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Exploring The Potential Of Interplanetary Communication Networks Using STK

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Abstract:

This research explores the feasibility of optical (laser) communication for Earth-Mars interplanetary missions, addressing the limitations of traditional radio frequency (RF) systems, such as bandwidth constraints and high latency. Using AGI's System Tool Kit (STK), a simulation model was developed with an Earth ground station (DSS-14 Goldstone), a Mars orbiter relay, and a Mars surface station. Key parameters, including a 193.5 THz frequency, 10 Mbps data rate, and QPSK modulation, were configured to replicate real-world conditions. The simulation confirmed stable line-of-sight connectivity and successful dual-hop communication via the Mars orbiter. Despite software limitations preventing a full link budget analysis, the results demonstrate optical communication as a viable high-speed alternative for deep-space missions. This study provides a foundation for future research on hybrid RF-optical systems and advanced protocols to enhance interplanetary networks. The simulation also highlighted the importance of orbit selection and synchronization for minimizing communication outages during planetary rotation and eclipses. This research not only supports the adoption of optical communication in next-generation missions but also emphasizes the role of advanced simulation tools in evaluating system performance. The findings contribute to ongoing efforts in deep-space communication planning and pave the way for future hybrid RF-optical network designs with enhanced reliability, scalability, and data throughput.

Keywords: Optical Communication, Deep-Space Communication, STK, Mars Missions, Interplanetary Communication, Laser Communication.

1. Introduction

1.1 Background

1.1.1 Overview

For the past few years, humanity has been searching for a potential planet to colonize. With technological advancements, the space mission have extended from HEO to natural satellites and planets. Engineers have designed the rovers to investigate and examine in detail. These rovers operate in severe environments where humans cannot sustain life. One of the successful missions that has been achieved is sending a mission to the moon. After a deep examination, the colonization of the Moon has been declared impossible as it doesn't include such an atmosphere and other important elements for life. Regardless of the absence of the elements, we can extract the minerals as a human resource, or else it can be used as a refueling station. Due to low gravity on the Moon, the mission doesn't rely on it and is set to launch for Mars.

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The colonization of Mars is considered feasible as it contains the elements and evidence of water. Despite challenges like low air pressure, a carbon dioxide-rich atmosphere, and a magnetic field for protection, Mars is set to be explored through a collaborative effort between humans and robots. Humans would conduct scientific exploration of Mars in cooperation with robotic probes controlled by human explorers on the planet's surface. Today, the unmanned missions are orbiting and sending signals from the Jovian planets as well as from deep space. The possibility of resource extraction is another advantage of colonizing Mars. Mars is rich in minerals and other resources, such as water, which could support future space missions and even supply Earth with valuable materials. For instance, the abundant iron and aluminum on the Red Planet could be used to construct a spacecraft and other infrastructure. Water on Mars, besides being utilized by humans, can also be turned into rocket fuel in the future. One of the primary reasons for exploring Mars is for the scientific insights that can be gained in the process. The surface of Mars can teach us about the formation of the universe, planets, and Earth [1].

Mars Pathfinder was originally designed as a technology demonstration to deliver an instrumented lander and a free-ranging robotic rover to the surface of the Red Planet. Both the lander and the 23-pound (10.6 kilogram) rover, Sojourner, carried instruments for scientific observations and to provide engineering data on the new technologies being demonstrated. Included were scientific instruments to analyze the Martian atmosphere, climate, geology, and the composition of its rocks and soil. Mars Pathfinder used an innovative method of directly entering the Martian atmosphere and landing. From landing until the final data transmission on Sept. 27, 1997, Mars Pathfinder returned 2.3 billion bits of information, including more than 16,500 images from the lander and 550 images from the rover, as well as more than 15 chemical analyses of rocks and soil and extensive data on winds and other weather factors. After various missions, Curiosity and perseverance are actively operating and have found the evidence of past habitable environments and keeps on exploring and collecting the samples. The exploration has gone beyond Mars to the edge of Solar System [2].

While the Mars mission has made a groundbreaking contribution, success cannot be made possible without continuous communication. To make it possible, NASA’s Deep Space Network (DSN) is used which is the world’s largest telecommunication system. It is an international array of giant radio antennas that supports interplanetary spacecraft missions, plus a few that orbit Earth. The DSN also provides radar and radio astronomy observations that improve our understanding of the solar system and the larger universe. It is a powerful system for commanding, tracking and monitoring the health and safety of spacecraft at many distant planetary locales.

1.2 DSN Locations

The Australian complex is located 40 kilometers (25 miles) southwest of Canberra near the Tidbinbilla Nature Reserve. The Spanish complex is located 60 kilometers (37 miles) west of Madrid at Robledo de Chavela. The Goldstone complex is located on the U.S. Army’s Fort Irwin Military Reservation, approximately 72 kilometers (45 miles) northeast of the desert city of Barstow, California. Each complex is situated in semi-mountainous, bowl-shaped terrains to shield against external radio frequency interference [3]. Each of the three Deep Space Network, or DSN, sites has multiple large antennas and is designed to enable continuous radio communication between several spacecraft and Earth. All three complexes consist of at least four antenna stations, each equipped with large, parabolic dish antennas and ultra-sensitive receiving systems capable of detecting incredibly faint radio signals from distant spacecraft. To hear the spacecraft’s faint signal, the antennas are equipped with amplifiers, but there are two problems. First, the signal becomes degraded by background radio noise, or static, emitted naturally by nearly all objects in the universe, including the sun and earth. The background noise gets amplified along with the signal. Second, powerful electronic equipment amplifying the signal adds noise of its own. The DSN uses highly sophisticated technology, including cooling the amplifiers to a few degrees above absolute zero, and special techniques to encode signals so the receiving system can distinguish the signal from the unwanted noise [3]. Antenna stations are remotely operated from a signal processing center at each complex. The centers house electronic systems that point and control the antennas, receive and process data, transmit commands and generate spacecraft navigation data.

1.2.1 Telemetry

Telemetry data is made up of crucial science and engineering information transmitted to Earth via radio signals from spacecraft as they explore the far reaches of our solar system. The Deep Space Network, or DSN acquires, processes, decodes and distributes this data [4].

1.2.2 Spacecraft Command

Space mission operations teams use the DSN Command System to control the activities of their spacecraft. Commands are sent to robotic probes as coded computer files that the craft execute as a series of action.

1.2.3 Tracking

The DSN Tracking System provides two-way communication between Earth-based equipment and a spacecraft, making measurements that allow flight controllers to determine the position and velocity of spacecraft with great precision [4].

1.2.4 Radio Science

DSN antennas are used by some space missions to perform science experiments using the radio signals sent between a spacecraft and Earth. Changes in radio signals between their transmission and receipt can provide lots of useful information about far off places in the solar system. Examples include probing the rings of Saturn, revealing the interior structure of planets and moons, and testing the theory of relativity [4].

1.2.5 Follow the Sun Operations

The DSN consists of three complexes located approximately 120 degrees apart (Canberra, Australia; Madrid, Spain; Goldstone, California) tracking NASA and non-NASA missions that explore the furthest points of our solar system. Historically, the complexes operated concurrently with three shifts per day, one operator per antenna, 24 hours a day, seven days a week. A new paradigm called Follow the Sun allows each of the three DSN sites to operate the entire network during their day shift. SCaN's Near Space Network (NSN) and Deep Space Network (DSN) enable more than 100 NASA and non-NASA missions to explore the unknown, innovate for the benefit of humanity, and inspire the world through discovery. NASA SCaN (Space Communication and Navigation) is the program office for all of NASA's space communications operations.

The space communications relies on two things: a transmitter and a receiver. A transmitter encodes a message onto electromagnetic waves through modulation, which changes properties of the wave to represent the data. These waves flow through space toward the receiver. The receiver collects the electromagnetic waves and demodulates them, decoding the sender's message. Many NASA missions rely on relay satellites in order to get their data to the ground. For example, the space station communicates through (TDRS), which transmit data to ground stations in New Mexico and Guam. The launched Perseverance will send data through orbiters around Mars, which forward the data to Earth. Relays offer unique advantages in terms of communications availability. For example, the placement of TDRS at three different regions above Earth offers global coverage and near-continuous communications between low-Earth orbit missions and the ground. Rather than waiting to pass over a ground station, TDRS users can relay data 24 hours a day, seven days a week [4].

1.3 Deep Space Communication Challenges

While NASA Deep Space Mission (DSN) and other radio-based communication have successfully enabled the missions, but for the manned mission beyond the Earth, the network face significant challenges. These include bandwidth limitations, interference, and latency.

1.3.1 Bandwidth

NASA encodes data on various bands of electromagnetic frequencies. These bandwidths, ranges of frequencies, have different capabilities. Higher bandwidths can carry more data per second, allowing spacecraft to downlink data more quickly. Currently, NASA relies primarily on radio waves for communications, but the agency is developing ways to communicate with infrared lasers. This type of transmission will offer missions higher data rates than ever before. NASA's Laser Communications Relay Demonstration (LCRD) will showcase the benefits of optical communications. The mission will relay data between ground stations in California and Hawaii over optical links, testing their capabilities. NASA will also furnish the space station with an optical terminal that can relay data to the ground via LCRD [5].

1.3.2 Data Rates

Higher bandwidths can mean higher data rates for missions. An upcoming optical terminal on Artemis II mission will send 4K, ultra-high definition video from lunar orbit. But bandwidth isn't the only constraint on data rates. Other factors that can affect data rates include the distance between the transmitter and receiver, the size of the antennas or optical terminals they use, and the power available on either end. NASA communications engineers must balance these variables to maximize data rates [5].

1.3.3 Latency

Communications don't occur instantaneously. They're bound by a universal speed limit: the speed of light, about 186,000 miles per second. For spacecraft close to Earth, this time delay is almost negligible. However, farther from Earth, latency can become a challenge. At Mars' closest approach about 35 million miles away, the delay is about four minutes. When the planets are at their greatest distance about 250 million miles away, the delay is around 24 minutes. This means that astronauts would need to wait between four and 24 minutes for their messages to reach mission control, and another four to 24 minutes to receive a response. As NASA prepares to send human on mars, communications engineers are developing ways for astronauts to stay connected with Earth while recognizing delays will be a part of the conversation [5].

