Space Elevator From Lunar Surface and/or Lunar Catching System

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by

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ABSTRACT

Space Elevator From Lunar Surface and/or Lunar Catching System

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This paper represents a conceptual design of a lunar space elevator with a catching module that will transport cargo payload to and from the lunar surface. The elevator will consist of a payload-catching module and a climbing module that will operate using solar and laser power. The catching module will collect the payload from the Lunar Gateway and deliver it to the lunar surface through the climbing module. The elevator's location is determined based on the characteristics of the NRHO orbit. The general study of orbital mechanics is done to analyze the behavior of the circular and elliptical orbits. The system architecture of the lunar elevator is decomposed into multiple subsystems to identify the key parameters of every subsystem. Every subsystem's input and output parameters are used to organize the N-2 diagram for a better representation of the system architecture. The communication system of the lunar space elevator is analyzed by computing blackout periods and link budget using the System Tool Kit.

ACKNOWLEDGEMENT

I would like to thank my project advisor, Dr. Periklis Papadopoulos, for guiding me through this project. His guidance helped me to think creatively and tackle the challenges throughout the project research. He was also my advisor during my Undergraduate Senior Design project, which prepared me well for my Master's project. I would also like to thank San Jose State University for the opportunity to pursue my Undergraduate and Graduate degrees in Aerospace Engineering.

TABLE OF CONTENTS

List of Tables

List of Figures

List of Symbols

Symbol	Definition	Units (SI)
$v_{orbital}$	Orbital velocity	Meter per second, m/s
r	Radius from Earth to satellite	Kilometers, km
a	Semi-major axis	Kilometers, km
F	force	Newtons, N
F_g	Force of gravity	Newtons, N
F_c	Centripetal force	Newtons, N
G	Universal gravitational constant	$\frac{Nm^2}{kg^2}$
M_E	Mass of Earth	Kilograms, kg
m	Mass of satellite	Kilograms, kg
v_{exit}	Exit velocity	Meter per second, m/s
KE	Kinetic energy	Joules, J
U	The potential energy of gravitation	Joules, J
E_{Total}	Total energy	Joules, J
RAAN	The right ascension of the ascending node	degrees
GEO	Geosynchronous orbit	---------------
NRHO	Near rectilinear halo orbit	---------------
$\boldsymbol{\nu}$	True anomaly	degrees
$\boldsymbol{\omega}$	Argument of periapsis	degrees
i	inclination	degrees
Ω	Longitude of ascending node	degrees

Symbol	Definition	Units (SI)
M	Moment at contact point	Newton meter, N*m
τ	Torque	Newton-meter, N*m
m_c	Mass of climber	Kilograms, Kg
r''	Linear acceleration	Meter/second^2, m/s^2
R_w	Radius of wheel	Meters, m
$g(r)$	Gravitation drag force from the center of the moon	---------------
α	Rotational acceleration	Radian/sec^2, rad/s^2
M_{moon}	Mass of moon	Kilogram, Kg
G	Gravitational constant	Newton meter/kilogram^2, N*m/kg^2
r_{moon}	Radius of the moon	Kilometer, Km
ω_{moon}	Angular velocity of the moon	Radian/second, rad/s
M_w	Mass of wheel	Kilogram, Kg
n_w	Number of wheels	---------------
$\frac{C}{N_0}$	Noise-to-signal ratio	Decibel Heartz, (dBHz)
P_T	Power of transmitter	Watts, W
G_R	Receiver gain	Decibel, dB
G_T	Transmitter gain	Decibel, dB
$\frac{1}{L}$	Path loss	Decibel, dB
T	System temperature	Kelvin, K

Chapter 1 - Introduction

1.1 Motivation

Space exploration has been considered challenging and expensive for every space agency worldwide. The Cold War era was meant to be a space race between the Soviet Union and the United States to prove their superiority. As technology advanced, space exploration became a curiosity for every nation to learn more about the other planets. The number of payload launches has drastically increased in the past few years. According to the Space-Track database, the number of payload launches by the United States increased four times from 2019 to 2021 [1]. Every launch requires a space launch vehicle, which costs millions of dollars and a lot of time. The Falcon Heavy launch vehicle costs about $1400 per kilogram for delivering a payload to low earth orbit (LEO), which is approximately 90 million dollars per launch [2]. The majority of the weight a rocket carries is the weight of the fuel which gets burned during the lift-off. Also, the cost of the rocket propellant adds up quickly for the rockets that carry heavy payloads to generate enough thrust. According to NASA's 2001 report, the cost of propellant for a space shuttle was $1,380,000 to carry 729,000 kg of fuel [3].

To overcome the problem of time and money, an alternative method of delivering payloads in space is proposed in this paper. The project objective is to design a lunar space elevator that will transport payloads to the moon's surface by minimizing or eliminating the use of space launch vehicles. The lunar space elevator will help reduce the cost and time spent on lunar missions and open a gateway for the direct transportation of payloads from the Earth to the moon, which will also help in lunar colonization.

1.2 Literature Review

This section covers the research related to the problem discussed in the motivation section. Many different approaches have been tried in the past or present to invent a mechanism that will help minimize the use of space launch vehicles to transport payloads in space. The primary goal of every approach is to reduce the time and money spent on every space mission. Future space exploration requires a gateway that will give easy access to space for transportation, which could be done by constructing a lunar space elevator. Throughout the literature review, various methods have been discussed that are used to minimize or eliminate the use of space launch vehicles.

1.2.1 Earth Space Elevator

The idea of constructing an Earth space elevator was first discussed in 1960 by Russian engineer Yuri Artsutanov to design a method of transporting payloads in space without using space launch vehicles. The concept was built based on the thought experiment of the Russian scientist Konstantin Tsiolkovsky, who invented the idea of a space elevator. Later on, the concept was developed by another American engineer named Jerome Pearson in 1974, who published his findings in an article, 'The Orbital Tower' [4]. The concept of the Earth space elevator was to design a cable anchored to the Earth's surface at one end and extend it to an altitude of about 35,800 km near the geosynchronous orbit [5]. The purpose of extending the cable to the geosynchronous orbit is to keep it in tension and to achieve system stability. A counterweight would be attached at the floating end of the cable to keep it in tension and stable.

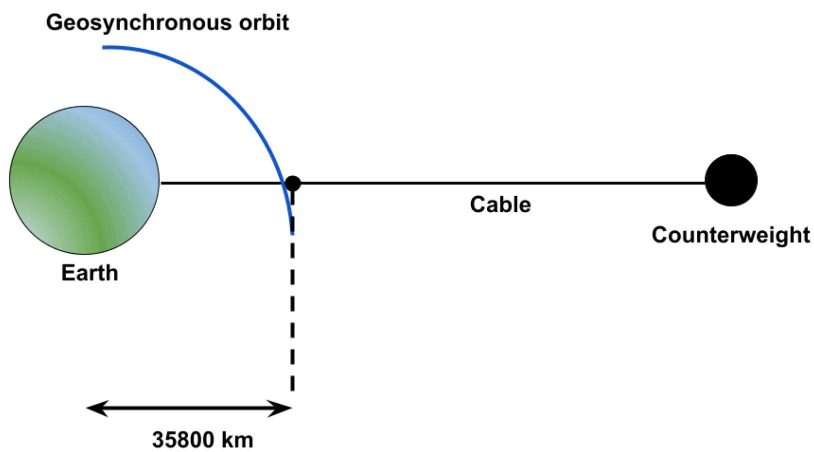


Figure 1.1 Earth space elevator [5].

The biggest challenge of this concept is choosing the right material for the cable that can provide great tensile strength with low density. Yuri Artsutanov realized that a super strong material is required to construct a long cable that can withstand its weight without collapsing. Later, in 1991, carbon nanotubes were invented to satisfy the required strength-to-weight ratio for the cable; however, it is quite challenging to build a longer structure. The only possibility of constructing a space elevator is by using a super-strong structure like carbon nanotubes [7]. One thing that was taken into consideration is that the cable has to be tapered as it moves towards the earth's surface. The diameter of the cable has to be increased as it moves towards the geostationary altitude to avoid any buckling [6, 4].

Table 1.1 – Material properties [5].

Material	Tensile Strength (GPa)	Density (kg/m^3)	Taper Ratio
Carbon Nanotubes	1.3×10^2	1.3×10^3	1.5
Steel	5	7.9×10^3	1.7 E 10^{33}
Kevlar	3.6	1.44×10^3	2.6 E 10^8

The appropriate choice of material for the construction of the cable is described in the table above. It shows how carbon nanotubes are considered the best choice as compared to steel and kevlar based on their strength-to-weight ratio. Moreover, the taper ratio in the table is calculated by a safety factor of 2 which will give enough room for failure [5].

1.2.2 Lunar Space Elevator

The lunar space elevator design is similar to the earth space elevator; however, the only difference between both concepts is that the lunar space elevator is constructed on the surface of the moon. In this design, the cable will be anchored to the surface of the moon from one end while extending the other end towards the earth to float freely in space. The concept of the lunar space elevator was first proposed by the American scientist Jerome Pearson in 1979 [4]. The goal of constructing such an elevator is to transport payloads from the moon to high earth orbit. In addition to the elevator, the climbing mechanism will transport the payloads from the lunar surface to the Lagrangian point at L1 using a robotic vehicle [4].

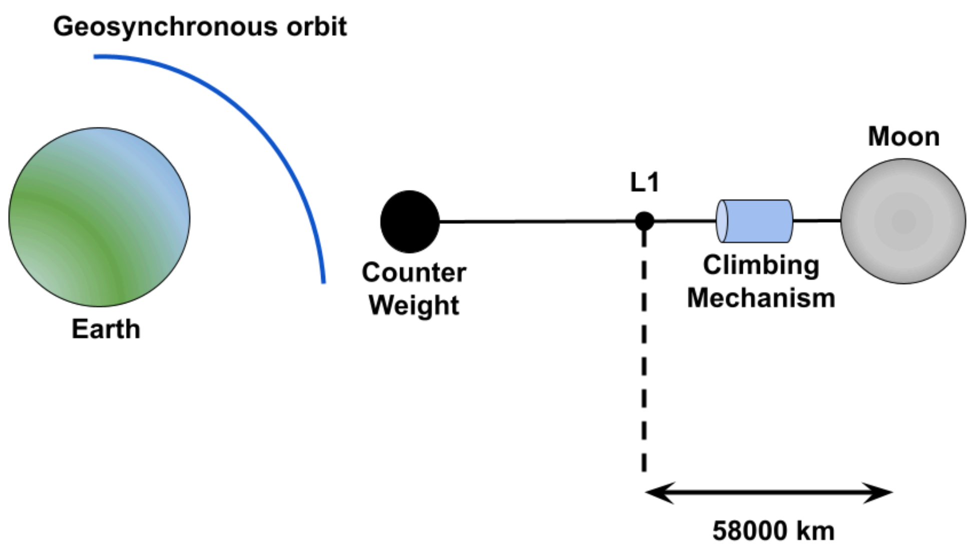


Figure 1.2 Lunar space elevator [5].

Figure 1.2 gives an idea of how the lunar elevator would work. The purpose of having a counterweight at the floating end is to provide stability to the tether. The floating end is extended towards the earth till the force of gravity and centrifugal force comes to an equilibrium. The robotic vehicle designed to deliver lunar payloads will be operated using solar energy, which will operate at the speed of 100km/hr [4]. One disadvantage of the lunar space elevator is that the tether will be longer for the lunar design, which could result in high oscillations in the system due to the forces acting on the tether [7]. However, the lunar elevator design seems more feasible than the others. Also, the only challenging issue that both designs share is the material selection for the tether. The entire concept is based on the elongated cable or tether that has to be super strong to withstand the weight of the capsule, including payloads and the weight of the cable itself. According to the Pearson technical report of 2005, the composite material used for the tether can lift a payload of 204 kg at the base [4].

1.2.3 SpinLaunch

Another method of launching the payload in space without using a space launch vehicle is using a slingshot mechanism that will shoot the payload at the speed of sound. Compared to the past few decades, advancements in technology have revolutionized the space industry. In every space mission, the majority of the rocket's weight is fuel, which burns rapidly to achieve the required velocity. According to a study conducted in Ref. [3], the prices of various propellants are mentioned in the table below.

Table 1.2 – Propellant price per Kg [3].

Type of propellant	Price per Kg ($)
LH2	6.1
RP-1	2.3
CH4	8.8
LOX	0.27
Solid	5
Hybrid	8
Hydrogen Peroxide	10.36
Hydrazine	75.8

The amount of money spent on rocket propellant in most space missions can be analyzed by calculating the mass of propellant used. During the flight, Falcon 9 rockets carry a propellant consisting of LOX and RP-1 which adds up to 498,206 kg of propellant, which is 312,200 kg of LOX and 186,006 kg of RP-1 [3]. By using the price table mentioned in the table above, the total cost of propellant comes to about $270,000.

A large amount of money is spent on rocket propellants during every launch; therefore, to minimize the use of propellants, a new technique of launching smaller payloads in space has been introduced by a company named SpinLaunch. The company was founded by an entrepreneur named Jonathan Yaney in 2014 [8]. The SpinLaunch is a slingshot mechanism that shoots the payload in the sky at a speed of about 5000 mph. The launcher consists of a vacuum chamber and a hypersonic tether that spins the blade at a higher speed to create a centrifugal force. Once the blades achieve a certain rpm, the rocket attached at the end of the blades launches through the exit tunnel [9].

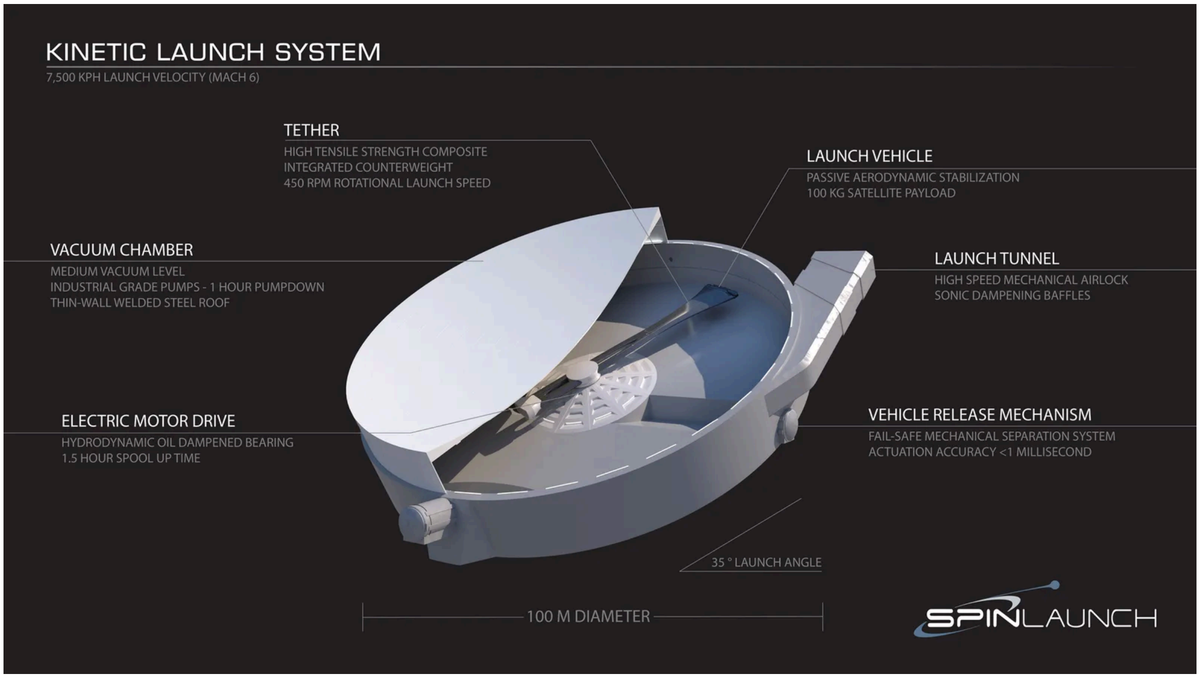


Figure 1.3 SpinLaunch design [8].

The average cost of launching a small satellite in space with the SpinLaunch will be under $500,000 [8]. Compared to the cost of rocket propellant, it seems quite cheaper and fuel-efficient to launch payloads in lower earth orbit. In addition to that, the rotating arm that spins the payload is powered by electricity which makes the design environmentally friendly. The rocket used to deliver the payload is a second-stage rocket that will ignite with chemical propulsion once it reaches the stratosphere and transport the payload to the lower earth orbit (LEO) [9]. According to the company SpinLaunch, the launching mechanism will reduce the launching cost ten times as compared to the conventional method of launching rockets.

1.2.4 Air Launch

One way to eliminate the launching payloads from the ground is to launch them in the air from a certain altitude. The best candidate for launching rockets from higher altitudes is by using an airplane. It looks similar to deploying missiles from a B-52 bomber plane. This method of launching rockets is called air launch. The launch of small satellites from a certain altitude has been practiced since 1990. An air launch booster called Pegasus, manufactured by Northrop Grumman, was launched on April 5, 1990, from a B-52 carrier aircraft to transport 192 kg of payload to space [10]. The payload was delivered by a three-staged rocket that was launched from an altitude of 13,200 m. The concept of air launch is that once the rocket is dropped from the carrier, it ignites the stage 1 motor and starts ascending towards the guided trajectory. It eliminates the use of solid rocket boosters that provide additional thrust to the rocket to lift from the ground.

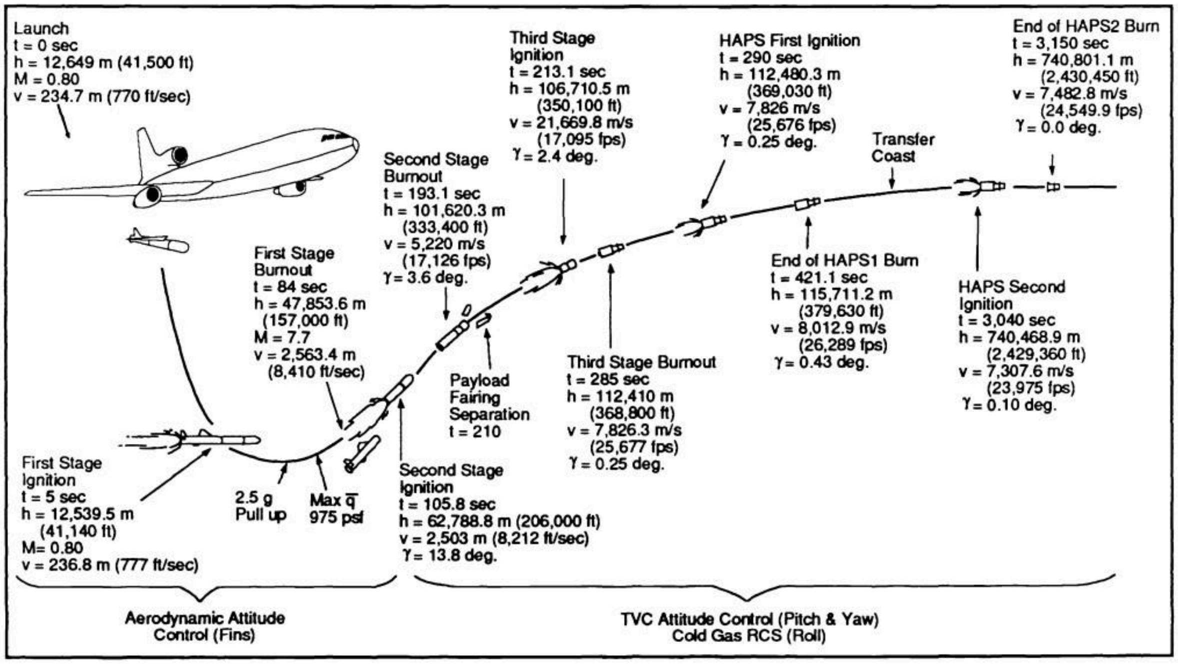


Figure 1.4 Launch sequence of Pegasus [10].

