. The habitation module will support long term manned deep space efforts for various purposes.

3.3.2 Propulsion

Depending on the specific location, a different final solution may be necessary with the propulsion system of each outpost. In general, the various propulsion systems used will have a high specific impulse, be capable of station keeping, and allow for the outpost to make a few significant orbital maneuvers in the case that an orbit transfer is required to support a specific mission or payload. Electronic and chemical propulsion systems will be utilized where possible for significant maneuvers and for attitude control respectively. The Gateway program will be utilizing a similar configuration, the HOPE outposts should build on the technology that will be matured and developed through the Artemis program.

3.3.3 Communications

A robust communications system will be an inherent characteristic of any HOPE outpost placed throughout the solar system. One of the driving needs being addressed by the HOPE program is to establish an intragalactic communications network, this will be established by having multiple HOPE outposts at various bodies of interest. These outposts will communicate with one another to relay messages back and forth, allowing for incredibly deep space missions to have an infrastructure in place to communicate with the Earth through a well-established network rather than having to broadcast from the spacecraft directly to Earth. This will increase the types and size of data being collected by various missions from distant locations as there will be less dependency on the system's ability to transmit long distance and nearby outposts will be able to receive and transmit on behalf of the spacecraft.

The general communications architecture will vary depending on location, however the overall approach and hardware should be relatively similar across each outpost. There will be multiband capability for receiving and transmission including, along with leveraging optical communication technologies for specialized purposes depending on the maturity level at the time. Typical space RF bands will be supported along with the various other forms of communications that may appear. The Lunar Gateway currently under development is the first step to having this infrastructure in place, as it will serve as a communications relay from the Moon to Earth and eventually deep space to the Earth. The notional concept of operations is depicted in figure 1.3 in section 1. The hope is to have a multiplanetary solution for what is being demonstrated by the Gateway.

3.3.4 Power

The power module of each HOPE outpost will vary between one another. Each location will have different solar availability, environmental constraints, and power budgets. This will cause each system to vary, although it would be ideal to keep every outpost as similar to one another as possible, this is highly unlikely due to the reasons mentioned.

Highly robust and advanced solar arrays are currently in development for deep space applications, eventually these will be utilized on systems such as the HOPE outposts. Another solution for power would be leveraging nuclear power systems, such as fission or radioactive decay systems where it is possible to lessen the dependency on the Sun at locations of interest where there is very little sunlight.

3.3.5 Autonomous Mission Support System

The Autonomous Mission Support System, AMSS, is the module of each HOPE outpost that will leverage machine learning and AI technologies to carry out tasks autonomously without or with minimal human input. These tasks may include, but are not limited to unmanned logistics management, manned tasks that would require crew to spend significant time on such as certain module replacement procedures or maintenance activities, communications encryption/decryption priority rating, and any other relevant tasks that may be taken on depending on the location and mission.

The main purpose of the AMSS would be to leverage emerging AI technologies for unmanned operations that would generally require crew to be onboard an outpost. This will allow for sustained uncrewed operations at each HOPE outpost as needed. This system will be able to make low and mid priority decisions ranked based on effects to the system.

3.3.6 Science Modules

The science modules in figure 3.3 represent any scientific module that may be a part of that specific HOPE outpost. The science modules will differ for each outpost as each body of interest will have specific science objectives in mind that will cause the modular design to be tailored to the deployment location.

Each HOPE outpost will have standard modules to support scientific experiments and science instruments for general use that would be applicable to retain at any location. The modular design aspect of the outposts will allow for the addition of modules designed specifically for each location of interest as needed or tailoring the exact configuration.

3.4 States and Modes

The following graphic represents the different state changes and triggers associated that our system would experience through various phases of an outpost's ConOps. Defining the various states and modes of the outpost system allows for further decomposition of the overall ConOps and allows for specific operations to be defined and traced to the lowest level.

These states describe the various points of the program level behavior and the specific triggers associated with each transition. These states are derived from the operational concept outlined in table 2.3 and the functional allocations found in table 3.1.

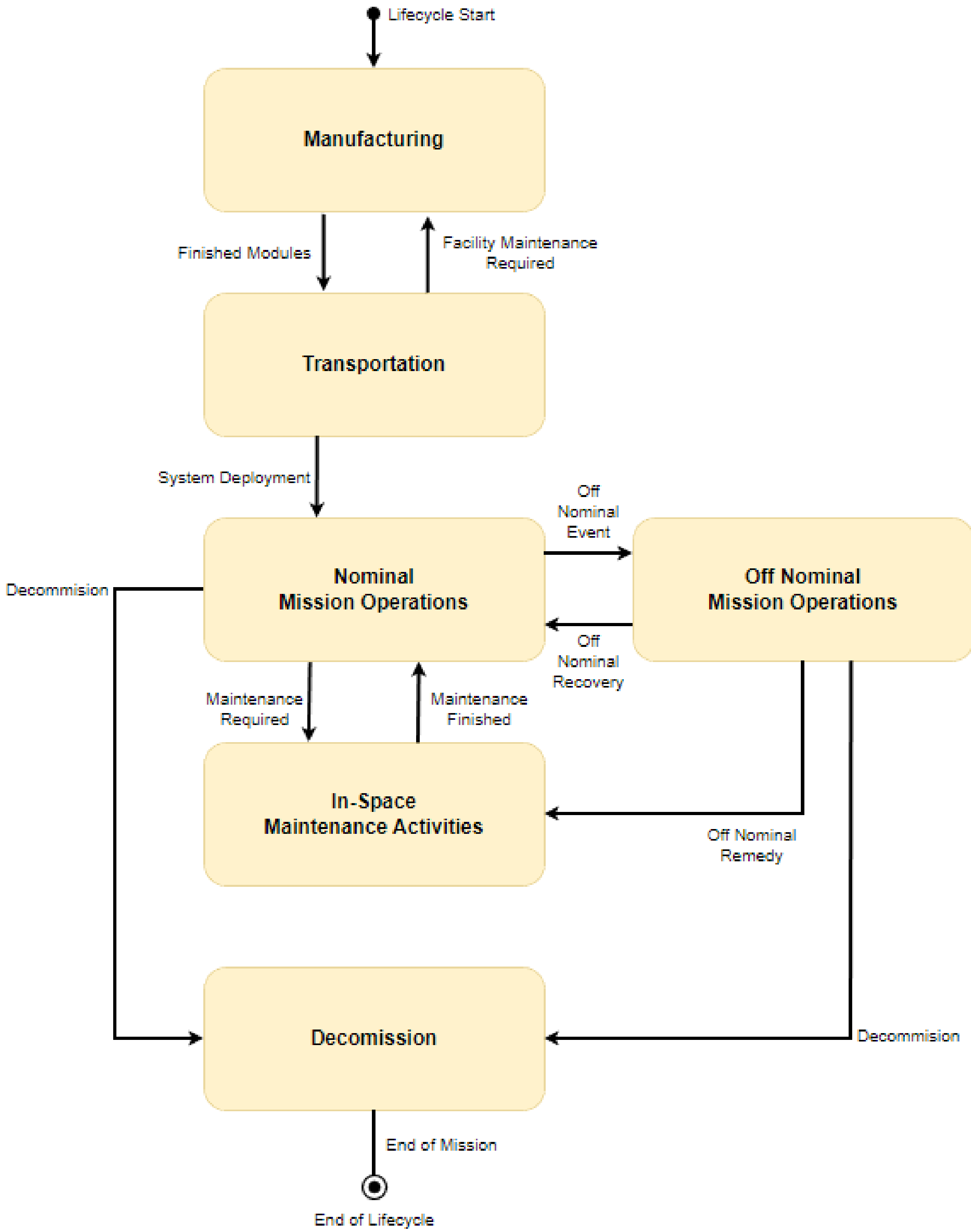

Figure 3.4 HOPE program level state machine diagram

The state machine diagram shown in figure 3.4 above depicts the few states expected for the outpost to go through its lifecycle. The diagram shows the various triggers required to move through the states found in the lifecycle. An example walk through the nominal lifecycle starts from being in a state of manufacturing where the various outpost components are being manufactured, to exit manufacturing a completed signal is required. Afterwards it is expected to go through some sort of transit stage, including ground transportation, air transportation, and space transportation for the outpost to reach the deployment site. A deployment trigger then takes the system from a transportation state to a nominal mission operations state, this encompasses all activities that may be encountered in a typical mission duration. From the nominal operations state, depending on the trigger, the outpost may enter an off-nominal state or a maintenance state. Eventually, the system will receive a decommission trigger that takes it to the decommission state where the system will be responsibly disposed of and then transition to the end of its lifecycle.

3.5 Conclusion

The logical decomposition of the HOPE system followed a tailored methodology as outlined in the previous sections. These methods were based on NASA's systems engineering handbook methodologies and others. The decomposition allowed for the allocation of different aspects of the system to the various solution domains as discussed previously. At a high level, the HOPE system has been defined with a functional and logical perspective. With this initial take at the logical decomposition finished, design solution considerations will be taken care of in the next section.

4. Design Solution

4.1 System Design Solution

With the physical and logical architecture both defined at a high level, the actual design solution may now be discussed. Taking the functional architecture that was derived from the stakeholder analysis, a notional physical architecture is decided, from which further decomposition may occur. This decomposition of the higher-level architectures is what will be addressed in this chapter. NASA's design solution process can be seen in figure 4.1 below, this method will be coupled with tenets from Wasson's problem-solving process.

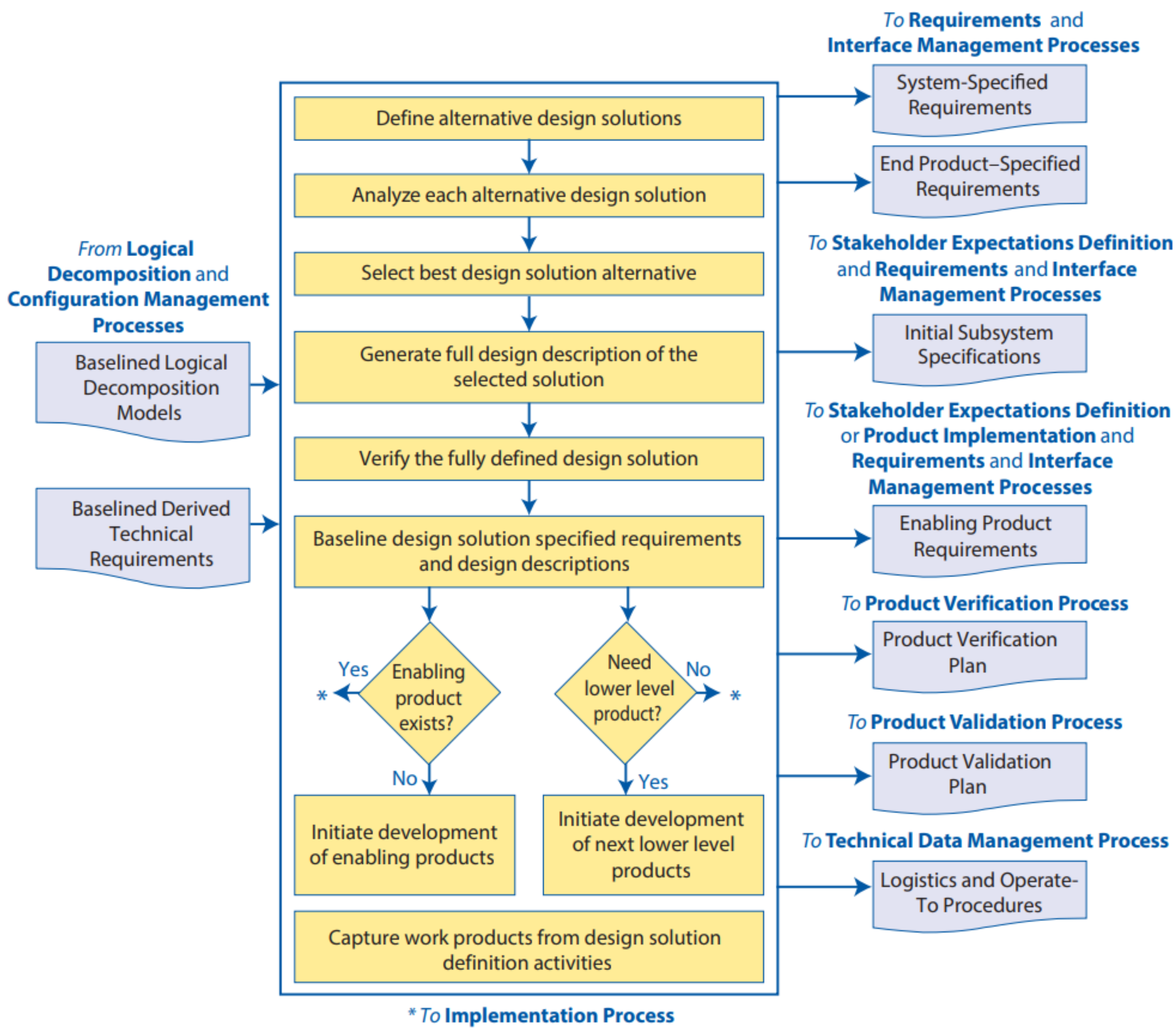

Figure 4.1 design solution definition process [29]

Although we have defined our system architecture to a baselined notional state, a key aspect of any architecture design process is to investigate alternative design solutions at every level. This is important to fully understand the choices being made for the proposed solutions and the tradeoffs associated with every decision, this understanding will allow for the decision-making process to have as much confidence as possible. Figure 4.2 below depicts a recursive and iterative process that may be used at a high level for any project or program.

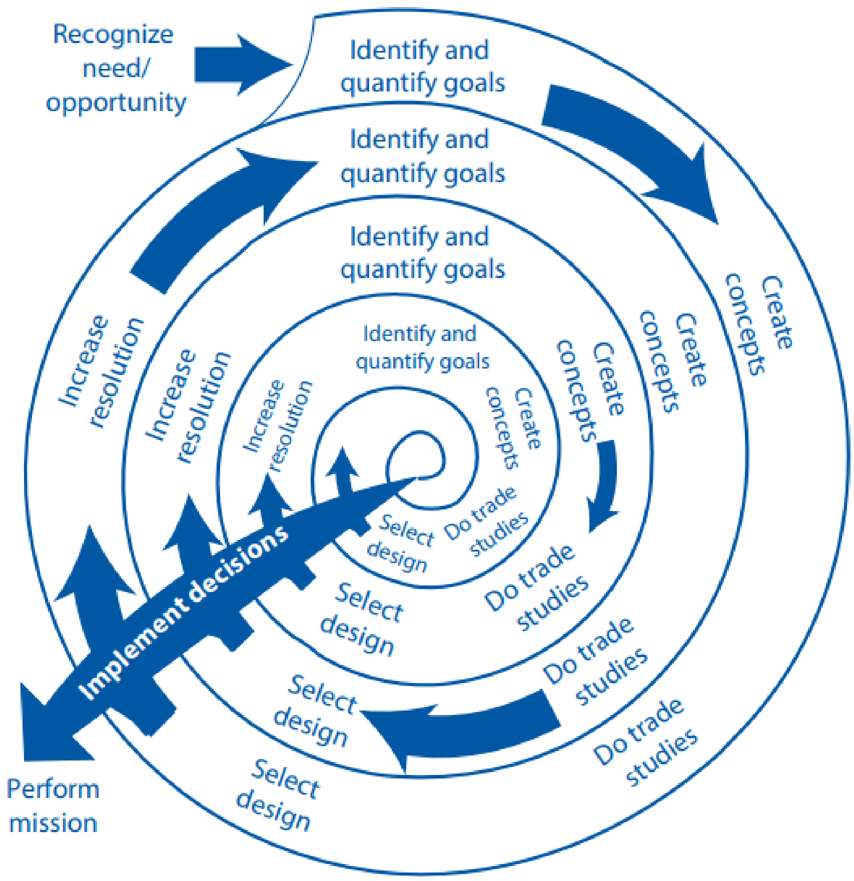

Figure 4.2 the doctrine of successive refinement [29]

This doctrine illustrated above is also present in Wasson's process, although Wasson emphasizes iterating at every step of the way. In figure 4.3 below, the design solution definition step is encompassed by the separate domain solution iterations and the final optimization step.