1.3.4 Interference

As communications transmissions travel over long distances or through the atmosphere, the quality of their data can deteriorate, garbling the message. Radiation from other missions, the Sun, or other celestial bodies can also interfere with the quality of transmissions. To make sure that mission operations centers receive accurate data, NASA uses methods of error detection and correction. Methods of error correction include computer algorithms that interpret noisy transmissions as usable data [5].

1.4 Optical Communication testing

NASA is developing laser communications to supplement the capabilities of current radio frequency systems, including bandwidth, spectrum and overall size of frequency packages and power used. This Laser uses light as a means of transmitting information over long distances. Within the context of NASA, laser communications technology sends data across space using lasers instead of radio frequencies. Various demonstrations have been done to test the laser including. [6]

1.4.1 Lunar Laser Communication Demonstration (LLCD)

In 2013, LLCD demonstrated laser communications at 622 megabits per second from and 20 megabits per second to lunar orbit. The mission validated the use of laser communications at the Moon and set the stage for further research and development.

1.4.2 Optical Payload for Lasercomm Science (OPALS)

The 2014 Optical Payload for Lasercomm Science (OPALS) experiment was a four- month laser communications demonstration onboard the International Space Station. OPALS downlinked a high-definition video of the 1969 Apollo 11 Moon landing in just seven seconds, when previously it took 12 hours to uplink the video using existing infrastructure.

1.4.3 Laser Communications Relay Demonstration (LCRD)

LCRD will be NASA’s first end-to-end laser relay system, demonstrating and testing NASA-developed laser technologies. LCRD will have two optical terminals, each capable of transmitting and receiving 1.2 gigabits per second. LCRD will spend two years relaying data for ground-based laser experiments before supporting missions in low Earth orbit.

1.4.4 Optical Communications and Sensor Demonstration (OCSD)

The Optical Communications and Sensor Demonstration (OCSD) was a set of three CubeSats launched in 2017. The OCSD demonstration conducted the first-ever high-speed laser communications downlink from a CubeSat to a ground station, using data rates of 2.5 gigabits per second.

1.4.5 TeraByte InfraRed Delivery (TBIRD)

TBIRD will demonstrate a direct-to-Earth laser communications link from a CubeSat in low-Earth orbit. The laser terminal onboard will be capable of delivering more than 50 terabytes of data per day.

1.4.6 Integrated LCRD Low-Earth Orbit User Modem and Amplifier Terminal

(ILLUMA-T) ILLUMA-T will be LCRD’s first user and bring laser capabilities to the International Space Station. The terminal will receive massive amounts of science data from experiments onboard and send it to LCRD, which will then relay it to the ground.

1.4.7 Orion Artemis II Optical Communications System (O2O)

O2O will leverage laser communications on Orion spacecraft, which will take humans to the Moon for the first time since the Apollo missions. O2O will enable live, ultra-high- definition video feeds between astronauts and Earth.

1.5 Deep Space Optical Communications (DSOC)

DSOC will test laser communications technologies against the unique challenges presented by deep space exploration. DSOC will fly on Psyche, a spacecraft set to study a unique metal asteroid orbiting the Sun between Mars and Jupiter.

1.5.1 LunaNet

LunaNet is NASA's plan for an internet on the Moon. Lunar orbiters or surface rovers using radio frequency or laser communications will be connected to LunaNet and receive services such as networking, navigation, and detection. This research address the questions like what are the primary challenges in interplanetary communication networks? How can STK be used to simulate interplanetary communication scenarios? And what are the best communication strategies (e.g., direct communication vs. relay systems) for missions to planets like Mars or moon? Advances in Delay-Tolerant Networking (DTN) and optics render communication promising through enhancing data transmission rates, network reliability, and communication latency. In the attempt to explore these possibilities, the System Tool Kit (STK) is applied in this study to simulate and examine different communication scenarios under diverse space conditions. STK allows engineers to simulate the behavior of signals, antennas, and spacecraft in real-world situations, giving insights into the performance of communication systems under different conditions. With the help of STK, this study hopes to investigate the possibilities of future interplanetary communication networks, overcoming major challenges like latency, bandwidth, and interference, and suggesting new solutions for future missions [7].

Research Objectives

i. Explore the impact of orbital mechanics on communication reliability.

ii. Investigate how different communication technologies (e.g., radio vs. optical) affect data throughput and latency.

Laser communication is a rapidly emerging technology in space communications for, higher data due to increasing need for higher bandwidth in deep space missions, laser communication is most preferred for interplanetary networks.

2. Literature Review

2.1 Mars-Earth Communication: Bands, Modulation, and Optics

Currently, the primary method for transmitting commands and information between Earth and spacecraft is through radio wave technology. Radio waves, which are widely used in space exploration, have a wavelength of about 3/64 inch (just over a millimeter) and a frequency of approximately 300 GHz, enabling rapid transmission. The time taken for communication is proportional to the distance between the receiver and transmitter: 1.3 seconds from Earth to the Moon, 5-20 minutes from Mars, 33-53 minutes from Jupiter, and over 20 hours from the Voyager spacecraft. NASA's Deep Space Network (DSN) uses large global antenna arrays to capture these radio signals, converting them into binary code and subsequently into other forms of data such as images, text, and videos. Various frequency bands are employed within the radio spectrum, including the X-band (7-8 GHz) for telemetry, tracking, and command (TT&C), the S-band (2-4 GHz) for TT&C and scientific data return, and the Ka-band, part of the extremely high radio spectrum, which allows efficient data transfer but is susceptible to interference from weather conditions. Thus, as we have already established, a communication link between Mars and Earth is important, however, it cannot be achieved via a physical medium. Therefore, it is crucial to consider the frequency band used for this link. In today's world, there are dedicated frequency bands for space missions. Selecting the appropriate band is essential for reliable communication due to potential issues such as propagation, interference, distance, and data transfer capabilities. To address these challenges when establishing a network on Mars, especially for communication between Mars and Earth, data transmission should be carefully tailored. Even though some missions still use low frequency bands, such as the Mars Reconnaissance Orbiter (X-band 8-12 GHz), low-frequency bands (below 20 GHz) have insufficient data transfer capabilities for high-speed deep space communication [8]. Although lower frequency bands offer advantages like reduced power usage, better obstacle penetration, and longer range, they cannot provide the high data rates needed for effective communication. Additionally, they require larger antenna sizes, which can be problematic when deployed in alien worlds. On the other hand, higher frequency bands offer more data-carrying capacity than lower frequencies. However, they need more power, a direct line of sight, and have more atmospheric propagation. Despite these disadvantages, it still does not disqualify them from being used in the space industry. Higher data rates, less congestion, and smaller antenna sizes make higher frequency channels crucial for space communication.

According to the Shannon-Hartley theorem, bandwidth is proportional to the bit rate, and more specifically, the equation states that the channel capacity in bps (C), is equal to the bandwidth of the channel in Hz (B), multiplied by the base 2 logarithm of 1 plus the average signal power (S) divided by the average noise power (N)

$$C = B(1 + \frac{S}{N})$$

Because traditionally, lower frequencies have been used, there are fewer allocations for higher frequencies, meaning that using higher frequencies means that more spectrum is available, and therefore there is a higher bandwidth, so more data can be transmitted at the same time. Therefore, higher frequencies allow for more efficient modulation algorithms to be used, which enables a higher bit rate. In 2019, NASA increased the data rate on the International Space Station by a factor of two, now making it 600 Mbps. This data rate requirement would be even greater in a Martian environment due to the numerous research instruments that future colonizing scientists will use. Therefore, relying on lower frequency bands with limited data capabilities would not be practical for Mars communication [8].

2.2 Voyager Missions

The Voyager 1 and Voyager 2 spacecraft, launched on September 5, 1977, and August 20, 1977, respectively, have set a benchmark for future deep space exploration missions. They have traveled approximately 22 billion kilometers and 18 billion kilometers, maintaining communication using Radio Frequency (RF) technology (Figure 2.1). Advanced signal processing techniques have been utilized to detect the faint signals sent by these spacecrafts, with NASA’s DSN playing a crucial role in sending commands and receiving data. The Voyagers were equipped with high-gain antennas that focus radio signals into narrow beams, enabling communication despite the vast distances. Continuous power was ensured using Radioisotope Thermoelectric Generators (RTGs).These missions exemplify the potential for successful deep space exploration, inspiring confidence that with rapid technological advancements and engineering solutions, humanity can explore more of the universe in the coming years [9].

Figure 2.1 Artist Illustration of Deep Space Communication established through Cassini spacecraft. [Image Courtesy: National Aeronautics and Space Administration].

2.3 NASA's Jupiter Icy Moons Orbiter

NASA's Jupiter Icy Moons Orbiter (JIMO) is a mission that will explore the icy moons of Jupiter (Callisto, Ganymede, and Europa). This orbiter will use nuclear power for a sustainable exploration duration. For communication, it will use a 32 GHz band, a 3-meter high-gain antenna, and a 1 kW 32 GHz band transmitter. These instruments will allow data transmissions of up to 10 Mbit/s at 6.5 Astronomical Units (AU). According to calculations in the International Telecommunication Union (ITU) Report ITU-R SA.2167, if these communication instruments were used for Mars communications at a range of 2.6 AU, it would significantly increase data transfer capabilities to up to 62 Mbit/s. This technique can be performed using STK to verify whether this communication technique can be implemented [10].

2.4 Deep Space Optical communication

Laser communications from deep space ranges conceived shortly after the invention of the laser was first seriously addressed by NASA through the Mars Laser Communication Demonstration (MLCD) Project which was aborted due to the cancellation of the host spacecraft called the Mars Telecommunications Orbiter. Since then, the Lunar Laser Communication Demonstration (LLCD), the farthest successful demonstration to date, was completed in 2013. The DSOC effort was preceded by the Deep-Space Optical Terminals (DOT) study for flight, initiated around 2009. The DSOC Project continued technology advancement started by the DOT Project through 2016. In January of 2017, NASA selected the Psyche Mission for development as part of the Science Mission Directorate's Discovery Program. Hosting the DSOC technology demonstration by accommodating the FLT on the Psyche spacecraft was included in the mission plan. The Psyche Mission science objectives are to explore the asteroid Psyche-16 with an approximately 3 year cruise to the asteroid.

