# Mars Telecommunications Constellation

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## 1 Abstract

The Mars Telecommunications Constellation is a proposed mission to establish a continuous ground coverage relay network over Mars capable of transmitting high data rates ($\geq$ 32 mega bits per second). The proposed architecture is a constellation of 8 12U cubeSats, each equipped with an ultra-high frequency (UHF) communications system for short range communication with assets at Mars, an optical communications system for communications with assets at Earth, and a solar sail as the sole source of on-board propulsion.

To establish the feasibility of this mission, 3 main aspects of the mission design and architecture were evaluated and developed. 1: The capabilities of optical communications systems, and their ability to fit within the mass and volume constraints of a cubeSat. 2: The capabilities of a cubeSat equipped with a solar sail, and its ability to navigate from Earth orbit to Mars Orbit. 3: Constellation design, with station keeping performed by a solar sail. In addition, the major cubeSat subsystems, with particular attention toward reducing cost through the use of commercial off-the-shelf (COTS) components, was developed, taking inspiration from the Mars Cube One (MarCo) architecture.

## 2 Introduction

Mars has been one of the centers of attention for planetary science missions for many years. While there are currently 8 science assets in orbit around or on the surface of Mars [1] , each of these assets is designed to handling its own communications with Earth, through the Deep Space Network (DSN). Some surface assets increase their data rate by relaying through the orbiting science assets, but these satellites are not in orbits conducive to continuously relaying information. One proposed solution to this problem was the Mars Telecommunications Orbiter (MTO), which would use optical communication to increase the available bandwidth by acting as a relay for Mars assets. While MTO was cancelled in 2005, the need for increased bandwidth to and from Mars is still present, and will only increase as Mars becomes the target of more robotic and human missions.

One solution to this problem is to deploy a constellation of 12U cubeSats, each equipped to serve as a communications relay. Additionally, these smallSats could be equipped with solar sails, allowing them to navigate from Earth orbit to Mars, vastly reducing the launch cost for the mission. The Mars Telecommunications Constellation is a proposed mission to provide Mars with global communications relay coverage capable of transmitting at least 32 megabits per second. Producing a constellation of smallSats is cost effective due to the economy of scale, which opens the opportunity for redundant units to be launched, reducing the impact of any one satellite failing.

An emphasis on the use of COTS hardware will reduce the development time and cost for this mission. This will allow the mission to use hardware that has only recently been proven at a high tech readiness level (TRL). Such hardware would be off limits for a larger, more expensive satellite, that has a longer development timeline. Additionally, since this mission will feature redundant satellites, a higher risk of failure can be tolerated for any one satellite.

This may allow higher risk, lower TRL hardware to be flown than would be tolerated on a flagship mission.

# 3 Definition of Terms

$G$ : Gravitational Constant
$m_x$ :mass of object x
$\mu = Gm$ : Gravitational Parameter
$G_{sc}$ : Solar Irradiance at 1 AU
$c$ : Speed of Light
$n_x$: mean motion of object x
$a_x$: semi-major axis of object x
$\alpha$ : Solar Sail Pitch Angle
$\sigma$ : Solar sail size to mass ratio
$A$ : Solar Sail Area
$\mathbf{\hat{n}}$: Unit Vector Normal to Solar Sail
$\mathbf{r_{x/i}}$ position vector of object x with respect to object i
$\mathbf{v_x}$ velocity vector of object x
$\mathbf{a_x}$ acceleration vector of object x

# 4 Background and Technology

The original concept for the Mars Telecommunications orbiter called for a large ( $1,000kg$) spacecraft to orbit mars in a high altitude ($5,000km$) orbit [2]. This orbit, higher than other-science focused orbiters, would be above ground targets for longer periods of time, allowing more data to be relayed. The MTO was to be equipped with X-band and Ka-band antennas, that could move independently to communicate with Mars ground targets. In addition, it was to have an optical communications system capable of communicating at $>$ 30 megabits per second. The MTO was to be the first demonstration of a deep space optical communications system, before the program was cancelled in 2005.

Though the MTO has been cancelled, the problem of communication with Mars still remains. MRO and Mars Odyssey are relied on to act as communication relays to the science assets on the surface. Data rates for the rovers direct to Earth vary between 500 bits to 32 kilobits per second [3]. MRO and Mars Odyssey can transmit up to 2 megabits and 256 kilobits per second, respectively. However, due to the science payloads' orbits, ground assets can only communicate with them for 8 minutes per sol. While relaying data is technically possible with the existing assets, the frequency of commands sent to ground assets, and the amount of data that they send back could be greatly increased with a dedicated, high-rate communications infrastructure.

