Lagrange-Based Options for Relay Satellites to Eliminate Earth-Mars Communications Outages During Solar Superior Conjunctions

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Abstract—**Recent conjunction class Mars human mission plans have generally assumed that there will inevitably be periods of communications outages between Earth and Mars. This has significant cost and risk implications for not only Mars missions, but also precursor missions in the lunar environment. But are there ways to avoid these outages? The potential exists for communications to be interrupted by Solar Superior Conjunctions (SSCs). Depending on the communications system, used, there can be communications outages up to as many as 78 days. The higher bandwidth systems experience the greatest outage. If these communications channels are interrupted due to an SSC, there are of course resulting challenges to mission operations. An outage of a few days to a few weeks could allow minor disturbances to become major concerns or even trigger subsystems failures. An inability to consult with the ground at the wrong time could result in loss of mission, loss of an element, or loss of life. Each planet in the solar system has a set of five Lagrange points associated with it and the Sun. At any given point in time, a planet or either its L4 or L5 point is visible to any other planet in the solar system, regardless of the position of the sun relative to the two. Thus, L4 and L5 have high value as relay systems to prevent communications outages. There are four sets of solar Lagrange points that may be of potential use in this study: Mars-Sun L4 and L5 points, Earth-Sun L4 and L5, Venus-Sun L4 and L5, and Mercury-Sun L4 and L5. A candidate relay satellite system will be identified, with consideration of both new technology developments and existing telecommunications satellites. This system may have implications for not only the Mars human mission architectures, but also Gateway and human lunar surface architectures as these other studies are tasked with paving the way to human Mars missions. If Mars communications outages can be eliminated, then the degree of autonomy necessary in Mars and precursor systems may be reduced.**

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1. INTRODUCTION

It is well known that communications between Mars and Earth will be a challenge for human Mars exploration. Many people discuss this challenge in the context of communications delay (Latency) and study teams have attempted to assess the impact of delay on operations for more than a decade. There are three major telecommunication link challenges facing crews and their supporting mission systems on their way to Mars, at Mars, and during their return. These link challenges are more frequently being referred to as "CL&A" or "CLA" for short. CLA is an acronym for [telecommunication link] Capacity, Availability, and Latency – the three main performance attributes of a communication link that are experienced by any communication link user. Communications outages with crews that will occur due to periods where link availability is not possible is frequently overlooked by human mission planners and is a challenge that may be even more critical than challenges caused by issues with link Capacity and long Latencies.

There are conditions, to be discussed in this paper, that cause reoccurring communications outages that will impact any long duration human Mars mission. If this outage is shown to place the lives of the crew at risk, then developing a capability to mitigate this risk will be a high priority. Because the planets in our solar system generally orbit along the same ecliptic plane with the sun, the conditions we discuss in this paper impact any long duration mission to planets along this ecliptic plane/across our solar system.

This paper serves to elevate the issue of communications outage and proposes one set of potential options that can be incorporated into Mars mission architectures or traded against other mitigation options.

2. DRIVING NEEDS FOR COMMUNICATIONS BETWEEN EARTH AND MARS DURING HUMAN MARS MISSIONS

Mars System Human Exploration Infrastructure

At this point in time there is no established Mars Program Office to define official elements of a human Mars mission. However, there are generic types of elements that are repeatedly found in Mars architectural studies.

All human Mars missions require some method of transportation element to deliver humans, surface elements, and other components of the architecture from the vicinity of Earth to the vicinity of Mars. With exceptions in only a handful of architectures, this transportation asset is generally a space-based asset that remains in space while the crew is on the surface. There may be a single instance of this asset, or there may be multiple transportation spacecraft performing this duty. At least one of these is a long duration habitat, which houses the crew during the transit period and can serve as a safe haven if the crew should need to evacuate the surface before the departure window for return to Earth has arrived.

Completing the transportation leg, most architectures feature a separate lander spacecraft that provides (usually) one-way delivery of cargo to the surface and two-way transportation of crew between the surface and the orbiting in-space transportation element. These landers may be reusable or expendable. Most architectures involve more than one such lander, even in reusable lander architectures.

Most human Mars exploration architectures involve a human surface stay in excess of a hundred days. Thus, there is also a long duration surface habitat. The habitat may be composed of a single element or multiple elements docked together.

A science-driven goal for exploration beyond the immediate location of the surface habitat yields a need for surface mobility assets. This may be as little as a single crew-operable unpressurized rover, or as expansive as a fleet of pressurized rovers. The NASA Constellation program established a paradigm of dual small pressurized rovers (SPRs), which has since become popular in many architectures for both Moon and Mars mission scenarios.

Other science and operational drivers often seek to make use of local resources. In-Situ Resource Utilization (ISRU) equipment may be co-manifested with a lander, mobile, or positioned at a specific location depending on the type of resource to be obtained and processed.

Additional support elements may provide some form of subsystems services, science support, or operations capability. Some may be attached to a habitat or lander, but in many cases these elements are positioned in separate locations based on their intended function (e.g. nuclear fission power source placed some distance from the habitat).