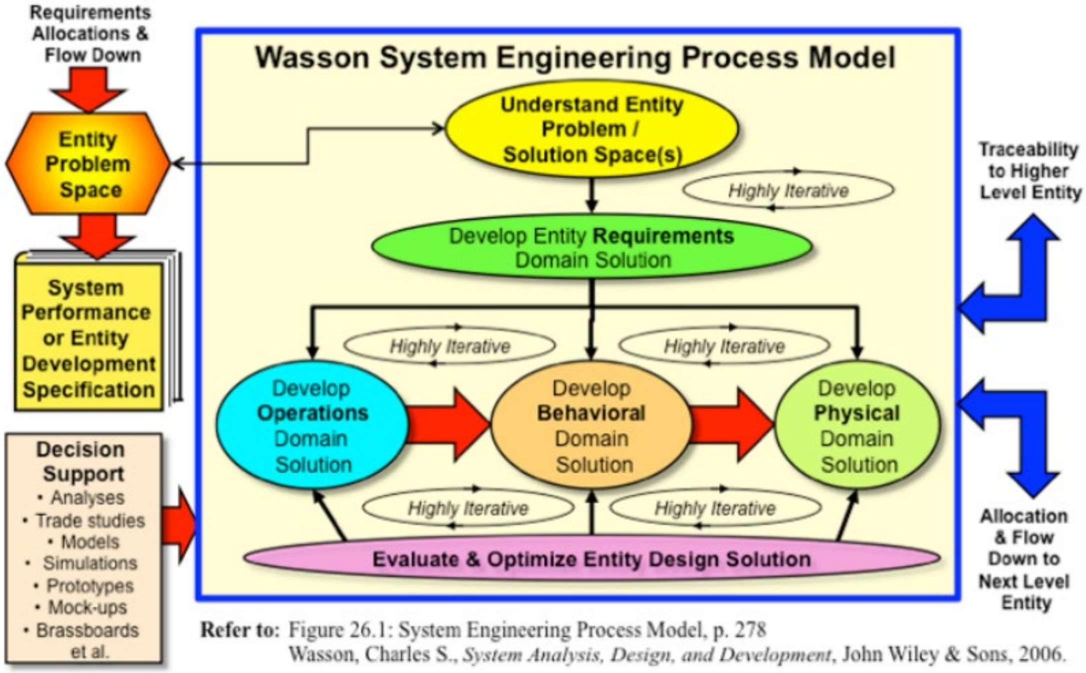

Figure 4.3 Wasson system engineering process model representation [27]

4.2 Alternatives

As is the case with any system architecture, there is always another way to achieve the same results. This sub section will discuss various aspects of the HOPE system and alternatives that may be considered. Although these will be the only considerations discussed in this report, these do not encompass every single item that may be subject to an alternative solution.

4.2.1 Space Station Approach

The current architecture proposes multiple long-term optionally manned space stations throughout the known galaxy to serve as communications and exploration hubs. This current architecture lends the way for HOPE to be leveraged for science and technology demonstration missions.

Although one of the core themes of the current architecture is to have as much human involvement as possible, another way to approach this problem would be to have much shorter duration or completely autonomous outposts to eliminate the need to have complex life support systems. These stations could support a human presence for less than a month and would essentially serve as a temporary stop along the way to a different outpost or serve as a simple auxiliary station for manned spacecraft to dock onto for resources and rehabilitation, not to use as a habitation platform.

By minimizing human presence onboard this alternative approach would allow for the outposts to become less complex, as they would just serve as an auxiliary input for the manned visiting spacecraft. This could reduce risk significantly for locations such as Jupiter where the radiation environment in orbit is significantly difficult to navigate if a human presence is necessary.

Although there are clear benefits to this approach, a hybrid approach may also be adopted. Based on location and significance, the outpost may support a long- or short-term human presence. This hybrid approach would be ideal for tailoring the overarching modular system for each mission and location; however, this would increase complexity and would cause a need to arise for an adjacent long-term outpost in nominal and off-nominal scenarios.

4.2.2 Propulsion Systems

The propulsion systems of each HOPE outpost may be different from one another based on location, although in the current architecture an electronic propulsion system is proposed. This technology is in the current architecture as that is what is being used by the lunar gateway and by the time humankind is at the point where something like HOPE is achievable, that electronic propulsion system has matured to where it is a viable option for all locations of interest.

On the other hand, there is no shortage of propulsion systems that may be utilized for these outpost stations, from cold gas thrusters, liquid propellant rocket engines, and solid propellant rocket engines to name a few. These options were not considered for the current architecture to reduce the number of consumables necessary for nominal operations of each outpost. Solid and liquid rocket engines would be an ideal option if many significant orbital maneuvers that require high thrust must be performed in as short a time as possible were expected, so these may be an option if the mission demands it. Cold gas thrusters could also be an option, although, would not be as applicable as a main propulsion system for an outpost with the current state of the art.

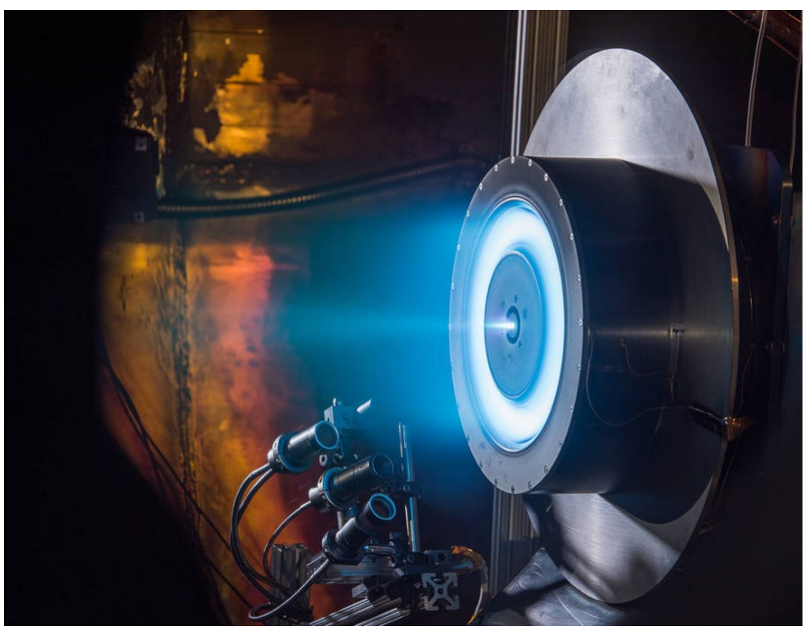

Figure 4.4 electronic propulsion system by Aerojet Rocketdyne for Lunar Gateway [33]

There may also be different solutions in the future such as viable solar propulsion, nuclear propulsion, laser, or antimatter propulsion systems that are either not viable now or are very early in development. One antimatter concept illustration from a 1985 article is shown in figure 4.5 below. The main importance that the electric propulsion system is being used is that the only consumable each outpost would be relying on is electricity generated by solar arrays or by nuclear means. These technologies should be utilized where possible when available.

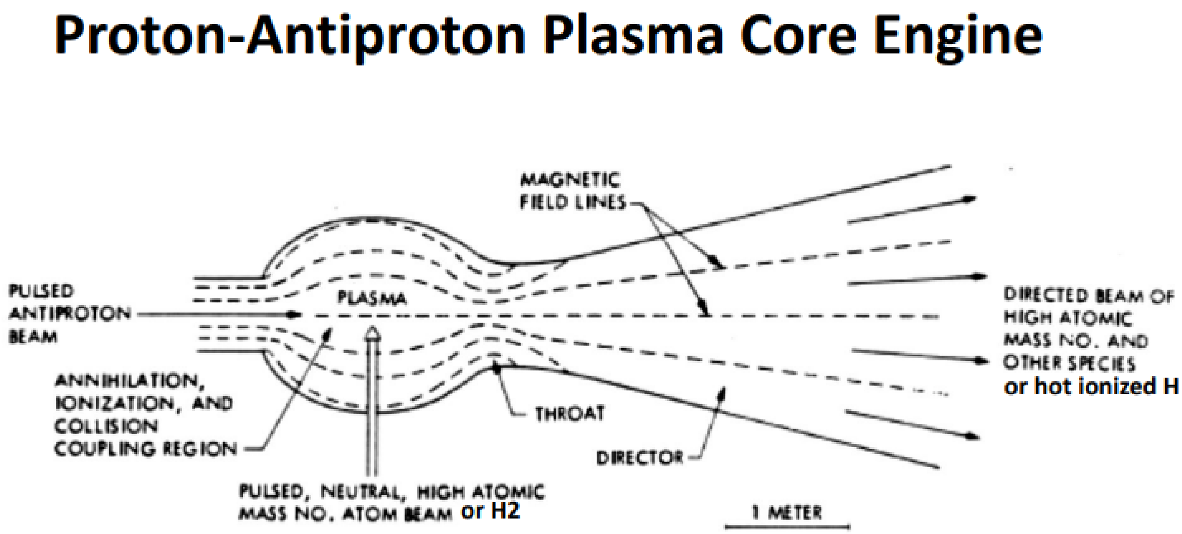

Figure 4.5 proton-antiproton antimatter engine concept [34]

4.2.3 Alternative Communications System Approach

The current architecture builds upon the scope and capabilities that are being developed for the lunar gateway. The proposed solution uses current state of the art RF methods of communications. Another direction to go with the HOPE communications network would be heavily leveraging optical communications, each outpost would be equipped with a receiver and transmitter for optical capabilities. By having optics as the primary form of communication, the network would be able to leverage state of the art technologies all throughout from the communication systems onboard each outpost to new optical communications based ground stations.

Figure 4.6 NASA's laser communications relay demonstration illustration [35]

Figure 4.6 above depicts NASA's recent foray into optical communications, when this technology has matured it can be utilized by future systems such as HOPE outposts. By utilizing optical communications, much higher data rates can be achieved. This will allow the outposts to communicate with one another and send messages long distances in much shorter times than if a conventional RF solution is used.

4.2 Defined System Solution

The current system is defined as discussed in chapter 3 and with the various alternatives being considered in the previous section, the first steps after having a baselined architecture have been satisfied. The various solution domains can be traced back to the top-level stakeholder analyses and the ConOps proposed fulfills the requirements defined for the system. As this is the lowest level of decomposition planned for the HOPE program in this effort, this is where the recursive and iterative process will be further applied throughout the life of this project.

4.3 Conclusion

This chapter concludes the system architecture design of the HOPE space program. Starting with the highest level of needs being addressed, the NASA and Wasson process have been leveraged for the resulting system design solution. As system design is a recursive and iterative process, some level of changes will be expected as further analysis and trade studies are conducted.

Now that a design solution is proposed, a look into the orbital behavior of an implementation of the HOPE program will be investigated next.

5. Orbital Mechanics Study

5.1 Introduction

A key area of analysis that HOPE and any program like HOPE will require is a thorough understanding of the orbital behaviors at each respective location and how each outpost may interact with one another. There will be numerous implementations of HOPE outposts throughout the galaxy, and although a systems thinking approach has been adopted there is no way to avoid addressing unique location specific considerations that will require design work to some degree for each outpost. Figure 5.1 below shows the solar system with planets to be used as a reference for the reader in the succeeding sections.

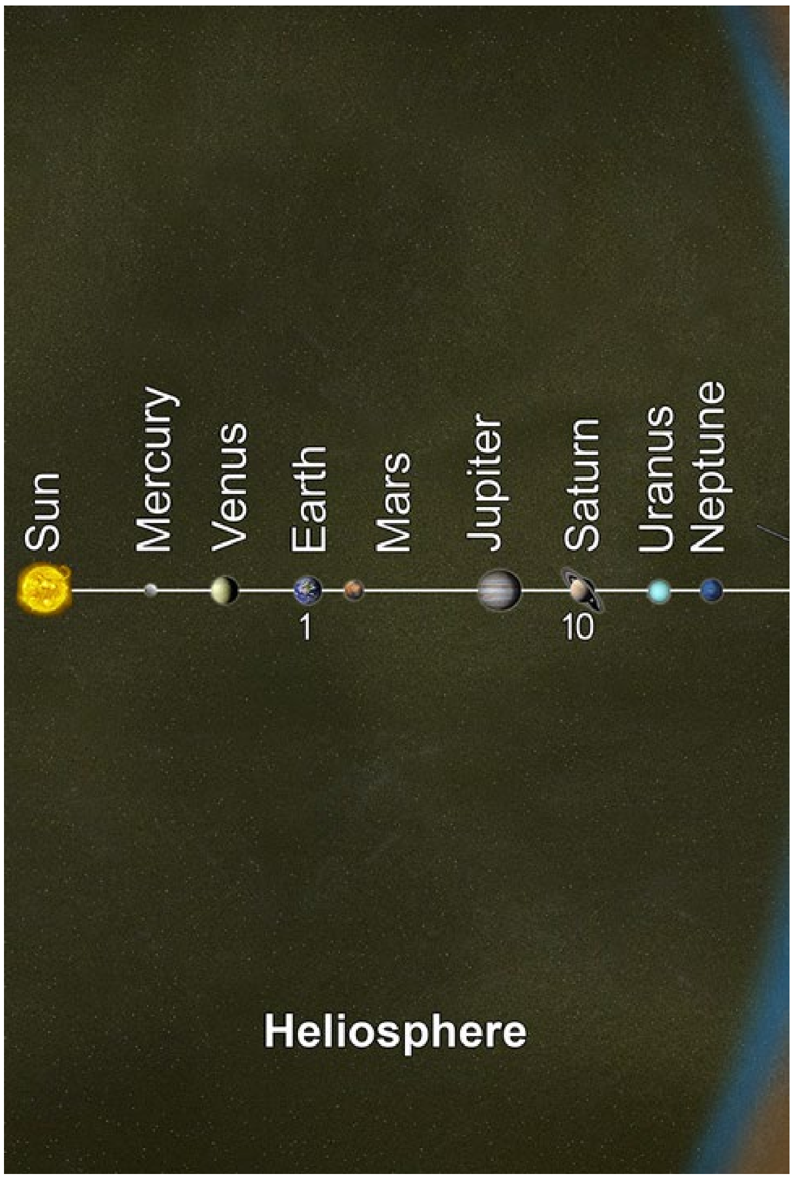

Figure 5.1 solar system infographic [36]

5.2 Problem Definition and Mission Design

This study will focus on one instance of the nominal operations of the HOPE system, data transmission from one body of interest to another. This scenario is reflective of what could be considered a nominal day to day interaction between stations. This mission assumes all the technology necessary to have these space stations on these planets exists and is at a point to support a sustainable human presence.

The orbits leveraged by the stations will be stable orbits about the body of interest to reflect a realistic situation where two outposts will have been deployed to their respective bodies of interest and are working in tandem to deliver a message. Mars has been chosen as it is the next in line after the current lunar focus to have human exploration missions as seen by NASA's Artemis mission plans and SpaceX's Mars goals set for the near future. Jupiter has been chosen as it is the next planet after Mars in order of distance, with the planet itself and all the moons it has, Jupiter holds many scientific opportunities to support in-situ resource utilization and reflects the beginnings of a science and research hub within the near galaxy. With this reasoning, it is logical that each will at some point have their own outposts that must communicate with one another and relay messages to the Earth via the HOPE network from deeper in space or from their own missions. It is important to note that while Jupiter has incredibly diverse research opportunities, it is also home to one of the most dangerous and difficult orbital environments for technology and humans.

5.2.1 Concept of Operations

A high-level operational concept will outline the mission scenario that will be considered for simulation and analysis, as shown in the table below. This is a scenario that is derived from the nominal operations system concept.

Table 5.1 concept of operations

Concept of Operations	
Step	Description
1	Station 1 in a stable orbit around Mars, station 2 in a stable orbit around Jupiter.
2	Orbits will synchronize to maximize line of sight.
3	Line of sight from station 2 to station 1 will be tracked as data transmission opportunities.
4	Data transfer from station 2 to station 1 will be complete after a set number of passes.
5	Station 1 would then transfer data to the next station if it is not the destination.

5.2.2 Simulation Summary

The spacecraft, orbital, and key mission parameters that will be used as inputs for each mode of analysis and simulation are outlined in the following table.

Table 5.2 mission summary

Key Mission Parameters	
Name	Value
Spacecraft 1	
Form Factor	Small Outpost
Mass	8,000 kg
Drag Area	150 m^2
Drag Coefficient	2.2
Reflectivity Area	10 m^2
Reflectivity Coefficient	1.8
Spacecraft 2	
Form Factor	Large Outpost
Mass	12,000 kg
Drag Area	220 m^2
Drag Coefficient	2.5
Reflectivity Area	45 m^2
Reflectivity Coefficient	1.8
Orbital Summary	
Spacecraft 1 orbit	
Body of Interest	Mars
Apogee	17,000 km
Perigee	16,000 km
Semimajor Axis	19,896 km
Eccentricity	0.02
Right Ascension of Ascending Node	45 degrees
Argument of Periapsis	90 degrees
Spacecraft 2 orbit	
Body of Interest	Jupiter
Apogee	1,800,000 km
Perigee	N/A
Semimajor Axis	1,871,492 km
Eccentricity	0
Right Ascension of Ascending Node	45 degrees
Argument of Periapsis	90 degrees

5.3 Analytical Work

This section outlines the various concepts, equations and overall methodology used to simulate the mission laid out in table 5.2. A communications study will be conducted adjacent to the orbital analysis.