Since the cancellation of the MTO, three technologies have been developed will allow for a more capable telecommunications relay infrastructure to be established at a lower cost. The first technology has been cubeSats, which have recently been proven to be capable of successfully operating on long-duration deep space missions. The second is solar sails, many of which are currently under development, which will greatly expand the trajectory modification capability of satellites with little to no propellant mass. The third is optical communications, which have been proven to be capable of transmitting high data rates.

## 4.1 Mars Cube One

The Mars InSight mission was accompanied by two cubeSats, which were designed to relay telemetry and other data from the InSight mission during entry, descent, and landing (EDL) [5]. Each cubeSat was 6U, and capable of independently flying to mars, performing deep space communication, navigation, and trajectory correction. The MarCO program served as a demonstration of the capability of nanoSats, and their ability to carry out deep space relay missions. Their architecture will serve as the foundation for the Mars Telecommunications Constellation.

### 4.2 Solar Sail Demonstrations

Solar sails are an essential part of this mission architecture, as they are used as both a cost reduction method, and a method to augment mission life. Relying on solar sails to propel the spacecraft from Earth orbit to Mars allows cubeSats to be deployed as secondary or ride share payloads, significantly reducing the cost to launch. Additionally, relying on solar sails for station keeping and trajectory control at Mars removes propellant as a mission life constraint.

Solar sail deployment methods for nanoSats are currently being investigated and developed by several groups of researchers, including the LightSail project, directed by the Planetary Society [6]. While no nanoSat has successfully navigated with a deployable solar sail, JAXA has successfully flown IKAROS, a 310 kg satellite that has seen 400 m/s $\Delta V$ from its solar sails [7]. NASA currently lists nanoSat deployable solar sails at TRL 6 [9]. The TRL level of nanoSat deployable solar sails is critical to this mission architecture, as it provides the only means of propulsion for each satellite. The launch of LightSail II, which will demonstrate cubeSat solar sail deployment and navigation, is scheduled for early 2019 [10].

### 4.3 Optical Communications Demonstrations

Optical communication systems (OCS) are capable of higher data rates, with less mass and power than a radio frequency (RF) communications system [12]. While higher data rates are important for increasing the commands that can be sent and science that can be received from assets on Mars, the other features of OCS make it especially desirable for smallSats or nanoSats, which have even more stringent mass and power requirements than their larger counterparts. NASA has recently demonstrated the capability of nanosats with OCS, where a 1.5U cubeSat achieved a 100 megabits per second data rate [13]. A scaled version of this same technology should be capable of very high data rates from Mars orbit.

While deep space optical communications systems have not been tested, the Laser Communications Relay Demonstration (LCRD) is set to launch in 2019. This mission is predicted to be able to transmit over 1 giga-bits per second [14], and has been identified as a candidate technology for future future Mars science missions [17].

Optical communications is a key technology for this mission architecture. While optical communications systems have been flown, a cubeSat sized optical communications system capable of high data rates in deep space must be demonstrated during the pre-phase A studies before this architecture can be pursued any further. This may require the development of a cubeSat to fly a modified version of the LCRD system in Earth Orbit.

## 5 Technical Approach

The proposed architecture is a constellation of cubeSats, each equipped with an optical communications system. The constellation will act as a relay for both ground and orbiting assets at Mars. To reduce launch cost and increase station keeping and trajectory modification capabilities, each spacecraft would be equipped with a solar sail, and navigate to Mars from Earth orbit.

### 5.1 Solar Sail

Much of the sizing of the mission depends on the volume and mass of the solar sail. Each cubeSat was modeled to be 12U, and to be 20 kg. A simulation of a solar sail spacecraft was created to determine how solar sail size affects the amount of time required to escape from Earth's orbit, and the amount of time required for the transfer to Mars.