The DSOC technology demonstration is planned during the early cruise and depending on health and status of the FLT, as well as Psyche Mission resources may be extended. The key objectives of the planned DSOC technology demonstration are (i) to validate the Consultative Committee for Space Data Systems (CCSDS) recommended photon-counting receivers combined with high peak power laser transmitters that can operate efficiently at a few bits per detected photon; (ii) to demonstrate link acquisition/re acquisition, tracking and laser beam pointing control needed for operating deep space links.

The baseline DSOC beacon based operational architecture is shown in figure. The system being developed consists of the following operation nodes: (i) the FLT on-board the Psyche mission spacecraft, capable of acquiring a 1064 nm uplink/beacon laser and transmitting a 1550 nm downlink laser; (ii) a Ground Laser Transmitter (GLT) transmitting a 1064 nm beacon with limited uplink data, located at the Optical Communication Telescope Laboratory, Table Mountain, CA; (iii) a Ground Laser Receiver (GLR) utilizing the Hale telescope at Palomar Mountain, CA, equipped with a photon-counting receiver; (iv) a Mission Operations Center (MOC) for coordinating ground operations (Figure 2.2) [11].

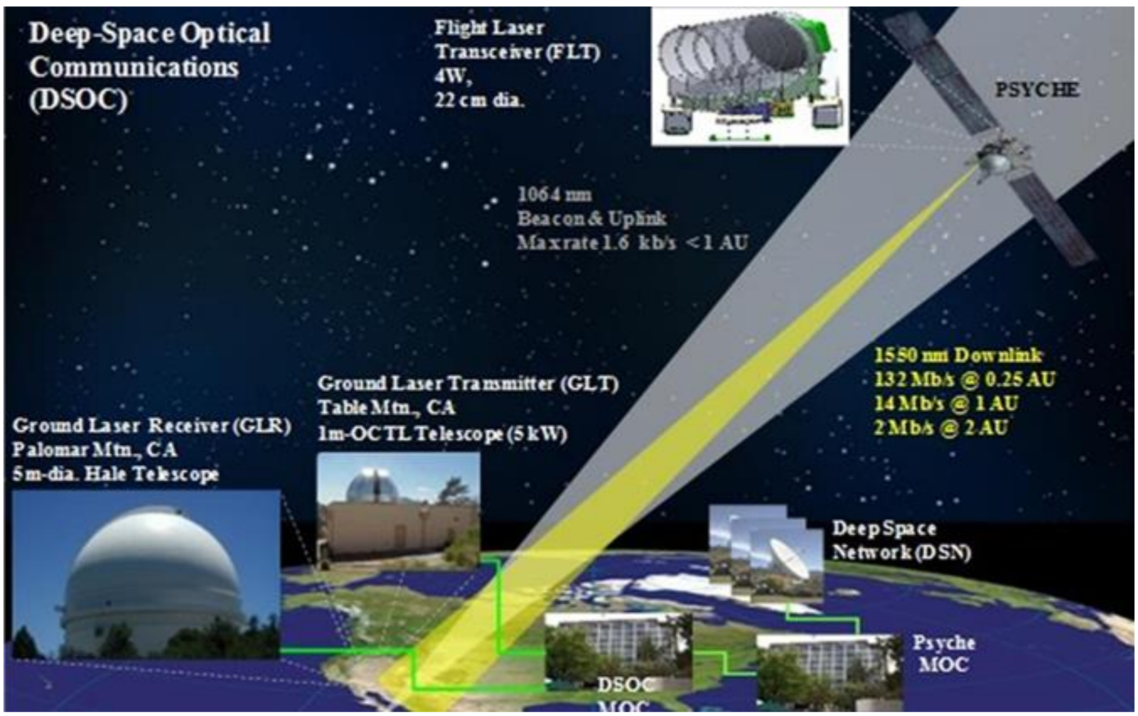


Figure 2.2: Planned DSOC operational architecture showing the four primary nodes: (i) FLT on-board the Psyche spacecraft; (ii) GLT; (iii) GLR; (iv) DSOC MOC along with the Psyche MOC and the DSN nodes that would support DSOC operations.

2.5 Advantages of optical over RF

2.5.1 Faster

Increasing operational frequencies into the visible and ultraviolet spectrum allows for extremely high data rates, which is crucial for space communication. This is not related to the speed of travel; the speed of light in a vacuum remains constant. Instead, optical communication can send more data in a fraction of the time compared to radio frequency communication.

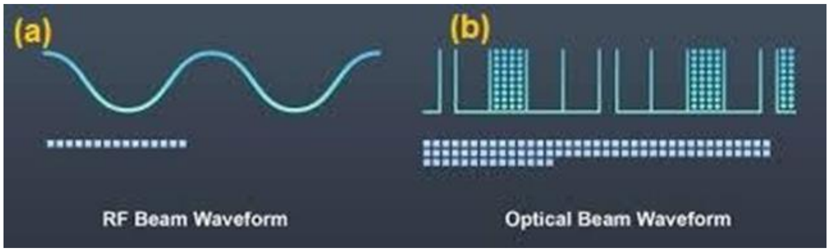


Figure 2.3 (a) RF Beam Waveform - The RF signal demonstrates a continuous, sinusoidal waveform capable of transmitting a moderate volume of data over time. Right: Optical Beam Waveform. (b) The optical signal is represented with pulsed, high-density data (Source: NASA)

2.5.2 Spectrum Occupying

While RF signals are commonly used for terrestrial data transfer and space exploration, obtaining a license for a unique frequency band that is appropriate for a specific mission can be challenging. However, optical communications use the light spectrum, which is not widely used in terrestrial applications. Additionally, optical communication systems focus on their target, resulting in a narrow beam that is less likely to interfere with other optical communications compared to radio frequencies.

2.5.3 Higher Security

Optical communication can provide a more secure communication environment because it uses a narrow beam of light that does not spread over the atmosphere. The direct line-of-sight communication makes it difficult to intercept or jam without being detected.

2.5.4 Compact and Lightweight Equipment

The use of optical communications eliminates the need for large and heavy antennas, particularly on a spacecraft. This reduction in equipment size and weight is critical for creating more compact and reliable space missions. However, optical communication also has some challenges. Because of its narrow beam, both communication nodes must maintain a direct line of sight and must be precise enough to hit each other's sensors. Space Communications and Navigation (SCaN) is developing a beacon system to help spacecraft hit their target while establishing an optical connection. Another challenge is the Earth's atmosphere. Even though it is crucial for life on Earth, clouds and mist can interrupt the laser and cause communication loss between spacecraft and ground stations. Establishing multiple ground stations or locating them at higher altitudes can help ensure more reliable communication. SCaN is currently working on multiple different solutions, such as Delay/Disruption Tolerant Networking (DTN). Despite these challenges, researchers recognize the potential of high-speed deep space communications and the possibilities for its development. While these benefits are well-known, some space industry organizations have already begun developing their optical communication technologies. NASA is currently working on multiple projects, and despite the experiments only starting in 2013, they have already achieved significant milestones in optical laser communication [12].

2.6 LCRD

The National Aeronautics and Space Administration's (NASA) Laser Communications Relay Demonstration (LCRD) completed the first 18 months of its Experiment Program in December 2023. During this time, LCRD performed experiments focusing on characterization of optical links and the system, as well as initial operations demonstrations (Figure 2.4). The LCRD mission architecture, which is designed to support a wide variety of experiments, is composed of flight and ground segments. The flight segment is onboard the Space Test Program Satellite-6 (STPSat-6) spacecraft in geosynchronous Earth orbit (GEO), and includes the LCRD flight payload and the spacecraft-provided High-bandwidth Radio Frequency (HBRF) terminal. The flight payload includes two optical space terminals (OST), OST1 and OST2, capable of simultaneous operation, as well as a data switch to interconnect the links for data relay. The ground segment includes two optical ground stations (Optical Ground Station 1, or OGS-1, in Table Mountain, California, and Optical Ground Station 2, or OGS-2, in Haleakalā, Hawaii) and a radio frequency ground station (RF GS) in New Mexico [13].

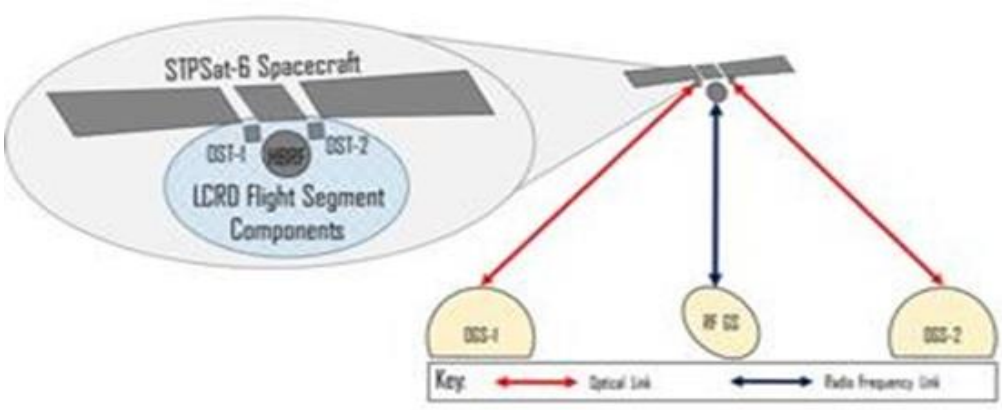


Figure 2.4 The LCRD mission architecture consists of a flight segment and a ground segment that will demonstrate two simultaneous bidirectional optical links.