5.3.1 Orbital Mechanics

The methodology used to simulate and analyze the orbital mechanics of the proposed ConOps is outlined as follows. Starting with the basic orbit equation of a generic body in equation 5.1 below. This equation and the succeeding can be found in [37], where the methodologies and resources for the orbital study originate.

$$r = \left({h^2}/{G * M}\right)/(1 + e * \cos(\theta)) \tag{5.1}$$

This gives a starting point for simulating the orbit about a body when using Keplerian elements. Since HOPE would be utilizing long term stationed outposts, a circular orbit or as close to circular would be ideal, this can be investigated through the total orbital energy. Equations 5.2 – 5.4 display the kinetic, potential, and total orbit energy equations respectively.

$$T = \frac{1}{2} * m * v^2 = \frac{1}{2} * m * [\dot{r} + (r * \dot{\theta})^2] \tag{5.2}$$

$$V = -G * M * m/r \tag{5.3}$$

$$E = T + V = \frac{1}{2} m \left[\dot{r} + \left(r\dot{\theta}\right)^2\right] - {GMm}/{r} = \frac{1}{2} m \,{(GM)^2}/{h^2}\,(e^2 - 1) \tag{5.4}$$

It is observed that when total energy of an orbit is zero or close to zero, as seen in equation 5.X, the orbit can be considered a stable orbit. These orbits will allow for a sustainable presence with as minimal station keeping efforts as possible. This stable orbit can be utilized anytime a separate orbit is unneeded for operations. By substituting in total energy equal to zero, it is possible to derive the required orbital velocity to maintain a circular orbit about any generic body, the result of which is shown in equation 5.5 below.

$$v_{circular} = \sqrt{(G * M)/(r)} \tag{5.5}$$

$$v = \sqrt{\left({2GM}/{r}\right) - \left({GM}/{a}\right)} \tag{5.6}$$

Equation 5.6 above will serve as a velocity check; this equation is called the energy equation and can be used to determine the velocity of a particle in an elliptical orbit given a few parameters.

The respective celestial bodies are chosen, and a low maintenance orbit is selected for each spacecraft, equations 5.1 – 5.5 encompass the necessary considerations to do so. Once this is done, the window of time each spacecraft may be in view of each other may be derived. Once the window of visibility is determined, the rate of data transfer for various methods may be compared.

Estimating relevant spacecraft parameters for simulation purposes is covered in [38], the resulting equations of interest are as follows:

$$C_D = (m * a_{drag})/(0.5 * A_{ref} * \rho * v^2) \tag{5.7}$$

$$a_{drag} = (F_D)/(m) \tag{5.8}$$

These equations will assist in determining and relating the various parameters associated with drag for each outpost.

5.3.2 Communications study

For the purposes of understanding the impacts of having the communications architecture laid out by HOPE, a high-level study will be conducted leveraging information from the orbital analysis and simulation to compare data transmission rates using typical DSN and recent optical experiment results.

The parameter of greatest interest when it comes to deep space communications in the traditional sense is the RF link budget. This study will focus on the direct link, the direct link budget describes the relationship between a direct transmitter to receiver link. This relationship gives insight on a few important parameters such as received signal strength and effective isotropic radiated power.

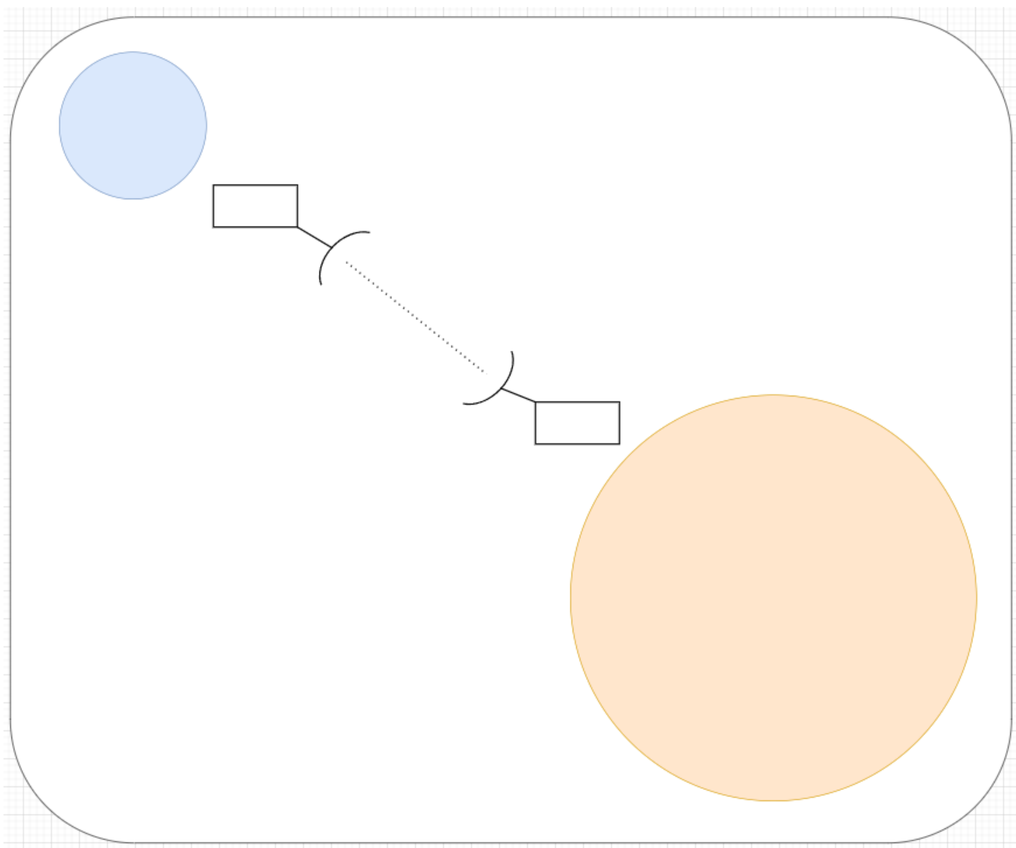

Figure 5.2 generic direct link scenario

For the purposes of this study, a simple comparison will be held between both outposts, the maximum line of sight time and data transmission rates. The orbital periods will be used to find the maximum line of sight time and that will be used in conjunction with typical data transmission rates for X-Band communications and laser communications. The methodology for this is outlined in equations 5.9 to 5.11 below.

$$T_{LoS} = (P_{Jupiter}/2) \tag{5.9}$$

$$Passes = T_{LoS}/\left({}^{P_{Mars}}/_{2}\right) \tag{5.10}$$

$$Total\ Data = (Data\ Rate) * T_{LoS} \tag{5.11}$$

5.4 Computational Approach

The knowledge and methodology laid out in the prior section was translated to multiple computational modes of analysis. The first method is to simulate the orbits via governing equations found in section 5.3 above in MATLAB manually. Once the MATLAB results are understood and can be used for the high-level communications study, the ConOps is then simulated in NASA's GMAT software.

5.4.1 MATLAB

MATLAB was utilized for basic plotting of each spacecraft's respective orbit; this was done to understand the mechanics fully before simulating it in different software. This simulation allows for an initial communications analysis to be conducted to begin understanding the benefits of the HOPE program. Both spacecraft have a simple low energy orbit about their celestial body and can act as a single instance transmitter and receiver along the chain of outposts.

5.4.2 GMAT

Both spacecraft operations were additionally modeled in GMAT, this allows for a further understanding of the interactions that may occur between the outposts. By modeling it in GMAT, it is possible to compare the results to the MATLAB results and see where things may be improved at either end. It is imperative that multiple resources be utilized to keep the results as neutral as possible.

5.5 Results

The computational results are shown in the succeeding sections below. These results represent a multidisciplinary study regarding a notional HOPE operational concept and contain elements of an orbital mechanics study concerned with communications.

5.5.1 MATLAB

These results come from MATLAB, and the framework from which comes from the analytical methodology found in section 5.3. These results represent one iteration of the study that may be conducted to understand the system and system behaviors.

Figures 5.3 and 5.4 below represent planar views of each respective outpost orbit about their planets. The orbit parameters can be reviewed in table 5.2.

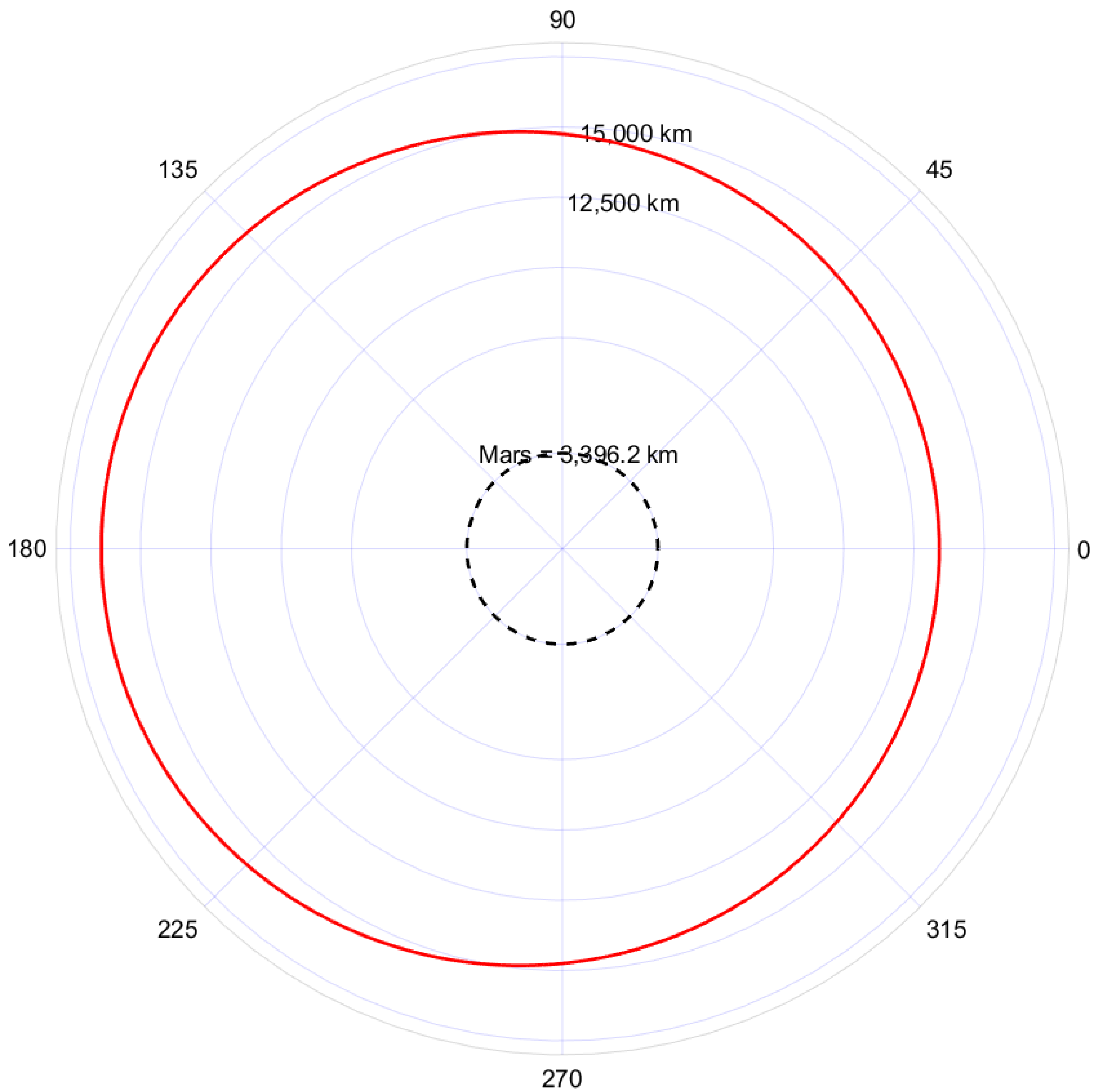

Figure 5.3 planar Mars orbit visualized

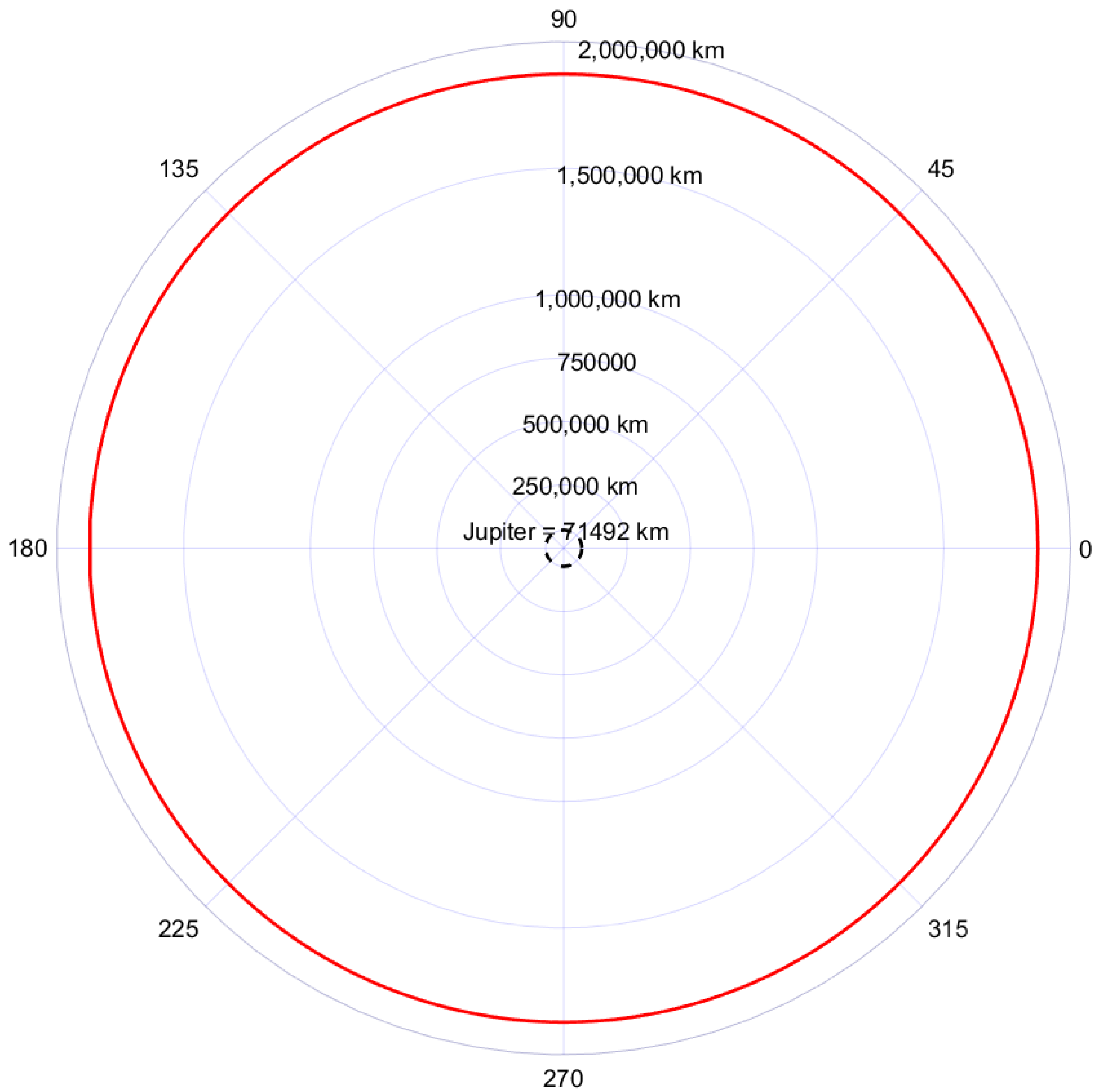

Figure 5.4 planar Jupiter orbit visualized

Table 5.3 below shows the results of the planar orbit study conducted in MATLAB. These results come from the code displayed in appendix A.1 and A.2, they are just a summary of the most relevant orbital parameters.