Another air launch was conducted by a company named Virgin Galactic which launched their first rocket called LauncherOne to deliver ten mini-satellites for NASA on January 17, 2021 [11]. The LauncherOne was launched from a Boeing 747 aircraft that was modified by Virgin Galactic. The idea of using aircraft as a launch pad is to minimize the launching cost to deliver payloads in space.

1.3 Project Proposal

As discussed in the literature review, various approaches have been done in the past to minimize the use of space launch vehicles for transporting payloads in space. Some approaches were merely a design concept, while others were validated with remarkable results. The primary goal of this research is to achieve a design that will not only reduce the cost and time of launch but also give easy access to space for future exploration.

The objective of this research paper is to construct a lunar space elevator for transporting payloads to and from the surface of the moon. The idea of constructing such an elevator is based on the approach discussed in section 1.2.2 of the literature review. The elevator will be constructed from the surface of the moon while anchoring one end to the lunar surface and extending the other end past the Lagrange point L1, which will float freely in space to catch the payloads launched from the earth.

1.4 Methodology

The idea of constructing a lunar space elevator can be divided into different phases. The problems that need to be tackled through the design process consist of problems related to structure, power, and orbital mechanics. For a feasible design, the choice of structure, the source of power, and the proper placement of the elevator have to be analyzed.

Meanwhile, the right approach is to construct the elevator by anchoring it to the lunar surface from one end and letting it float in space from the other end. There will be a catching module at the floating end of the elevator that will catch the payloads launched from the earth. To transport the payload to the surface of the moon, there will be a climbing module that will carry and deliver the payload back and forth to the elevator. The climber will be powered using a solar or laser-based propulsion system. The design will go through various iterations depending on the problems encountered throughout the process.

Chapter 2: Determining the Optimal Elevator Location

2.1 Introduction

Before constructing the lunar space elevator, the optimal location for the placement of the floating end of the elevator has to be determined. There will be various design aspects that need to be looked at during the placement of the elevator. Some of the expected challenges are the optimal location of the elevator and the material selection for the tether. During the designing phase of the elevator, the most challenging part of the design is to find an optimal location that provides stability and easy access to the lunar surface.

The lunar elevator design proposed by the American scientist Jerome Pearson in the literature review is constructing the elevator on the lunar surface. The floating end of the cable will be extended towards the earth while passing through the Lagrange point L1. However, the only issue with such a design is the length of the cable, which would be about 58,000 km long or more. Some of the key challenges of constructing a longer cable floating in space are the strength and stability of the cable. The stability can be achieved by attaching a counterweight at the floating end of the cable; however, constructing a cable that can withstand the weight of the payload and the tensile stress is quite challenging. Therefore, the construction of a longer-space elevator does not seem feasible.

The length of the elevator needs to be reasonable which would minimize the structural and stability challenges. Throughout this chapter, the study of lunar orbits and the idea of constructing a Lunar Gateway has been discussed which helps to come up with a feasible design of a lunar space elevator.

2.2 Lunar Orbits

There has to be an optimal location where the floating end of the lunar elevator can be placed to achieve stability and strength. To determine the feasible location for the lunar space elevator, the study of orbits revolving around the moon needs to be discussed.

The moon revolves around the earth in an elliptical orbit with an orbit period of 27.3 days; however, the rotation of the moon around the Earth is synchronized with its rotation on its axis. Due to such a tidal lock, the moon always faces the Earth on the same side [12]. Similar to the Earth's orbits, the moon also has orbits that are used by the spacecraft to revolve around the celestial body. Most of the lunar orbits are unstable due to their uneven gravitational force which is why spacecraft orbiting the moon have to make frequent small perturbations to stay in the orbit and to avoid crashing on the lunar surface.

To achieve orbital stability, there are methods to design trajectories by inclining these orbits with respect to their reference frames. By making such adjustments, the inclined orbits achieve stability due to an even distribution of gravitational force and help the spacecraft to stay in orbit without making course adjustments. Such orbits are also called frozen orbits and are highly useful for running observation missions around the moon [13]. Some of the frozen orbits are found at an inclination of 27^0, 50^0, 77^0, 85^0, and 103^0 [14].

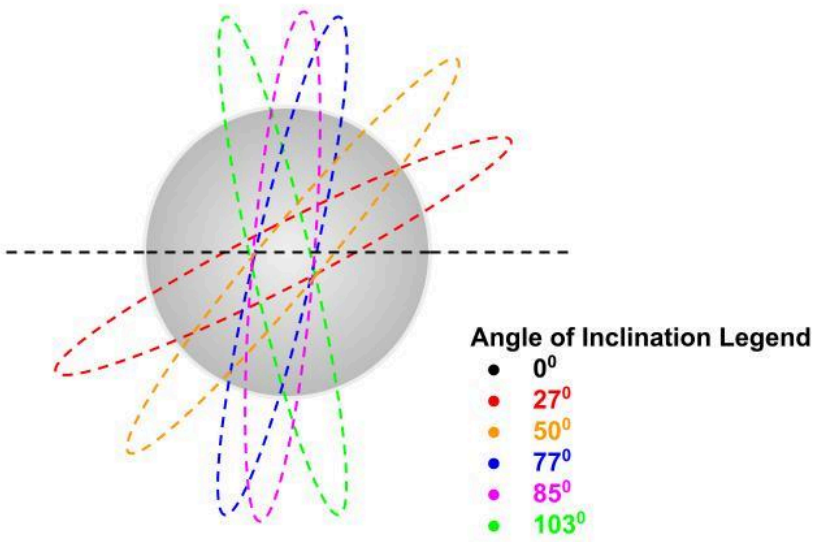


Figure 2.1 Frozen lunar orbits.

2.2.1 Near-Rectilinear Halo Orbit

Besides frozen lunar orbits, scientists have discovered a new lunar orbit, which is suggested to be an optimal orbit for upcoming lunar missions. NASA is planning to construct a lunar space station by the next decade that will help engineers run future lunar missions conveniently. The modules of the space station will be launched separately based on the launch schedules and will be assembled in space over time. The first module of the Lunar Gateway is planned to launch by 2025, which will initiate the construction of the lunar space system [15]. For orbiting the moon, Gateway has to be placed in a stable orbit that will minimize the perturbations to be made during station keeping. As discussed earlier, most of the lunar orbits are unstable and require maneuvers to stay in orbit; however, NASA's recent discovery of the Near-Rectilinear Halo Orbit (NRHO) has made it possible to place the Gateway in a stable orbit.

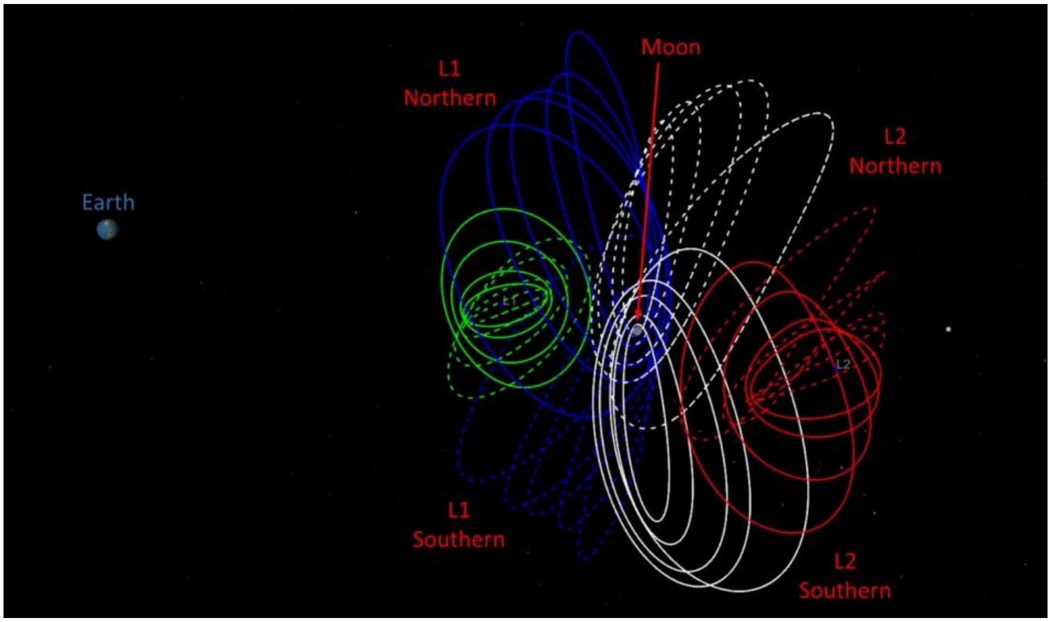


Figure 2.2 Halo orbits [16].

NRHO orbit came from a family of halo orbits that are placed near the Lagrange points; however, it differs from the halo orbits in terms of stability. Due to its stable characteristics, NRHO orbit minimizes the number of burns required by the spacecraft to stay in orbit [16]. Such orbital characteristics are required to place the Gateway into orbit to achieve easy accessibility to the lunar surface. Many NRHO orbits are currently under study to find the optimal orbit that will bring the Gateway closer to the lunar surface for easy access while keeping its stability characteristics. Based on the scientists' calculations, the optimal NRHO orbit is found with a period length of 5.9 days. The closest distance of the orbit to the lunar surface is about 2000 km, and the farthest distance is about 68,000 km [17].

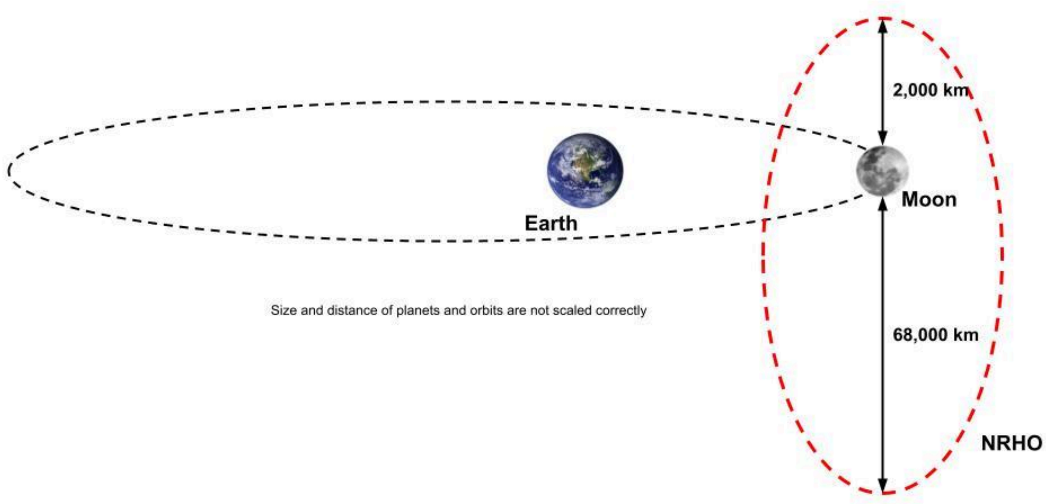


Figure 2.3 Near-rectilinear halo orbit for lunar Gateway.

Another advantage of using an NRHO orbit is constant communication with the ground stations on the Earth. Due to the lunar synchronized rotation, the lunar hemisphere is always facing the Earth which causes loss of communication when the spacecraft reaches the other side of the moon. With the help of NRHO orbit, the Gateway will constantly communicate with the ground stations on the earth by eliminating the blackout periods.

2.2.2 Capstone

Before setting up the Gateway in NRHO orbit, the characteristics of the orbit have to be validated to eliminate future mission failures. On June 28, 2022, NASA launched a 12U satellite of 25 kg named CAPSTONE to validate the orbit characteristics of the newly discovered NRHO orbit. The goal of the satellite is to check the orbit stability and test the communication system between a Lunar Reconnaissance Orbiter and CAPSTONE [18]. The spacecraft payload consists of an imager, a communication system, and a flight computer. Due to size constraints, the spacecraft cannot carry excessive fuel; therefore, the spacecraft has used a Ballistic Lunar Transfer (BLT) to enter the NRHO. The BLT lowers the ΔV of the spacecraft during the direct transfer to NRHO orbit which makes it easier for the spacecraft to correct the trajectories when needed. CAPSTONE took four months to reach its destination by using such trajectories [18]. The data collected through the CAPSTONE will be used for setting up the Gateway in NRHO and for planning future lunar missions based on NASA's Artemis program.

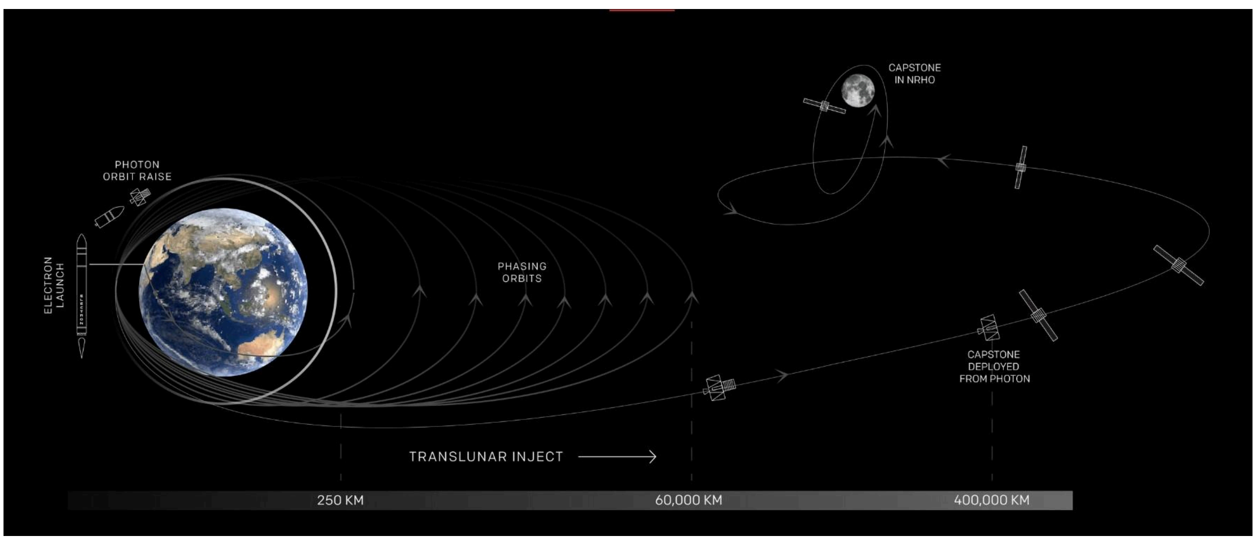


Figure 2.4 Trajectory of CAPSTONE spacecraft [19].

2.2.3 Gateway

Lunar Gateway is a part of NASA’s Artemis future missions, which would help the astronauts with easy access to the moon. The Gateway will orbit the moon in the newly discovered NRHO orbit like a lunar space station. Similar to the ISS collaboration, the United States will collaborate with its international partners like Canada, Europe, and Japan to build a

Lunar Gateway. Every partnered space agency is working on different modules of the Gateway, which will be launched individually according to the launch schedules. The Gateway design consists of various modules:

1. International Habitat (I-Hab): The International Habitat provided by the European Space Agency (ESA) will be a station for the astronauts to live and to perform research for the upcoming space missions.

2. ESPRIT Refueling Module (ERM): The ESPRIT Refueling Module will also be provided by ESA, which carries fuel tanks, cargo, and other supplies used by the crew during the missions.

3. Habitation and Logistics Outpost (HALO): The HALO module will be provided by ESA, which carries life support equipment like food and water for the crew. It is also equipped with a high-rate lunar communication system that will help the crew to communicate with each other during lunar activities.

4. Orion: Orion is a spacecraft that helps astronauts travel back and forth from the Earth to the Moon. It will also help to deliver the other modules from the Earth to the Gateway.

5. CANADARM3: The CANADARM3 is a robotic arm provided by the Canadian Space Agency that will help astronauts to perform maintenance tasks during the spacewalk.

6. Power and Propulsion Element (PPE): PPE will serve as the powerhouse for the Gateway that will provide power for all the electronics. The propulsion system will help the gateway to make attitude or altitude adjustments if necessary. PPE also includes roll-out solar arrays that will generate 60kW of electricity for the Gateway.

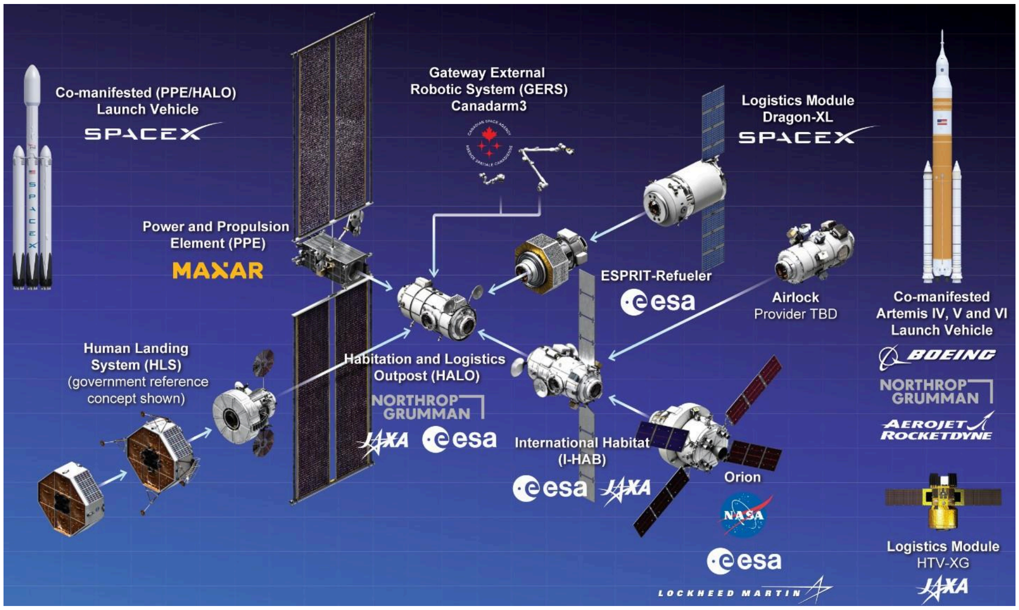


Figure 2.5 Configuration of lunar Gateway [20].

Every module of the Lunar Gateway will be delivered to NRHO orbit individually according to the Artemis mission schedules. The initial assembly of the Gateway will be started once the PPE and HALO modules are delivered by SpaceX Falcon Heavy in 2025. Due to BLT, the modules will take about one year to reach the NRHO. The I-Hab will be delivered by Orion to dock with the HALO module. The rest of the modules will be launched by the end of September 2028 [20]. Once all the modules are assembled, the Gateway will become a lunar space station that enables the astronauts to easily access the moon and other planets.