2.7 The Lunar Laser Communication Demonstration (LLCD)

The Lunar Laser Communication Demonstration (LLCD) was the first attempt at optical communication as part of the Lunar Atmosphere and Dust Environment Explorer (LADEE) mission. The satellite was launched on September 6, 2013, aboard a Minotaur V spacecraft, and it impacted the Moon on April 14, 2014, as part of the mission. Before the impact, LLCD successfully transmitted optical data to Earth, testing optical communications for the first time. The LLCD mission achieved a downlink speed of 622 Mbps and an uplink speed of IAC-24-A3,IP,30,x85538 20 Mbps from the Moon to Earth. Achieving such high data transfer rates while occupying less weight and space compared to traditional RF systems was a significant milestone for the space industry [14].

3. System Toolkit (STK)

3.1 About STK

In this chapter the adopted methodology used in the System Tool Kit (STK) performance has been discussed. It is a platform for analyzing and visualizing complex systems in the context of our ongoing research mission. STK deals with the Interaction with data from platforms across the aerospace, defense, telecommunications, and other industries. It generates a Simulation model of our intended research/missions and communicates the results with reports, graphs, and stunning 3D animations. Satellites and their missions play a critical part in our everyday lives. Everything we do somehow is now connected to satellites in space. We use satellites to communicate, conduct banking transactions, tell the time, navigate our way around a city or the country for that matter, forecast the weather, protect our national security, create precise maps, examine the oceans, analyze the sun, map the galaxy, the list is practically endless [15]

3.2 STK Use

For the design package for satellite communication, there is software STK that is developed by America's AGI (Analytical Graphics, Incorporated). STK is an advanced satellite analysis tool in the aerospace industry. It shows 2D map which includes aero planes, satellites and carrier rocket etc. STK also possesses a 3D display environment. It is used as simulation software for conducting satellite communications. It performs the following main functions [15].

1. Orbital mechanics and the six orbital (Keplerian) elements used to find or place a satellite in orbit.
2. Visibility and coverage of the satellite
3. The altitudes satellites operate in, and the missions satellites perform at those altitudes.
4. Linking different segments of a space system together and how we communicate with and operate spacecraft from the ground.
5. Creating satellite constellations.
6. Launching rockets into space and having them join up with orbiting spacecraft
7. Determining when a satellite will overfly your location
8. Linking ground, airborne, and space segments together, and creating linkages around the world.

3.3 STK Astrogator

The application STK Astrogator supports trajectory design for spacecraft and interactive simulation of maneuvers. That makes it a perfect planning tool for space missions. For spacecraft trajectory, it has a dedicated Mission Control Sequence that can define an entire space mission, providing a visualization of the different segments involved. These include the craft's initial and launch states, its maneuvers and sequencing.

STK Astrogator uses the following flight-proven algorithms:

- Force models for third-body effect
- Solar radiation pressure
- Atmospheric drag
- Geopotential models
- Thermal pressure and albedo
- Solid and ocean tides
- Numerical integrators

The application uses search profiles to define goals and, where necessary, to modify variables to reach them. Its target sequence uses a root-finding algorithm to change the value of independent variables. It also offers users both versatility and flexibility to configure spacecraft and space missions. They can build mission control sequences, define key physical values such as fuel tank capacity and outline departure and arrival conditions of the proposed mission. Its visualization capability provides multiple views of space missions including 3D views from different perspectives. It is also possible to model multiple spacecraft flying in formation using the application, which helps in the analysis of satellite and constellation maintenance missions and other situations requiring proximity operations. STK Astrogator also works with additional plugins, making it scalable as well as adaptable, and it has extensive reporting capabilities [16].

3.4 STK SOLIS

The STK SOLIS application provides a complete spacecraft simulation environment. It is extremely useful for modelling the potential impact space conditions will have on spacecraft during missions. SOLIS enables engineers to evaluate system capabilities in spacecraft and consider any constraints early in the spacecraft's lifecycle. It will configure spacecraft components, including sensors, actuators, communications power and payload. SOLIS also allows engineers to create and save templates of optimal configurations to help with rapid assessments [17].

It can also emulate flight software using mission sequence modelling, along with telemetry and real-time commanding. Not only that, but it can also generate control system configurations automatically, for flight avionics. STK SOLIS has distinct modelling functions to visually determine the spacecraft's attitude in relation to its environment [18]. They are:

- Attitude determination
- Attitude control
- Attitude disturbance
- Power and thermal

It also provides mode control to determine orbit, velocity and tracking and supports both the design and operations of spacecraft. It has a target planning function for rapid generation of mission sequences, which incorporates actual spacecraft algorithms. That means you are only using real and accurate constraints in your modelling [19]. For spacecraft design, SOLIS enables operators to specify mission requirements and analyze the system concepts to meet them. It will analyze and refine conceptual designs, verify final versions and provide independent validation [20].

3.5 Benefits of STK to Space Missions

More and more, spacecraft simulation is playing a vital role in space missions. Given the time and sheer expense of designing, constructing and launching spacecraft, it is critical that engineers can minimize margins of error. At the same time, the overcrowded environment of space makes those challenges more acute. It makes sense, therefore, to be able to plan in detail on the ground, using sophisticated modelling, visualization and simulation software. Those applications provide detailed and accurate analytics to help ensure the success and safety of space missions.

STK Astrogator is ideal for interactive spacecraft maneuvering and designing trajectories. It can accommodate finite, impulsive and optimal finite modelling for rendezvous and proximity operations, low thrust, interplanetary travel and station keeping. STK SOLIS provides accurate spacecraft simulation environments, to support rapid development, and the assembling, testing and integration of spacecraft, assets and systems. An effective simulation environment provides an opportunity for the planning of close proximity operations and for refining space situational awareness methods [21].

4. Methodology

STK was downloaded using https://downloadly.ir/ which is freely available software. To start with the main STK viewer screen was opened where the set time period for the simulation to align with a real mission (Figure 4.1). Initially, the central body was set to Mars to insert the Mars- orbiter.

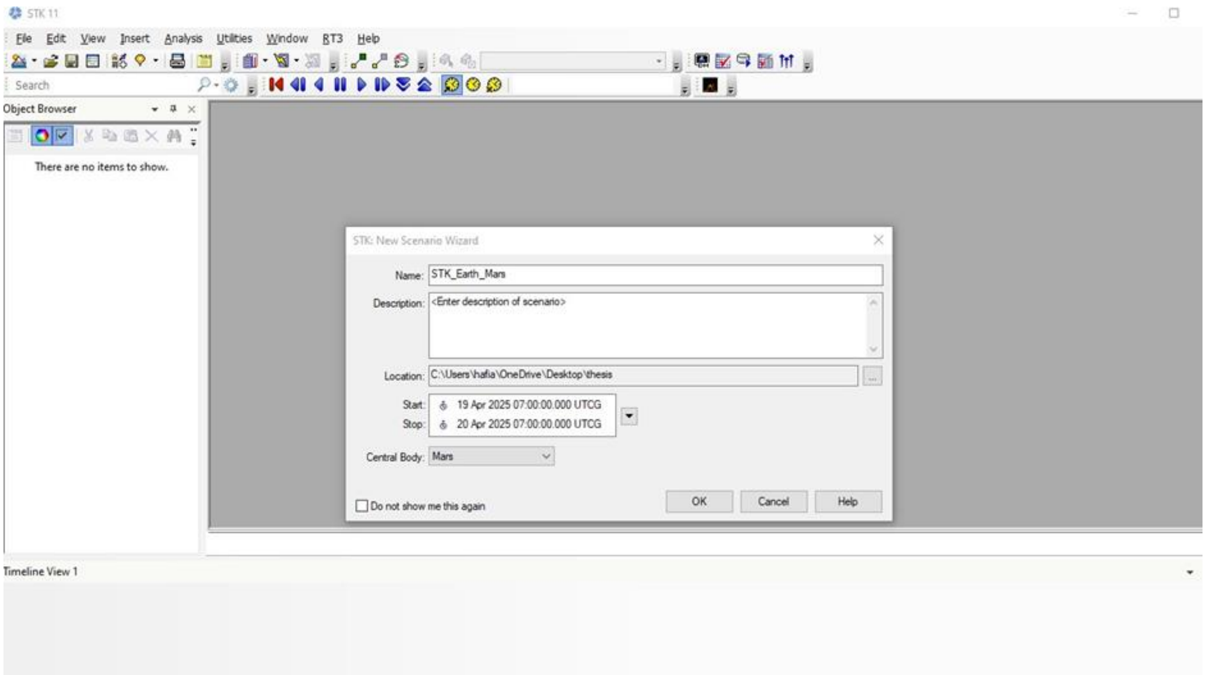


Figure 4.1 STK Scenario setup

The following methodology was adopted for ongoing research.

4.1 Characteristics of Earth and Mars as Celestial Bodies

1. Insert Earth and Mars as central bodies in the scenario.
2. Add the Mars orbit data and define the correct ephemeris data for accurate positioning.
3. Insert a satellite in Mars orbit (e.g., Mars Relay Satellite) using predefined orbital elements or by defining a custom orbit (Figure 4.2).
4. Adjust altitude, inclination, and eccentricity based on desired mission parameters.