Table 5.3 planar orbit study summary

MATLAB orbital summary	
Mars Outpost	
Parameter	Value
Orbital Period	85,233 seconds
Angular Momentum	29,172 km^2/s
Orbital Energy	-1.08 km^2/s^2
Orbital Velocity	1.43 km/s
Jupiter Outpost	
Parameter	Value
Orbital Period	1,429,700 seconds
Angular Momentum	15,393,000 km^2/s
Orbital Energy	-33.8 km^2/s^2
Orbital Velocity	8.22 km/s
Communications	
Line of Sight Transmission Passes	16.77 passes
Line of Sight Window Time	42,617 seconds
Total Line of Sight Time per Jupiter Outpost Orbital Period Allowance	714,850 seconds
Lasercom Data Transfer	107,228 GB @ 1.2 gigabit/s [39]
X-Band Data Transfer	313 GB @ 3.5 megabit/s [40]

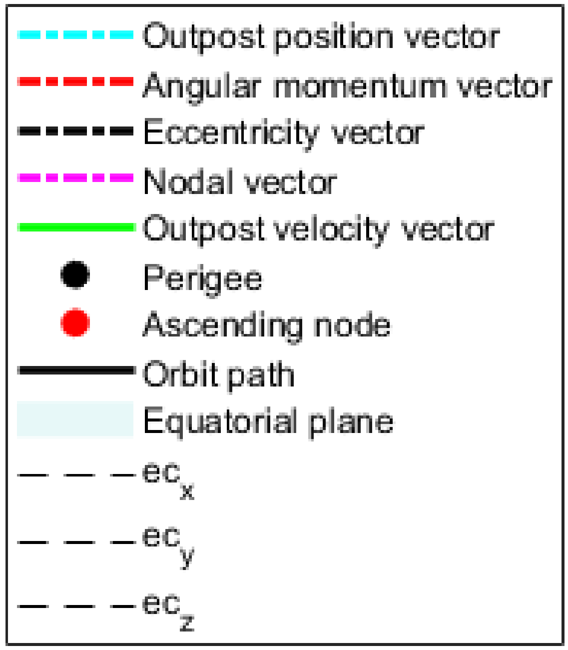

Figure 5.5 orbit plot legend

Figure 5.5 above is the legend for the succeeding orbit plots, only the results from plotting the Mars orbit in the three-dimensional space are included. Figures 5.6 and 5.7 show the example orbit from a top view perspective to see the orbit in its entirety. Figures 5.8 through 5.10 show multiple close ups of the spacecraft position in the orbit path.