A circular restricted, 4 body simulation was created, where the cubeSat was subject to the gravity of the Sun, the Earth, and Mars. The sun was modeled as an initially fixed point, and the Earth and Mars were fixed on circular orbits, with their positions calculated with Equation 1.

$$\mathbf{r_x} = a_x cos(n_x t)\hat{\mathbf{i}} + a_x sin(n_x t)\hat{\mathbf{j}} \tag{1}$$

For this analysis, Mars and Earth were assumed to have co-planar, zero eccentricity orbits. CubeSats were initially placed on a Geosynchronous orbit about Earth, and were subject to the dynamics described by Equation 2.

$$\mathbf{a_{sat}} = \sum -\frac{G m_i r_{sat/i}}{\|r_{sat/i}\|^3} + F_{sail} \tag{2}$$

Where the summation is over the Earth, Mars, and the Sun. The solar sail was modeled to be an ideal reflecting solar sail, whose specific force is described by Equation 3.

$$F_{sail} = 2\frac{G_{sc} cos(\alpha)^2 \|a_{Earth}\|^2}{c\|r_{sat/sun}\|^2}\frac{A_{sail}}{m_{sat}}\hat{\mathbf{n}} \tag{3}$$

The solar sail was pointed to achieve optimal energy gain, based on the work performed by MacDonald et al [11]. This formulation was adapted to the planar restricted motion developed for this simulation.

For this problem, three reference frames were used. The first is an inertial reference frame $(\hat{i}, \hat{j}, \hat{k}, 0)$, with its origin at the Sun. The inertial frame's X-Y plane is orbital plane, which all motion is constrained to. Its Z axis is consistent with the right hand rule.

The second frame rotates with the Earth's. Its x axis $(\hat{\mathbf{x}}_{\mathbf{Earth}})$ is parallel to $\mathbf{r_{Earth/Sun}}$. Its z axis $(\hat{\mathbf{z}}_{\mathbf{Earth}})$ is parallel to the inertial Z axis. Its y axis $(\hat{\mathbf{y}}_{\mathbf{Earth}})$ is consistent with the right hand rule.

The third fame is attached to the cubeSat. Its x axis $(\hat{\mathbf{x}}_{\mathbf{sat}})$ is parallel to $\mathbf{r_{Sat/Sun}}$. Its z axis $(\hat{\mathbf{z}}_{\mathbf{sat}})$ is parallel to the inertial Z axis. Its y axis $(\hat{\mathbf{y}}_{\mathbf{sat}})$ is consistent with the right hand rule. $\alpha$ is defined as the angle between $(\hat{\mathbf{x}}_{\mathbf{sat}})$ and $(\hat{\mathbf{n}})$. $\theta$ is definied as the angle between $\hat{i}$ and $(\hat{\mathbf{x}}_{\mathbf{sat}})$.

To find the optimal $\hat{\mathbf{n}}$, first the optimal pitch angle $(\alpha)$ must be found. Solving the optimal control control problem yields Equation 4.

$$\alpha = arctan\left(\frac{3v_x}{4v_y} + \sqrt{\frac{1}{2} + \left(\frac{3v_x}{4v_y}\right)^2}\right) \tag{4}$$

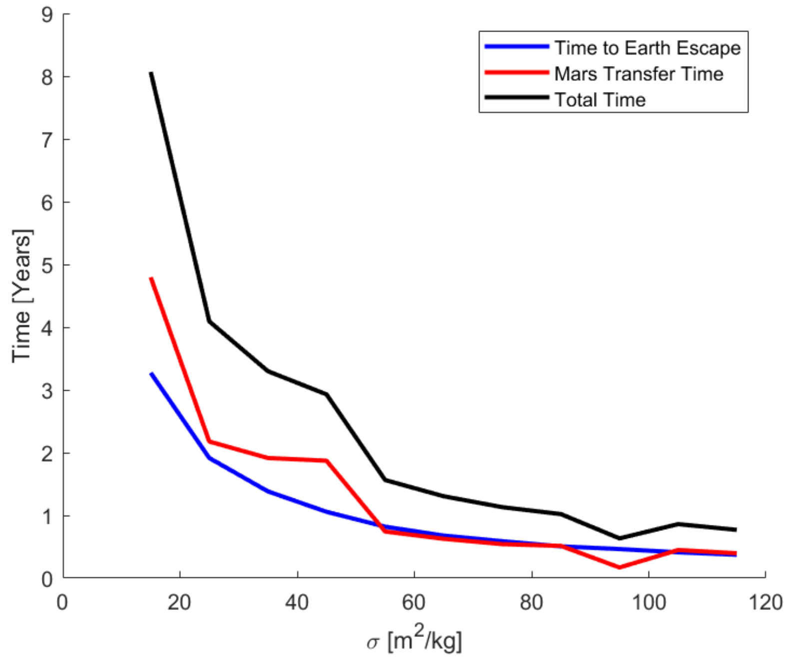


Figure 1: This figure shows how changing the sail size to mass ratio ($\sigma$) influences time required for three key mission events: Time to escape from Earth, Transit Time from Earth to Mars, and Total Transfer Time.