2.3 Location of Lunar Elevator

The possibility of constructing a lunar elevator depends on the optimal location where the floating end of the elevator will be placed. For a feasible design, two aspects of the elevator design need to be considered: the length of the elevator and the location of the floating end. As discussed in previous sections, most lunar orbits are unstable due to the uneven gravitational field of the moon. There are ways to achieve the stability of an orbit by adjusting its inclination; however, it is still challenging to achieve easy access to the lunar surface.

Based on NASA's Artemis Program, the idea of setting up a Lunar Gateway would also make the idea of constructing a lunar elevator possible. Instead of extending the floating end of the elevator past the Lagrange point L1, it can be placed on the NRHO, where the Lunar Gateway will be placed. The reduction of the length of the elevator will reduce tremendously from 58,000 km to 2,000 km. Instead of using a human landing module from the Gateway, an elevator can be used to deliver the payload to and from the lunar surface. It will reduce the amount of fuel used by the landers to ascend and descend from the lunar surface.

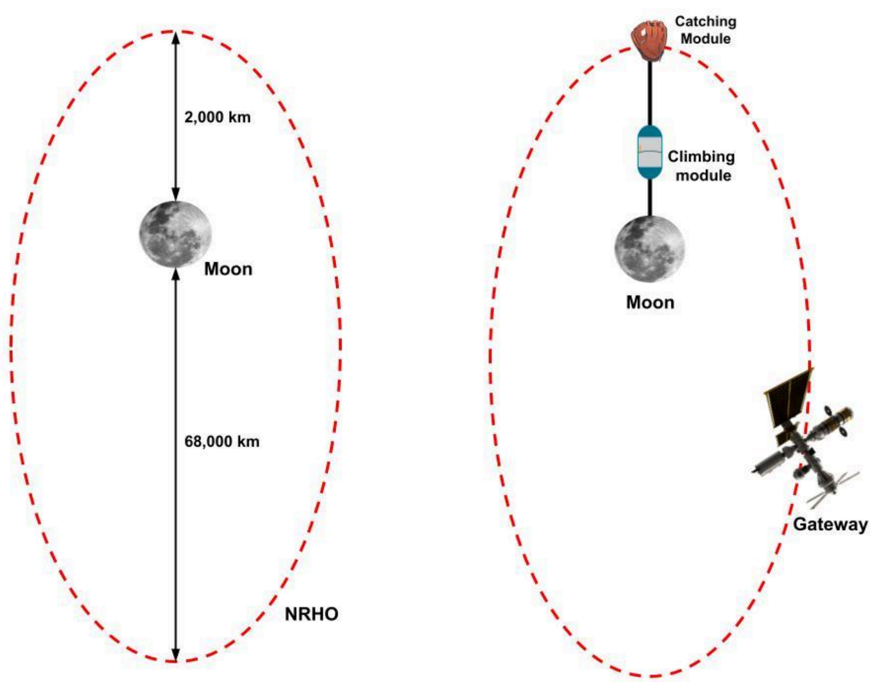


Figure 2.6 Conceptual design of the lunar space elevator with a lunar catching system.

2.4 Conclusion

This chapter concludes with the optimal location of the lunar space elevator. The conceptual design of the lunar space elevator includes the climbing module, the catching module, and the tether. The idea is to anchor the tether from one end to the surface of the moon and place the floating end near the Lunar Gateway in NRHO. The length of the tether will be 2,000 km, with a catching module attached at the floating end, which would act as a counterweight for stability. The payload will be released from the Gateway and get caught by the catching module. The climbing module will transport the payload to the surface of the moon.

Chapter 3: Conceptual Design of Lunar Space Elevator

3.1 Introduction

In the previous chapter, the optimal location of the lunar space elevator is determined by placing the floating end in the Non-rectilinear halo orbit. The goal is to design an elevator that will collect payload from the Lunar Gateway through the catching module and deliver it to the surface of the moon via the climbing module. Since the orbital period of the NRHO is about 5.9 days, the Lunar Gateway will have the ability to launch the payload once a week during its closest contact with the catching module. In this chapter, the conceptual design and the mission operations of the lunar space elevator will be discussed.

3.2 Design Elements of Lunar Space Elevator

The conceptual design of the lunar space elevator consists of various elements that will enable the elevator to deliver the cargo payload to the lunar surface. After determining the optimal location for the floating end of the elevator, the design of the catching and the climbing module has to be discussed. The design will consist of five major elements that will complete the transportation process of the payload.

1. Dragon Spacecraft
2. Payload Catching Module
3. Climbing Module
4. Tether
5. Robotic Arm

3.2.1 Dragon Spacecraft

There are many ways to transport the cargo to the surface of the moon. According to the Artemis program, the Artemis IV mission is proposing a human landing system (HLS) that will transit humans and cargo to and from the lunar surface [20]. Once the cargo is delivered to the lunar surface, the spacecraft will make a power ascent and rendezvous with the Gateway. To minimize the fuel consumption, landing, and launching costs, there is an alternative to transport the crew and cargo to the lunar surface safely and efficiently by using a lunar space elevator.

For the Gateway Logistics services, NASA gave the contract to SpaceX to design a cargo spacecraft that will transport the crew and cargo to the lunar surface. SpaceX is currently working on a space vehicle called Dragon XL that is capable of carrying about 5000 kg of payload, including pressurized and unpressurized cargo, which would be essential for the crew onboard [21]. An alternative method of transporting the crew and cargo to the lunar surface is by climbing down the lunar elevator. The Dragon XL spacecraft can be used to deliver the payload from the Gateway to the elevator's catching module. Rather than using a human landing module to land on the lunar surface, there will be a short flight for the spacecraft to rendezvous with the payload-catching module.

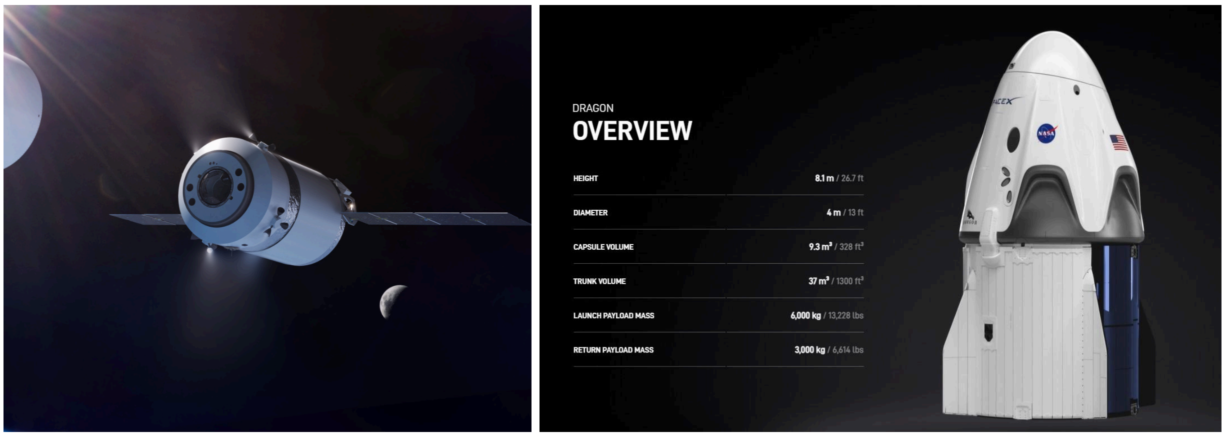


Figure 3.1 Specifications of Dragon spacecraft (right) and Dragon XL (left) [21].

3.2.2 Payload Catching Module

The catching module will be connected to the floating end of the tether at about 2000 km away from the lunar surface. Based on the optimal location of the elevator, the catching module will be placed near NRHO which enables the Lunar Gateway to launch the Dragon XL spacecraft and rendezvous with the payload catching module efficiently. The catching module will be equipped with an airlock module similar to the gateway's airlock module, which consists of a universal docking adapter for autonomous docking of the Dragon XL. Once the spacecraft is docked to the catching module, it will transfer the payload to the climbing module which is connected to the other end of the catching module. The payload will be transported to the lunar surface by climbing down the tether via a climbing mechanism. To be on schedule, the climber has about five days to complete the transfer of cargo payload to and from the lunar surface. Before the Gateway reaches the perilune, the Dragon XL spacecraft will be ready to launch from the catching module and rendezvous with the Gateway. The transportation of the cargo can be increased by using multiple spacecraft that can be exchanged at the rendezvous point, which will give the crew enough time to prepare the next shipment.

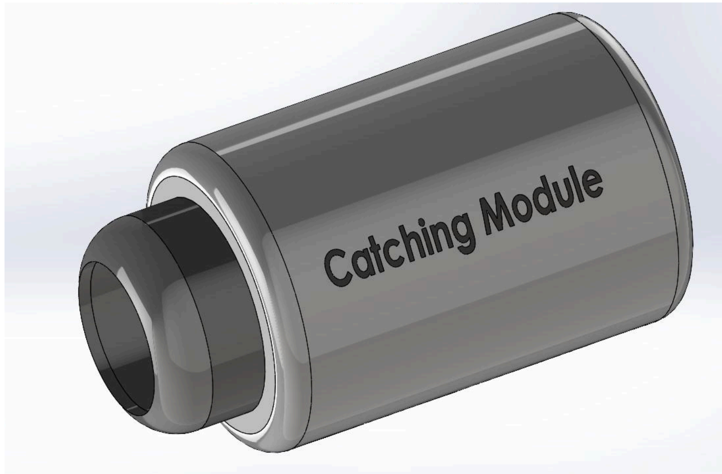


Figure 3.2 Conceptual CAD design of payload catching module.

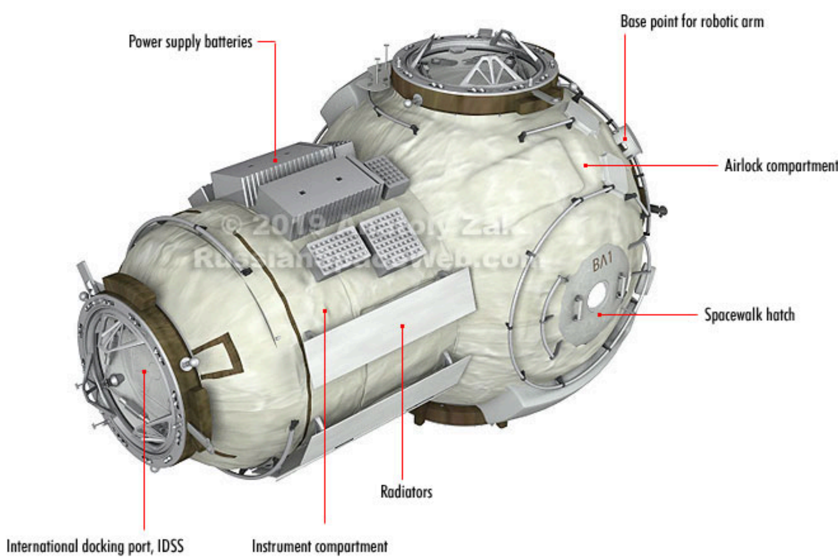


Figure 3.3 Russian airlock module [22].

3.2.3 Climbing Module

The climbing module of the lunar elevator will be considered essential in transporting the payload to and from the lunar surface. After docking to the catching module, the payload will be transferred to the climber's cargo bay and secured properly before initiating the descending phase. The climbing mechanism includes a drivetrain that consists of various mechanical components like wheels, electric motors, actuators, and belts. One of the most common drivetrain used in the industry is the linear motor drive [23]. Such technology has been widely used in industrial applications like manufacturing, packaging, automation, printing, etc.

For the initial design, several constraints need to be considered before choosing the suitable mechanical components for the climbing mechanism. The two major design constraints that need to be addressed are the weight of the payload and the speed of the climbing module. As mentioned previously, the Dragon XL spacecraft is capable of carrying about 5000 Kg of payload. Therefore, for design simplification, it is practical to set a baseline for a maximum payload capacity of 5000 Kg to be hauled in the climbing module. There will be additional weight of the climbing module, the catching module, the spacecraft, and the tether that need to be considered in the design process. The second constraint is the speed of the climbing module. The orbital period of the NRHO is about 5.9 days which gives a window of roughly five days to transport the payload to and from the lunar surface. The floating end of the elevator is assumed to be placed at a distance of 2000 km near the perilune, which gives easy access to the Gateway for transferring the payloads. By comparing the total distance and time, it is concluded that the minimum speed required to climb back and forth the tether is about 17 km/hr. According to the JSETEC competition of 2011, various tether climber designs were proposed, which resulted in prototyping a tether climber that can travel on a rope tether at a speed of 60km/hr and on a belt at a speed of 32 km/hr [23]. Based on the competition results, it is possible to design a climbing mechanism consisting of wheels, electric motors, actuators, and belts.

Figure 3.4 Conceptual CAD design of payload climbing module.

3.2.4 Tether

Tether is the most essential element of the lunar space elevator design. The entire payload transportation system depends on the tensile strength of the tether. In the previous sections, the length of the tether is determined to be 2000 km; however, the best selection for the material is the most challenging part of the design. As discussed earlier in Chapter 1, the architecture of the lunar elevator is possible by using a firm structure like carbon nanotubes but the mass production of such material is quite challenging. In addition to carbon nanotubes, scientists have discovered other materials like single-crystal graphene and hexagonal boron nitride that can be used for constructing the tether [24].

Table 3.1 – Material strength [24].

Material	Tensile Strength (GPa)
Graphene	130
Carbon Nanotubes	200
Hexagonal Boron Nitride	100

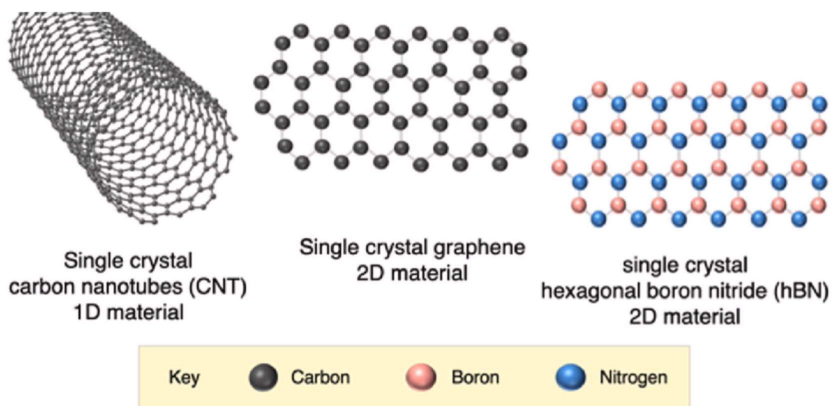


Figure 3.5 Tether material proposed for space elevator [24].

3.2.5 Robotic Arm

The robotic arm will serve as a supplemental component to the catching module that will help the crew members in stationkeeping. The International Space Station is also equipped with a European Robotic Arm (ERA) which was launched in July 2021 [25]. The purpose of the ERA is to help the astronauts relocate and repair the components on the ISS. ERA is capable of moving 8000 kg of payload from one point of the station to another [25]. It can be operated manually by the astronauts or programmed to work autonomously as well. The onboard cameras and sensors of ERA enable the robotic arm to inspect any leakage or damage to the external components of the ISS. In recent operations, ERA has successfully relocated the airlock module and installed a radiator for the Multipurpose Laboratory Module on the ISS [26]. Having such technology installed in the Lunar catching module will assist the astronauts in performing general repairs on the elevator and minimize the need for the spacewalk.

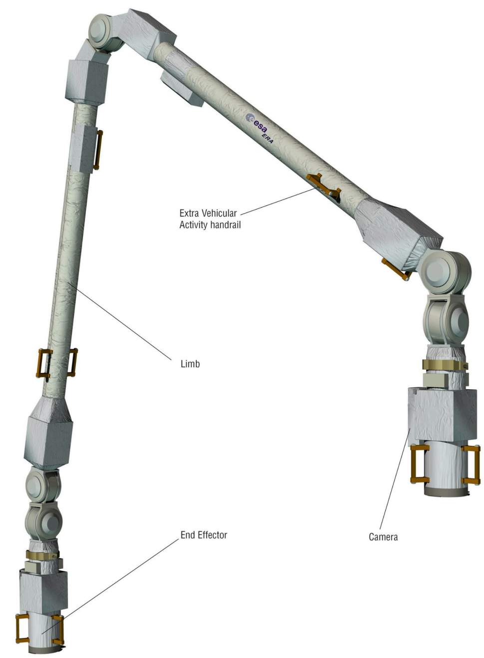


Figure 3.6 European robotic arm (ERA) [25].

3.3 Propulsion System

The lunar elevator will require a propulsion system that provides a thrust force to the climbing module during the ascent and descent phases. Conventional spacecraft generally rely on chemical propulsion and electric propulsion to travel in space. To overcome the force of gravity, spacecraft are equipped with solid rocket boosters that provide additional thrust force during the lift-off. The only disadvantage of using such technology is that the launch vehicles have to carry excessive fuel during the space missions which limits the weight of the payload transported to space. There are alternative sources of energy that can generate power without carrying excessive fuel; however, the amount of power required to generate enough thrust is quite challenging. The practice of using solar energy to generate power is very cost-effective in the space industry. Most of the satellites and spacecraft are equipped with solar panels that provide power to the onboard electronics during the missions. Solar energy is sufficient to power up the spacecraft, but it requires large panels to provide enough energy to propel the space vehicles which will increase the size and weight of the spacecraft.

Another method of generating thrust force is by using a ground-based laser propulsion system. In 1972, C.E. Backus introduced the idea of using a laser beam to power the photovoltaic (PV) arrays [27]. Similar to solar panels, the PV arrays are powered by using a source of light. Instead of using sun rays, a powerful laser beam is used to transmit power to the PV arrays. One of the advantages of using a laser beam instead of solar rays is that the panels work more efficiently under a consistent source of light [27]. By using high-power lasers, it is possible to generate enough power to ascend and descend the climbing module of the lunar elevator.

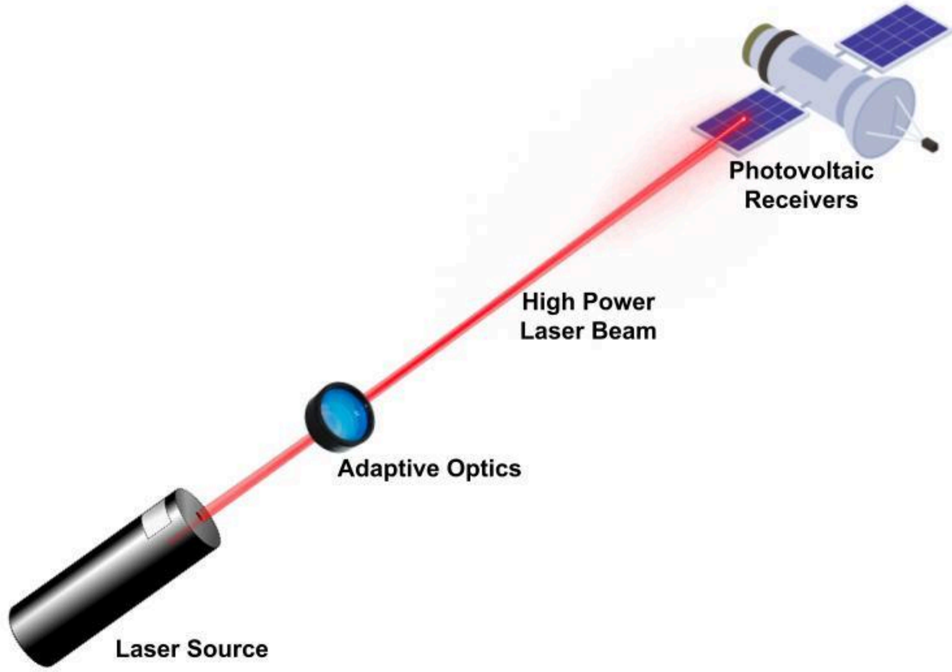


Figure 3.7 Ground-based laser system.