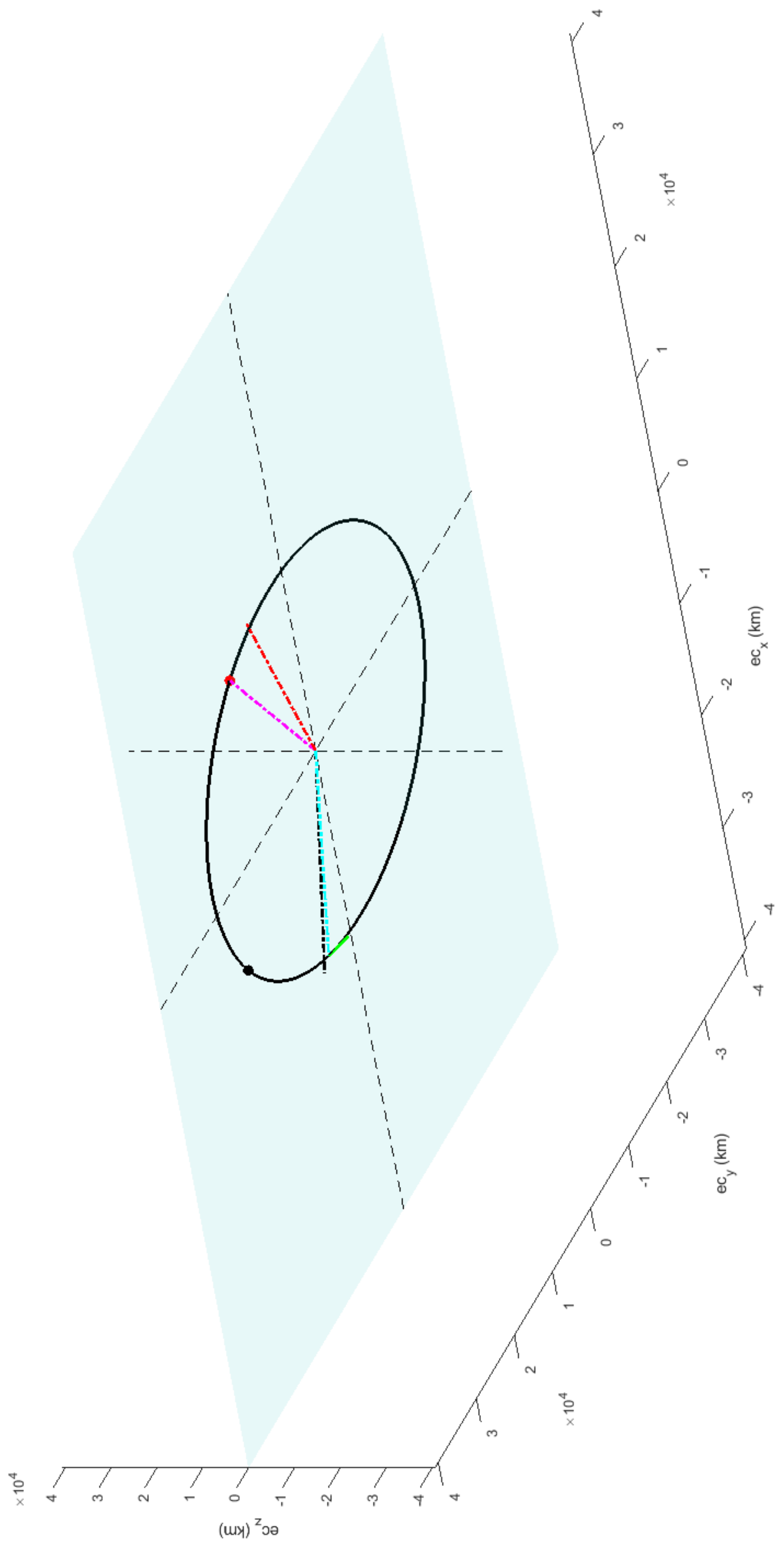

Figure 5.6 Mars outpost orbit

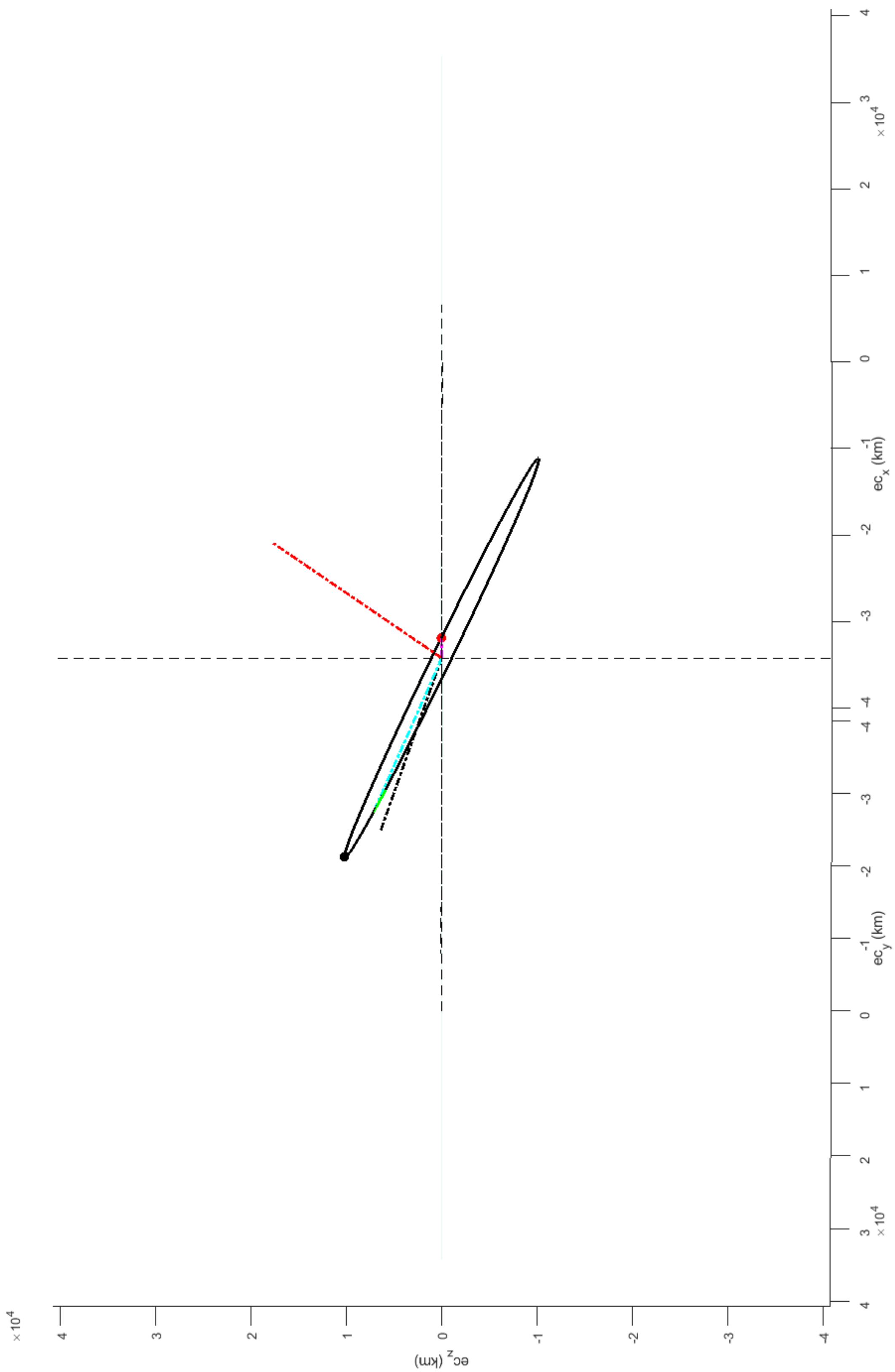

Figure 5.7 Mars outpost orbit view rotated

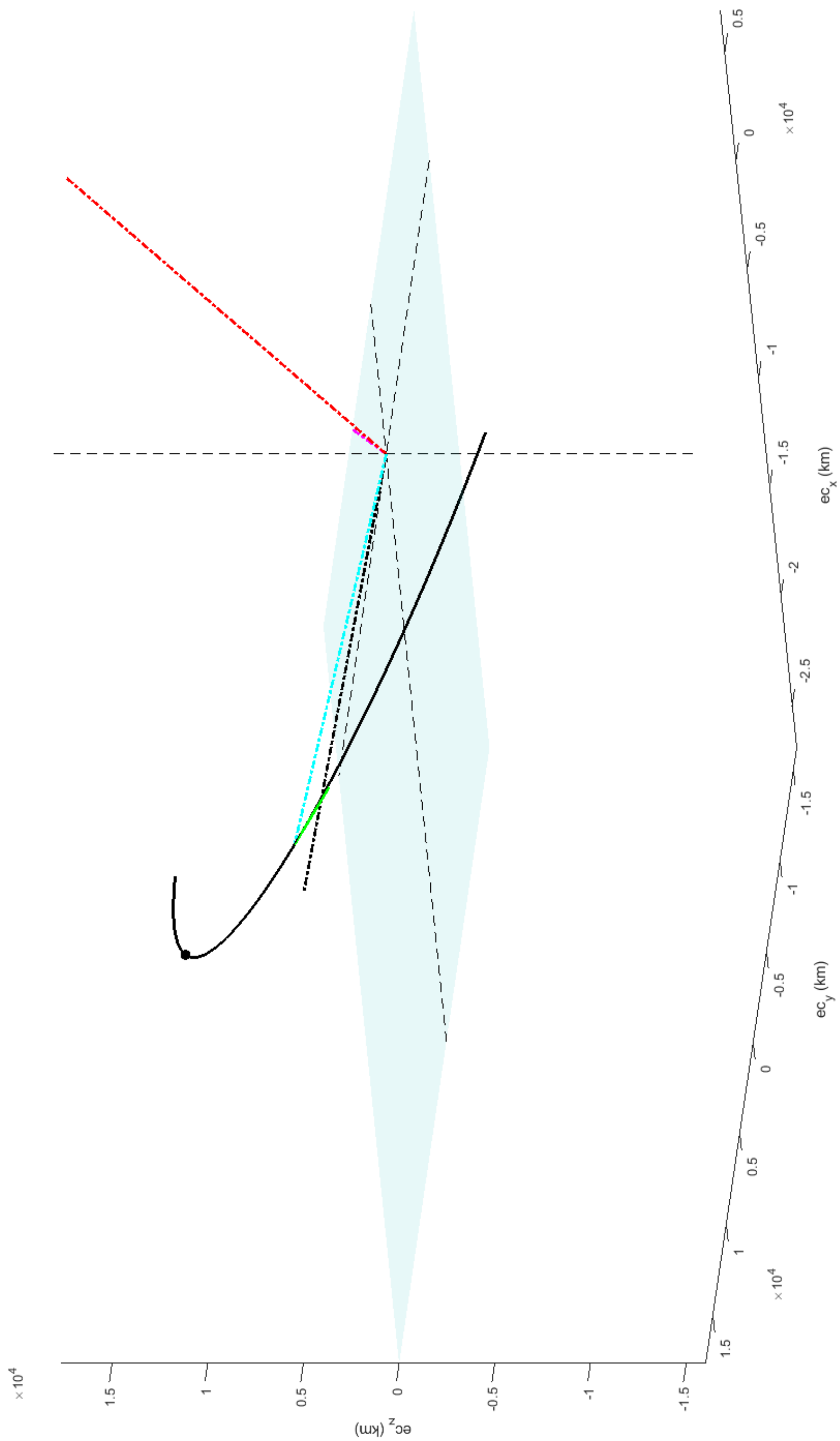

Figure 5.8 Mars outpost orbit close up

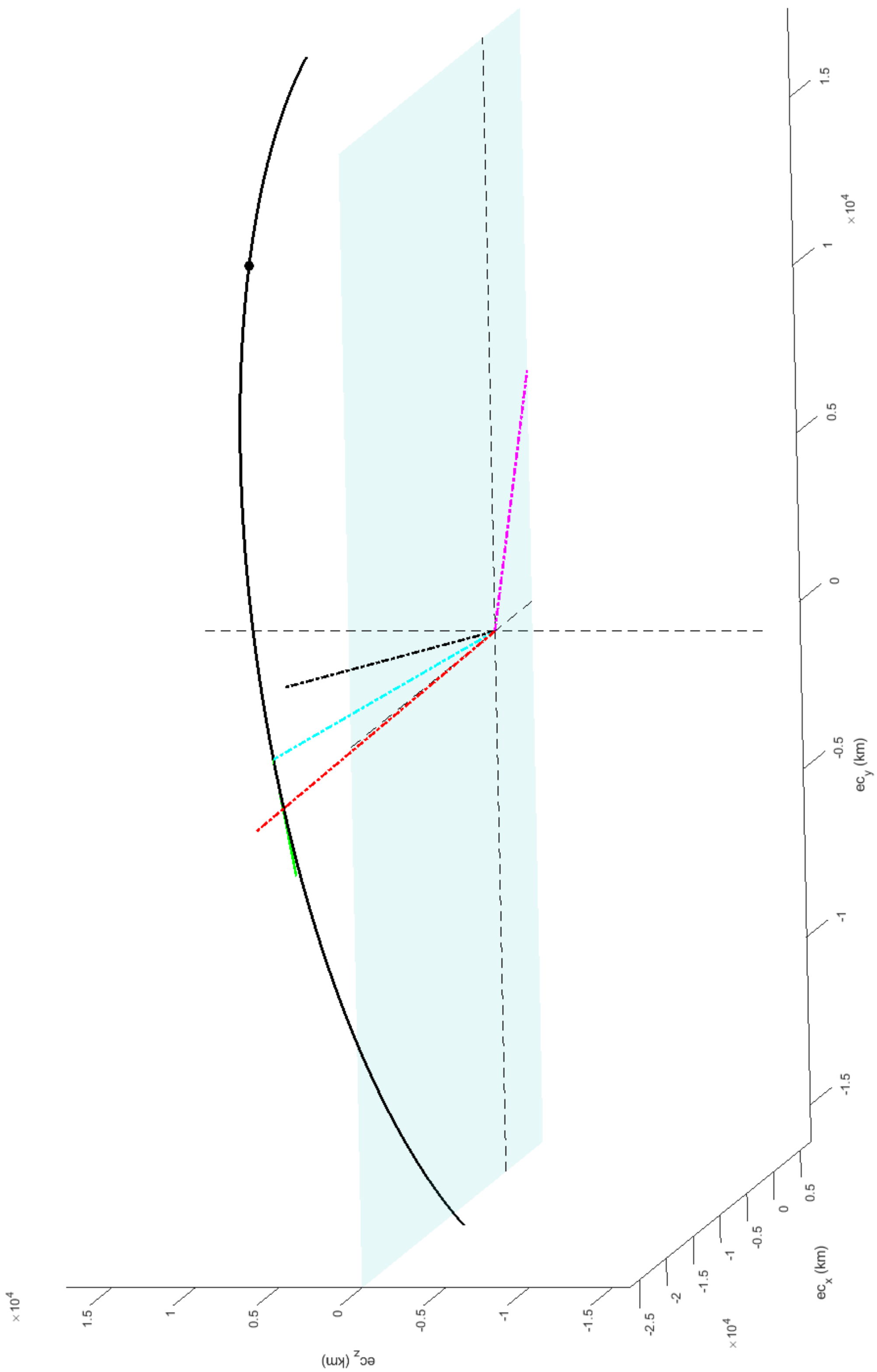

Figure 5.9 Mars outpost orbit close up alt. view

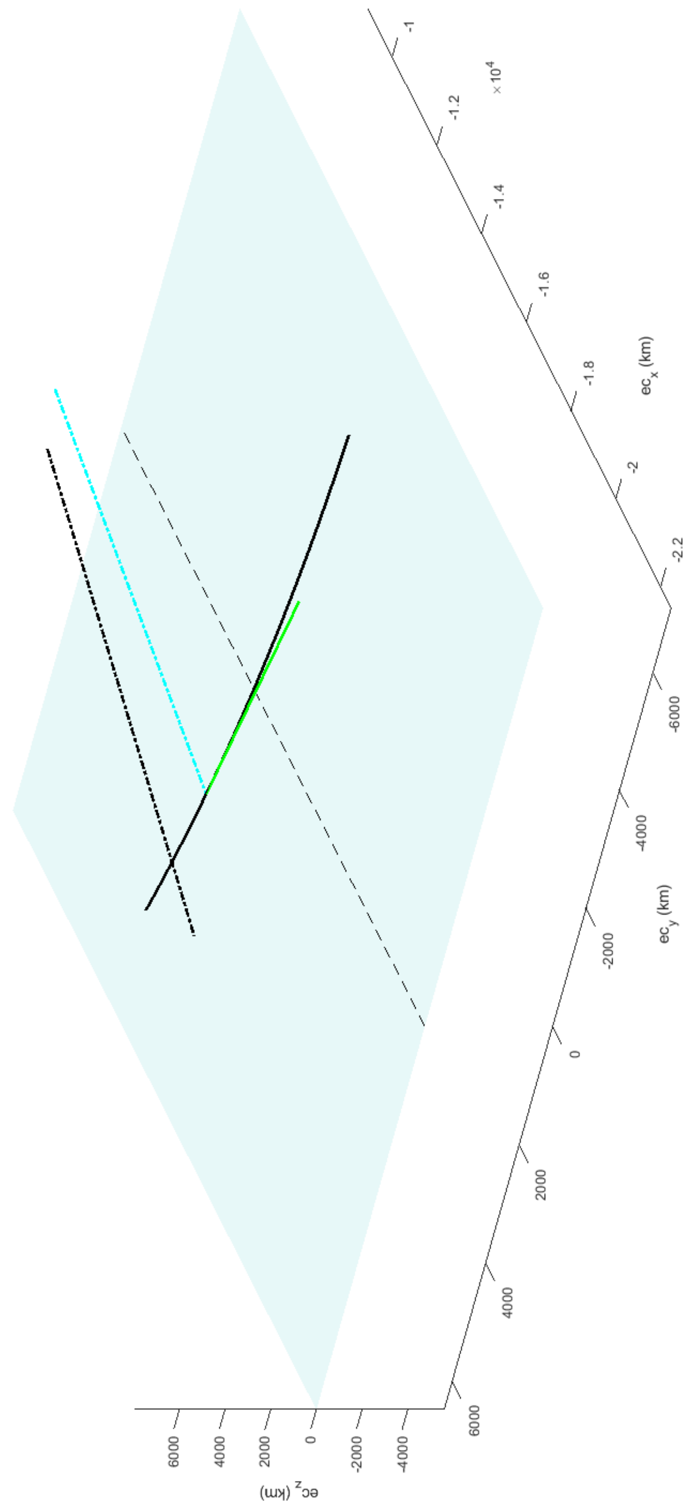

Figure 5.10 Mars outpost orbit close up alt. view 2

5.5.2 GMAT

These results come from NASA's GMAT tool, this is a free tool by NASA for simulating orbits and mission design. These represent the logical next step once the system is understood from the MATLAB implementation, to simulate and visualize the mission in a higher fidelity model that may contain further considerations with the physics and multi-object domain that may not be considered in the MATLAB effort.