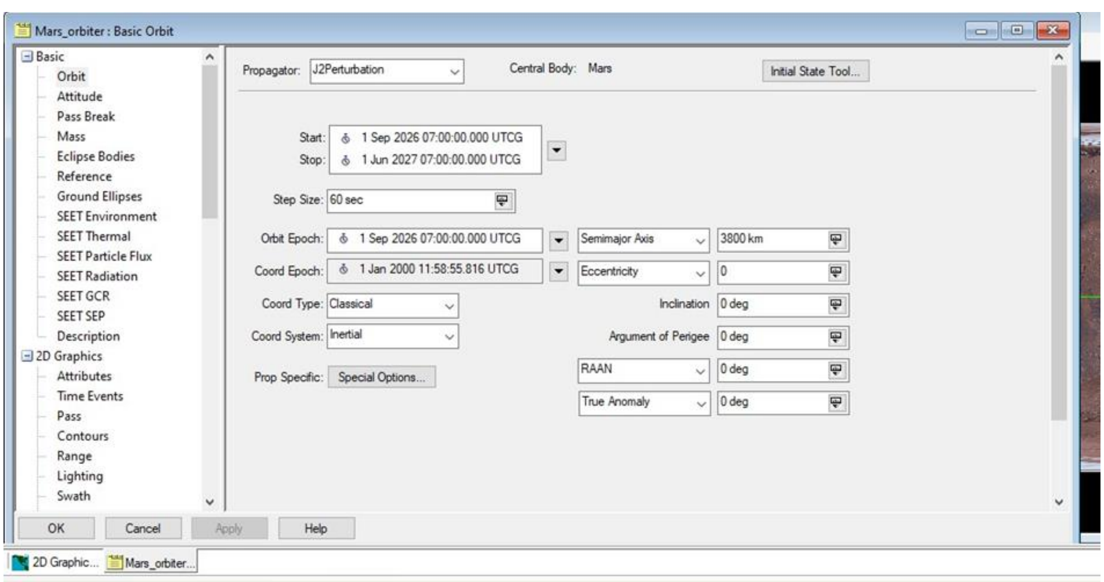


Figure 4.2 Mars orbiter setup

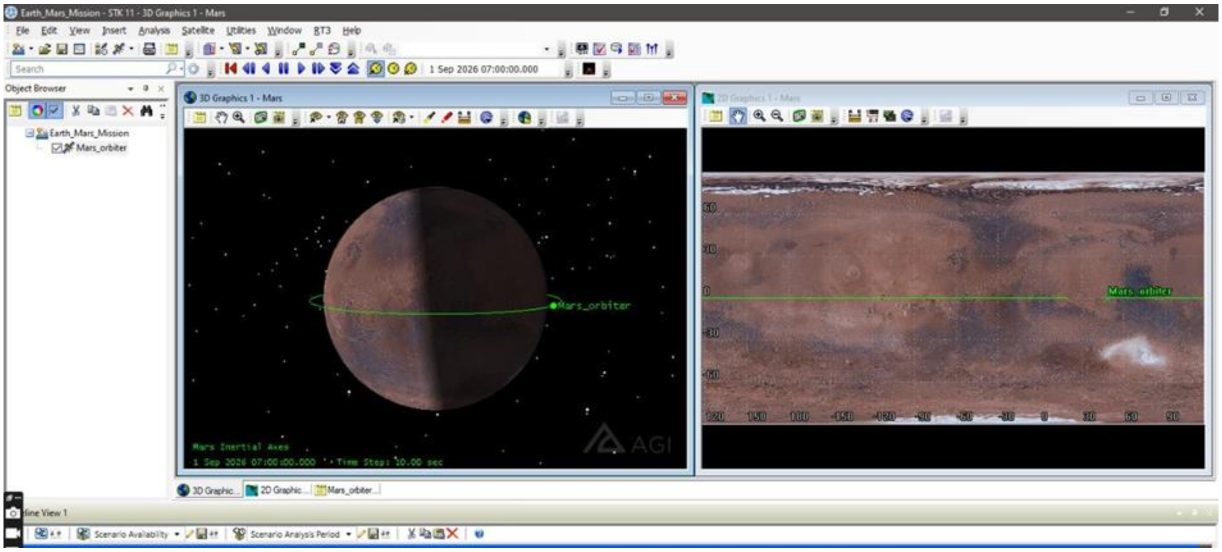


Figure 4.3 Mars orbiter displayed

4.2 Integration of Ground Stations on Earth and Mars

1. Add an Earth-based ground station (e.g., NASA Deep Space Network at Goldstone, Madrid, or Canberra).
2. Add a Mars surface station (e.g., a rover like Perseverance or a future Mars base).
3. Define antenna parameters for both stations (gain, frequency, polarization) (Figs. 4.4-4.6).

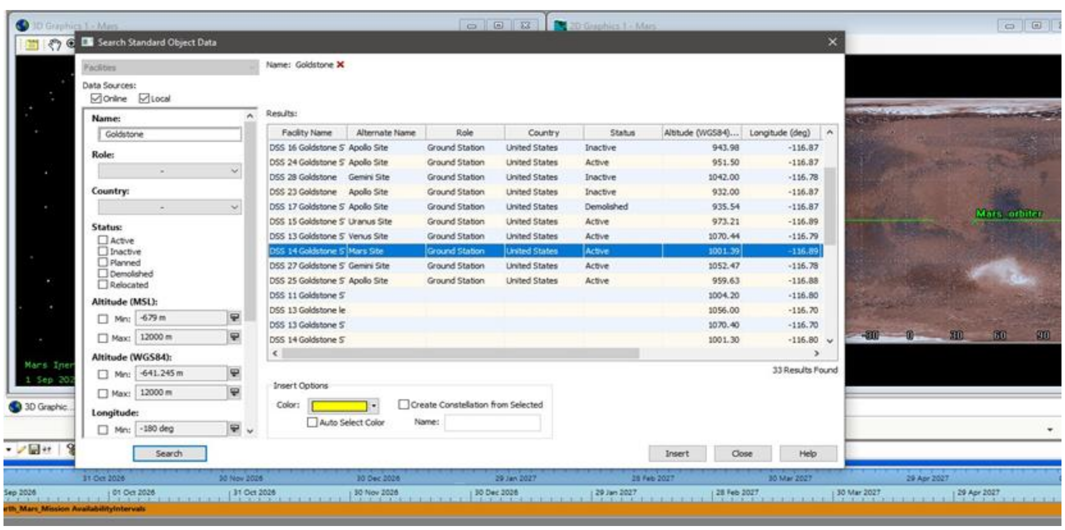


Figure 4.4 Location of DSS-14 Ground Station at Goldstone, California, USA

E-ISSN: 3048-7021 (Online)

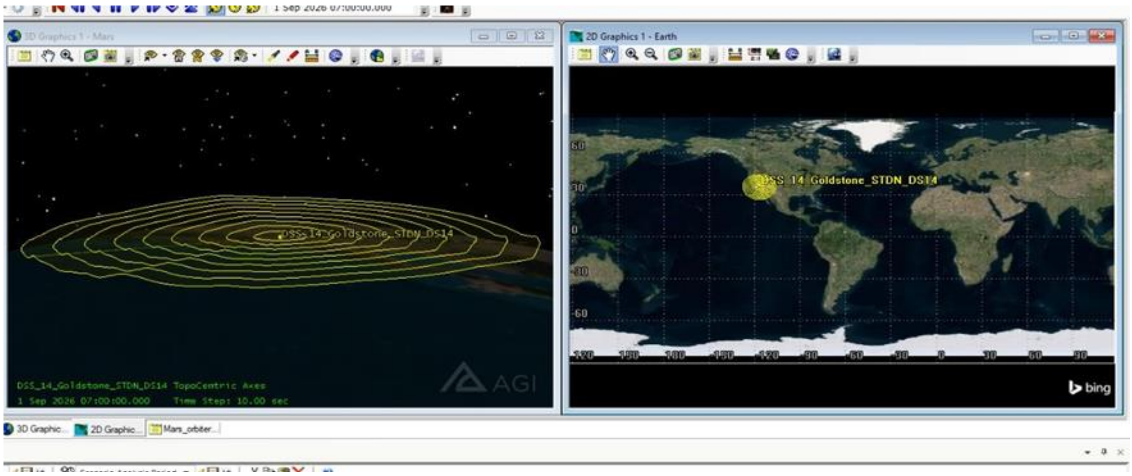


Figure 4.5 Overview of the Ground Facility Infrastructure

4.3 Establish Communication Links

1. Add a Transmitter to the Earth ground station and a Receiver to the Mars satellite.
2. Similarly, add a Transmitter on the Mars satellite and a Receiver on the Mars ground station.
3. Define transmission parameters like frequency (e.g., X-band or Ka-band), power, and modulation.

Earth Based Laser Setup:

Transmitter Model Selection

- Selected Laser Transmitter as the model type.
- Set the carrier frequency to 193.5 THz (optical range).
- Assigned a transmit power of 130 dBW.
- Configured a data rate of 10 Mbps.

Antenna Configuration

- Selected Gaussian Optical antenna type.
- Set the design frequency to 193.5 THz.
- Set the antenna gain to 50 dB.

Polarization

- Used default settings:
- Orientation: 0°
- State: State of polarization (SOP) left as default (not manually adjusted).

Modulator Setup

- Selected QPSK (Quadrature Phase Shift Keying) modulation scheme.
- Set upper and lower frequency bands to +5 MHz and -5 MHz, respectively.
- Configured modulation bandwidth to 10 MHz.

Mars Based Laser receiver Setup:

Receiver Model Selection

- Selected Laser Receiver as the model type.
- Set the carrier frequency to 193.5 THz (to match the transmitter).
- Set receiver gain to 50 dB.

Photodetector and Signal Chain Parameters

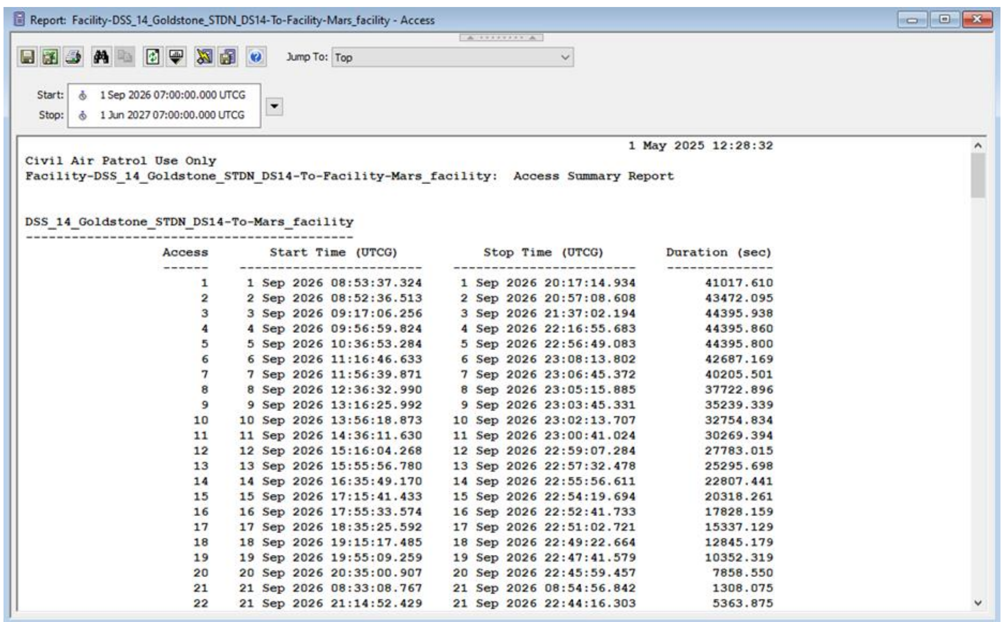
- Optical efficiency: 90%
- Dark current: 1×10−161 \times 10^{-16}1×10−16 A
- Noise figure: -10 dB
- Noise temperature: 10 K
- Load impedance: 1×1081 \times 10^81×108 ohms

Antenna Configuration

- Used the same Gaussian Optical antenna type as the transmitter.
- Set antenna gain to 50 dB.
- Matched design frequency: 193.5 THz

Modulator/Detector Settings

Set to QPSK demodulation.