The climbing module will be equipped with photovoltaic arrays that will be powered by using a high-power laser placed near the anchor point of the elevator on the surface of the moon. Since the lunar gravitational force is less as compared to the earth's gravity, it would require less power to lift the climbing module from the lunar surface. The space elevator idea proposed in Ref. [23] also used a laser-based power source for the climber; however, the only difference is that it is based on constructing a space elevator from the earth's surface and is 100,000 km long. As compared to the design in Ref. [23], many aspects of the proposed lunar elevator design have changed. The length of the tether, the weight of the entire elevator, and the gravitational force acting on the elevator have reduced drastically which requires less energy to ascend and descend the elevator.

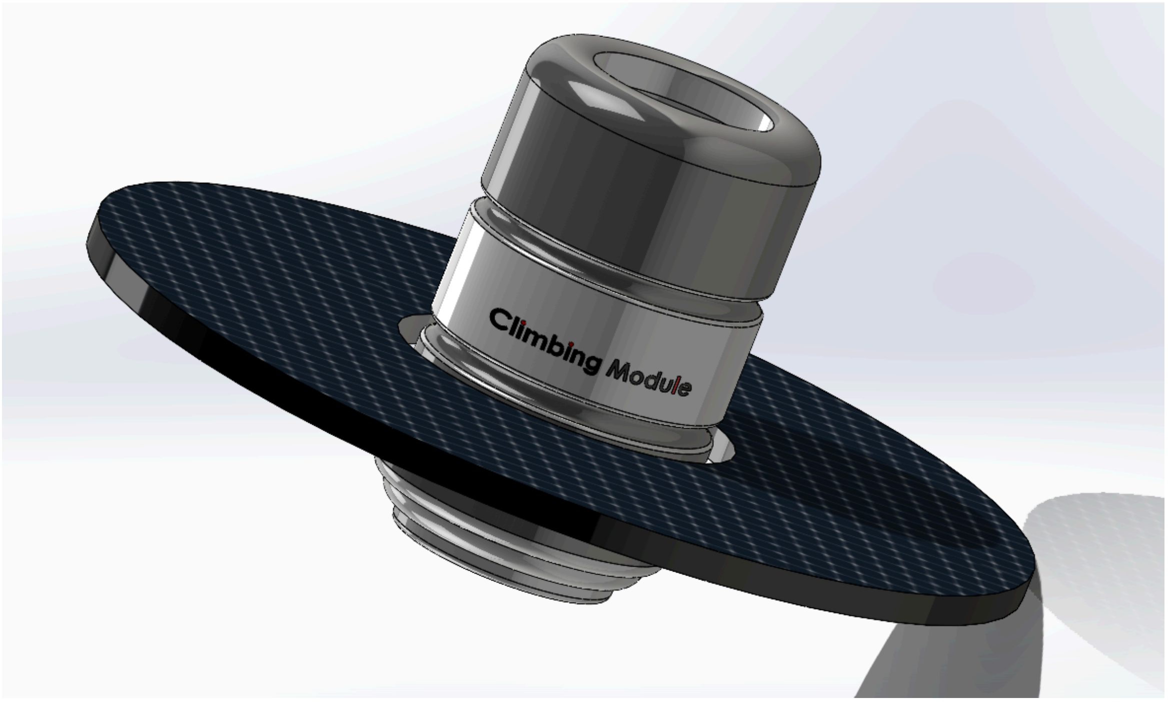


Figure 3.8 CAD model of the climbing module with photovoltaic receiver.

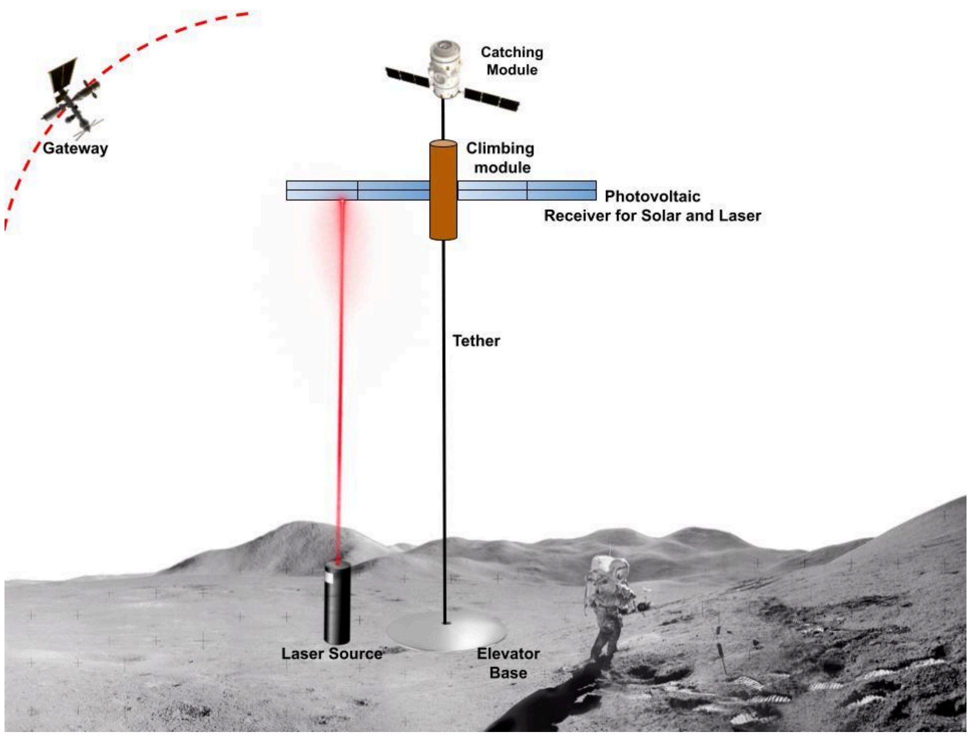


Figure 3.9 Conceptual design of the lunar space elevator with a power source.

3.4 Conclusion

This chapter concludes the conceptual design of the lunar space elevator by discussing the design elements that will assist in delivering the cargo payload on the moon. Some of the design elements require more in-depth research to have actual data that will be used to develop the preliminary design. The challenging aspect of the design is finding the material for the tether that can withstand the stress of the elevator. Figure 3.9 represents a conceptual design for the transportation process of the payload to the lunar surface. The upcoming chapters will cover the detailed design process and the mission operations of the project.

Chapter 4: Orbital Mechanics

4.1 Introduction

Orbital mechanics is a modern study of tools and techniques used to study the motion of celestial objects due to the force of gravity. It is a part of astrodynamics that mainly focuses on the dynamics of objects traveling in space. The prime focus of orbital mechanics is to plan trajectories for spacecraft by performing calculations based on the behavior of orbits. The equations that govern the orbital calculations are derived by using Newton's and Kepler's Laws of motion. The study of orbits is based on the laws of a famous Austrian mathematician, Johannes Kepler, who invented three laws of planetary motion in the early 16th century. Later, in 1687, Sir Isaac Newton validated Kepler's law using his three laws of motion [28]. The contribution of both physicists has revolutionized the study of orbital mechanics and astrodynamics for modern astronomers and physicists to explore further in space.

4.2 Characteristics of orbits

The fundamental principle behind orbital science is based on the thought experiment of Sir Isaac Newton. Throughout his experiment, Newton tried to study the effect of gravitational force on the objects that revolve around the Earth. He suggested firing a cannonball from a high mountain at the perfect speed, height, and angle so that the ball would return to the same spot after completing one revolution of the earth. After testing various hypotheses, he concluded that the ball would orbit the earth forever if the speed of the ball was higher than the orbital velocity and lower than the escape velocity [29, 30]. Figure 4.1 shows the projectiles of the cannonball based on Newton's thought experiment.

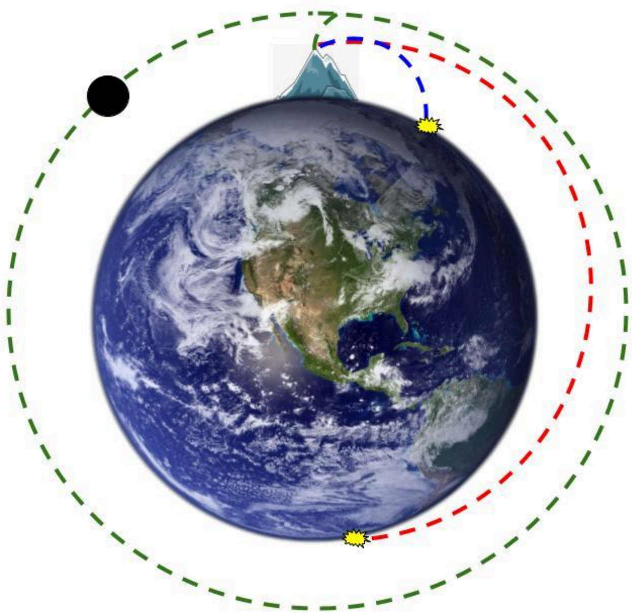


Figure 4.1 Cannonball projectiles based on Newton's thought experiment.

4.2.1 Circular Orbits

The findings of Sir Isaac Newton laid a foundation for the modern astrodynamics that governs the calculations performed for planning spacecraft trajectories. The two common shapes of orbits are circular and elliptical orbits. Although the purpose of both orbits is to keep the objects revolve around the planet, there are many differences in energy that the objects experience in the orbit during the revolution. The eccentricity of an orbit determines its shape and how elliptical it is. The orbit eccentricity is measured between 0 and 1. The higher eccentricity makes the orbit elliptical, whereas the lower eccentricity brings the orbit to a circular shape [31]. Most circular orbits, like geosynchronous orbits, have an eccentricity of 0, which means the distance of the revolving body from the center of the orbit stays the same throughout the entire revolution. Besides eccentricity, the objects that travel in circular orbit have constant kinetic and potential energy due to a constant orbital velocity.

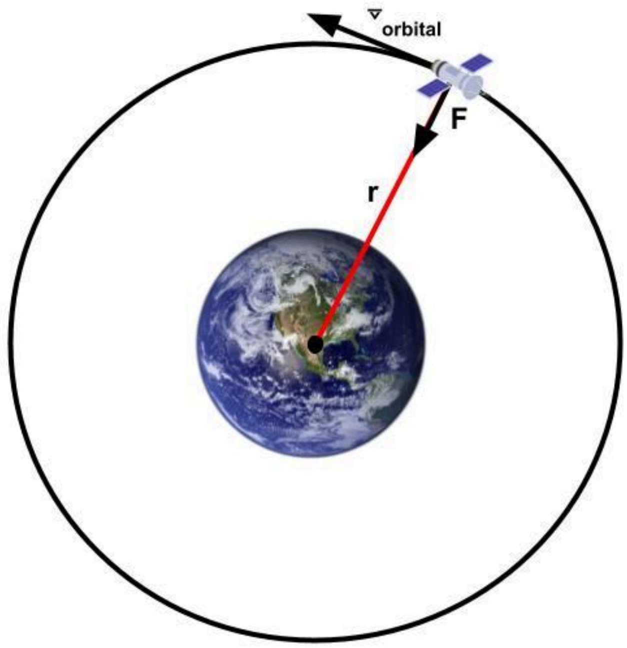


Figure 4.2 Circular orbit.

4.2.2 Elliptical Orbits

Elliptical orbits are derived from Kepler’s first law of planetary motion, which states that every planet revolves around the sun in an elliptical path. Unlike circular orbits, the eccentricity of elliptical orbits is greater than zero which generates two foci on the major axis of an ellipse. The sum of the distances from each focus of an ellipse is constant for every point placed on an elliptical orbit [32].

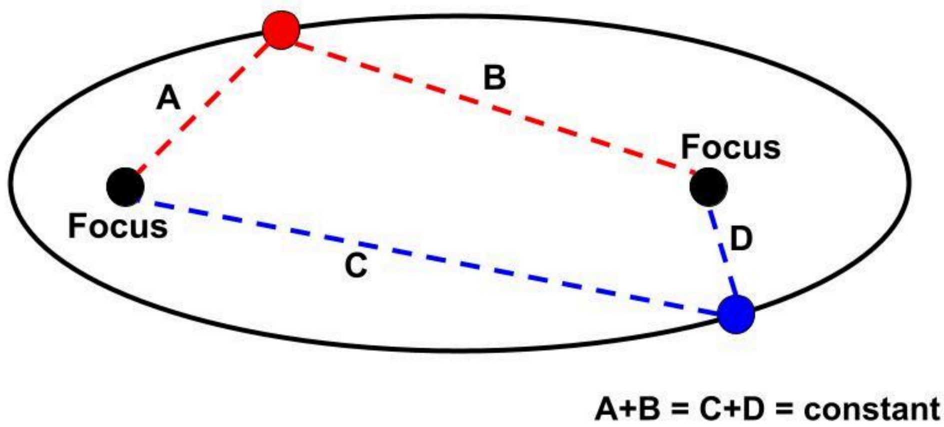


Figure 4.3 Elliptical orbit showing the sum of distance is constant at any point on the ellipse.

According to the law of energy conservation, the total energy stays constant; however, the orbital velocity does not stay constant throughout the revolution. Therefore, the object travels faster near the periapsis and slower near the apoapsis to maintain the law of conservation of energy. The radius of an orbit affects the kinetic and potential energy of the object. As the object comes closer to periapsis, the orbital radius decreases, which makes the object travel faster due to a sudden increase in kinetic energy and a decrease in gravitation potential energy. To maintain the law of energy conservation, when an object reaches the apoapsis, the radius of an orbit increases, which makes the object travel slower due to lower kinetic energy and higher gravitation potential energy. However, the total energy remains constant throughout the entire revolution.

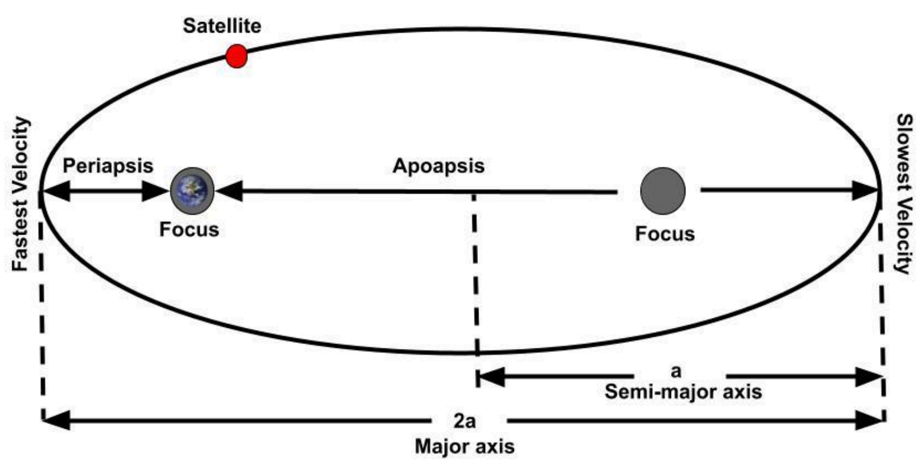


Figure 4.4 Elliptical orbit.

4.2.3 Energy Equations

Equations 4.1 and 4.2 are derived from Newton's second law of motion and universal law of gravitation, which is further used to derive the kinetic and potential energy equations for objects traveling in circular and elliptical orbits [33].

Newton's Second Law of Motion:

$$F = ma \tag{4.1}$$

Newton's universal law of gravitation

$$F_g = \frac{GM_E m}{r^2} \tag{4.2}$$

Centripetal force equation:

$$F_c = \frac{mv^2}{r} \tag{4.3}$$

By combining equations 4.2 and 4.3, the exit velocity equation can be derived as follows:

$$F_g = F_c$$

Becomes,

$$\frac{GM_E m}{r^2} = \frac{mv^2}{r} \tag{4.4}$$

Solving equation 4.4 for exit velocity becomes,

$$v_{exit} = \sqrt{\frac{GM_E}{r}} \tag{4.5}$$

The kinetic energy and gravitation potential energy for circular orbits can be expressed as follows:

$$KE = \frac{1}{2}mv^2 = \frac{GM_E m}{2r} \tag{4.6}$$

$$U = \frac{-GM_E m}{r} \tag{4.7}$$

Total Energy equation for circular orbit:

$$E_{total} = KE + U = \frac{-GM_E m}{2r} \tag{4.8}$$

Total Energy equation for elliptical orbit:

$$E_{total} = \frac{-GM_E m}{2a} \tag{4.9}$$

4.3 Rocket equation

In modern days, space launch vehicles overcome the Earth's gravitation force by producing enough thrust during the liftoffs. The goal of space launch vehicles is to achieve the maximum velocity required to exit the Earth's atmosphere and deliver the payloads to their desired orbit. To overcome the force of gravity, the launch vehicles have to generate higher thrust which requires a large amount of propellent onboard. More than 50 percent of the rocket's weight is propellant, which burns over time as the rocket propels upward. The whole idea is based on one equation known as a rocket equation. In 1897, a Russian scientist named Konstantin Tsiolkovsky invented the rocket equation, which calculates the change in velocity of the rocket required to reach space [33]. The equation helps to calculate the equivalent velocity of the engine's exhaust during the flight and determines the overall change in velocity of the rocket.

Rocket Equation:

$$\Delta v = v_{eq} ln \frac{m_0}{m_f} \tag{4.10}$$

The key parameter for every space flight is the Δv, which determines the amount of thrust required to perform maneuvers during flight and transfer into different orbits. To transfer the payload from the Gateway to the catching module, Δv will be the key parameter that needs to be taken into account. For a proper transfer, the launched payload from the Gateway must maintain a certain Δv to rendezvous with the catching module.

4.4 Kepler's Laws

Kepler's laws of planetary motion are considered the foundation of astrodynamics. In the 16th century, a famous Austrian mathematician, Johannes Kepler, invented three laws of planetary motion that revolutionized the field of astrodynamics for space exploration. Modern tools and techniques used in orbital mechanics are derived by using Kepler's laws of planetary motion. With his laws, Kepler defined the shape of the orbits and how all the celestial bodies behave in the solar system. During his research in the early 16th century, Johannes Kepler invented three laws of planetary motion that were described as follows: [33]

1. First Law: Every planet revolve around the sun in elliptical orbits where the sun is considered as one of the focus points.

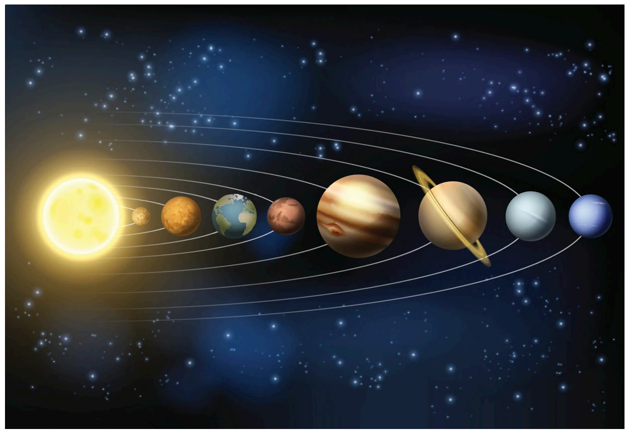


Figure 4.5 Solar system with planets orbiting around the sun [31].