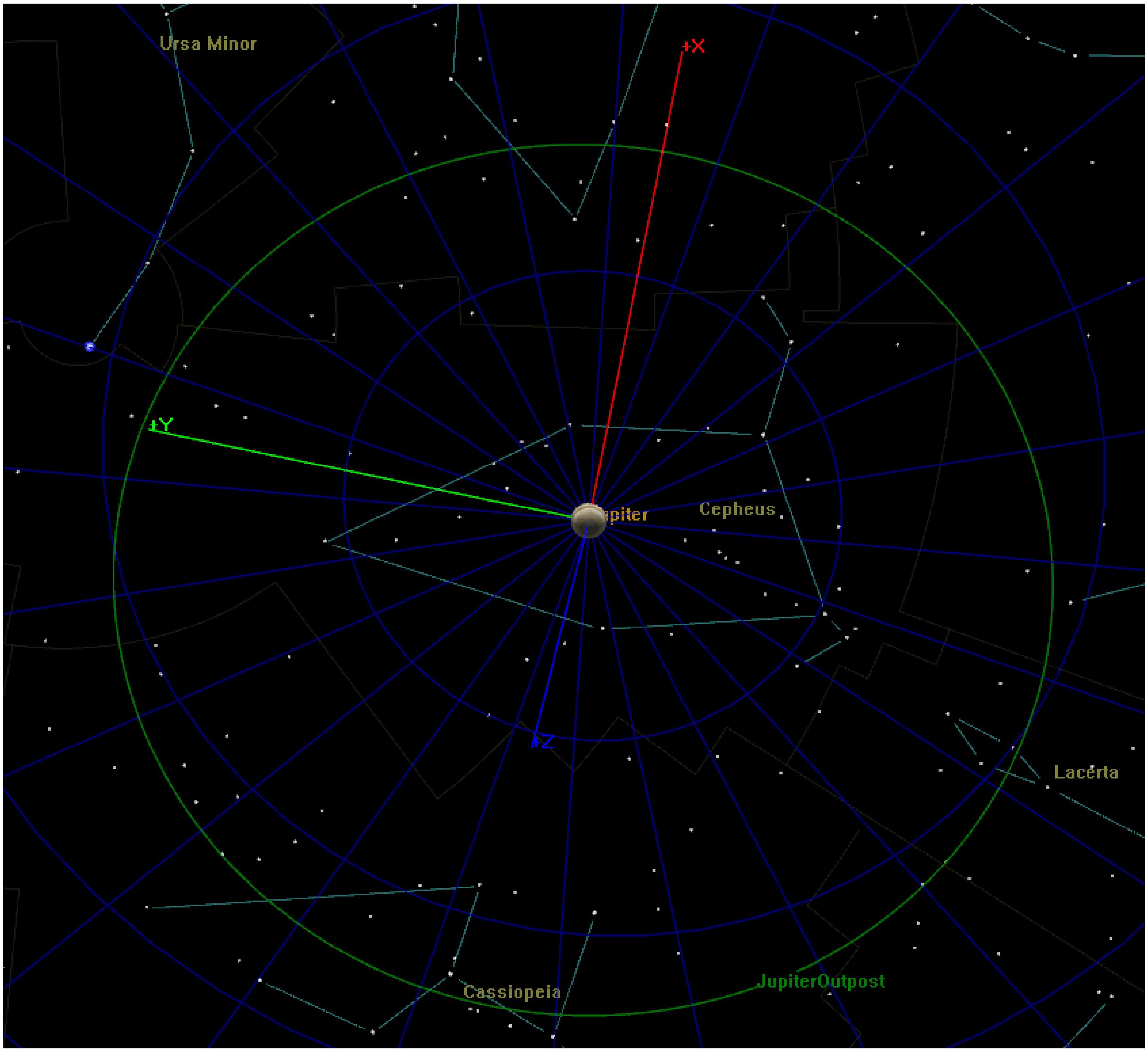

Figure 5.11 Jupiter outpost orbit visualization

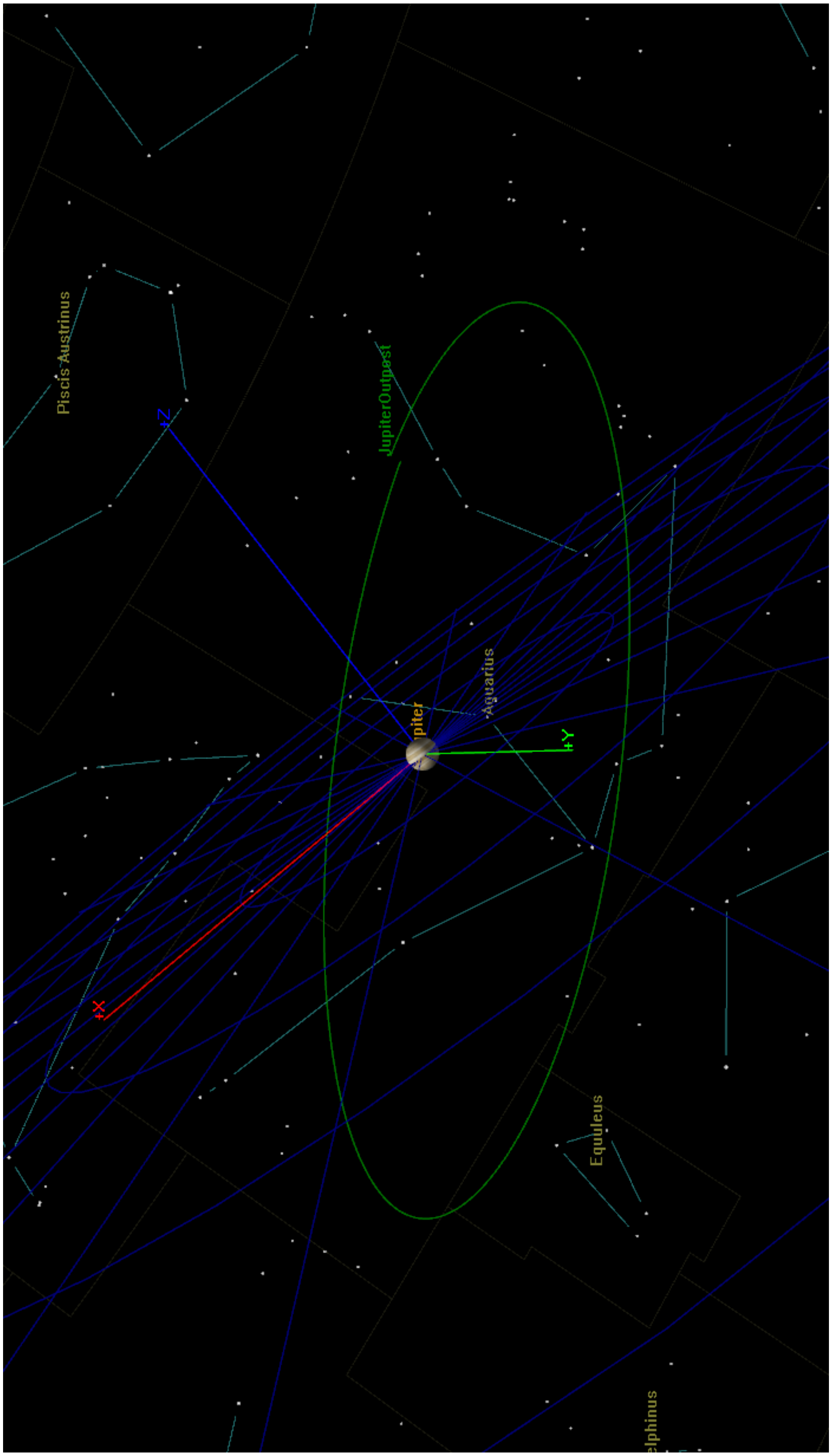

Figure 5.12 Jupiter outpost orbit alt. view

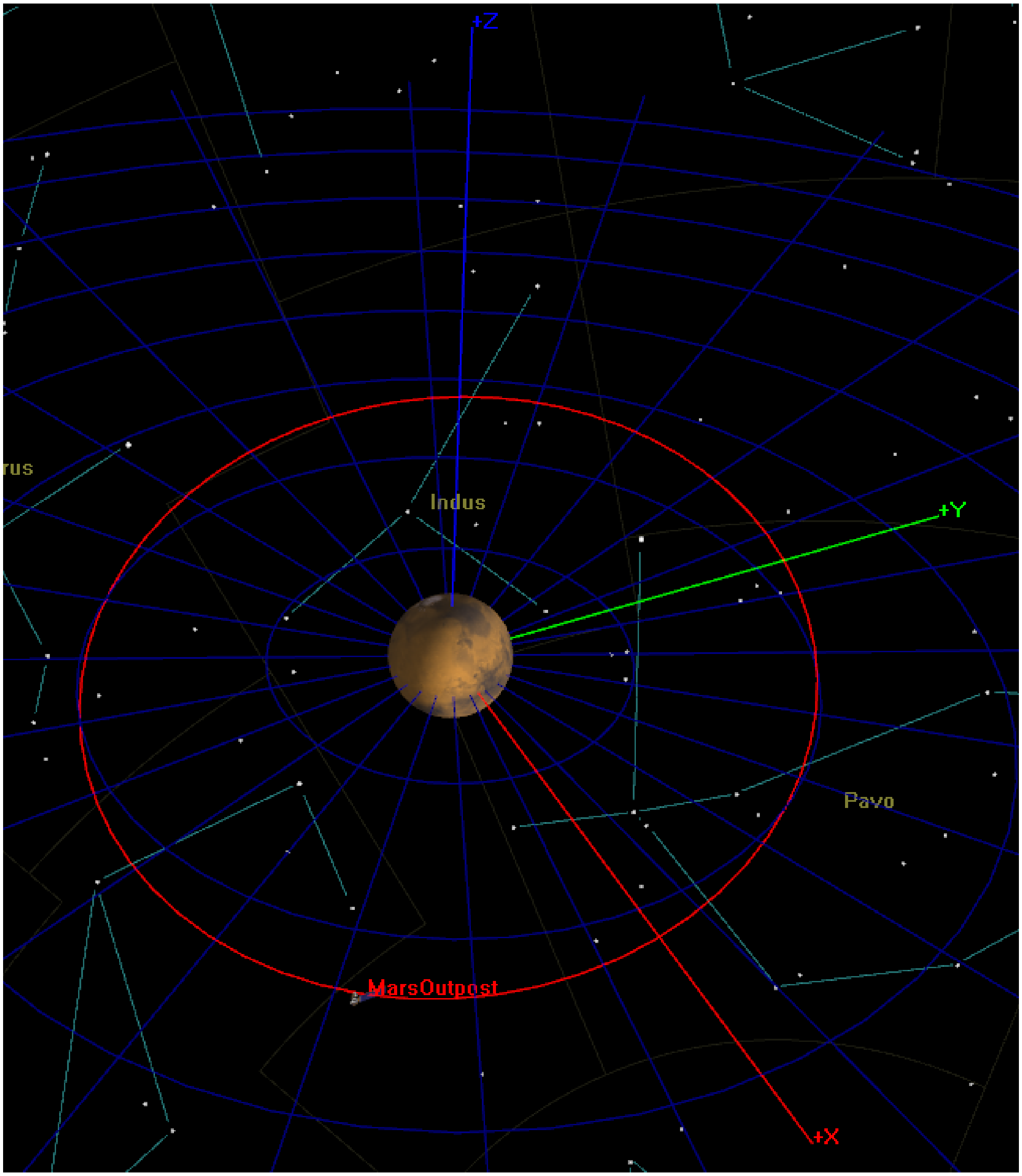

Figure 5.13 Mars outpost orbit visualization

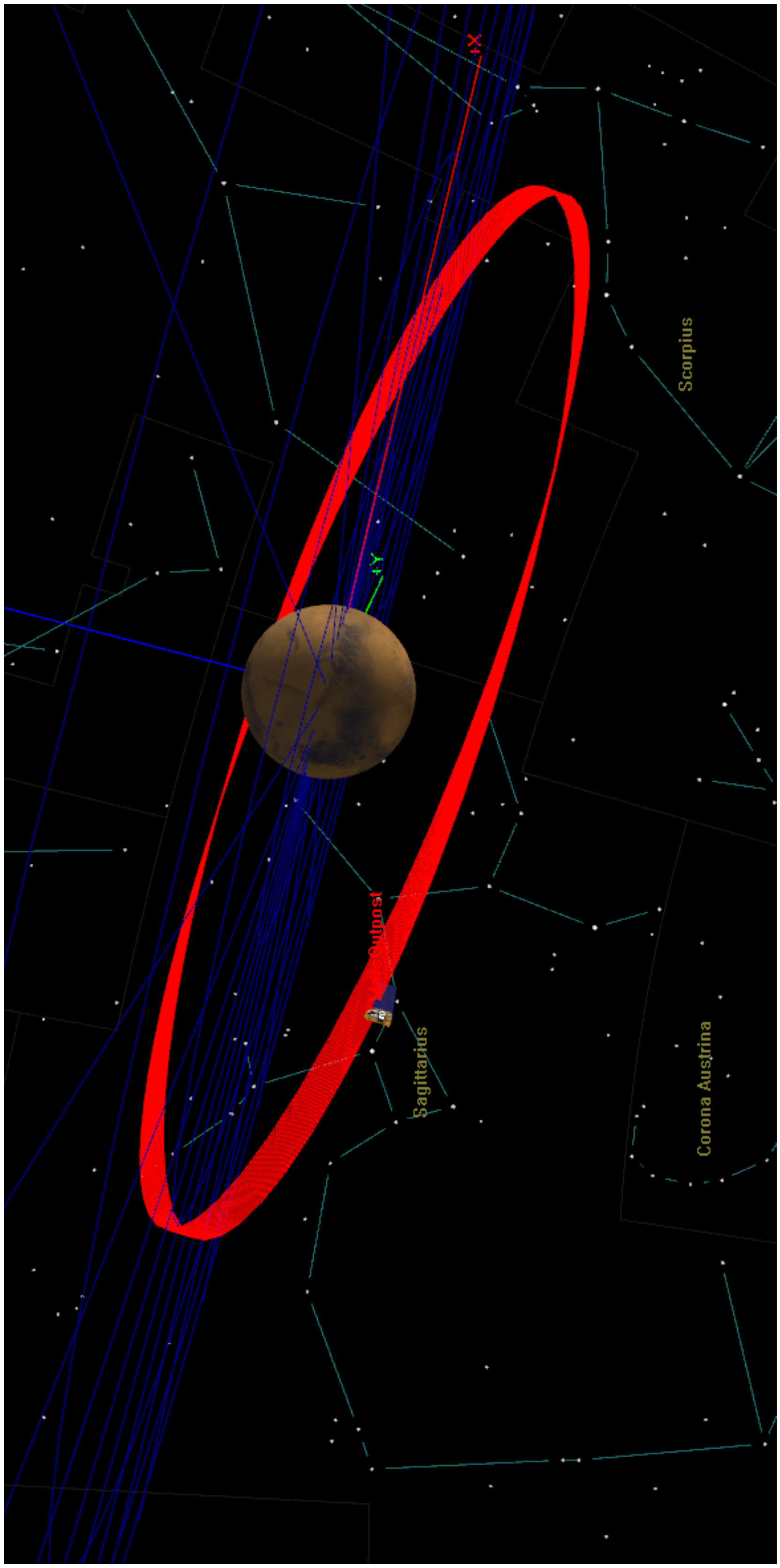

Figure 5.14 Mars outpost orbit alternate view with Jupiter orbital period

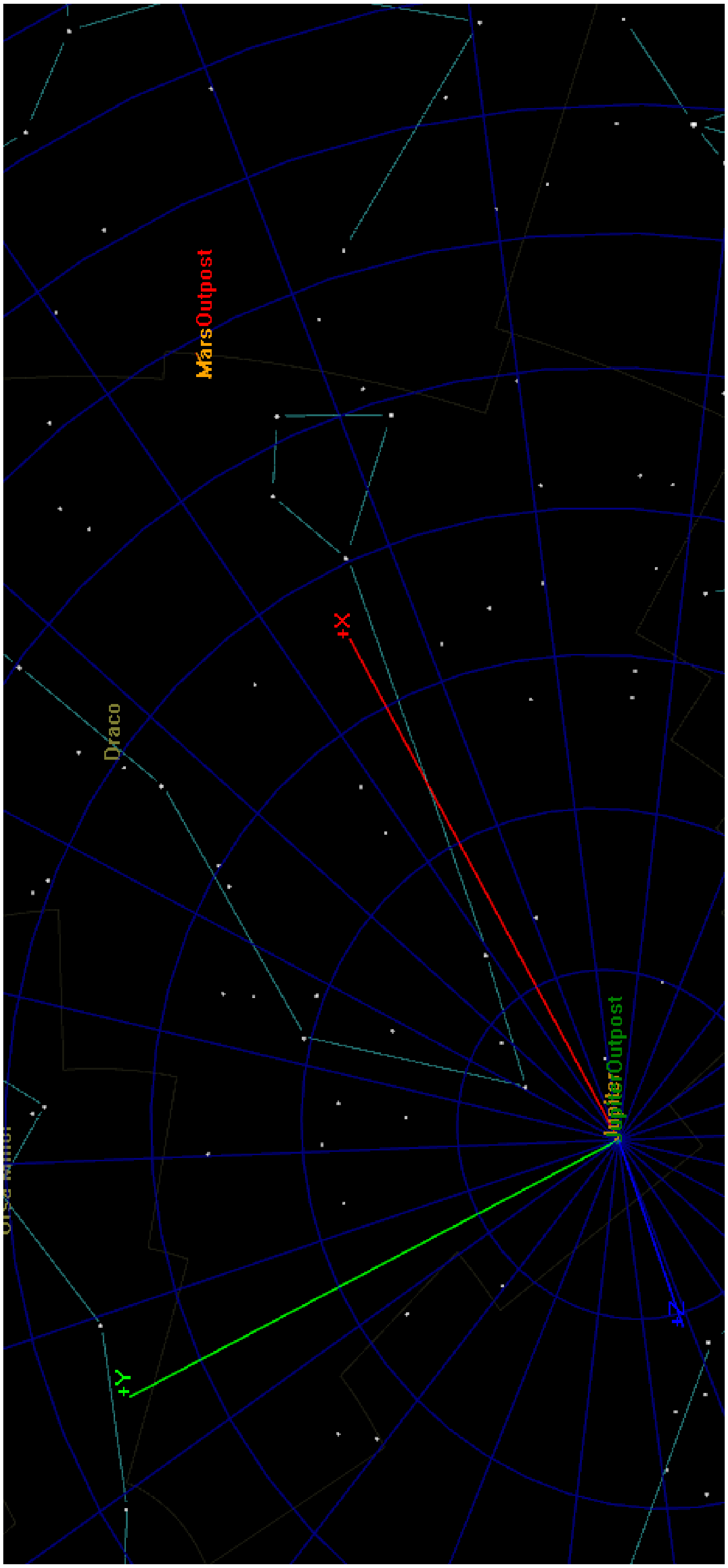

Figure 5.15 Mars and Jupiter outpost distance visualization

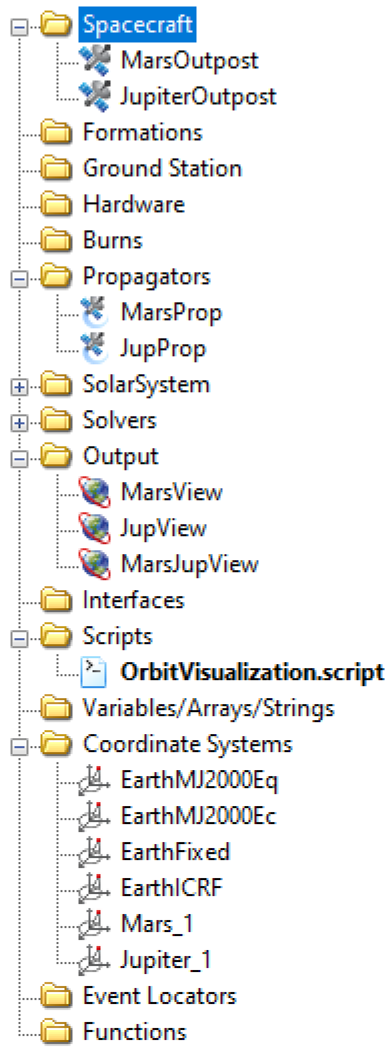

Figure 5.16 GMAT resource tree

5.6 Discussion

Now that the operational concept has been looked at through two different methods, they can be compared and discussed appropriately. Table 5.2 outlines the overall mission context and houses some of the inputs used for both MATLAB and GMAT results. Sections 5.3.1 to 5.4 outline the analytical and computational tools and how they are tied to the described methodologies.

Looking first at the MATLAB planar orbit results, figures 5.3 and 5.4 represent one iteration of a planar orbit study. As seen in appendix A.1 and A.2 the planar orbit study allows for the characterization of these orbits, of which the results are displayed in table 5.3 above. As seen in the table and figures, the orbits are both circular in nature and low maintenance, this is confirmed by their slightly negative orbital energies found in table 5.3. Based on the figures and orbital summary it can be concluded that these orbits are a good first step in the study, ignoring some external factors that will be introduced into the model as the fidelity increases.

Next, with the planar behavior understood, the study is taken to the next level of fidelity by considering them in a three-dimensional space. This will increase the accuracy of the model being built in MATLAB and will require further considerations that were ignored for the planar study, for this study it was chosen to work using the Keplerian elements as a basis to fully describe the simulated orbits. Figures 5.11 through 5.14 depict each outpost and their respective orbits, with 5.14 displaying the behavior with respect to the orbital period of the Jupiter outpost. It is possible to visualize the distance within GMAT through figure 5.15, a zoomed-out view of both planets, although it is difficult to make out the Mars outpost, it has been labelled. Figure 5.16 displays the resource tree in GMAT when running this script; the different outposts, reference frames, and propagators to support the multi planetary mission can be seen with the exact parameters for each input being available in appendix B.1.

5.7 Conclusion

With the analytical and simulation work done here, the initial interactions captured between each outpost can be investigated as the Jupiter outpost will have a much longer orbital period than the Mars outpost. This delta in orbital period means that the Mars outpost will make multiple passes to send and receive from the Jupiter outpost, the results of which are shown in table 5.3 and the preceding sections. This section serves as the beginning to understanding how a large-scale distributed space system like HOPE can be analyzed.

6. Considerations

6.1 Environmental Considerations

A core theme of the HOPE program and future large scale space programs that must be present are the environmental aspects that come with each stage of the lifecycle. When considering environmental factors, an immediate benefit of HOPE comes from no longer depending on the Earth for all materials, processing, manufacturing, and post processing considerations, these will be largely handled in-situ or off planet. A long-term environmental consideration with programs like HOPE where in-situ resources are utilized are that wherever these activities are occurring, humankind has already gotten an abundance of lessons learned from the Earth and will apply holistic, sustainable, and humane solutions for every aspect of the program lifecycle.

6.2 Economic Considerations

Large scale state of the art programs like HOPE requires lots of time, financial investments, resources, and large workforces. There will always remain the question of "Why not invest those resources in things right here on Earth", in an age where commercial space travel is not too far off it is still fair to say that the majority of cutting-edge, boundary pushing technologies will not directly benefit the common person. This is a valid question to ask when there are so many problems right here on Earth that must be solved, world hunger, wars, homelessness, economic disparities and more; These are highly complex issues and are incredibly difficult to even fathom solutions for. This is a very relevant topic in the current state of space exploration, as it was in the past, and will be for future programs.

There is an inherent disconnect that exists for many people between the idea of large space programs and the common person. If someone truly investigates this topic, starting with earliest space programs such as the Mercury, Apollo, Space Shuttle Program or even SpaceX's Falcon and NASA's current Artemis program, there is a myriad of benefits that can be traced from these cutting-edge programs to the common people. Historic programs allow us to see the long-term effects that a large-scale ambitious space program may have on the worldwide and domestic economy, while more recent programs in turn have opened many doors even sooner than their historic counterparts.

The greatest pieces of evidence come from both the Apollo and space shuttle program by NASA, arguably the largest space programs globally that pushed the boundaries of what was considered possible for humankind. Both programs were driven by presidential directives for an overarching goal, these goals accomplish a multitude of overall national visions such as increasing humankind's knowledge of the solar system and beyond; rejuvenating interest in science and engineering; developing technologies with terrestrial applications; facilitate further space exploration and commercialization; and boosting the U.S. economy [41].

With private companies such as SpaceX, Virgin Orbit and Rocket Lab dominating the small satellite launch provider market, there has been a large shift in the dynamics of small satellite missions. The greatest shift has been accessibility to these space missions and the barrier to entry gradually decreasing, this shift coupled with the growing CubeSat market has allowed for more opportunities for historically disenfranchised groups whether it is small businesses or educational outreach missions by universities and high school students. In figure 6.1 below, we can see the growing commercial and academic missions through the years.

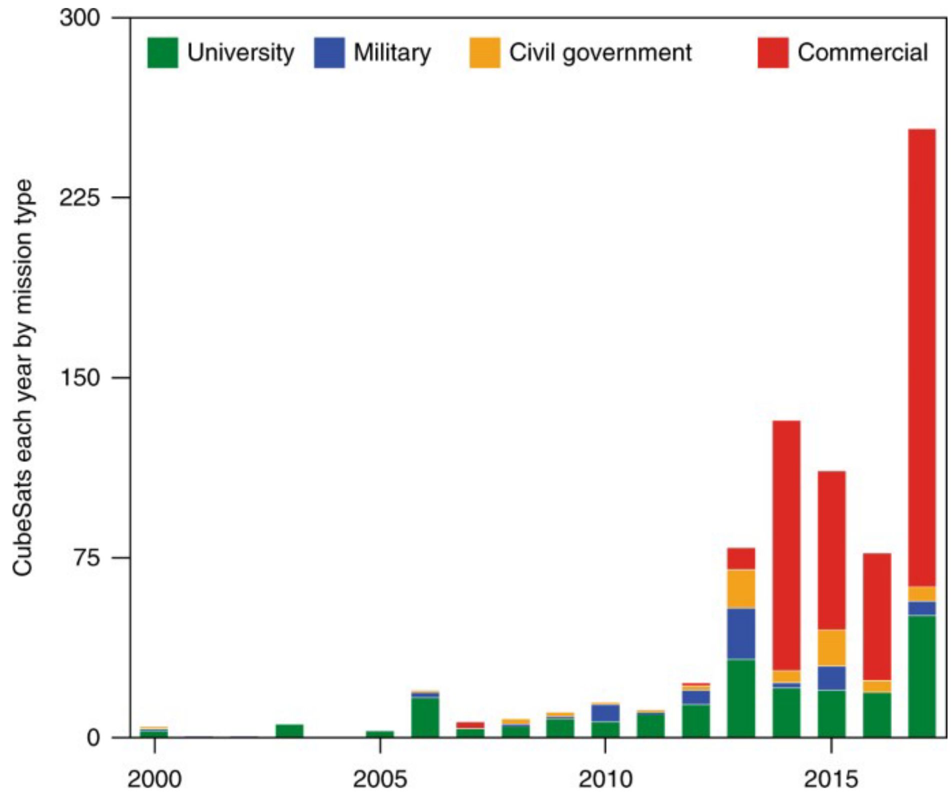

Figure 6.1 cubesat missions by year [42]

At an initial glance it may seem like there is a large disconnect from these large-scale space programs to the common people, however based on historic and current evidence it is hopefully apparent that this disconnect truly does not exist. Programs like HOPE will help to drive innovation that trickle down technologies that reach the common people, more jobs for people on earth, and inspiring the future generation to reach higher goals.

7. Conclusion

7.1 Next Steps

With the conclusion of this design study, the system has only been partially developed. Regarding the system architecture, design has been conducted to the system level with a conceptual approach to each element. The orbital study only analyzes a single proposed implementation of the HOPE outpost system, there are many ways one could expand upon this design study to bring it to the next steps.

The fundamental elements of a high-level system architecture and the necessary background work have been conducted in the first half of this design report. A few suggestions to expand upon this research may include further decomposition to the subsystem levels and below; continuing the current scope carried out in a recursive and iterative nature; Refinement of the various solution domains; and continuing trade studies to narrow down on solution domain choices to name a few. There are many paths to take the system architecture down, it has been left open ended intentionally to accommodate for future technologies and other architects to take over as their own.