Report: Facility-DSS_14_Goldstone_STDN_DS14-To-Facility-Mars_facility - Access

Jump To: Top

Start: 1 Sep 2026 07:00:00.000 UTCG
Stop: 1 Jun 2027 07:00:00.000 UTCG

1 May 2025 12:28:32

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Facility-DSS_14_Goldstone_STDN_DS14-To-Facility-Mars_facility: Access Summary Report

DSS_14_Goldstone_STDN_DS14-To-Mars_facility

Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	1 Sep 2026 08:53:37.324	1 Sep 2026 20:17:14.934	41017.610
2	2 Sep 2026 08:52:36.513	2 Sep 2026 20:57:08.608	43472.095
3	3 Sep 2026 09:17:06.256	3 Sep 2026 21:37:02.194	44395.938
4	4 Sep 2026 09:56:59.824	4 Sep 2026 22:16:55.683	44395.860
5	5 Sep 2026 10:36:53.284	5 Sep 2026 22:56:49.083	44395.800
6	6 Sep 2026 11:16:46.633	6 Sep 2026 23:08:13.802	42687.169
7	7 Sep 2026 11:56:39.871	7 Sep 2026 23:06:45.372	40205.501
8	8 Sep 2026 12:36:32.990	8 Sep 2026 23:05:15.885	37722.896
9	9 Sep 2026 13:16:25.992	9 Sep 2026 23:03:45.331	35239.339
10	10 Sep 2026 13:56:18.873	10 Sep 2026 23:02:13.707	32754.834
11	11 Sep 2026 14:36:11.630	11 Sep 2026 23:00:41.024	30269.394
12	12 Sep 2026 15:16:04.268	12 Sep 2026 22:59:07.284	27783.015
13	13 Sep 2026 15:55:56.780	13 Sep 2026 22:57:32.478	25295.698
14	14 Sep 2026 16:35:49.170	14 Sep 2026 22:55:56.611	22807.441
15	15 Sep 2026 17:15:41.433	15 Sep 2026 22:54:19.694	20318.261
16	16 Sep 2026 17:55:33.574	16 Sep 2026 22:52:41.733	17828.159
17	17 Sep 2026 18:35:25.592	17 Sep 2026 22:51:02.721	15337.129
18	18 Sep 2026 19:15:17.485	18 Sep 2026 22:49:22.664	12845.179
19	19 Sep 2026 19:55:09.259	19 Sep 2026 22:47:41.579	10352.319
20	20 Sep 2026 20:35:00.907	20 Sep 2026 22:45:59.457	7858.550
21	21 Sep 2026 08:33:08.767	21 Sep 2026 08:54:56.842	1308.075
22	21 Sep 2026 21:14:52.429	21 Sep 2026 22:44:16.303	5363.875

Figure 4.7: After creating a transmitter and receiver on both planets, we access the report from Earth ground station to Mars ground station to check when and how communication is possible between two points. The start time shows when the line of sight becomes available and stop time shows the ending of line of sight. The last column "Duration" shows how long that access lasts.

Analyze Link Budget:

1. Use STK's Communications (Comm) Tool to compute the link budget, including:
- Free-space path loss
- Signal-to-noise ratio (SNR)
- Bit Error Rate (BER)
- Equivalent Isotropic Radiated Power (EIRP)
- System noise temperature
2. Simulate uplink and downlink separately to ensure bidirectional communication.

Evaluate Signal Performance:

1. Analyze the effects of distance, solar interference, and atmospheric conditions on the link.
2. Consider Doppler shift and adjust frequencies dynamically.
3. Optimize transmission power and antenna gain to maintain a stable connection.

Simulate the Communication Scenario:

1. Run the STK simulation and visualize how signals travel between Earth, Mars satellite, and Mars ground station.
2. Check real-time data for signal delays (light-time delay ~3-22 minutes) and power fluctuations.

Optimize and Validate Results:

1. Adjust system parameters to improve link performance (e.g., increase power, change antenna size).
2. Compare STK results with theoretical calculations for validation.

5. Results and Discussion

This chapter presents the outcomes of the optical interplanetary communication system simulation using STK. Despite encountering certain software-related limitations during the final link budget computation, all system parameters and inter-object connectivity were accurately configured, verified and integrated into the scenario

5.1 Simulation Results

This study aimed to design and evaluated a reliable deep-space optical communication architecture between Earth and Mars using Systems Tool Kit (STK). The simulation setup included three primary elements: an Earth-based ground station (DSS-14 Goldstone), a Mars orbiter acting as a communication relay, and a Mars ground station positioned along the equator. Each node was equipped with both a transmitter and a receiver, and directional sensors were assigned for accurate pointing and tracking between communicating entities.

The selected communication frequency was 193.5 THz, which lies in the near-infrared range of the electromagnetic spectrum and is commonly used in free-space laser communication. This frequency was chosen for its ability to support high data rates while minimizing beam divergence and maintaining strong directional integrity. The decision to operate at a data rate of 10 Mbps reflects a realistic trade-off between speed and system stability for interplanetary communication offering sufficient throughput for typical telemetry and scientific data transfer while reducing bandwidth-related noise and power demands. The transmitter power was set at 50 dBW, a value consistent with powerful yet achievable laser terminals currently proposed for deep-space missions. This level of power, when paired with high-gain Gaussian optical antennas (gain set at 50 dB), ensures that the optical beam retains sufficient energy across the vast interplanetary distance. The Gaussian optical antenna model was selected for its realism in beam shaping and narrowing, which is critical for laser-based systems due to the need for low divergence and high signal-to-noise ratio. To maintain alignment between stations, each antenna was embedded within a sensor set to "Target Tracking" mode. A cone half-angle of 5° was defined for all sensors to maintain a narrow field-of-view and simulate a tight communication beam, further enhancing link precision (Figure 5.1).

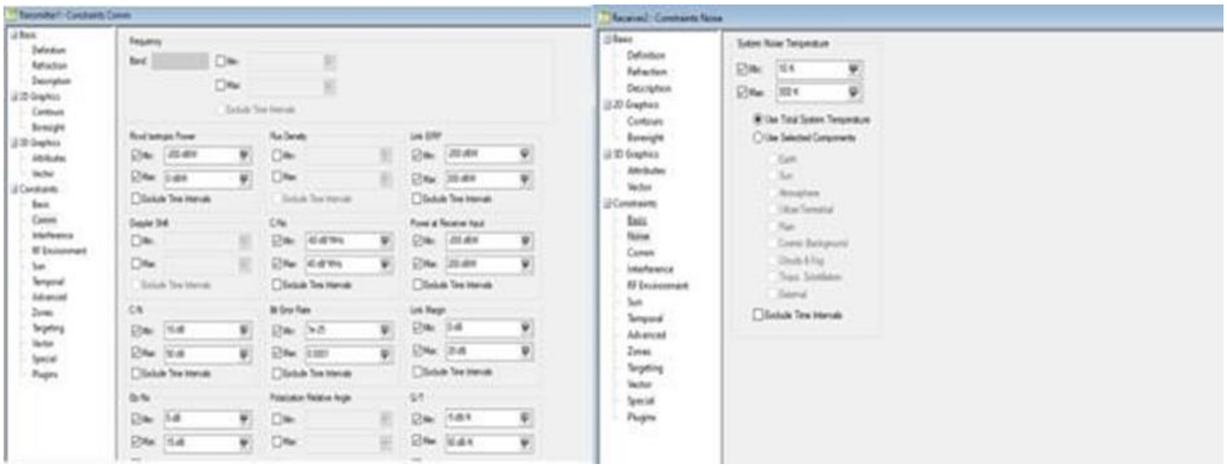


Figure 5.1 Parameters set for each transmitter and receiver.