2. Second Law: The area swept by a vector joined between the sun and other planets is equal at the equal length of time which means the area swept by the moon at apogee in one month is equal to the area swept by the moon at perigee in one month.

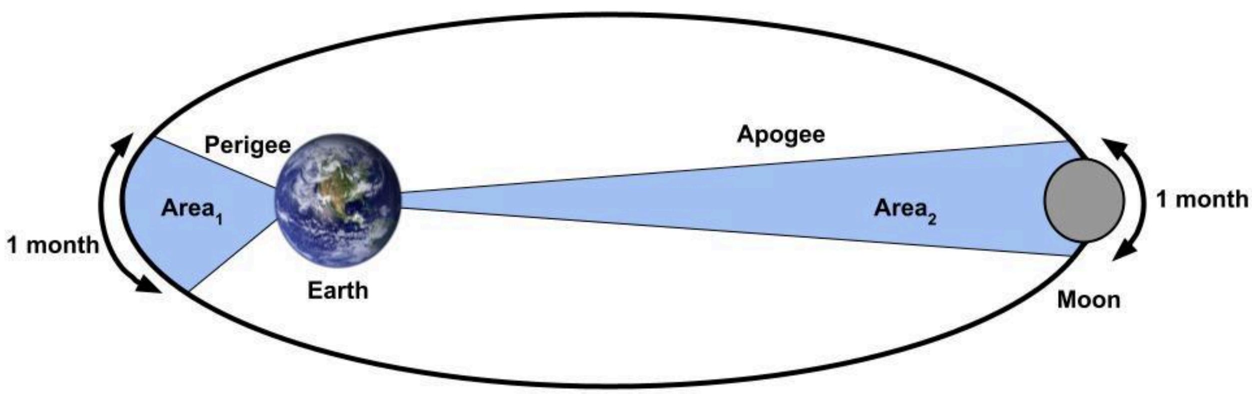


Figure 4.6 Elliptical orbit representing Kepler's second law of planetary motion.

3. Third law: the ratio of the period of any planet and the distance between the sun and that planet is constant. The equation that best describes Kepler's third law is described as follows:

$$T^2 = (distance\ of\ planet\ from\ the\ sun)^3 \tag{4.11}$$

Table 4.1 Table representing Kepler's third law of planetary motion [32].

Planet	Distance from the sun, D (10^6 km)	Period, T (days)	$\frac{D^3}{T^2}$ (10^{19})
Mercury	57.9	88	2.5
Earth	149.6	365.2	2.5
Mars	228	687	2.5
Jupiter	778.5	4,331	2.5
Saturn	1432	10,747	2.5
Uranus	2867	30,589	2.5
Neptune	4515	59,800	2.5

4.4.1 Elements of an Orbit

The selection of an orbit is determined by various factors for every space mission. Most of the satellites launched into space are used for communication, navigation, and surveillance. The selection of an orbit depends on the mission objectives. For example, geostationary orbit is widely used by satellites for land surveillance, weather forecasting, or telecommunications. The reason why GEO is chosen for such missions is because it orbits around the Earth's equator at 0-degree inclination with an eccentricity of zero and provides better coverage across the globe. Many other factors determine if the orbit is suitable for the space mission based on its characteristics. Some of the parameters are referred to as Kepler's parameters, which are used to define the characteristics of an orbit. Such parameters are as follows: [34]

- Apoapsis: The farthest point on the orbit from the focus point is considered apoapsis.
- Periapsis: The closest point on the orbit from the focus point is considered as periapsis.
- Inclination: The angle between the reference plane and the orbital plane is called an inclination angle.
- RAAN: RAAN determines the point on the orbital plane at which the revolving body passes the equatorial plane.
- Argument of periapsis: The angle between the periapsis and the ascending node is known as the argument of periapsis.
- True anomaly: The angle between the revolving body in the orbit and the periapsis is called the true anomaly. It determines the location of the object traveling in the orbit by calculating the angle.

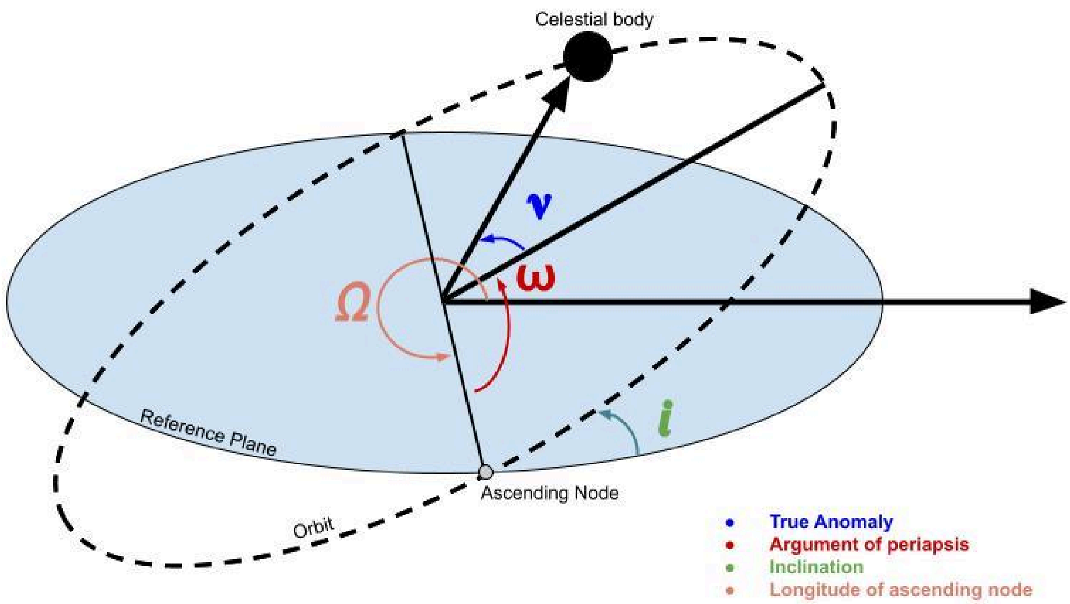


Figure 4.7 Characteristics of an orbit (Kepler's parameters).

4.5 Characteristics of NRHO

As discussed in Chapter 2, NRHO is an orbit chosen for the Gateway by NASA for their upcoming Artemis mission. NRHO came from a family of halo orbits placed near the Lagrange points, and based on its stable characteristics, it is considered suitable for placing the Gateway in that orbit. Throughout Chapter 3, it also found suitable for the lunar space elevator as well which will give the Gateway easy access to the catching module for transferring the payload. Based on Kepler's laws of planetary motion and the parameters discussed in the previous section, many other characteristics of NRHO need to be considered.

NRHO is an orbit around the moon at 90 degrees of inclination with a major axis of about 70,000 km. The periapsis of the orbit is at 2,000 km, and the apoapsis is at 68,000 km. The closest periapsis distance will give the Gateway easy access to the catching module; however, due to the shorter orbital radius at the periapsis, the orbital velocity will be higher at the rendezvous point, which needs to be taken into account. Moreover, NRHO is placed at 90 degrees inclination, which makes it a polar orbit of the moon. The catching module of the elevator will be placed near the north pole of the moon which might interrupt the ground communication from the lunar surface with the Gateway.

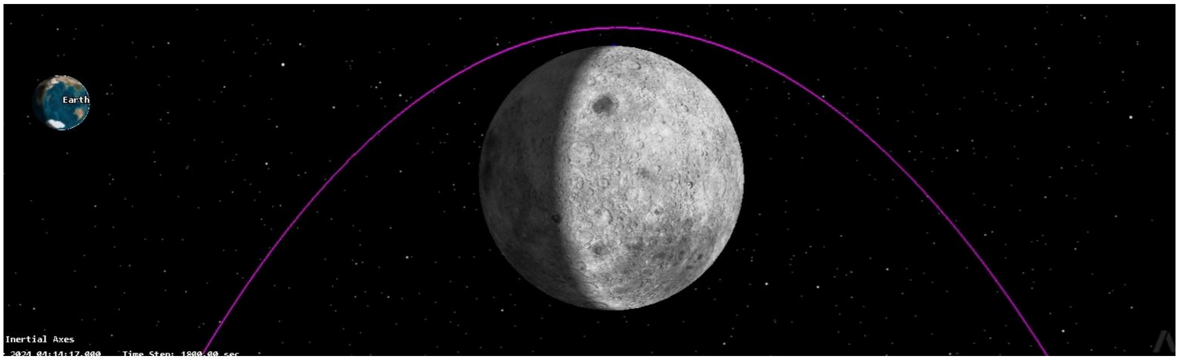


Figure 4.8 Perilune of NRHO where the catching module will be placed.

Chapter 5: System Decomposition

5.1 Introduction

The designing process involves various iterations to accomplish an optimal design that has better performance and low cost. In every project, trade-off study plays a crucial role that takes place based on the mission requirements. The key elements that help to perform the trade-off study are the parameters that drive the mission requirements. To derive these parameters, the system has to be decomposed into different subsystems for outlining the input and output variables.

The goal of building a lunar space elevator is to minimize the use of spacecraft to deliver cargo to and from the lunar surface. This chapter addresses the general mission requirements that need to be satisfied to accomplish the mission objectives. Once the requirements are outlined, the system is divided into various subsystems to identify the key variables that can be tuned to accomplish an optimal design.

5.2 Design Requirements

The design process involves various system engineering tools and techniques that make it easier to organize the project. The complexity of the design becomes easier to understand once the design architecture is decomposed into smaller subsystems. However, the requirements of the project have to be addressed before the system is decomposed into subsystems. Once the mission requirements have been outlined, they can be decomposed into subsystems accordingly. One of the best tools used in project management is setting S.M.A.R.T goals which helps engineers to keep track of progress. It helps to label every task according to its characteristics. The acronym S.M.A.R.T stands for:

- S: Specific
- M: Measurable
- A: Achievable
- R: Relevant
- T: Time-bound

Based on such tools and techniques, the requirements of this project are outlined in Table. 5.1.

Table 5.1 System requirements.

Subsystem	ID	Requirement	Justification	S.M.A.R.T
Structure	1.1	Payload Weight: 5000 kg	The climber must be able to transport up to 5000 kg of payload.	S
	1.2	Tether Strength	The tether must be able to withstand the weight of the climber and the cargo	M
Mechanical	2.1	Climber Speed: > 34 km/hr Orbital Period: 5.9 days	The climber must be able to go back and forth from the catching module to the lunar surface within the orbital period of the Gateway.	T
Power	3.1	Power Output: 4MW	PV cells must generate enough power for the climber to lift the payload from the lunar surface and transport it to and from the catching module.	S, M
	3.2	MMRTG power output: 110 W	MMRTG should be able to provide power to the onboard electronics on the climber and the catching module.	S, M
Comms	4.1	Ka-band: 16 Mbps S-Band:	The climbing module, catching module, and the lunar ground station should communicate with the Gateway by using high-gain antennas.	M
TPS	5.1	Climber Indoor Temperature	The TPS should protect the electrical components from extremely cold weather conditions at the lunar north pole.	M
Propulsion	6.1	Δv	The dragon spacecraft must maintain its Δv according to the catching module during the docking phase.	S, M

5.3 Subsystems

The design of the lunar space elevator is divided into five different subsystems for a better understanding of the system architecture. The decomposition of the subsystems consists of structural, mechanical, communication, power, and thermal protection subsystems. Each subsystem consists of parameters that feed into the system to output the desired results according to the mission requirements. The parameters derived from the equations are further used to perform trade studies by comparing the cost and performance.

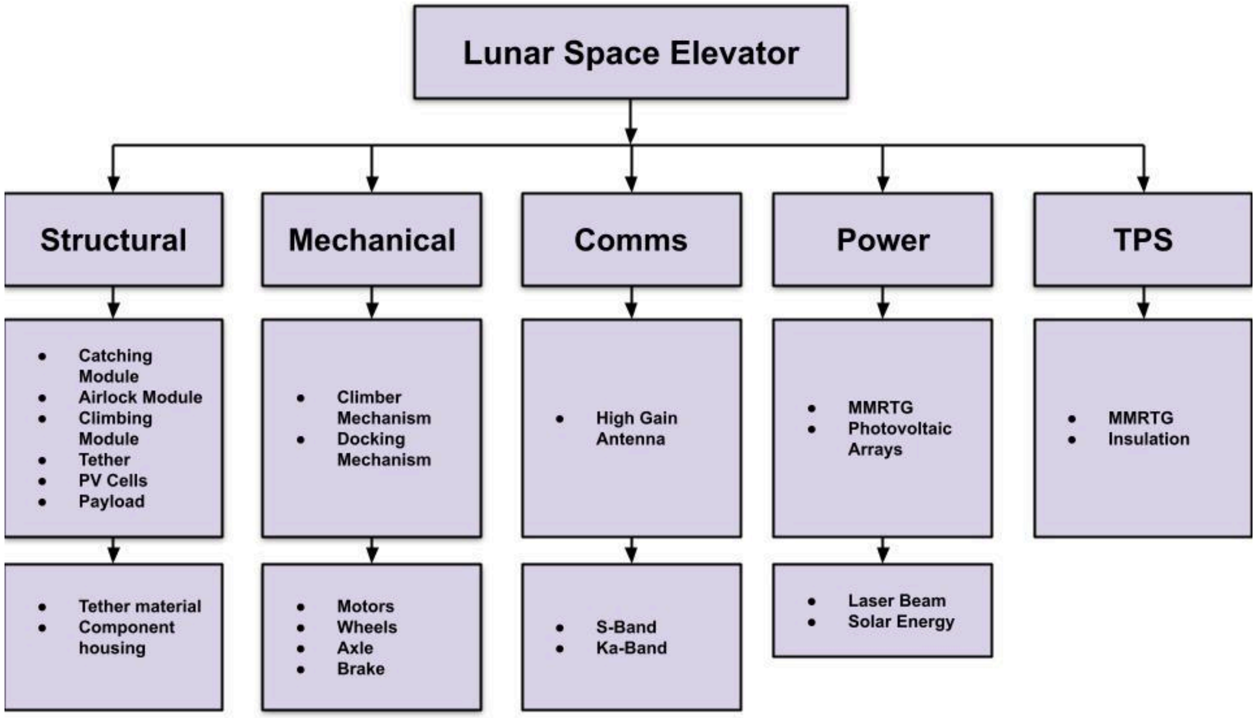


Figure 5.1 Subsystems of lunar space elevator.

5.3.1 Structural Subsystem

The structural subsystem consists of the overall structure of all the elevator modules. The initial design phase of the lunar elevator consists of CAD drawings of the catching and climbing modules. The catching module will consist of an International Docking System that enables the spacecraft to dock with the elevator. The IDS will capture the incoming spacecraft using a soft capture system and latch it properly through the passive docking mechanism. After stabilizing, the spacecraft will be pulled towards the catching module through the soft capture system and sealed completely by using the hard capture system. One benefit of using an IDS is that it is an androgynous docking system, which means it can mate the spacecraft with similar docking configurations [37].

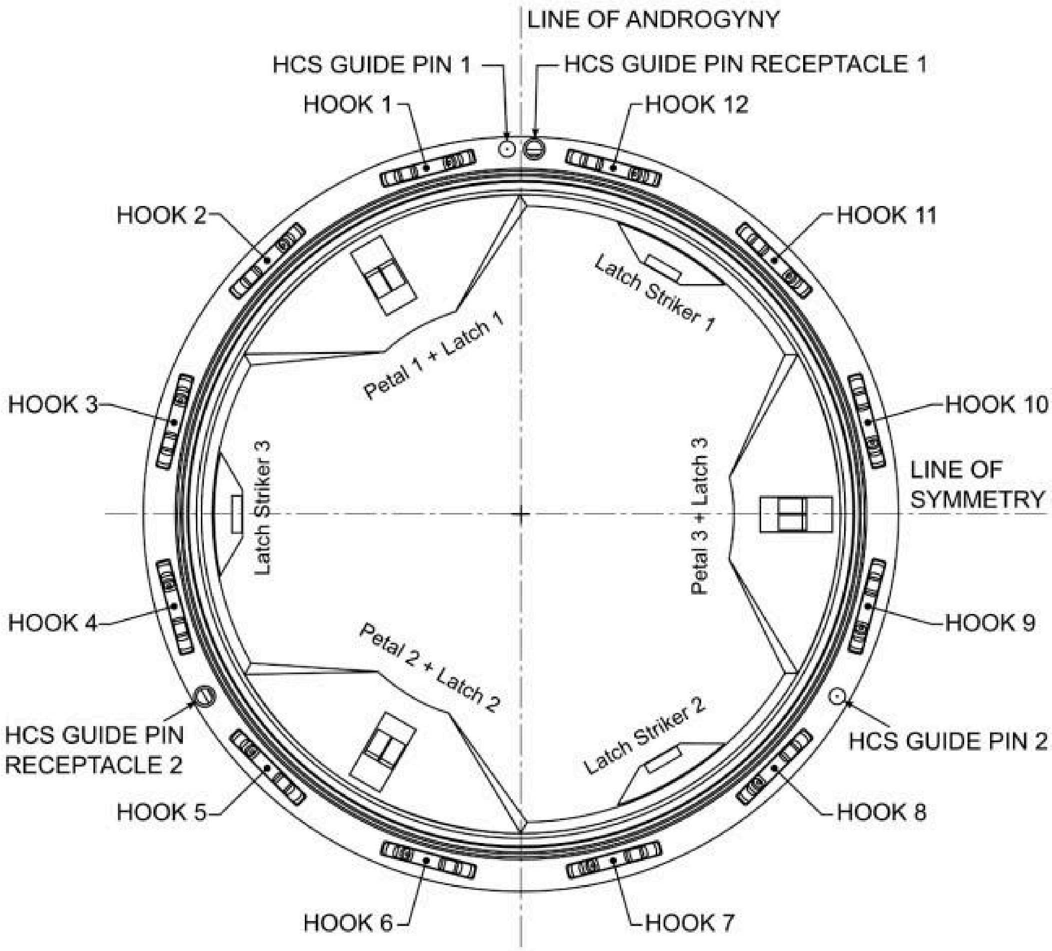


Figure 5.2 Schematics of International Docking System (IDS) [36].

The other end of the catching module will be attached to an airlock module that pressurizes the system before transferring the cargo from the catching module to the climbing module. The climbing module will be equipped with photovoltaic arrays around the climber that provide power to the mechanical and electrical components of the system. The most important element of the structural subsystem is the tether, which is quite challenging to manufacture due to the availability of the required material. For constructing a 2000 km elevator, the structure has to be tapered with high tensile strength. The study of finding the best suitable material for the elevator is beyond the scope of this project. For a general idea, the input and output parameters of the structural subsystem are described in Figure 5.3.