Where $v_x = \mathbf{v_{sat}} \cdot \hat{\mathbf{x}}_{\mathbf{sat}}$ and $v_y = \mathbf{v_{sat}} \cdot \hat{\mathbf{y}}_{\mathbf{sat}}$. The reference frame definitions, and this angle, can easily be used to find $\hat{\mathbf{n}}$.

Equation 2 was used to to numerically integrate the planar trajectory of a cubeSat, from Geostationary orbit, until it crossed Mars' orbital radius. This was simulated with a fixed time-step leapfrog integrator. Simulations were run for 12U cubeSats with solar sails ranging from 300 to 2300 $m^2$. In each simulation, the time to escape Earth and Mars transfer time was was recorded (1).

Time to Earth escape was defined as the amount of time from the beginning of the simulation, where the cubeSat was in a geosynchronous parking orbit, to when the cubeSat left the Earth's sphere of influence. Mars transfer time was defined as the amount of time between the cubeSat leaving the Earth's sphere of influence, and it crossing Mars' orbit ($\|r_{sat/sun}\| > a_{mars}$).

While the time to Earth escape varies smoothly as sail size is increased, the Mars transfer time had unexpected variations. This is largely due variation in the direction each cubeSat left Earth's orbit. Additional control needs to be implemented to optimize that part of the trajectory.

These simulations demonstrated that it is possible for a cubeSat with a small solar sail to reach Mars Orbit. Next, the influence of solar sail size on the volume and mass budget was analyzed. The solar sail is assumed to made of Mylar or Kapton, with an area density of $6g/m^2$ [15]. The boom, which span the diagonals of a square sail. are assumed to have similar properties to the booms developed for the "Advanced Composites-Based Solar Sail System [16], which have a linear density of 46 g/m. The sail and deployer are assumed to have a volume proportional to the NEA Scout solar sail drums, which has a volume to sail area ratio of 7.5 $cm^3/m^2$. Once the sail mass and boom mass were calculated, a factor of 1.3