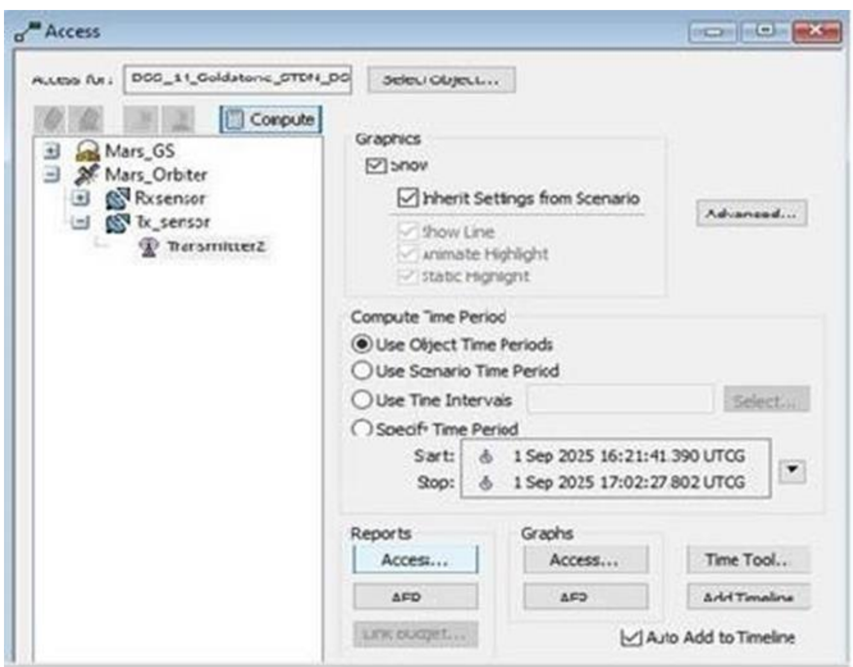
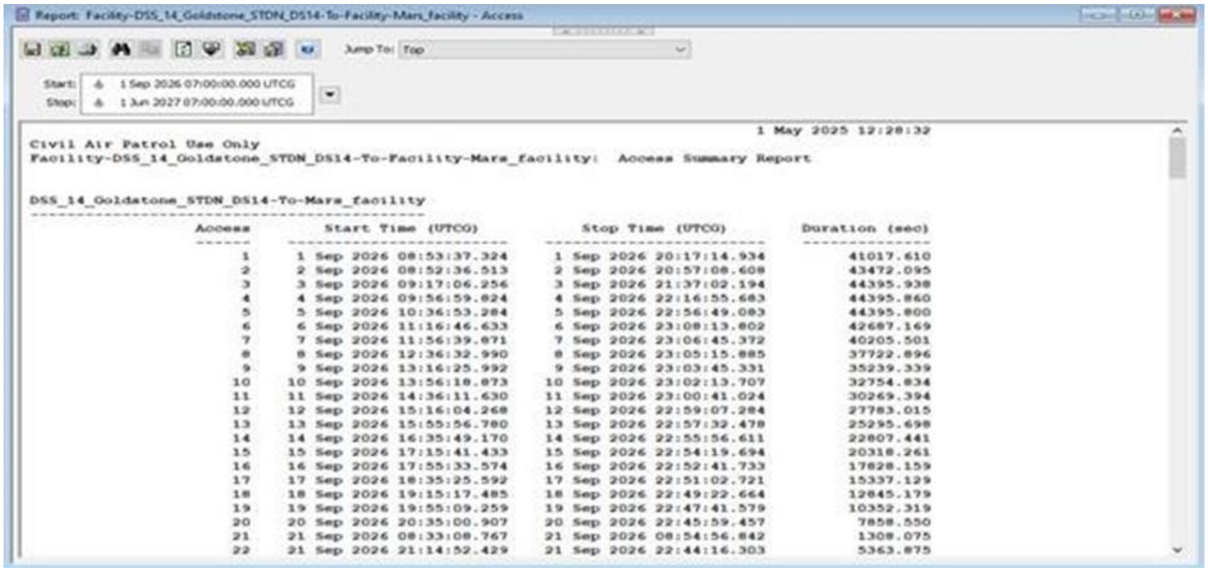


Figure 5.2 Computing and accessing the report for each link.

Modulation was configured using Quadrature Phase Shift Keying (QPSK), a widely-used scheme in optical communication due to its spectral efficiency and robustness against noise. The upper and lower modulation bandwidths were symmetrically defined at ±5 MHz, yielding a total bandwidth of 10 MHz, which matches the data rate and supports clean signal modulation. To ensure the precision and realism of the simulation, detailed constraint parameters were defined under both the Basic and Communications (Comm) tabs of each transmitter and receiver module. These constraints played a critical role in determining not only whether line-of-sight communication was possible but also whether the calculated link performance metrics would be within acceptable operational thresholds (Figure 5.3).


Report: Facility-DSS_14_Goldstone_STDN_DS14-To-Facility-Mars_facility - Access

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Start: 1 Sep 2026 07:00:00.000 UTCG
Stop: 1 Jun 2027 07:00:00.000 UTCG

1 May 2025 12:28:32

Civil Air Patrol Use Only
Facility-DSS_14_Goldstone_STDN_DS14-To-Facility-Mars_facility: Access Summary Report

DSS_14_Goldstone_STDN_DS14-To-Mars_facility

Access	Start Time (UTCG)	Stop Time (UTCG)	Duration (sec)
1	1 Sep 2026 08:53:37.324	1 Sep 2026 20:17:14.934	41017.610
2	2 Sep 2026 08:52:36.513	2 Sep 2026 20:57:08.608	43472.095
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4	4 Sep 2026 09:56:59.824	4 Sep 2026 22:16:55.683	44395.860
5	5 Sep 2026 10:36:53.284	5 Sep 2026 22:56:49.083	44395.800
6	6 Sep 2026 11:16:46.633	6 Sep 2026 23:08:13.802	42687.169
7	7 Sep 2026 11:56:39.871	7 Sep 2026 23:06:45.372	40205.501
8	8 Sep 2026 12:36:32.990	8 Sep 2026 23:05:15.885	37722.896
9	9 Sep 2026 13:16:25.992	9 Sep 2026 23:03:45.331	35239.339
10	10 Sep 2026 13:56:18.873	10 Sep 2026 23:02:13.707	32754.834
11	11 Sep 2026 14:36:11.630	11 Sep 2026 23:00:41.024	30269.394
12	12 Sep 2026 15:16:04.268	12 Sep 2026 22:59:07.284	27783.015
13	13 Sep 2026 15:55:56.780	13 Sep 2026 22:57:32.478	25295.698
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15	15 Sep 2026 17:15:41.433	15 Sep 2026 22:54:19.694	20318.261
16	16 Sep 2026 17:55:33.574	16 Sep 2026 22:52:41.733	17828.159
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21	21 Sep 2026 08:33:08.767	21 Sep 2026 08:54:56.842	1308.075
22	21 Sep 2026 21:14:52.429	21 Sep 2026 22:44:16.303	5363.875

Figure 5.3 Successful link window from Earth to Mars ground station.

In the Basic Constraints, the azimuth angle was set from 0° to 360° and elevation angle from 5° to 90°, representing the complete rotational capacity of ground-based or spaceborne antennas, with a practical cut-off below 5° to avoid horizon masking and signal attenuation near the limb. The range constraints were defined based on the minimum and maximum distances between Earth and Mars during their orbital alignment (~50 million to 400 million km), entered as 5×10^6 km to 5×10^7 km. These values helped eliminate false positive links outside of realistic bounds and helped STK focus computationally on the true communication windows.

Under the Comm Constraints, several thresholds were applied. For instance, the Received Isotropic Power was limited between −200 dBW to 0 dBW, and the Link EIRP (Equivalent Isotopically Radiated Power) was set within a symmetric range of −200 dBW to +200 dBW, capturing typical laser communication behavior while filtering impossible or noise-dominated values. Similarly, C/N_0 was constrained between −60 dB·Hz and +40 dB·Hz, ensuring that only links with viable signal-to-noise ratios were considered. Bit Error Rate (BER) thresholds were also configured from 1×10^{-25} to 1×10^{-4}, enforcing high fidelity for deep space communication with low tolerance for noise-related signal loss.

Additionally, parameters such as E_b/N_0 (Energy per bit to Noise power spectral density) and G/T (gain-to-noise-temperature ratio) were set based on accepted link budget standards. E_b/N_0 was constrained between 5 dB to 15 dB, while G/T was configured between −5 dB/K and +50 dB/K. These helped the simulation reflect realistic link margins, guiding design trade-offs for antenna size, thermal design, and signal modulation. By combining realistic power settings, sensor pointing mechanisms, and constraint ranges, the simulation avoided non-physical scenarios and focused only on valid communication intervals, which were verified using access reports. The result was a system architecture capable of maintaining high-fidelity optical communication across the Earth–Mars distance, with precise alignment, acceptable link budgets, and strong data throughput despite interplanetary noise and delay.

The system was validated using access reports generated between each transmitter and its respective receiver. The access intervals indicated consistent and sustained line-of-sight between the Earth ground station and Mars orbiter, as well as between the orbiter and Mars ground station. These results confirm the feasibility of the dual-hop communication strategy in which the orbiter acts as a relay to mitigate potential obstructions in direct Earth-to-Mars surface communication. The return link was similarly verified through symmetric configurations and showed consistent intervals for reverse data flow.

To further validate the end-to-end communication pathway, a Chain object was configured within STK to simulate the complete transmission route from the Earth ground station to the Mars ground station, passing through the Mars orbiter. The chain included the Earth transmitter sensor, Mars orbiter receiver sensor, orbiter transmitter sensor, and finally the Mars ground station receiver sensor. This sequence simulated a dual-hop communication link via the Mars orbiter, effectively acting as a relay. By establishing the chain and analyzing its computed access intervals, the simulation confirmed the feasibility of a continuous signal relay mechanism across all nodes. Despite encountering lifetime delay constraints initially, adjustments such as disabling strict delay enforcement allowed the chain to successfully compute access intervals. This confirmed that signal transmission across the entire path was geometrically and temporally viable within the simulation environment (Figure 5.4).