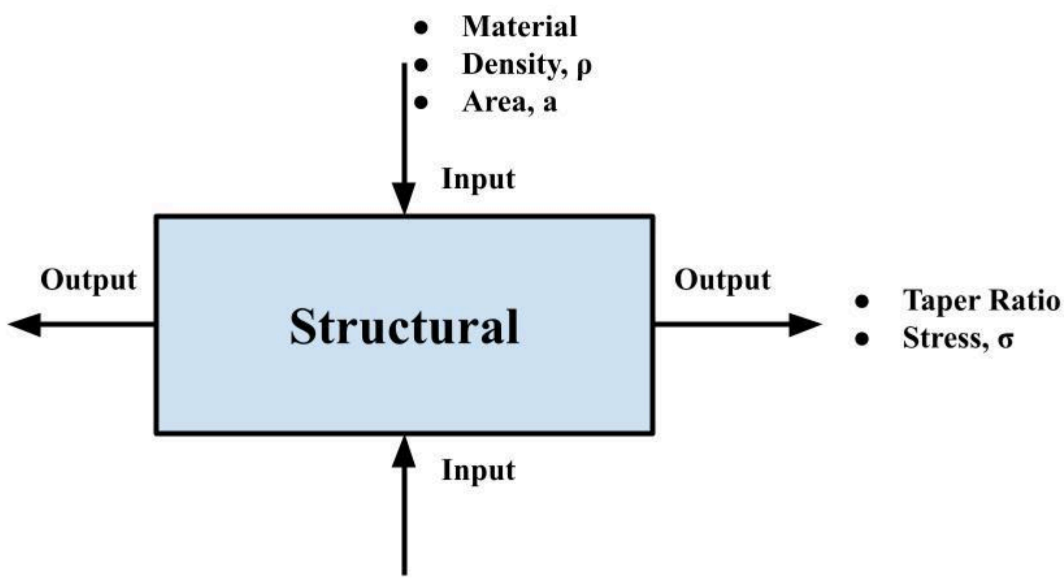


Figure 5.3 Block diagram of the structural subsystem.

5.3.2 Mechanical Subsystem

The mechanical subsystem consists of the climbing and the docking mechanism. The climbing mechanism includes the mechanical components that ascend and descend the climber along the tether. For a general idea of how a climbing mechanism works, a pinched-wheel climber is analyzed to highlight the essential parameters of the design. The climbing mechanism will consist of a pair of wheels connected with a tether placed in between. One wheel is fixed, while the other is a floating wheel that determines the compression on the tether. For climbing up and down, traction is needed between the wheels and the tether, which is considered as another key parameter of the design [38].

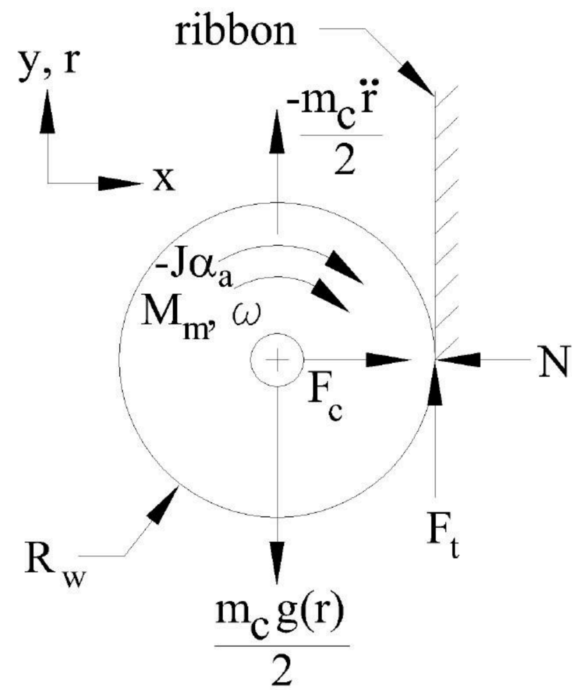


Figure 5.4 Free-body diagram of pinched-wheel climber [23].

The example of pinched-wheel design is derived from Ref. [23] and [38] presented in the International Space Elevator Consortium. To derive the equation of motions for the rolling wheel, a free-body diagram is illustrated in Figure 5.4 that represents only one wheel rolling along the tether. The floating wheel clamped on the other side of the tether will act the same once it is compressed against the tether. The friction between the wheels and the tether is responsible for the climber's ascent and descent. In the FBD diagram shown in Figure 5.4, various forces act on the wheel vertically and horizontally. The idea of deriving the equations of motion from the free-body diagram is to extract the key parameters that will affect the design of the climber. Some of the useful parameters are the size of the wheel, the number of wheels, and the rotational acceleration of the wheel. To derive the equation of motions of the wheel, total moments acting at the point of contact are summed as follows:

$$\sum M = \tau - \frac{m_c r'' R_w}{2} - \frac{m_c g(r) R_w}{2} - J\alpha = 0 \tag{5.1}$$

which becomes,

$$\tau = \frac{m_c r'' R_w}{2} + \frac{m_c g(r) R_w}{2} + J\alpha \tag{5.2}$$

The term g(r) represents the drag forces acting due to the gravity of the moon.

$$g(r) = \frac{M_{moon} * G}{r^2_{moon}} - r_{moon} * \omega^2_{moon} \tag{5.3}$$

The mass of the climber is distributed based on the number of wheels used, which is represented as follows:

$$m_w = \frac{m_c}{n_w} \tag{5.4}$$

Substituting Equation 5.4 to 5.2 becomes,

$$\tau = m_w r'' R_w + m_w g(r) R_w + J\alpha \tag{5.5}$$

To relate the angular quantities to linear quantities, the following expressions are used:

$$r = R\theta \tag{5.6}$$

$$r' = R\theta' \tag{5.7}$$

$$r'' = R\theta'' = R\alpha \tag{5.8}$$

Substituting Equation 5.8 to 5.5 becomes,

$$\tau = m_w \alpha R^2_w + m_w g(r) R_w + J\alpha \tag{5.9}$$

Which becomes,

$$\tau = \alpha(m_w R^2_w + J) + m_w g(r) R_w \tag{5.10}$$

Solving for the angular acceleration,

$$\alpha = \frac{\tau - m_w g(r) R_w}{m_w R^2_w + J} \tag{5.11}$$

Equation 5.11 describes the angular acceleration of the climber’s wheels which provides some input parameters like wheel mass, radius of the wheel, and the number of wheels. These parameters can be used to design the climbing mechanism according to the requirements.

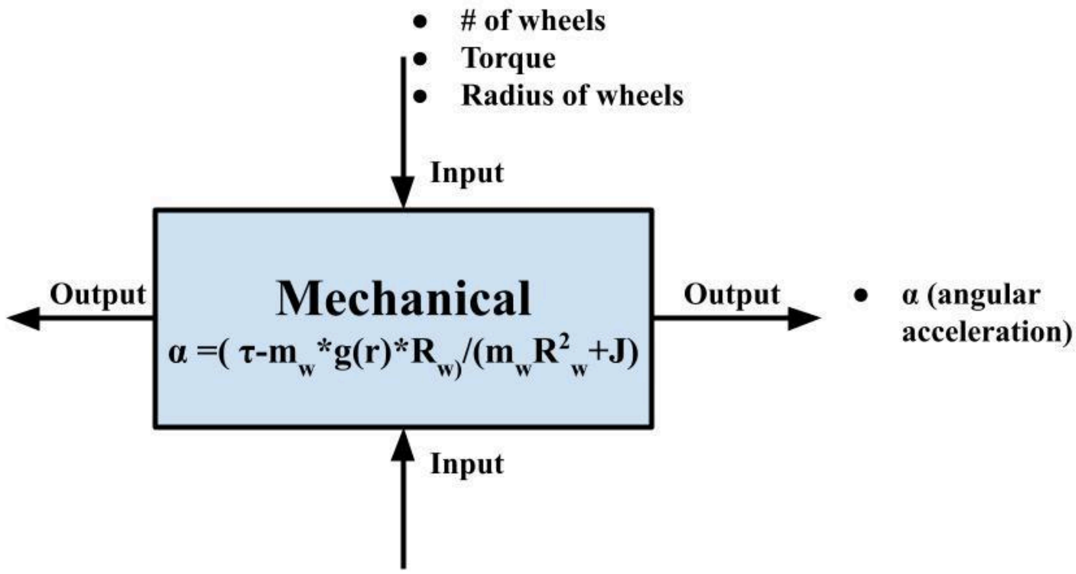


Figure 5.5 Block diagram of the mechanical subsystem.

5.3.3 Communication Subsystem

The communication subsystem includes the antennas and the receivers that help the climbing module to communicate with the Gateway and the ground stations on the Moon and the Earth. One advantage of using NRHO orbit is that Gateway will be visible to the Earth the whole time which eliminates any communication interruptions due to the blackout period. The Gateway is equipped with fixed low-gain antennas and steerable high-gain antennas that will provide better coverage to send large amounts of data back to Earth [39]. Since the apolune distance is extremely larger than the perilune distance, the Gateway will take a long time at the lunar south pole which can affect the communication between the elevator and the Gateway. To avoid any blackouts, the catching module will be equipped with high-gain antennas with Ka-bandwidth that will communicate with the Earth's ground station during the Gateway's blackout period. The climbing module will be equipped with high-gain antennas with S-bandwidth to communicate with the catching module and the lunar ground station. The key parameter that controls the communication subsystem is the bandwidth that outputs the rate of the data transferred or received. The data rates of the Gateway with respect to the band described in the paper [39] are represented in Table 5.2.

Table 5.2 Gateway data rates with respect to the band [39].

Link	Band	(Mbps)	
		Uplink	Downlink
Gateway to Earth	X	5	2
Gateway to Earth	Ka	20	100
Gateway to Moon	Ka	16	40

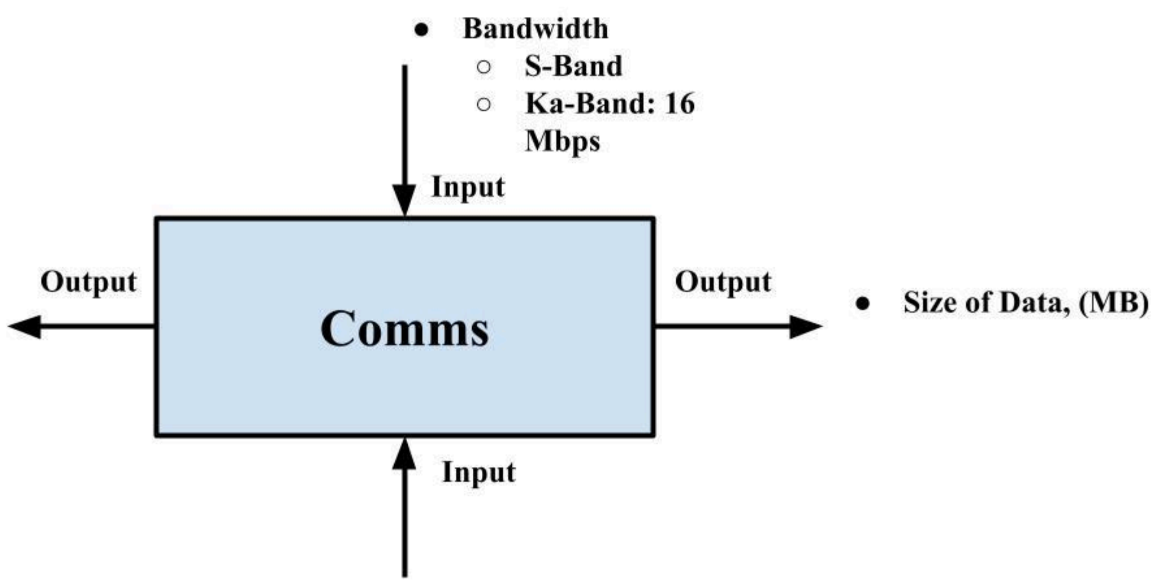


Figure 5.6 Block diagram of the communication subsystem.

5.3.4 Power Subsystem

The power subsystem is responsible for powering the onboard electronics of every module of the elevator. Both catching and climbing modules will have their separate power sources. The most amount of work will be done by the climbing module to transport the payload to and from the lunar surface. Therefore, the climber will be equipped with photovoltaic arrays that can be charged by using solar and laser energy. The amount of power required to lift the payload from the lunar surface will depend on the type of mechanical components used for the climber. The onboard electronics on the climbing and catching module can be powered by using

Multi-Mission Radioisotope Thermoelectric Generator (MMRTG). The generator provides 110 W of power and has a life span of about 14 years [35]. Both the climber and the catching module will be equipped with separate MMRTG that can provide power to the onboard electronics. To minimize the amount of weight on the climber, additional solar panels will be installed on the lunar surface near the ground station that will charge the laser beam that charges the climber's onboard photovoltaic cells. According to the research paper presented at the International Space Elevator Consortium, 4MW of power is required for the electric motors to lift a 20,000 kg climber [39]. However, the report was based on lifting a payload from the Earth's surface, which includes Earth's gravitational force. For this project, the climber is operating on the lunar surface, which minimizes the force of gravity to one-sixth of the earth's gravitational force. Moreover, the weight of the climber would be much smaller than 20,000 kg, which would also reduce the amount of power required. For the power subsystem, the input parameter that drives the system is the power that outputs the amount of torque the motor is producing. The climber should operate at a constant speed, which requires a variable amount of power depending on the mechanical load.

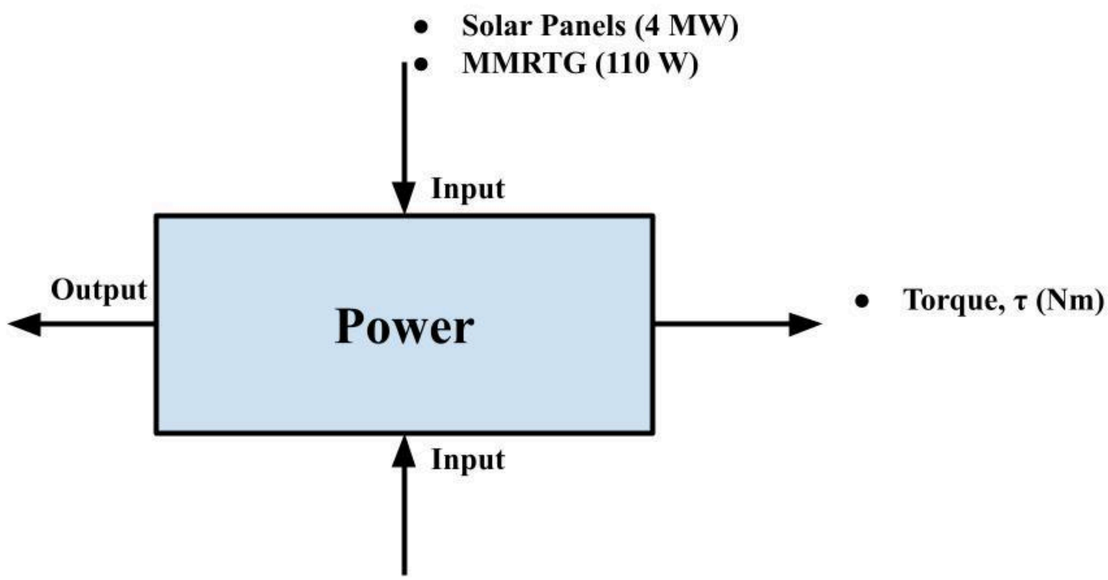


Figure 5.7 Block diagram of the power subsystem.

5.3.5 Thermal Protection Subsystem

The thermal protection system consists of the insulation foam required in the climbing module to protect the electronics from extremely cold temperatures at the lunar north pole. The lowest temperature recorded at the lunar poles is 25 Kelvin, which is extremely cold for the electronics to operate efficiently. The structure of the climber needs to be covered with a thick coating of insulating foam that will keep the interior warmer. The MMRTG used to power the electronics also produces heat through the metal tubes, which can be used as a thermal protection system for the electronics.

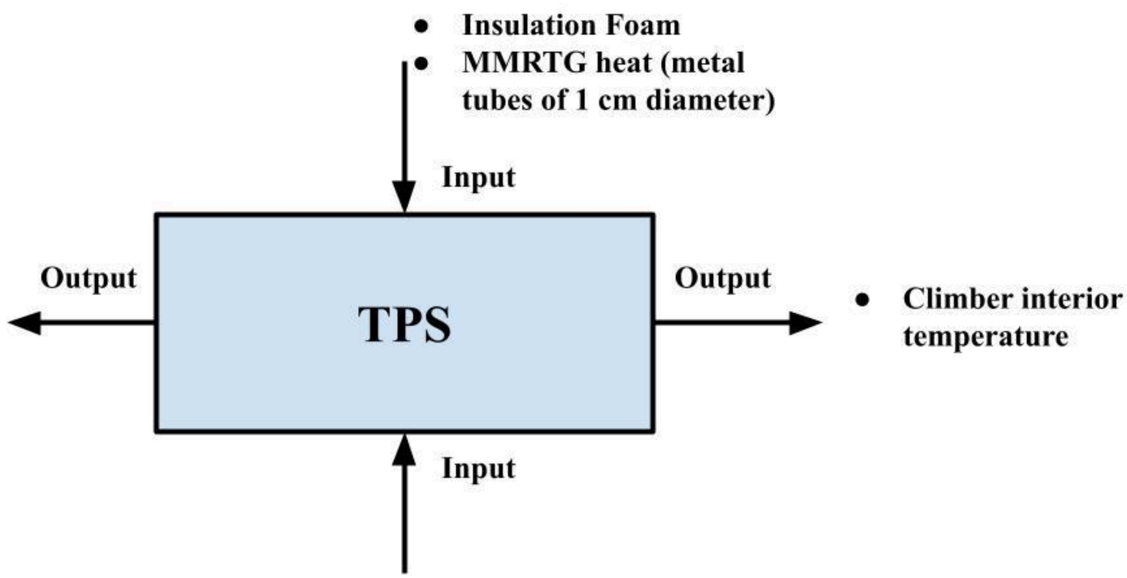


Figure 5.8 Block diagram of the thermal protection subsystem.

5.4 N-2 Diagram

After the decomposition of the system architecture into different subsystems, the key parameters are extracted from each subsystem which gives a better understanding of the design. However, each subsystem interacts with one another, which needs to be analyzed as well. Another system engineering tool that can be used is creating an N-2 diagram which represents the interaction of subsystems within the system. The N-2 diagram is useful for a better representation of the elements flowing in the system. By combining all the subsystems, an N-2 diagram is generated, which is represented in Figure 5.9.