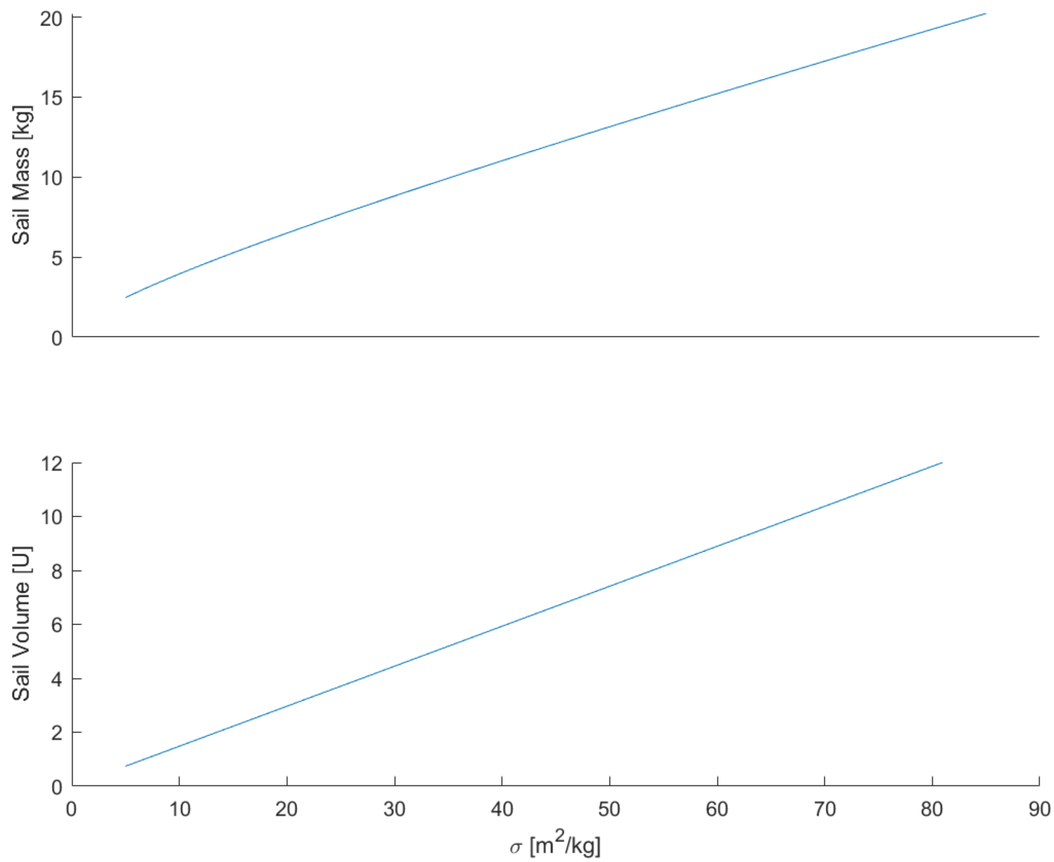


Figure 2: This figure shows the relationship between $\sigma$ and the mass and volume taken up by the solar sail. This plot is for a 12U cubeSat with a total mass of 20kg.

was applied to get the total sail system mass. These values were used to estimate the mass and volume of a solar sail based on its area (Figure 2.

This data, in combination with the relationship between $\sigma$ and total time, can be used to pick a solar sail size that meets the volume, mass, and lifespan requirements imposed by the rest of the system.

## 5.2 Configuration and Sizing

The architecture for this mission will be heavily based on the flight-proven architecture used on MarCO. Additional sizing and hardware selection is drawn from the architecture proposed by Robert Staehle.

### 5.2.1 Interplanetary cubeSats

Robert Staehle et al. proposes a 6U cubeSat (StaehleSat), equipped with a solar sail and optical communications system. This architecture is designed for inter-planetary science missions, and is capable of carrying 2U of payload. The key problems identified by Staehle are survivability of solar panels in the deep space radiation environment, and data rates for the small optical communications system. Using a similar architecture to StaehleSat for a communications relay satellite, but increasing the satellite to a 12U cubeSat, would allow additional mass and volume to be dedicated to critical subsystems, such as the power system, the solar sail, or the optical communications system.

#### 5.2.2 Power

The power system will consist of deployable solar panels and batteries. They will be sized to meet the power requirements imposed by the attitude control system and the communications system.

#### 5.2.3 Optical Communications

The optical communications will be based on the LCRD system, and will be scaled to meet the bandwidth requirements for this mission.

#### 5.2.4 RF Communications

Each cubeSat will be equipped with a UHF transmitter for short range communication with ground assets. The sizing and power consumption for this system will be based on the bandwidth requirements for this mission.

#### 5.2.5 Attitude Determination and Control

The attitude control system will consist of reaction wheels and a small cold gas thruster system for momentum dumping. It will be sized to meet the pointing requirements imposed by the communications system.

# 6 Mission Profile

## 6.1 Launch

CubeSats will be launched as secondary or ride-share payloads to Geosynchronous orbit. Once in an orbit at geo, they will deploy their solar sails, and begin maneuvering to escape Earth.

## 6.2 Earth Escape

Once at a geosynchronous orbit, cubeSats will use the optimal energy gain approach to achieve Earth escape, similar to the approach outlined in 5.1. This results in a trajectory that spirals out from Earth until escape velocity is achieved (Figure 3, 4).

## 6.3 Mars Transfer and Orbit Insertion

Transfer to Mars will be achieved using the optimal energy gain approach (Figure 5, 6). This trajectory can be controlled to ensure a smooth insertion into the appropriate constellation orbit.