Any program like HOPE can be designed at the architecture level with many different design choices, however the backbone of taking these concepts into conception will rely heavily on expansive analyses on lots of different parts of the system. This design study decided to begin work that is required to consider what may be necessary at a high level for a Jupiter implementation. With the current system architecture, further analysis can be done on investigating a Jupiter implementation of the program. Alternatively, other bodies of interest may be investigated for feasibility and to see what may be required for such an implementation. The current architecture also supports notional amounts of mechanical design, one may begin to visualize what such an implementation of HOPE may look like and the manufacturing concerns. Another possible route to investigate with the current architecture would be an in-depth investigation on communications between bodies of interest and the infrastructure or specific considerations that would be necessary to support a multibody communications network such as a link budget study considering specific link scenarios, losses, and transmission rates or synchronizing orbits to maximize transmission efficiency. These suggestions are just a few ways that someone could take the work started in this design study and expand upon it.

Larger undertakings could include a full system architecture decomposed to levels below the subsystems in a full digital model, this would reflect where many larger programs and designs are heading in the current state of the industry, leveraging model-based systems engineering tools. This undertaking would include traceability from the highest level of the system to the lowest, from requirements, to behaviors, physical and logical representations, and more. The benefits of designing a system digitally with these strong traceable linkages allow for as much risk reduction as possible as early as possible among many other core benefits of the digital engineering landscape.

7.2 Lessons Learned

Reaching the conclusion of this first effort on HOPE, an opportunity presents itself to reflect upon the design study. Specifically thinking about the various lessons learned to be implemented next time or if this study were to be conducted again. Some of these lessons learned encompass the system architecture design approach and others pertain to the orbital mechanics study carried out in the second half of this report. Both studies offer unique opportunities for reflection and how one may approach a similar problem.

One lesson from the system architecture design process is the methodology, it was chosen to tailor two different approaches to see the benefits or cons of doing so. Both methodologies leveraged came from well-established and widely used sources, one being NASA's Systems Engineering Handbook, and the other being Wasson's Problem-Solving Methodology that is widely adopted in the private industry. It would be an interesting study to see how much may differ from following either methodology exactly, rather than tailoring a mashup of the two in the manner that was done for this report. There are no benefits or drawbacks for either methodology that would warrant one to declare the other as supreme, rather each specific project or program must consider either approach and decide themselves which makes the most sense for the problem at hand. In some cases, a tailored approach such as the one in this report may be adopted, it is all up to the system architects and/or the relevant directives if one is working under the umbrella of a larger entity.

Another aspect of the project that may be considered a lesson is the approach to and overall mission design for the orbital mechanics study of the report. The problem posed here is reflective of a single instance and singular mission concept of the HOPE program. An alternative approach that would result in a substantial study would be to investigate a true galactic distributed space system network implementation of the HOPE program, and to focus on characterizing the communications framework. Characterizing that aspect of the system is vital to understanding how viable a program like HOPE is and the technological gaps that must be addressed before it becomes viable.

An overall lesson to implement for next time would be to put a larger emphasis on the human safety factor of the program, there are a lot of assumed technologies in this design study that support a long termed manned deep space orbital presence. These risks and the mitigations necessary to implement a program like HOPE will be instrumental in the viability of space station programs that will exist in the future.

7.3 Conclusion

The HOPE program is an intragalactic space station program that will be leveraged as a communications network for relaying messages from any point in the galaxy to another without having to rely on a direct line of sight from the sender to the receiver. Messages will be transmitted from one station to another until the destination is reached, this will allow for more opportunities for communication throughout the galaxy. The modular space stations will allow for tailoring each respective body of interest's station to that body's scientific objectives and environmental requirements resulting in a science and exploration hub at key locations in the galaxy.

A notional system architecture has been designed to the system level, with relevant systems engineering trade studies being conducted to lead to the decisions made to result in the proposed design solution. This design is not the be-all and end-all solution that may exist for the HOPE program and it should not be, this is simply the initial take at attempting to define a possibility within the solution space of the proposed problem.

An orbital analysis has also been conducted jointly with the architecture design, to study and model a single implementation of the outpost system and how it may behave in this instance. This simulation follows one of the proposed operational concepts within the system level use cases to demonstrate the viability of one such instance. This analysis is an example of how something like a use case may be developed at the system architectural level and trickle to downstream engineering in the form of an orbital analysis.

These elements can be considered the first attempt at defining Humanity's Orbital Presence Endeavour.

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Appendix A: MATLAB Code

A.1 Jupiter planar orbit plotter

```
%%%%%Jupiter Orbit%%%%%
clear all, clc

%Define Constants
M_jup = 1898.13E24; %kg, Mass of Jupiter
R_jup = 71492; %km, equatorial radius of Jupiter
G = 6.67E-20; %km^3/kg*s^2, Universal Gravitational Constant

%Parameters of interest
R_p = 1800000 + R_jup; %km Perigee
R_a = 1800000 + R_jup; %km Apogee
e = (R_a - R_p)/(R_a + R_p); %Eccentricity
h = sqrt( (R_p)*(1+e)*(G*M_jup) ); %km^2/s Specific Angular Momentum
a = (R_a + R_p)/2; %Semi major Axis
P = 2*pi*sqrt( (a^3)/(G*M_jup) ); %Orbital Period
E = ( -G*M_jup )/( 2*a ); %Orbit Energy
V = sqrt( 2*( ((G*M_jup)/(R_a))+E ) ); %m/s Velocity
V_circ = sqrt((G*M_jup)/(R_a)); %m/s, velocity to maintain circular orbit check

%Simulation Time
t0 = 0;
tf = P;
dt = 1E-1;
tspan = t0:dt:tf;

%Define Initial Conditions
r_0 = R_a; %Starting at Apogee
rdot_0 = 0; %m/s Velocity
theta_0 = 0; %Defining Apogee at 0 degrees
thetadot_0 = V/R_a; %deg/s
x0 = [r_0; rdot_0; theta_0; thetadot_0];

%ode45 EOM
[rSOL, thetaSOL] = ode45( @(t,x)R2BEOM(t,x,G,M_jup), tspan, x0 )
```

```
rSOL = 14296705×1

10^6 ×

         0
    0.0000
    0.0000
    0.0000
    0.0000
```

```
    0.0000
    0.0000
    0.0000
    0.0000
    0.0000
      ⋮
thetaSOL = 14296705×4
```

10^6 ×

```
    1.8715         0         0    0.0000
    1.8715   -0.0000    0.0000    0.0000
    1.8715   -0.0000    0.0000    0.0000
    1.8715   -0.0000    0.0000    0.0000
    1.8715   -0.0000    0.0000    0.0000
    1.8715   -0.0000    0.0000    0.0000
    1.8715   -0.0000    0.0000    0.0000
    1.8715   -0.0000    0.0000    0.0000
    1.8715   -0.0000    0.0000    0.0000
    1.8715   -0.0000    0.0000    0.0000
      ⋮
```

```
%Mars
thetajup = linspace(0,2*pi)
```

```
thetajup = 1×100

         0    0.0635    0.1269    0.1904    0.2539    0.3173    0.3808 ⋯
```

```
rjup = R_jup*ones(100,1)
```

```
rjup = 100×1

       71492
       71492
       71492
       71492
       71492
       71492
       71492
       71492
       71492
       71492
      ⋮
```

```
%Plot
figure,
polarplot(thetaSOL(:,3), thetaSOL(:,1), 'r-');
hold on
polarplot(thetajup,rjup,'k--')
pax = gca;
pax.ThetaColor = 'k';
pax.RColor = 'k';
rticks([0 71492 250000 500000 750000 1000000 1500000 2000000]);
```

```
 rticklabels({'','Jupiter = 71492 km','250,000 km','500,000
km','750000','1,000,000 km','1,500,000 km','2,000,000 km'});
 thetaticks(0:45:315);
 pax.GridColor = 'blue';
 title('Jupiter Outpost Orbit Visualized');
 set(findall(gcf, 'type', 'line'),'linewidth',2);
 set(gca,'fontsize', 14);
```

A.2 Mars planar orbit plotter

```
%%%%%Mars Orbit%%%%%
clear all, clc

%Define Constants
M_mars = 0.64169E24; %kg, Mass of Mars
R_mars = 3396.2; %km, equatorial radius of Mars
G = 6.67E-20; %km^3/kg*s^2, Universal Gravitational Constant

%Parameters of interest
R_p = 17000 + R_mars; %km Perigee
R_a = 17000 + R_mars; %km Apogee
e = (R_a - R_p)/(R_a + R_p); %Eccentricity
h = sqrt( (R_p)*(1+e)*(G*M_mars) ); %km^2/s Specific Angular Momentum
a = (R_a + R_p)/2; %Semi major Axis
P = 2*pi*sqrt( (a^3)/(G*M_mars) ); %Orbital Period
E = ( -G*M_mars )/( 2*a ); %Orbit Energy
V = sqrt( 2*( ((G*M_mars)/(R_a))+E ) ); %m/s Velocity

%Simulation Time
t0 = 0;
tf = P;
dt = 1E-1;
tspan = t0:dt:tf;

%Define Initial Conditions
r_0 = R_a; %Starting at Apogee
rdot_0 = 0; %m/s Velocity
theta_0 = 0; %Defining Apogee at 0 degrees
thetadot_0 = V/R_a; %deg/s
x0 = [r_0; rdot_0; theta_0; thetadot_0];

%ode45 EOM
[rSOL, thetaSOL] = ode45( @(t,x)R2BEOM(t,x,G,M_mars), tspan, x0 )
```

```
rSOL = 884664×1
```

```
10^4 ×

           0
      0.0000
      0.0000
      0.0000
      0.0000
      0.0001
      0.0001
      0.0001
      0.0001
      0.0001
        ⋮
thetaSOL = 884664×4

10^4 ×

      2.0396         0         0    0.0000
      2.0396   -0.0000    0.0000    0.0000
      2.0396   -0.0000    0.0000    0.0000
      2.0396   -0.0000    0.0000    0.0000
      2.0396   -0.0000    0.0000    0.0000
      2.0396   -0.0000    0.0000    0.0000
      2.0396   -0.0000    0.0000    0.0000
      2.0396   -0.0000    0.0000    0.0000
      2.0396   -0.0000    0.0000    0.0000
      2.0396   -0.0000    0.0000    0.0000
        ⋮
```

```
%Mars
thetamars = linspace(0,2*pi)
```

```
thetamars = 1×100

           0    0.0635    0.1269    0.1904    0.2539    0.3173    0.3808 ⋯
```

```
rmars = R_mars*ones(100,1)
```

```
rmars = 100×1

10^3 ×

      3.3962
      3.3962
      3.3962
      3.3962
      3.3962
      3.3962
      3.3962
      3.3962
      3.3962
      3.3962
        ⋮
```

```
%Plot
figure,
```

```
polarplot(thetaSOL(:,3), thetaSOL(:,1), 'r-');
hold on
polarplot(thetamars,rmars,'k--')
pax = gca;
pax.ThetaColor = 'k';
pax.RColor = 'k';
rticks([0 3400 7500 10000 12500 15000 17500 20000 25000]);
rticklabels({'','Mars = 3,396.2 km','','','12,500 km', '15,000 km','', '',''});
thetaticks(0:45:315);
pax.GridColor = 'blue';
title('Mars Outpost Orbit Visualized');
set(findall(gcf, 'type', 'line'),'linewidth',2);
set(gca,'fontsize', 14);
```

A.3 Planar orbit restricted 2 body equations of motion function

```
function xdot = R2BEOM(t,x,G,M_earth)

%Pre-allocate xdot
xdot = zeros(4,1);

%EOM
xdot(1) = x(2);
xdot(2) = ( x(1)*((x(4))^2) ) - ( (G*M_earth)/(x(1))^2 );
xdot(3) = x(4);
xdot(4) = -( (2*x(2)*x(4))/(x(1)) );

end
```

A.4 Keplerian orbit plotter

```
clear all, clc

%%%Define Keplerian elements of outpost orbit and constants for body of
interest
%Constants
G = 6.67E-20; %km^3/kg*s^2, Universal Gravitational Constant
M = 0.64169E24; %kg, mass of Mars

%Six keplerian elements
a = 20396; %km, semi major axis
e = 0; %eccentricity
i = 30; %deg, inclination
```

```
omega = 90; %deg, argument of periapsis
OMEGA = 45; %deg, Right ascension of ascending node
theta = 45; %deg, true anomaly

%%%Rotation from ECI frame to perifocal frame needed later
%Define Rotation matrices to go from ECI frame to perifocal 1->2->3->P
ECI_ECI2 = [cosd(OMEGA), -sind(OMEGA), 0; sind(OMEGA), cosd(OMEGA),  0; 0, 0,
1];

ECI2_ECI3 = [1, 0, 0;  0, cosd(i), -sind(i); 0, sind(i), cosd(i)];

ECI3_P =  [cosd(omega), -sind(omega), 0; sind(omega), cosd(omega), 0; 0, 0, 1];

EC_P = ECI_ECI2*ECI2_ECI3*ECI3_P;

%%%Find relevant vectors from given keplerian elements
r = a*(1-e^2) / (1+e*cosd(theta) ); %position vector
h = sqrt(G*M*r*(1+e*cosd(theta) ) ); %specific angular momentum

r_P = [ r*cosd(theta); r*sind(theta); 0 ]; % position, perifocal

v_P = (G*M/h)*[-sind(theta); e+cosd(theta); 0]; % velocity, perifocal

%%%Now apply rotation matrix to ECI vectors
r_EC = EC_P*r_P; %Position vector in P frame
v_EC = EC_P*v_P; %Velocity vector in P frame

%Normalize vecotrs for plotting purposes
r = r_EC;
R = norm(r);
v = v_EC;
V = norm(v);
h = cross(r,v);
H = norm(h);
n = cross([0;0;1],h);
N = norm(n);
e = cross(v,h)/(G*M) - r/R;
E = norm(e);

B = 360 - omega;
R_ascnd = a*(1-E^2)./(1+E.*cosd(B));

%%%Plot outpost orbit
plot3([0,r(1,1)],[0,r(2,1)],[0,r(3,1)],'c-.','lineWidth',2) %Position vector
hold all
axis([-2*a 2*a -2*a 2*a -2*a 2*a]);
```

```
 plot3([0,(a-a*E)*h(1,1)/H],[0,(a-a*E)*h(2,1)/H],[0,(a-a*E)*h(3,1)/H],'r-
.','linewidth',2) %Angular momentum
 plot3([0,(a-a*E)*e(1,1)/E],[0,(a-a*E)*e(2,1)/E],[0,(a-a*E)*e(3,1)/E],'k-
.','linewidth',2) %Eccentricity
 plot3([0,R_ascnd*n(1,1)/N],[0,R_ascnd*n(2,1)/N],[0,R_ascnd*n(3,1)/N],'m-
.','linewidth',2) % Nodal
 plot3([r(1,1),r(1,1)+R*v(1,1)/8],[r(2,1),r(2,1)+R*v(2,1)/8],[r(3,1),r(3,1)+R*v(
3,1)/8],'g-','lineWidth',2) %Velocity vector

 thetas = [0:0.1:360];
 rvals = a*(1-E^2)./(1+E.*cosd(thetas));
 rvals_P = zeros(length(thetas),3);
 rvals_ECI = zeros(length(thetas),3);

 %Mark perigee and ascending node locations
 for j = 1:length(thetas)
     rvals_P(j,1) = rvals(j)*cosd(thetas(j));
     rvals_P(j,2) = rvals(j)*sind(thetas(j));
     rvals_ECI(j,:) = EC_P*transpose(rvals_P(j,:));
     if thetas(j) == 0

plot3(rvals_ECI(j,1),rvals_ECI(j,2),rvals_ECI(j,3),'k.','MarkerSize',25);
%Perigee marker
     end
     if thetas(j) == ceil(B)

plot3(rvals_ECI(j,1),rvals_ECI(j,2),rvals_ECI(j,3),'r.','MarkerSize',25); %OMEGA
marker
     end
 end

 %continue plotting
 plot3(rvals_ECI(:,1),rvals_ECI(:,2),rvals_ECI(:,3),'color','k','linewidth',2);
%Orbit path
 u = linspace(-50000,50000,50);
 v = linspace(-50000,50000,50);
 [x,y] = meshgrid(u,v);
 z = 0*x;
 surf(x,y,z,'FaceAlpha',0.1,'EdgeColor','none'); %Equatorial plane
 plot3([-2*a,2*a],[0,0],[0,0],'k--')
 plot3([0,0],[-2*a,2*a],[0,0],'k--')
 plot3([0,0],[0,0],[-2*a,2*a],'k--')
 xlabel('ec_x (km)');
 ylabel('ec_y (km)');
 zlabel('ec_z (km)');
```

```
legend('Outpost position vector','Angular momentum vector','Eccentricity vector','Nodal vector','Outpost velocity vector','Perigee','Ascending node','Orbit path','Equatorial plane','ec_x','ec_y','ec_z');
```