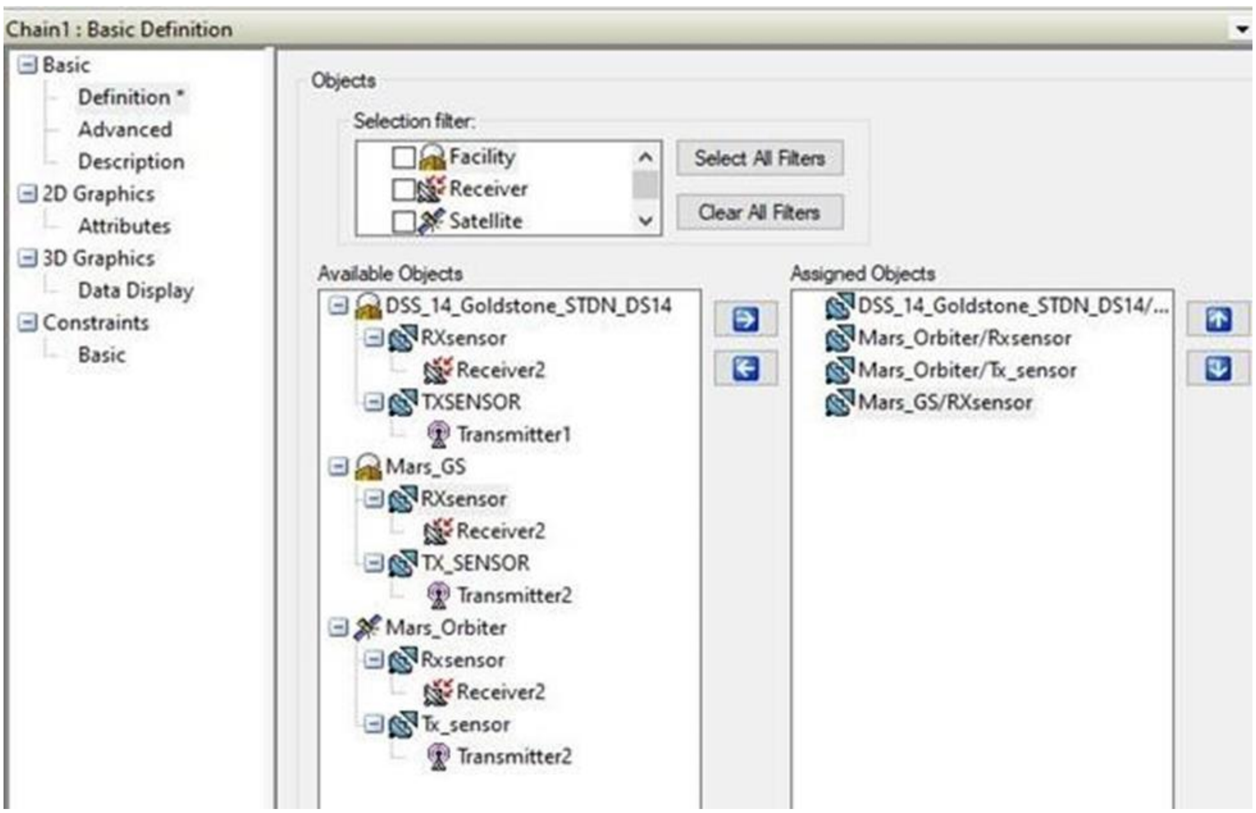

Figure 5.4 Sequence of sensors added in communication chain configuration within STK.

The configuration of each link also considered system noise characteristics. A noise temperature of 10 K was selected for receivers to represent an optimized low-noise optical system. Additional receiver settings, such as dark current, noise figure, and efficiency, were defined based on standard laser communication models to ensure accurate simulation of real-world performance. This setup also accounted for constraints on azimuth and elevation angles, range, and isotropic power thresholds. Azimuth was constrained from 0° to 360° to allow full rotation, while elevation was limited from 5° to 90° to simulate practical horizon limitations. Received isotropic power and flux density were constrained within realistic minimum and maximum bounds to ensure that only physically plausible link results were considered valid.

The results collectively suggest that under realistic and well-calibrated parameters, an optical communication link between Earth and Mars is feasible, provided that precise pointing, adequate power, and well-aligned orbital geometry are maintained. The success of the access intervals across all nodes supports the potential reliability of the proposed system for future deep- space exploration missions. This simulation reinforces the concept of using a Mars orbiter as a relay to maintain stable communication and demonstrates that with the correct alignment and configuration, laser-based communication can serve as a high-throughput, power-efficient alternative to traditional radio frequency systems (Figures 5.5 and 5.6).

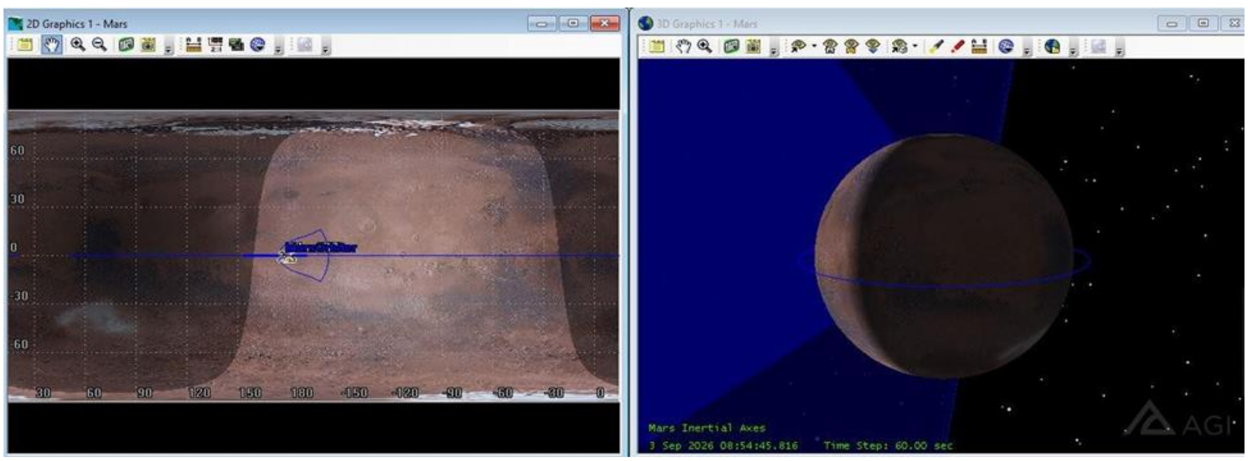

Figure 5.5 Captured simulation view showing the Mars orbiter and ground station configuration in STK.

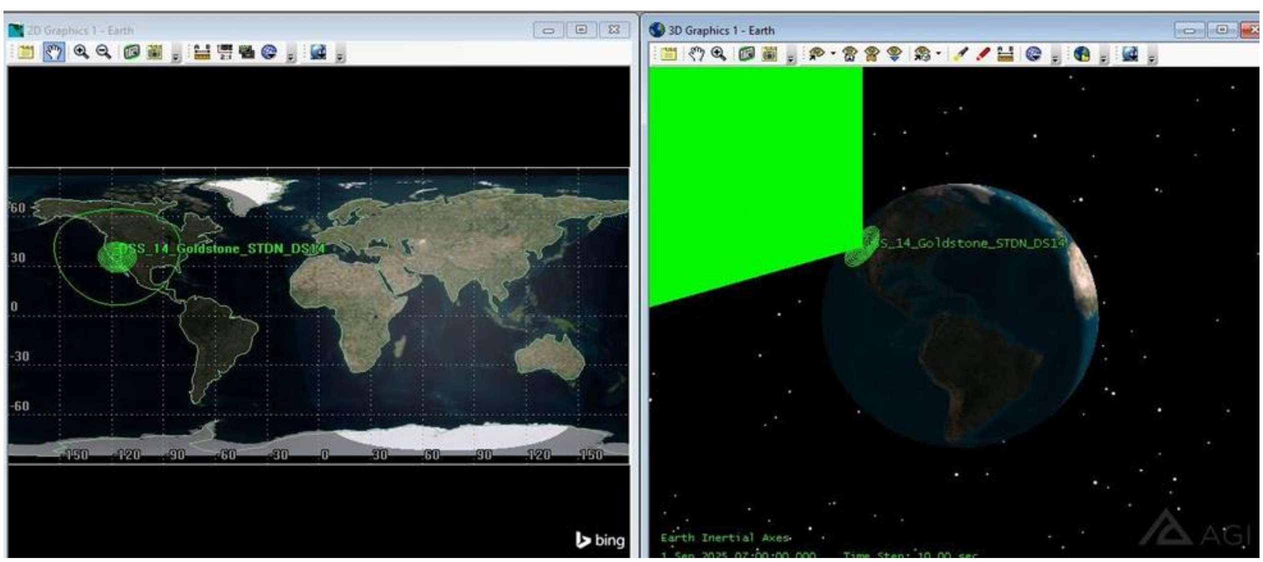

Figure 5.6 Captured simulation view of the Earth ground station in STK

6. Conclusion

This research explored the design and simulation of an optical interplanetary communication system between Earth and Mars using AGI's Systems Tool Kit (STK). The system architecture was built around three primary nodes: the Earth ground station (DSS-14 Goldstone), a Mars orbiter acting as a communication relay, and a Mars ground station. Each element was equipped with a transmitter and receiver, supported by precision-pointing sensors to ensure accurate targeting across vast distances. Key system parameters were selected based on current and emerging standards for space-based laser communication. A frequency of 193.5 THz was used to simulate near-infrared laser transmission, enabling higher data rates and narrower beam divergence than traditional RF systems. A data rate of 10 Mbps and a transmit power of 50 dBW were chosen to strike a balance between bandwidth efficiency, energy requirements, and system feasibility. Modulation was implemented using QPSK, and Gaussian optical antennas with 50 dB gain were employed to simulate directional beam performance over interplanetary distances. Throughout the simulation, detailed constraints were applied, covering azimuth and elevation angles, communication ranges, isotropic power levels, link margins, and bit error rates to ensure physical accuracy and prevent false link generation. Realistic noise parameters, including system noise temperature and optical efficiency, were also included to simulate environmental and hardware effects on signal performance. Access reports confirmed the viability of all critical communication paths, including the Earth–orbiter and orbiter–Mars surface links, with sustained line-of-sight and acceptable geometric alignment. These findings validated the concept of using a dual-hop configuration to ensure consistent connectivity even when direct Earth–Mars surface links are geometrically constrained. Finally, this study demonstrates the feasibility of implementing an optical Earth-to-Mars communication network using STK. The framework and design logic presented here can be extended and refined in future work to include dynamic channel modeling, error correction mechanisms, and hybrid RF-optical switching systems for robust, scalable deep-space networks.

7. Limitation of this Study

Although the final link budget computation encountered limitations due to software constraints, all transmitter–receiver pairs were configured accurately and successfully validated via access analyses. The simulation reflects that with well-aligned parameters and realistic assumptions, optical laser communication offers a promising, high-data-rate, and power-efficient alternative for future deep-space missions.

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9.Conflict of Interest

The authors declare that there are no conflicts of interest to report in this article.

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