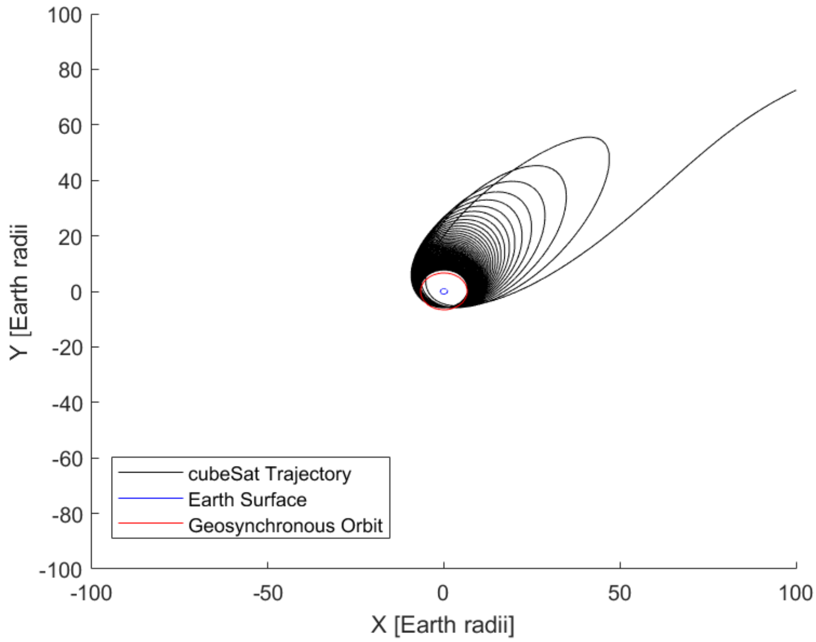


Figure 3: Earth escape trajectory of a cubeSat with $\sigma = 85m^2/kg$.

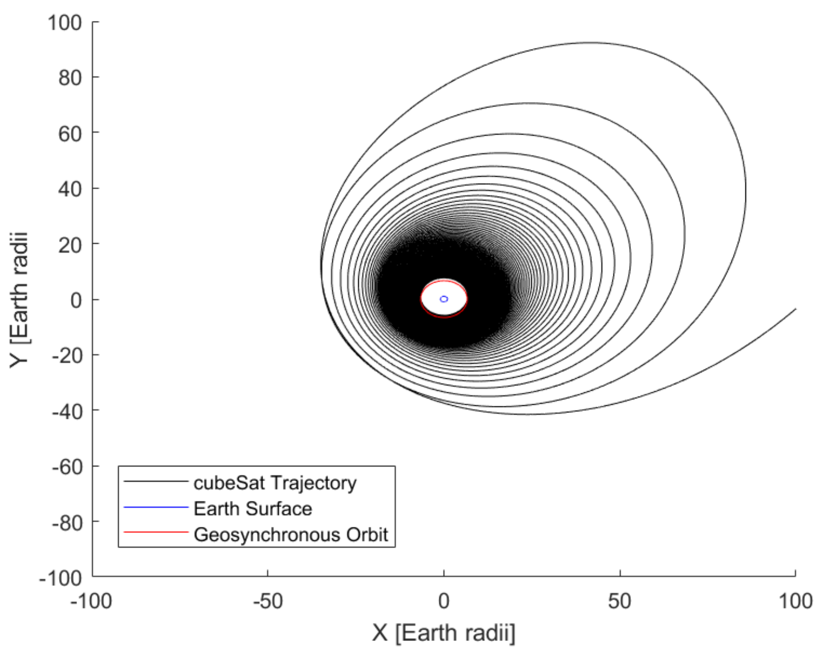


Figure 4: Earth escape trajectory of a cubeSat with $\sigma = 25m^2/kg$.

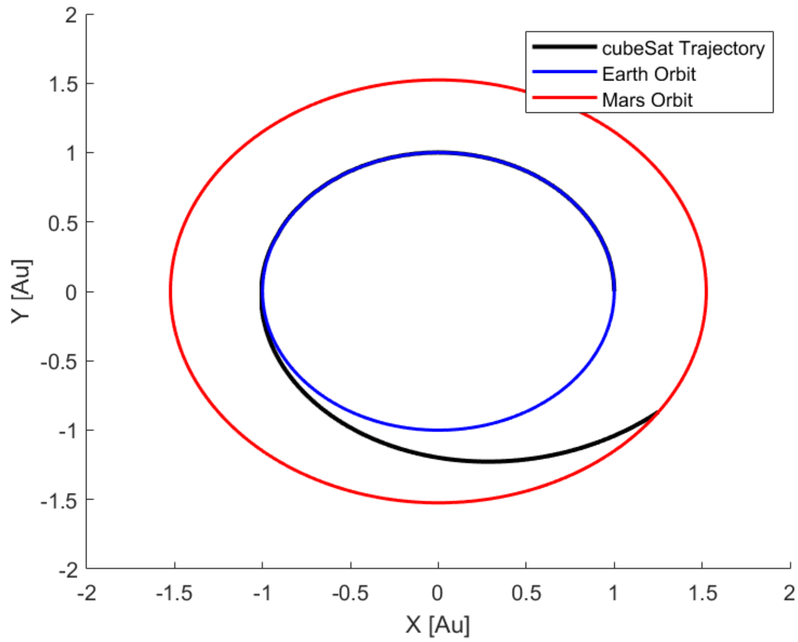


Figure 5: Mars transfer trajectory of a cubeSat with $\sigma = 85m^2/kg$.