A.5 Communications Study

```
clear all, clc

%%%%Communications study
P_Mars = 88466; %seconds
P_Jup = 1429670; %seconds
P_jup_obs = P_Jup/2; %LoS window for Mars to Jupiter outpost

Passes = P_jup_obs/(P_Mars/2) %Amount of passes Mars will make while Jupiter outpost is in LoS window
Total_observable_time = Passes*(P_Mars/2) %seconds, amount of time that outposts will be in direct LoS
%Typical DSN data transmission for
X_rate = 3.5; %Megabit/s, X band transmission rate
Laser_rate = 1200; %Megaabit/s, Optical transmission rate

Total_Data_X = (X_rate*Total_observable_time)/8000 %Gigabytes, Total data possible via X Band
Total_Data_Laser = (Laser_rate*Total_observable_time)/8000 %Gigabytes, Total data possible via optical
```

Appendix B: GMAT Script

B.1 Orbit visualization output script

```
%General Mission Analysis Tool(GMAT) Script
%Created: 2023-07-01 17:35:07


%----------------------------------------
%---------- Spacecraft
%----------------------------------------

Create Spacecraft MarsOutpost;
GMAT MarsOutpost.DateFormat = TAIModJulian;
GMAT MarsOutpost.Epoch = '21545';
GMAT MarsOutpost.CoordinateSystem = Mars_1;
GMAT MarsOutpost.DisplayStateType = Keplerian;
GMAT MarsOutpost.SMA = 19896.00000000468;
GMAT MarsOutpost.ECC = 0.01999999999953192;
GMAT MarsOutpost.INC = 14.99999999999159;
GMAT MarsOutpost.RAAN = 44.99999999999647;
GMAT MarsOutpost.AOP = 45.0000000006586;
GMAT MarsOutpost.TA = 229.9999999993738;
GMAT MarsOutpost.DryMass = 8000;
GMAT MarsOutpost.Cd = 2.2;
GMAT MarsOutpost.Cr = 1.8;
GMAT MarsOutpost.DragArea = 150;
GMAT MarsOutpost.SRPArea = 10;
GMAT MarsOutpost.SPADDragScaleFactor = 1;
GMAT MarsOutpost.SPADSRPScaleFactor = 1;
GMAT MarsOutpost.AtmosDensityScaleFactor = 1;
GMAT MarsOutpost.ExtendedMassPropertiesModel = 'None';
GMAT MarsOutpost.NAIFId = -10000001;
GMAT MarsOutpost.NAIFIdReferenceFrame = -9000001;
GMAT MarsOutpost.OrbitColor = Red;
GMAT MarsOutpost.TargetColor = Teal;
GMAT MarsOutpost.OrbitErrorCovariance = [ 1e+70 0 0 0 0 0 ; 0 1e+70 0 0 0 0 ; 0
0 1e+70 0 0 0 ; 0 0 0 1e+70 0 0 ; 0 0 0 0 1e+70 0 ; 0 0 0 0 0 1e+70 ];
GMAT MarsOutpost.CdSigma = 1e+70;
GMAT MarsOutpost.CrSigma = 1e+70;
GMAT MarsOutpost.Id = 'SatId';
GMAT MarsOutpost.Attitude = CoordinateSystemFixed;
GMAT MarsOutpost.SPADSRPInterpolationMethod = Bilinear;
GMAT MarsOutpost.SPADSRPScaleFactorSigma = 1e+70;
GMAT MarsOutpost.SPADDragInterpolationMethod = Bilinear;
GMAT MarsOutpost.SPADDragScaleFactorSigma = 1e+70;
```

```
GMAT MarsOutpost.AtmosDensityScaleFactorSigma = 1e+70;
GMAT MarsOutpost.ModelFile = 'aura.3ds';
GMAT MarsOutpost.ModelOffsetX = 0;
GMAT MarsOutpost.ModelOffsetY = 0;
GMAT MarsOutpost.ModelOffsetZ = 0;
GMAT MarsOutpost.ModelRotationX = 0;
GMAT MarsOutpost.ModelRotationY = 0;
GMAT MarsOutpost.ModelRotationZ = 0;
GMAT MarsOutpost.ModelScale = 1;
GMAT MarsOutpost.AttitudeDisplayStateType = 'Quaternion';
GMAT MarsOutpost.AttitudeRateDisplayStateType = 'AngularVelocity';
GMAT MarsOutpost.AttitudeCoordinateSystem = Mars_1;
GMAT MarsOutpost.EulerAngleSequence = '321';

Create Spacecraft JupiterOutpost;
GMAT JupiterOutpost.DateFormat = TAIModJulian;
GMAT JupiterOutpost.Epoch = '21545';
GMAT JupiterOutpost.CoordinateSystem = Jupiter_1;
GMAT JupiterOutpost.DisplayStateType = Keplerian;
GMAT JupiterOutpost.SMA = 1871491.999999994;
GMAT JupiterOutpost.ECC = 1.708296118938597e-14;
GMAT JupiterOutpost.INC = 45.00000000000026;
GMAT JupiterOutpost.RAAN = 90.0000000000003;
GMAT JupiterOutpost.AOP = 0;
GMAT JupiterOutpost.TA = 124.2839717115716;
GMAT JupiterOutpost.DryMass = 12000;
GMAT JupiterOutpost.Cd = 2.5;
GMAT JupiterOutpost.Cr = 1.8;
GMAT JupiterOutpost.DragArea = 220;
GMAT JupiterOutpost.SRPArea = 45;
GMAT JupiterOutpost.SPADDragScaleFactor = 1;
GMAT JupiterOutpost.SPADSRPScaleFactor = 1;
GMAT JupiterOutpost.AtmosDensityScaleFactor = 1;
GMAT JupiterOutpost.ExtendedMassPropertiesModel = 'None';
GMAT JupiterOutpost.NAIFId = -10001001;
GMAT JupiterOutpost.NAIFIdReferenceFrame = -9001001;
GMAT JupiterOutpost.OrbitColor = Green;
GMAT JupiterOutpost.TargetColor = LightGray;
GMAT JupiterOutpost.OrbitErrorCovariance = [ 1e+70 0 0 0 0 0 ; 0 1e+70 0 0 0 0
; 0 0 1e+70 0 0 0 ; 0 0 0 1e+70 0 0 ; 0 0 0 0 1e+70 0 ; 0 0 0 0 0 1e+70 ];
GMAT JupiterOutpost.CdSigma = 1e+70;
GMAT JupiterOutpost.CrSigma = 1e+70;
GMAT JupiterOutpost.Id = 'SatId';
GMAT JupiterOutpost.Attitude = CoordinateSystemFixed;
GMAT JupiterOutpost.SPADSRPInterpolationMethod = Bilinear;
GMAT JupiterOutpost.SPADSRPScaleFactorSigma = 1e+70;
```

```
GMAT JupiterOutpost.SPADDragInterpolationMethod = Bilinear;
GMAT JupiterOutpost.SPADDragScaleFactorSigma = 1e+70;
GMAT JupiterOutpost.AtmosDensityScaleFactorSigma = 1e+70;
GMAT JupiterOutpost.ModelFile = 'aura.3ds';
GMAT JupiterOutpost.ModelOffsetX = 0;
GMAT JupiterOutpost.ModelOffsetY = 0;
GMAT JupiterOutpost.ModelOffsetZ = 0;
GMAT JupiterOutpost.ModelRotationX = 0;
GMAT JupiterOutpost.ModelRotationY = 0;
GMAT JupiterOutpost.ModelRotationZ = 0;
GMAT JupiterOutpost.ModelScale = 1;
GMAT JupiterOutpost.AttitudeDisplayStateType = 'Quaternion';
GMAT JupiterOutpost.AttitudeRateDisplayStateType = 'AngularVelocity';
GMAT JupiterOutpost.AttitudeCoordinateSystem = Jupiter_1;
GMAT JupiterOutpost.EulerAngleSequence = '321';


%----------------------------------------
%---------- ForceModels
%----------------------------------------

Create ForceModel MarsProp_ForceModel;
GMAT MarsProp_ForceModel.CentralBody = Mars;
GMAT MarsProp_ForceModel.PrimaryBodies = {Mars};
GMAT MarsProp_ForceModel.Drag = None;
GMAT MarsProp_ForceModel.SRP = Off;
GMAT MarsProp_ForceModel.RelativisticCorrection = Off;
GMAT MarsProp_ForceModel.ErrorControl = RSSStep;
GMAT MarsProp_ForceModel.GravityField.Mars.Degree = 4;
GMAT MarsProp_ForceModel.GravityField.Mars.Order = 4;
GMAT MarsProp_ForceModel.GravityField.Mars.StmLimit = 100;
GMAT MarsProp_ForceModel.GravityField.Mars.PotentialFile = 'Mars50c.cof';
GMAT MarsProp_ForceModel.GravityField.Mars.TideModel = 'None';

Create ForceModel JupProp_ForceModel;
GMAT JupProp_ForceModel.CentralBody = Jupiter;
GMAT JupProp_ForceModel.PointMasses = {Jupiter};
GMAT JupProp_ForceModel.Drag = None;
GMAT JupProp_ForceModel.SRP = Off;
GMAT JupProp_ForceModel.RelativisticCorrection = Off;
GMAT JupProp_ForceModel.ErrorControl = RSSStep;

%----------------------------------------
%---------- Propagators
%----------------------------------------
```

```
Create Propagator MarsProp;
GMAT MarsProp.FM = MarsProp_ForceModel;
GMAT MarsProp.Type = RungeKutta89;
GMAT MarsProp.InitialStepSize = 60;
GMAT MarsProp.Accuracy = 9.999999999999999e-12;
GMAT MarsProp.MinStep = 0.001;
GMAT MarsProp.MaxStep = 2700;
GMAT MarsProp.MaxStepAttempts = 50;
GMAT MarsProp.StopIfAccuracyIsViolated = true;

Create Propagator JupProp;
GMAT JupProp.FM = JupProp_ForceModel;
GMAT JupProp.Type = RungeKutta89;
GMAT JupProp.InitialStepSize = 60;
GMAT JupProp.Accuracy = 9.999999999999999e-12;
GMAT JupProp.MinStep = 0.001;
GMAT JupProp.MaxStep = 2700;
GMAT JupProp.MaxStepAttempts = 50;
GMAT JupProp.StopIfAccuracyIsViolated = true;

%----------------------------------------
%---------- Coordinate Systems
%----------------------------------------

Create CoordinateSystem Mars_1;
GMAT Mars_1.Origin = Mars;
GMAT Mars_1.Axes = ObjectReferenced;
GMAT Mars_1.XAxis = R;
GMAT Mars_1.ZAxis = N;
GMAT Mars_1.Primary = Mars;
GMAT Mars_1.Secondary = Earth;

Create CoordinateSystem Jupiter_1;
GMAT Jupiter_1.Origin = Jupiter;
GMAT Jupiter_1.Axes = ObjectReferenced;
GMAT Jupiter_1.XAxis = R;
GMAT Jupiter_1.ZAxis = N;
GMAT Jupiter_1.Primary = Jupiter;
GMAT Jupiter_1.Secondary = Mars;

%----------------------------------------
%---------- Subscribers
%----------------------------------------

Create OrbitView MarsView;
GMAT MarsView.SolverIterations = Current;
```

```
GMAT MarsView.UpperLeft = [ 0.002352941176470588 0 ];
GMAT MarsView.Size = [ 0.5 0.45 ];
GMAT MarsView.RelativeZOrder = 465;
GMAT MarsView.Maximized = true;
GMAT MarsView.Add = {MarsOutpost, Mars};
GMAT MarsView.CoordinateSystem = Mars_1;
GMAT MarsView.DrawObject = [ true true ];
GMAT MarsView.DataCollectFrequency = 1;
GMAT MarsView.UpdatePlotFrequency = 50;
GMAT MarsView.NumPointsToRedraw = 0;
GMAT MarsView.ShowPlot = true;
GMAT MarsView.MaxPlotPoints = 20000;
GMAT MarsView.ShowLabels = true;
GMAT MarsView.ViewPointReference = Mars;
GMAT MarsView.ViewPointVector = [ 30000 0 0 ];
GMAT MarsView.ViewDirection = Mars;
GMAT MarsView.ViewScaleFactor = 1;
GMAT MarsView.ViewUpCoordinateSystem = Mars_1;
GMAT MarsView.ViewUpAxis = Z;
GMAT MarsView.EclipticPlane = Off;
GMAT MarsView.XYPlane = On;
GMAT MarsView.WireFrame = Off;
GMAT MarsView.Axes = On;
GMAT MarsView.Grid = Off;
GMAT MarsView.SunLine = Off;
GMAT MarsView.UseInitialView = On;
GMAT MarsView.StarCount = 7000;
GMAT MarsView.EnableStars = On;
GMAT MarsView.EnableConstellations = On;

Create OrbitView JupView;
GMAT JupView.SolverIterations = Current;
GMAT JupView.UpperLeft = [ 0.1364705882352941 0.1821428571428571 ];
GMAT JupView.Size = [ 0.4982352941176471 0.4464285714285715 ];
GMAT JupView.RelativeZOrder = 455;
GMAT JupView.Maximized = false;
GMAT JupView.Add = {JupiterOutpost, Jupiter};
GMAT JupView.CoordinateSystem = Jupiter_1;
GMAT JupView.DrawObject = [ true true ];
GMAT JupView.DataCollectFrequency = 1;
GMAT JupView.UpdatePlotFrequency = 50;
GMAT JupView.NumPointsToRedraw = 0;
GMAT JupView.ShowPlot = true;
GMAT JupView.MaxPlotPoints = 20000;
GMAT JupView.ShowLabels = true;
GMAT JupView.ViewPointReference = Jupiter;
```

```
GMAT JupView.ViewPointVector = [ 0 0 1000000 ];
GMAT JupView.ViewDirection = Jupiter;
GMAT JupView.ViewScaleFactor = 1;
GMAT JupView.ViewUpCoordinateSystem = Jupiter_1;
GMAT JupView.ViewUpAxis = Z;
GMAT JupView.EclipticPlane = Off;
GMAT JupView.XYPlane = On;
GMAT JupView.WireFrame = Off;
GMAT JupView.Axes = On;
GMAT JupView.Grid = Off;
GMAT JupView.SunLine = Off;
GMAT JupView.UseInitialView = On;
GMAT JupView.StarCount = 7000;
GMAT JupView.EnableStars = On;
GMAT JupView.EnableConstellations = On;

Create OrbitView MarsJupView;
GMAT MarsJupView.SolverIterations = Current;
GMAT MarsJupView.UpperLeft = [ 0.0711764705882353 0.513095238095238 ];
GMAT MarsJupView.Size = [ 0.6958823529411765 0.1630952380952381 ];
GMAT MarsJupView.RelativeZOrder = 441;
GMAT MarsJupView.Maximized = false;
GMAT MarsJupView.Add = {MarsOutpost, JupiterOutpost, Mars, Jupiter};
GMAT MarsJupView.CoordinateSystem = Jupiter_1;
GMAT MarsJupView.DrawObject = [ true true true true ];
GMAT MarsJupView.DataCollectFrequency = 1;
GMAT MarsJupView.UpdatePlotFrequency = 50;
GMAT MarsJupView.NumPointsToRedraw = 0;
GMAT MarsJupView.ShowPlot = true;
GMAT MarsJupView.MaxPlotPoints = 20000;
GMAT MarsJupView.ShowLabels = true;
GMAT MarsJupView.ViewPointReference = Jupiter;
GMAT MarsJupView.ViewPointVector = [ 0 0 30000 ];
GMAT MarsJupView.ViewDirection = Mars;
GMAT MarsJupView.ViewScaleFactor = 1;
GMAT MarsJupView.ViewUpCoordinateSystem = Jupiter_1;
GMAT MarsJupView.ViewUpAxis = Z;
GMAT MarsJupView.EclipticPlane = Off;
GMAT MarsJupView.XYPlane = On;
GMAT MarsJupView.WireFrame = Off;
GMAT MarsJupView.Axes = On;
GMAT MarsJupView.Grid = Off;
GMAT MarsJupView.SunLine = Off;
GMAT MarsJupView.UseInitialView = On;
GMAT MarsJupView.StarCount = 7000;
GMAT MarsJupView.EnableStars = On;
```

```
 GMAT MarsJupView.EnableConstellations = On;


 %----------------------------------------
 %---------- Mission Sequence
 %----------------------------------------

 BeginMissionSequence;
 Propagate Synchronized MarsProp(MarsOutpost) JupProp(JupiterOutpost)
{JupiterOutpost.ElapsedSecs = 1446970};
```