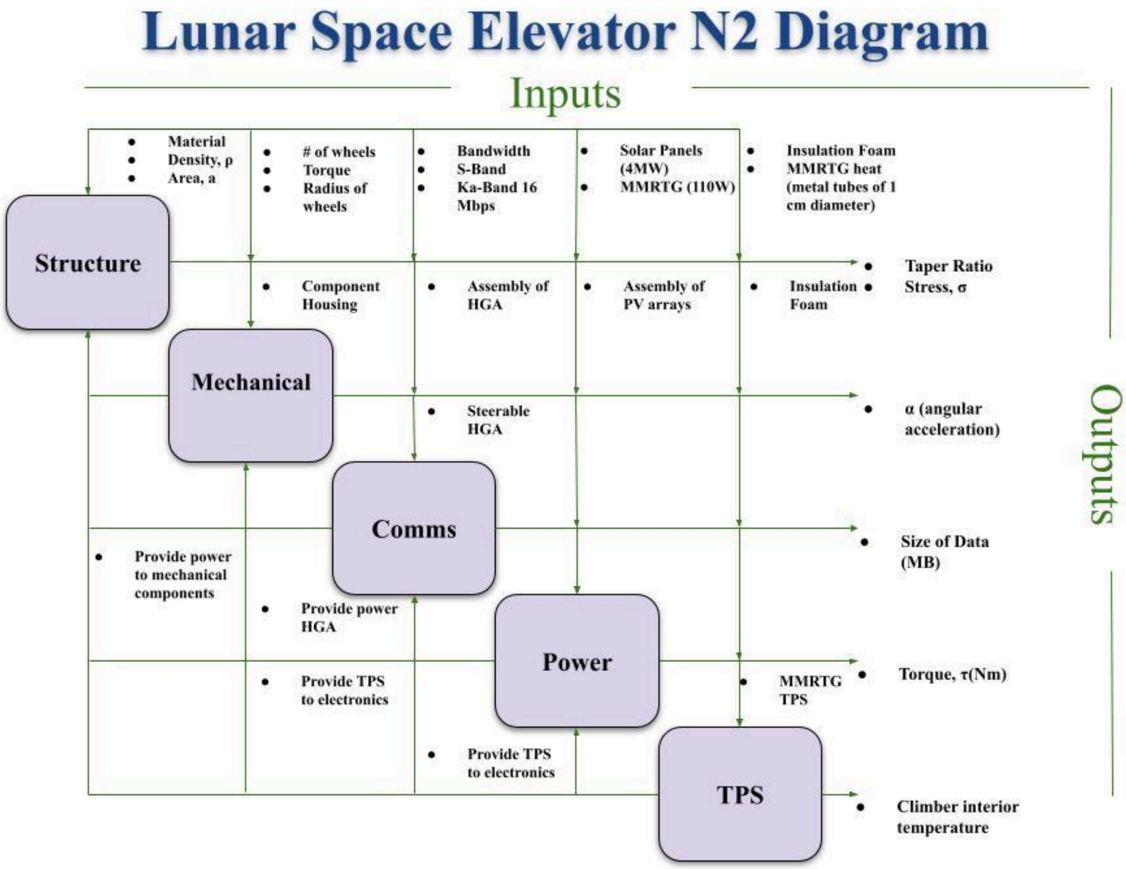


Figure 5.9 N-2 diagram of lunar space elevator.

Chapter 6: Communication analysis using System Tool Kit (STK)

6.1 Introduction

Like every space mission, communication is the key element that is responsible for the mission's success. It is challenging to monitor and track the mission status without proper communication, especially when the mission operations are done millions of miles away from the Earth. The goal of placing the Lunar Gateway in NRHO orbit is to create an outpost in lunar orbit that improves communication for future lunar missions. One of the advantages of NRHO orbit is that it is visible to the Earth the whole time. Therefore, it is beneficial to build a lunar space elevator near the perilune of the NRHO, which gives easy access to the Gateway for transporting payloads to the lunar surface. The only disadvantage of having a space elevator at the lunar north pole is that it will suffer a major communication blackout due to the characteristics of NRHO orbit. Due to the short distance at the perilune, the Gateway will have less time to stay in contact with the catching module and lunar ground station. NRHO is a polar elliptical orbit, which is beneficial for the Earth's ground stations but challenging for the Lunar ground station. To avoid any communication interruption, there must be an alternative method of communication that will share the mission status reports between the Gateway, Earth ground station, and the lunar ground station. The best way of calculating the blackout periods is by simulating the real-time scenario in a software called System Tool Kit (STK).

The orbital period of NRHO is 5.9 days, and the Gateway will spend most of the time at the lunar south pole due to the longest distance of apolune. The idea of creating constant communication between the ground stations and the Gateway is to use a deep space network. NASA uses DSN to communicate with the spacecraft and satellites traveling deep in space. For constant communication, NASA uses three sites on the Earth that are placed accordingly at different locations to avoid blackouts [36]. The three locations where the ground stations for DSN are built are:

1. Goldstone (Barstow, CA, United States)
2. Madrid (Madrid, Spain)
3. Canberra (Canberra, Australia)

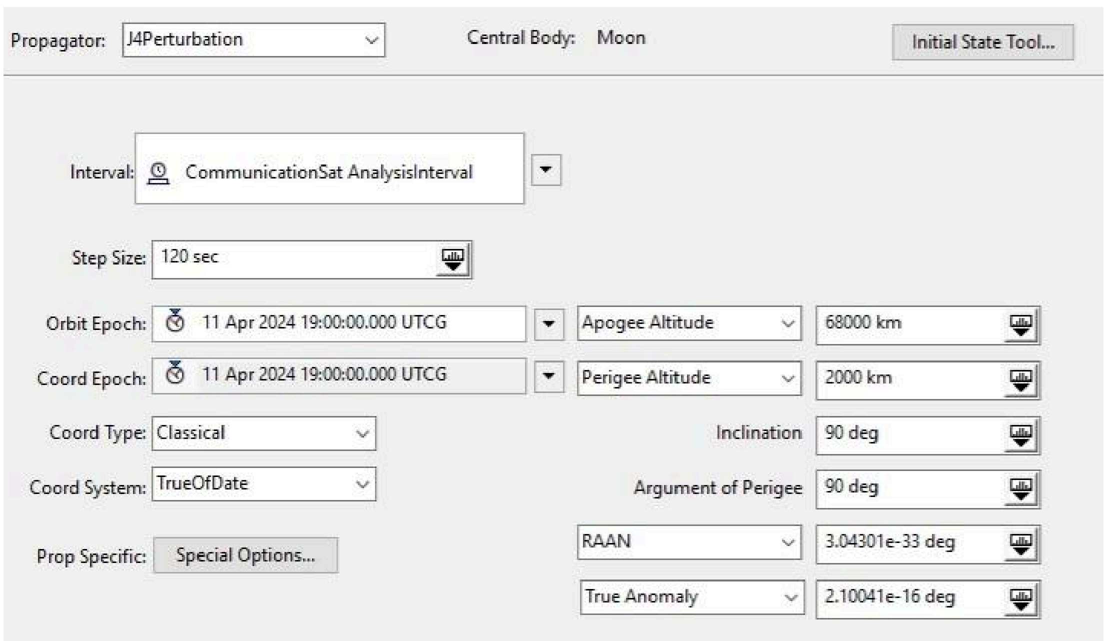
For STK analysis, only the Goldstone facility will be used to set up a scenario for calculating the blackout periods.

6.2 Communication between Gateway and lunar ground station

One of the advantages of the Gateway is that it can communicate with the lunar ground station and relay the information back to the Earth. Since the lunar ground station will be placed at the surface of the north pole, the Earth would not have access to communicate directly with it. The only way to communicate with the lunar ground station is via the Gateway. However, the Gateway will also suffer a huge blackout while traveling through the apolune. Therefore, the catching module will be an alternative to keep communication intact. The catching module will be placed at the perilune of NRHO at a distance of 2000 km above the lunar surface, which can communicate with the Earth's ground stations through DSN.

The lunar ground station will be equipped with movable receivers and transmitters that can rotate accordingly to target the Gateway's receivers and transmitters when it pass through the apolune to transfer the payload to the Lunar catching module. Due to a short apolune distance, the communication time window will be less as the Gateway travels faster at the apolune compared to perilune. To calculate the exact access time, STK is used for creating a real-time scenario. For modeling the Gateway, a satellite is placed in a circular orbit inclined at 90 degrees with a perilune distance of 68,000 km and an apolune distance of 2000 km. To align the orientation of the NRHO orbit along the Earth, the argument of perigee angle is adjusted to 90 degrees. The orbital period of NRHO is 5.9 days; therefore, the scenario period is set to 8 days for better visualization.

Table 6.1 Orbital settings of NRHO orbit in STK.



After simulating the scenario, an access report is generated that provides the exact time and duration of the communication window between the Gateway and the lunar ground station. Based on the report, the Gateway has access to the lunar ground station communication only twice throughout the orbital period. In 8 days, the Gateway has a window of about 3.2 hours to receive and transmit data from the lunar ground station, which is very short compared to the orbital period.

Table 6.2 Access report of the lunar ground station from the Gateway.

Access Report				
	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
	1	11 Apr 2024 19:00:00.000	11 Apr 2024 20:05:36.699	3936.699
	2	19 Apr 2024 01:25:28.257	19 Apr 2024 03:36:41.731	7873.474
Min Duration	1	11 Apr 2024 19:00:00.000	11 Apr 2024 20:05:36.699	3936.699
Max Duration	2	19 Apr 2024 01:25:28.257	19 Apr 2024 03:36:41.731	7873.474
Total Duration				11810.173

6.3 Communication between Gateway and Earth's ground station

As mentioned previously, the Gateway serves as an outpost in the polar lunar orbit that will provide constant communication to the Earth's ground stations. The advantage of NRHO orbit and the DSN is that they will eliminate any interruptions in communication. Since three ground communication facilities on the Earth use the deep space network to communicate in space, the Barstow facility will be used to simulate in STK to analyze the access report and the link budget.

The initial setup of the scenario consists of the Gateway in the NRHO orbit and the Earth ground station in Barstow, California. To create a ground station, the facility coordinates are used to set up a place in the scenario. Then, a satellite is used to create the Gateway in the NRHO orbit. The orbital settings of the NRHO are displayed in Table 6.1.

Table 6.3 Access report of the earth ground station from the Gateway.

Access Report					
	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Duration (hrs)
	1	4/11/2024 18:59:59	4/12/2024 6:10:57	40258.50	11.18
	2	4/12/2024 16:31:59	4/13/2024 6:59:25	52046.17	14.45
	3	4/13/2024 17:32:08	4/14/2024 7:42:55	51047.44	14.17
	4	4/14/2024 18:25:46	4/15/2024 8:23:17	50250.80	13.95
	5	4/15/2024 19:16:59	4/16/2024 9:02:08	49508.74	13.75
	6	4/16/2024 20:07:33	4/17/2024 9:41:47	48854.24	13.57
	7	4/17/2024 20:58:26	4/18/2024 10:26:43	48497.39	13.47
	8	4/18/2024 21:50:20	4/19/2024 11:05:09	47688.89	13.24
Min. Duration	1	4/11/2024 18:59:59	4/12/2024 6:10:57	40258.50	11.18
Max.Duration	2	4/12/2024 16:31:59	4/13/2024 6:59:25	52046.17	14.45
Total Duration				388152.158	107.82

After running the simulation, Table 6.3 is generated which represents the time duration of the Gateway's access to the Earth ground station within the eight days. The Gateway has access to the Barstow facility every day for at least 11 hours, which is expected as the Earth rotates on its axis, which runs into a blackout period of about 12 hours. The maximum access to the Barstow ground station is about 14.45 hours due to the Earth's tilted axis. The access report shows that Gateway's placement in the NRHO orbit is useful for maintaining communication with the Earth ground station via DSN. That is why the DSN is supported by three different facilities placed on different continents to eliminate communication interruption. During the

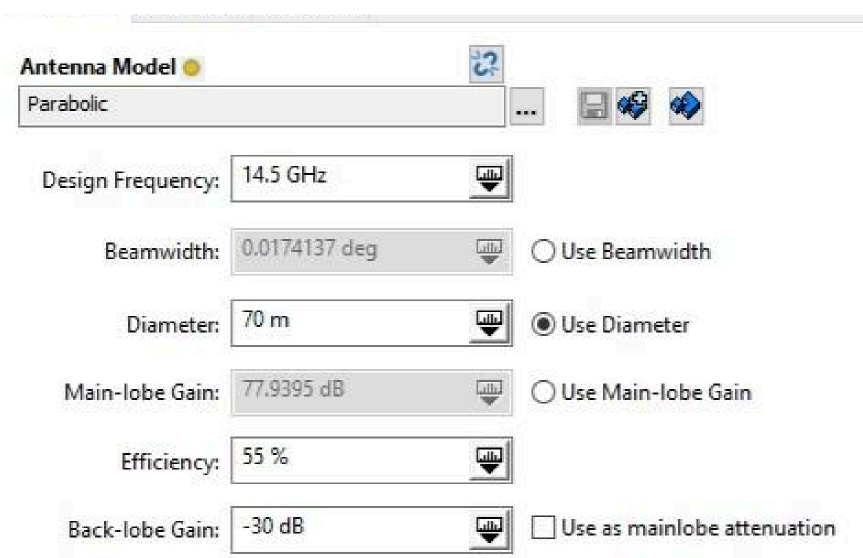
Barstow ground station blackout, the other facilities will kick in and maintain the communication connection.

Another aspect of running the STK simulation is to calculate the link budget between the transmitter and the receiver. The link budget is a calculation of analyzing the gains and losses of the signal during a communication. These calculations can be done analytically or computationally. The classical method of calculating the link budget is described in Ref. [40] by an equation as follows:

$$\frac{C}{N_0} = P_T * G_T * \frac{1}{L} * \frac{G_R}{T} * \frac{1}{k} \tag{6.1}$$

The idea of this equation is to calculate noise to the signal ratio, which can be optimized by tuning the EIRP (Equivalent Isotropic Radiated Power). The EIRP is the power required by the transmitter to transmit the signal properly to the receiver. To compute the link budget using STK, a transmitter is assigned to the Gateway and a receiver to the Earth's ground station. The receiver is mounted to a motor that can rotate the antenna to target the transmitter. The key parameter of the receiver is the diameter of the antenna. The facility at Barstow uses a DSS-14 antenna with a diameter of 70 m and is used to run the simulation [40].

Table 6.4 Antenna setting of the earth's ground station receiver.



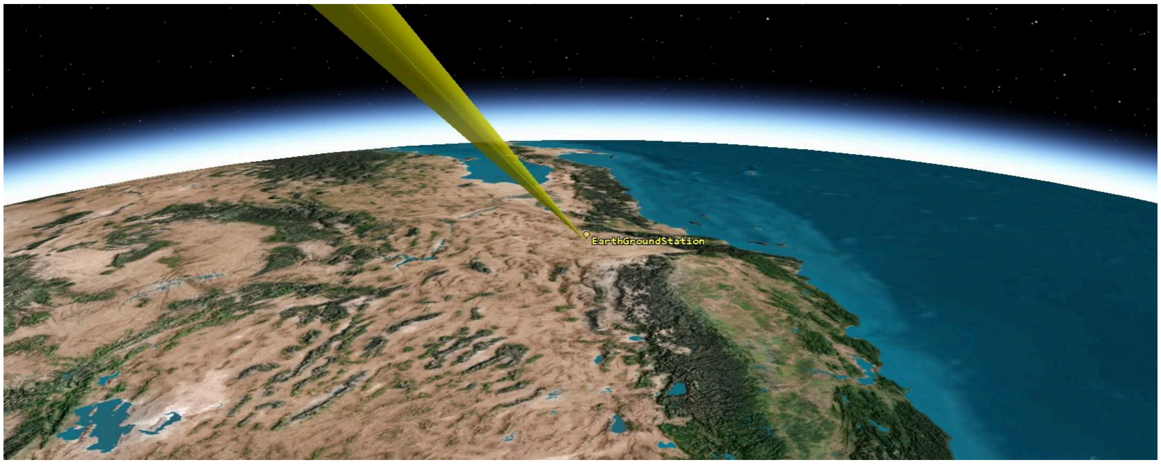


Figure 6.1 Spaceview of the receiver at the Barstow facility targeting the Gateway's transmitter.

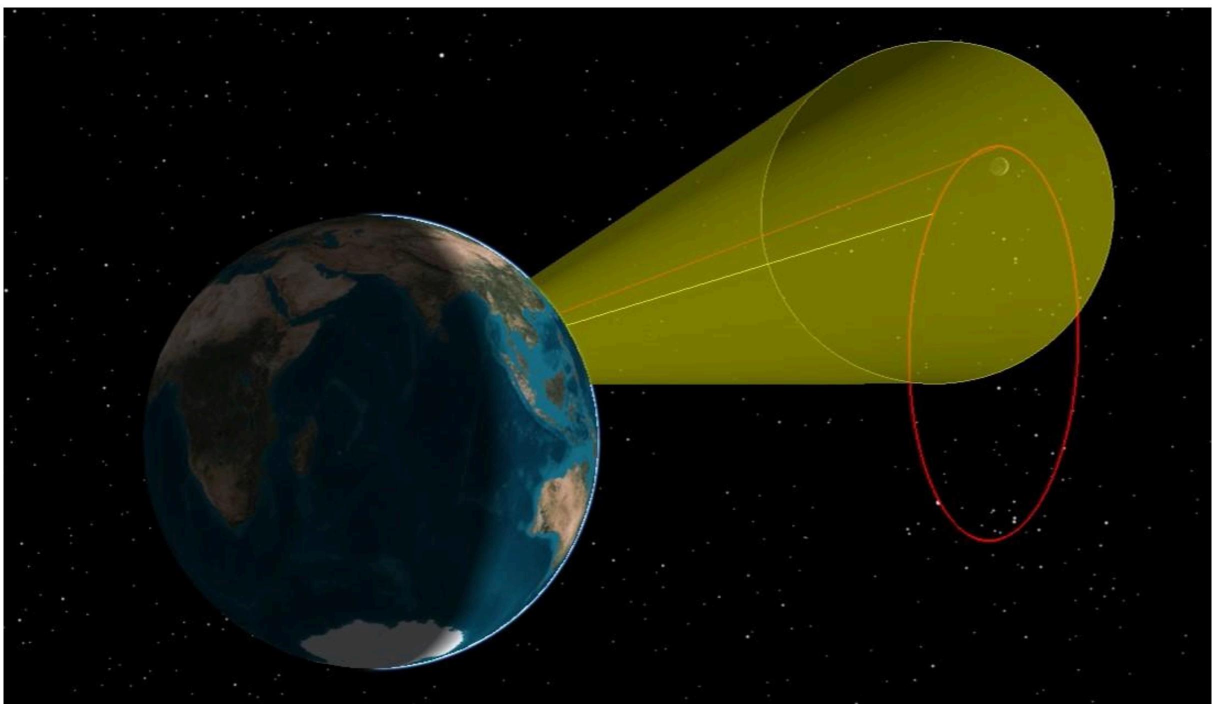


Figure 6.2 Earth's view of the receiver's antenna targeting the Gateway.

After simulating the scenario for eight days, the noise to the signal ratio is computed, and the C/N graph is generated below in Figure 6.3. The x-axis displays the time in UTCG, and the y-axis shows the noise to the signal ratio in decibels (dB). The values of the link budget are tabulated in Appendix A.