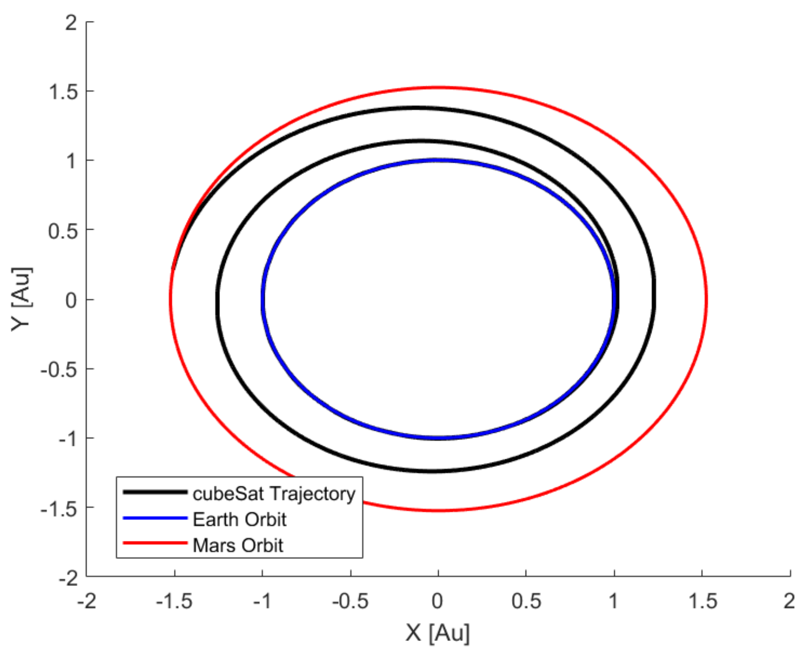


Figure 6: Mars transfer trajectory of a cubeSat with $\sigma = 25m^2/kg$.

### 6.4 Constellation Design and Operation

Constant global coverage is one of the key requirements for this mission, and it drives the choice of orbit for this mission. Orbit also drives communications and power system sizing, which are affected by the orbit's altitude and maximum time eclipsed.

While there are many types of constellations, the parameter that drives the number of satellites in the constellation is the altitude, as this dictates the coverage area for each satellite.

One feature of this mission architecture is the capability of solar sail spacecraft to operate in non-keplarian orbits, due to their ability to produce a constant force out of the orbital plane. This opens up the opportunity to use levitated cylindrical orbits, which are orbits whose plane does not intersect the central body [18]. They are able to achieve this by cancelling out the out of plane gravity component with sail thrust. By placing satellites on mirrored cylindrical orbits above and below Mars, the constellation may be able to achieve uninterrupted line of site with Earth, removing the need for inter-satellite relays during occultation.

To maintain global coverage, station keeping will be required to keep the constellation appropriately spaced. Any orbit selected must have small enough disturbances that the solar sail is capable of rejecting them, so that station keeping thrusters and propellant are not required.

Station keeping and disturbance analysis will need to be performed during pre-phase A studies, to ensure the solar sail size and orbit are compatible.

### 6.5 End of Life

The end of life plan is to use the solar sails to spiral into Mars, similar to the method used for Earth escape. The cubeSat will be destroyed on on entry into the Martian atmosphere.

## 7 Conclusion

The Mars Telecommunications Constellation will take advantage of the emerging technologies of optical communications and solar sails, and package them in a cubeSat architecture. These new technologies, combined with commercial off-the-shelf components, allow this mission to achieve their objective of providing continuous high-data rate communications relays to the entire surface of Mars, while costing less than previously proposed MTO. This new capability will allow future missions to Mars greater freedom to use data-heavy instrumentation, or to implement missions that require constant communication.

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