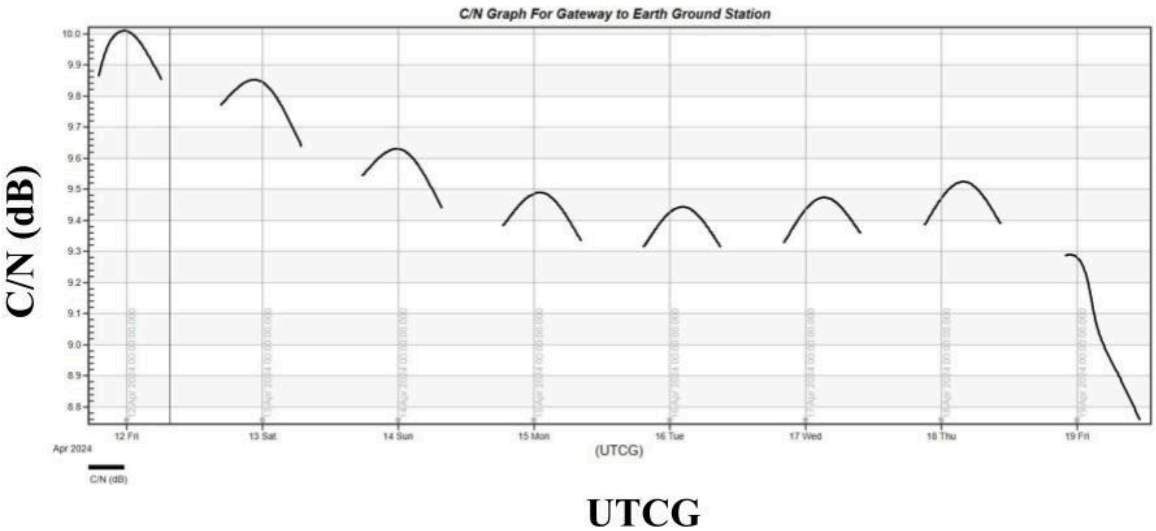
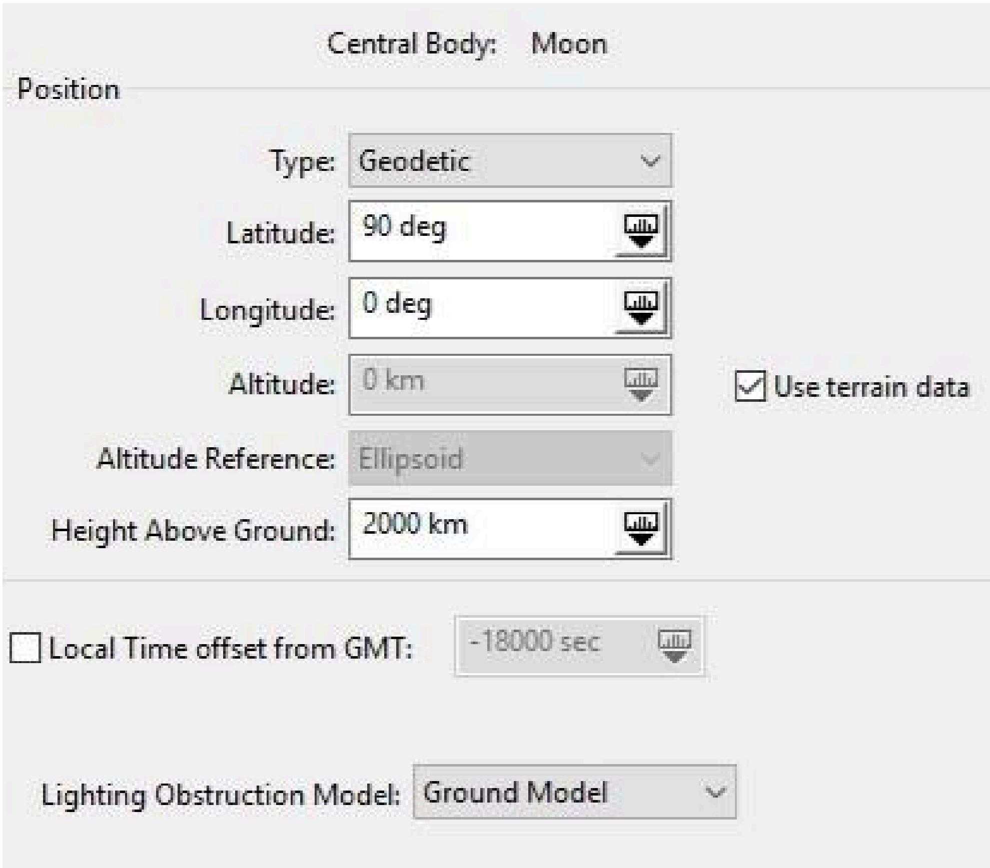


Figure 6.3 C/N graph for the communication between the Gateway and the earth's ground station.

6.4 Communication between catching module and Earth's ground station

The previous analysis shows that the Gateway has uninterrupted communication with the Earth's ground stations via DSN. However, the lunar ground station is unable to communicate with the Earth's ground station due to its placement at the lunar north pole. The only way that a lunar ground station can communicate with the Earth's ground station is through the Gateway. However, the Gateway has limited access to the lunar ground station throughout its orbital period. To avoid communication interruptions, the catching module will be equipped with receivers and transmitters that act as a median between the lunar and the Earth ground stations.

Table 6.5 STK settings of the catching module.



The catching module is placed above the north pole at a distance of 2000 km near the NRHO orbit. Like the Gateway, the catching module will also access the Earth's ground stations through the DSN.

Table 6.6 Access report of the Earth ground station from the lunar catching module.

Access Report					
	Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)	Duration (hrs)
	1	4/11/2024 19:00:00	4/12/2024 6:11:29	40289.20	11.19
	2	4/12/2024 15:57:12	4/13/2024 7:18:27	55274.24	15.35
	3	4/13/2024 16:50:50	4/14/2024 8:17:18	55588.54	15.44
	4	4/14/2024 17:49:45	4/15/2024 9:06:52	55026.46	15.29
	5	4/15/2024 18:51:22	4/16/2024 9:47:44	53781.59	14.94
	6	4/16/2024 19:53:07	4/17/2024 10:21:35	52107.90	14.47
	7	4/17/2024 20:53:23	4/18/2024 10:50:18	50214.35	13.95
	8	4/18/2024 21:51:41	4/19/2024 11:15:33	48231.32	13.40
Min. Duration	1	4/11/2024 19:00:00	4/12/2024 6:11:29	40289.20	11.19
Max.Duration	3	4/13/2024 16:50:50	4/14/2024 8:17:18	55588.54	15.44
Total Duration				410513.61	114.03

Like the Gateway, the catching module has similar access to the Earth's ground stations using the DSN. However, the catching module has 7 hours more access to the Earth's ground station due to its stationary behavior. The stations can maintain constant communication by switching to the available communication network.

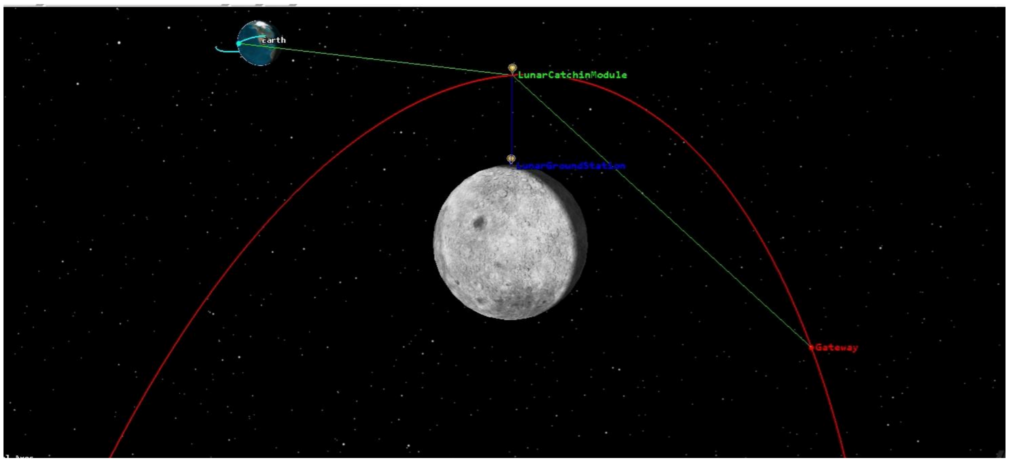


Figure 6.4 Spaceview of the communication network between the stations.

6.5 Conclusion

This chapter concludes the STK analyses of the communication between the stations. The goal of using STK is to create real-time scenarios of the space environment. Due to the nature of the three-body problem, it is challenging to perform the calculations analytically. The simulations performed in STK give a general idea of how to keep constant communication between the lunar ground station, the Gateway, the catching module, and the Earth's ground stations. The access reports provide the time frames when the communication is accessible between the stations. Also, the noise to the signal ratio can be calculated easily through the simulations.

The scope of this project is to design a lunar space elevator with a payload-catching module that will transport the payload to and from the lunar surface. The idea of constructing a lunar space elevator is encouraged by the historical ideas of building a space elevator, as discussed in the literature review. The discovery of the NRHO orbit and the future Artemis mission of constructing a Lunar Gateway also supplemented the design phase of the elevator to locate the optimal placement for the floating end of the elevator. The historical studies of the space elevator motivated this project to develop a conceptual design of the lunar elevator. The system architecture is decomposed into multiple subsystems to study the system's complexity. Many aspects of the system architecture require in-depth analysis, which is beyond the project's goal. The general method of outlining the key parameters of each subsystem is practiced throughout this project using system engineering tools. Besides the literature review and mathematical equations, computational tools like SolidWorks and STK are practiced to create real-time scenarios and simulations. To conclude the project, a conceptual design of the lunar space elevator with detailed system architecture and real-time scenarios of three-body problems is presented in this report.

6.6 Future Recommendations

This project demands an in-depth study of each subsystem in terms of design and analysis, which will require a lot of time and resources. Every subsystem of this project can become an individual project that can be researched in detail to identify the cost, risk, and time required to transform the concept into reality. The structural subsystem can be discussed in detail by designing every component of the elevator individually to perform FEA and CFD analysis for simulating real-time results. One of the most important structural design elements is the structure of the tether, which requires in-depth research to determine the best material that can withstand the weight and stress of the elevator. The mechanical subsystem requires detailed research to build an actual climber by performing FEA and CFD analysis for the mechanical components. For the electrical subsystem, the power budget needs to be analyzed by calculating the power requirements of individual electrical components. Lastly, the stability of the elevator is the most important element that needs to be researched which will bring the concept of space elevator into reality.

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APPENDIX A - Link Budget Data

Time (UTCG)	EIRP (dBW)	C/N (dB)	Eb/No (dB)	BER
11 Apr 2024 19:00:00	30	9.86	12.87	2.4E-10
11 Apr 2024 20:00:00	30	9.93	12.94	1.8E-10
11 Apr 2024 21:00:00	30	9.97	12.98	1.4E-10
11 Apr 2024 22:00:00	30	10.00	13.01	1.3E-10
11 Apr 2024 23:00:00	30	10.01	13.02	1.2E-10
12 Apr 2024 0:00:00	30	10.01	13.02	1.2E-10
12 Apr 2024 1:00:00	30	10.00	13.01	1.3E-10
12 Apr 2024 2:00:00	30	9.98	12.99	1.4E-10
12 Apr 2024 3:00:00	30	9.95	12.96	1.6E-10
12 Apr 2024 4:00:00	30	9.92	12.93	1.8E-10
12 Apr 2024 5:00:00	30	9.89	12.90	2.1E-10
12 Apr 2024 6:00:00	30	9.86	12.87	2.5E-10
12 Apr 2024 6:10:57	30	9.85	12.86	2.5E-10

Time (UTCG)	EIRP (dBW)	C/N (dB)	Eb/No (dB)	BER
12 Apr 2024 16:31:59	30	9.77	12.78	3.6E-10
12 Apr 2024 17:31:58	30	9.79	12.80	3.4E-10
12 Apr 2024 18:31:58	30	9.81	12.82	3.1E-10
12 Apr 2024 19:31:58	30	9.83	12.84	2.8E-10
12 Apr 2024 20:31:58	30	9.84	12.85	2.7E-10
12 Apr 2024 21:31:58	30	9.85	12.86	2.6E-10
12 Apr 2024 22:31:58	30	9.85	12.86	2.5E-10
12 Apr 2024 23:31:58	30	9.85	12.86	2.6E-10
13 Apr 2024 0:31:58	30	9.84	12.85	2.7E-10
13 Apr 2024 1:31:58	30	9.82	12.83	2.9E-10
13 Apr 2024 2:31:58	30	9.79	12.80	3.3E-10
13 Apr 2024 3:31:58	30	9.76	12.77	3.8E-10
13 Apr 2024 4:31:58	30	9.73	12.74	4.4E-10
13 Apr 2024 5:31:58	30	9.69	12.70	5.2E-10
13 Apr 2024 6:31:58	30	9.65	12.66	6.2E-10
13 Apr 2024 6:59:24	30	9.63	12.64	6.6E-10

Time (UTCG)	EIRP (dBW)	C/N (dB)	Eb/No (dB)	BER
13 Apr 2024 17:32:08	30	9.54	12.55	9.9E-10
13 Apr 2024 18:32:07	30	9.56	12.57	9.1E-10
13 Apr 2024 19:32:07	30	9.58	12.59	8.3E-10
13 Apr 2024 20:32:07	30	9.60	12.61	7.7E-10
13 Apr 2024 21:32:07	30	9.62	12.63	7.2E-10
13 Apr 2024 22:32:07	30	9.63	12.64	6.9E-10
13 Apr 2024 23:32:07	30	9.63	12.64	6.8E-10
14 Apr 2024 0:32:07	30	9.63	12.64	6.9E-10
14 Apr 2024 1:32:07	30	9.62	12.63	7.2E-10
14 Apr 2024 2:32:07	30	9.60	12.61	7.7E-10
14 Apr 2024 3:32:07	30	9.58	12.59	8.5E-10
14 Apr 2024 4:32:07	30	9.55	12.56	9.7E-10
14 Apr 2024 5:32:07	30	9.52	12.53	1.1E-09
14 Apr 2024 6:32:07	30	9.48	12.49	1.3E-09
14 Apr 2024 7:32:07	30	9.45	12.46	1.5E-09
14 Apr 2024 7:42:55	30	9.44	12.45	1.5E-09

Time (UTCG)	EIRP (dBW)	C/N (dB)	Eb/No (dB)	BER
14 Apr 2024 18:25:45	30	9.38	12.39	1.9E-09
14 Apr 2024 19:25:44	30	9.41	12.42	1.8E-09
14 Apr 2024 20:25:44	30	9.43	12.44	1.6E-09
14 Apr 2024 21:25:44	30	9.45	12.46	1.5E-09
14 Apr 2024 22:25:44	30	9.47	12.48	1.3E-09
14 Apr 2024 23:25:44	30	9.48	12.49	1.3E-09
15 Apr 2024 0:25:44	30	9.49	12.50	1.2E-09
15 Apr 2024 1:25:44	30	9.49	12.50	1.2E-09
15 Apr 2024 2:25:44	30	9.48	12.49	1.3E-09
15 Apr 2024 3:25:44	30	9.47	12.48	1.4E-09
15 Apr 2024 4:25:44	30	9.45	12.46	1.5E-09
15 Apr 2024 5:25:44	30	9.42	12.43	1.6E-09
15 Apr 2024 6:25:44	30	9.39	12.40	1.8E-09

15 Apr 2024 7:25:44	30	9.36	12.37	2.1E-09
15 Apr 2024 8:23:16	30	9.33	12.34	2.4E-09

Time (UTCG)	EIRP (dBW)	C/N (dB)	Eb/No (dB)	BER
15 Apr 2024 19:16:58	30	9.31	12.32	2.6E-09
15 Apr 2024 20:16:57	30	9.34	12.35	2.3E-09
15 Apr 2024 21:16:57	30	9.37	12.38	2.0E-09
15 Apr 2024 22:16:57	30	9.39	12.40	1.8E-09
15 Apr 2024 23:16:57	30	9.41	12.42	1.7E-09
16 Apr 2024 0:16:57	30	9.43	12.44	1.6E-09
16 Apr 2024 1:16:57	30	9.44	12.45	1.5E-09
16 Apr 2024 2:16:57	30	9.44	12.45	1.5E-09
16 Apr 2024 3:16:57	30	9.44	12.45	1.5E-09
16 Apr 2024 4:16:57	30	9.43	12.44	1.6E-09
16 Apr 2024 5:16:57	30	9.41	12.42	1.7E-09
16 Apr 2024 6:16:57	30	9.39	12.40	1.9E-09
16 Apr 2024 7:16:57	30	9.36	12.37	2.1E-09
16 Apr 2024 8:16:57	30	9.33	12.34	2.4E-09
16 Apr 2024 9:02:07	30	9.31	12.32	2.6E-09

Time (UTCG)	EIRP (dBW)	C/N (dB)	Eb/No (dB)	BER
16 Apr 2024 20:07:31	30	9.33	12.34	2.4E-09
16 Apr 2024 21:07:30	30	9.36	12.37	2.1E-09
16 Apr 2024 22:07:30	30	9.39	12.40	1.9E-09
16 Apr 2024 23:07:30	30	9.42	12.43	1.7E-09
17 Apr 2024 0:07:30	30	9.44	12.45	1.5E-09
17 Apr 2024 1:07:30	30	9.46	12.47	1.4E-09
17 Apr 2024 2:07:30	30	9.47	12.48	1.3E-09
17 Apr 2024 3:07:30	30	9.47	12.48	1.3E-09
17 Apr 2024 4:07:30	30	9.47	12.48	1.3E-09
17 Apr 2024 5:07:30	30	9.46	12.47	1.4E-09
17 Apr 2024 6:07:30	30	9.44	12.45	1.5E-09
17 Apr 2024 7:07:30	30	9.42	12.43	1.6E-09

17 Apr 2024 8:07:30	30	9.40	12.41	1.8E-09
17 Apr 2024 9:07:30	30	9.37	12.38	2.0E-09
17 Apr 2024 9:41:45	30	9.36	12.37	2.1E-09

Time (UTCG)	EIRP (dBW)	C/N (dB)	Eb/No (dB)	BER
17 Apr 2024 20:58:24	30	9.38	12.39	1.9E-09
17 Apr 2024 21:58:23	30	9.41	12.42	1.7E-09
17 Apr 2024 22:58:23	30	9.44	12.45	1.5E-09
17 Apr 2024 23:58:23	30	9.47	12.48	1.3E-09
18 Apr 2024 0:58:23	30	9.49	12.50	1.2E-09
18 Apr 2024 1:58:23	30	9.51	12.52	1.1E-09
18 Apr 2024 2:58:23	30	9.52	12.53	1.1E-09
18 Apr 2024 3:58:23	30	9.52	12.53	1.1E-09
18 Apr 2024 4:58:23	30	9.52	12.53	1.1E-09
18 Apr 2024 5:58:23	30	9.51	12.52	1.2E-09
18 Apr 2024 6:58:23	30	9.49	12.50	1.2E-09
18 Apr 2024 7:58:23	30	9.46	12.47	1.4E-09
18 Apr 2024 8:58:23	30	9.43	12.44	1.6E-09
18 Apr 2024 9:58:23	30	9.40	12.41	1.8E-09
18 Apr 2024 10:26:41	30	9.39	12.40	1.9E-09

Time (UTCG)	EIRP (dBW)	C/N (dB)	Eb/No (dB)	BER
18 Apr 2024 21:50:18	30	9.29	12.30	2.8E-09
18 Apr 2024 22:50:17	30	9.29	12.30	2.8E-09
18 Apr 2024 23:50:17	30	9.28	12.29	2.9E-09
19 Apr 2024 0:50:17	30	9.26	12.27	3.2E-09
19 Apr 2024 1:50:17	30	9.20	12.21	4.0E-09
19 Apr 2024 2:50:17	30	9.11	12.12	5.7E-09
19 Apr 2024 3:50:17	30	9.04	12.05	7.5E-09
19 Apr 2024 4:50:17	30	8.99	12.00	8.9E-09
19 Apr 2024 5:50:17	30	8.95	11.96	1.0E-08
19 Apr 2024 6:50:17	30	8.92	11.93	1.2E-08
19 Apr 2024 7:50:17	30	8.88	11.89	1.3E-08

19 Apr 2024 8:50:17	30	8.84	11.85	1.5E-08
19 Apr 2024 9:50:17	30	8.81	11.82	1.8E-08
19 Apr 2024 10:50:17	30	8.77	11.78	2.0E-08
19 Apr 2024 11:05:06	30	8.76	11.77	2.1E-08