This typically results in a Mars system infrastructure that consists of distributed assets, including multiple elements on the surface separated by nontrivial numbers of kilometers (up to as great as 100 km in the case of pressurized rovers) and one or more elements in orbit at any given time.

Nominal Communications Activity

On a day to day basis, all the aforementioned Mars assets will be in near-constant communication with Earth (this is unlike rovers exploring Mars today [1], due to the presence of human crews). Telemetry from each Mars-vicinity element (both orbital and surface) will be continuously streaming (albeit, delayed) to Mission Control for situational awareness, monitoring and response, and science data will be streaming to Earth in parallel and provided to science investigators across the globe. Crews will have a significant dependence on data streaming to them from Earth throughout the mission, not only to conduct mission operations, but also for maintaining psychosocial health. [2], [3] Crewmembers will send and receive many types of messages with teams, family, friends and the general public on Earth (text, voice, high and low definition video, haptic), stream live or exchange file-based videos (from maintenance to training, public outreach, scientific and family/personal). Video intended for scientific analysis or public consumption will likely involve very high definition (e.g. 4K resolution). Commands may also be received from Earth to remotely operate (teleoperate) equipment in the Mars vicinity as Mars rovers and spacecraft are teleoperated today, to relieve crews from these tasks while in the Mars environment.

These Mars assets, distributed in multiple locations across and above the surface, may either directly transmit to and receive from Earth, or (more likely) may use a common local relay asset.

3. SOLAR SUPERIOR CONJUNCTIONS AND COMMUNICATIONS OUTAGES

As a function of orbital mechanics, Earth and Mars orbit the Sun at different speeds. Thus, there is a periodic occurrence, approximately every 26 months, where the Sun lies directly between Earth and Mars. This is called a solar superior conjunction (SSC) and is illustrated in Figure 1.

AN SSC causes degradation in a communications signal, or even complete outage, lasting for days to weeks or even months depending on the type of communications signal. Until now, this has only been an issue for robotic Mars missions such as the missions operated by the NASA Jet Propulsion Laboratory. Some of the JPL team members responsible for Mars operations will take vacation during SSCs because there is nothing they can do to communicate with the Mars robots during this time.

Table 1 describes outages expected due to SSCs in the 2030 to 2041 timeframe.

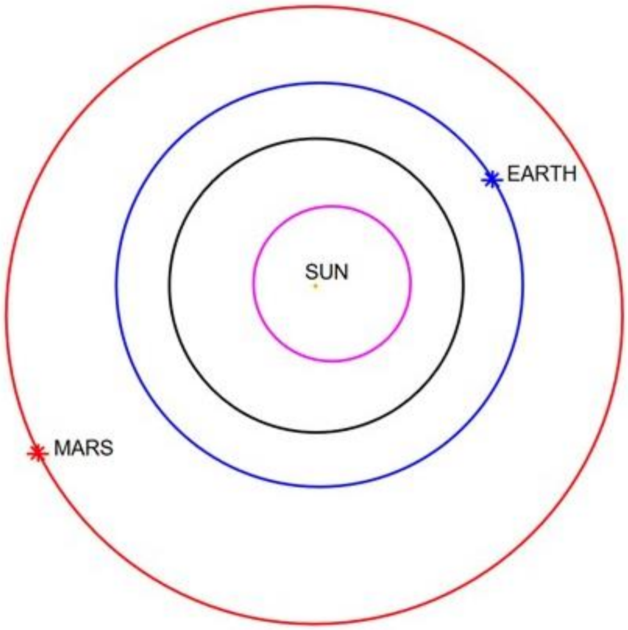


Figure 1. Solar Superior Conjunction

Table 1. Outages During Solar Superior Conjunction [4], [5]

Date	Optical Outage (days)	X-band Outage (days)	Ka-band Outage (days)
5/25/2030	78.1	23.5	7.7
7/11/2032	66.4	19.0	1.5
8/19/2034	60.9	17.1	0.0
9/23/2036	59.8	17.3	3.1
11/1/2038	63.3	19.0	6.3
12/17/2040	74.0	21.7	5.7

For most conjunction class Mars mission concepts involving long duration human occupancy (inclusive of Mars orbit, Martian moons, and Mars surface), there will be an SSC at some point while the crew is in the vicinity of Mars. (No analysis has been done as of the time of this writing to determine if these outages will occur during the surface periods of opposition class human Mars missions.) In the vast majority of conjunction class mission concepts this outage will occur while the crew is on the surface. The higher bandwidth systems – that are necessary to support the high data rates required by human habitation and human-centric science – are unfortunately the most susceptible to interruption during SSCs.

4. CHALLENGES TO HUMAN MARS MISSIONS DUE TO COMMUNICATIONS OUTAGES

A critical question is how serious are the communications outages posed by SSCs? Is it acceptable to conduct a conjunction class human mission to Mars and simply allow the Mars expedition to lose contact with Earth for the duration of the SSC, or be limited to low data rate communications? (It is not yet known if this is an issue for the shorter surface stay times of an opposition class mission.)

There are, of course, numerous scientific and operational considerations that would prefer uninterrupted communications. Remotely operated robotic assistants could perform more efficient science if the SSC does not interfere with operations.

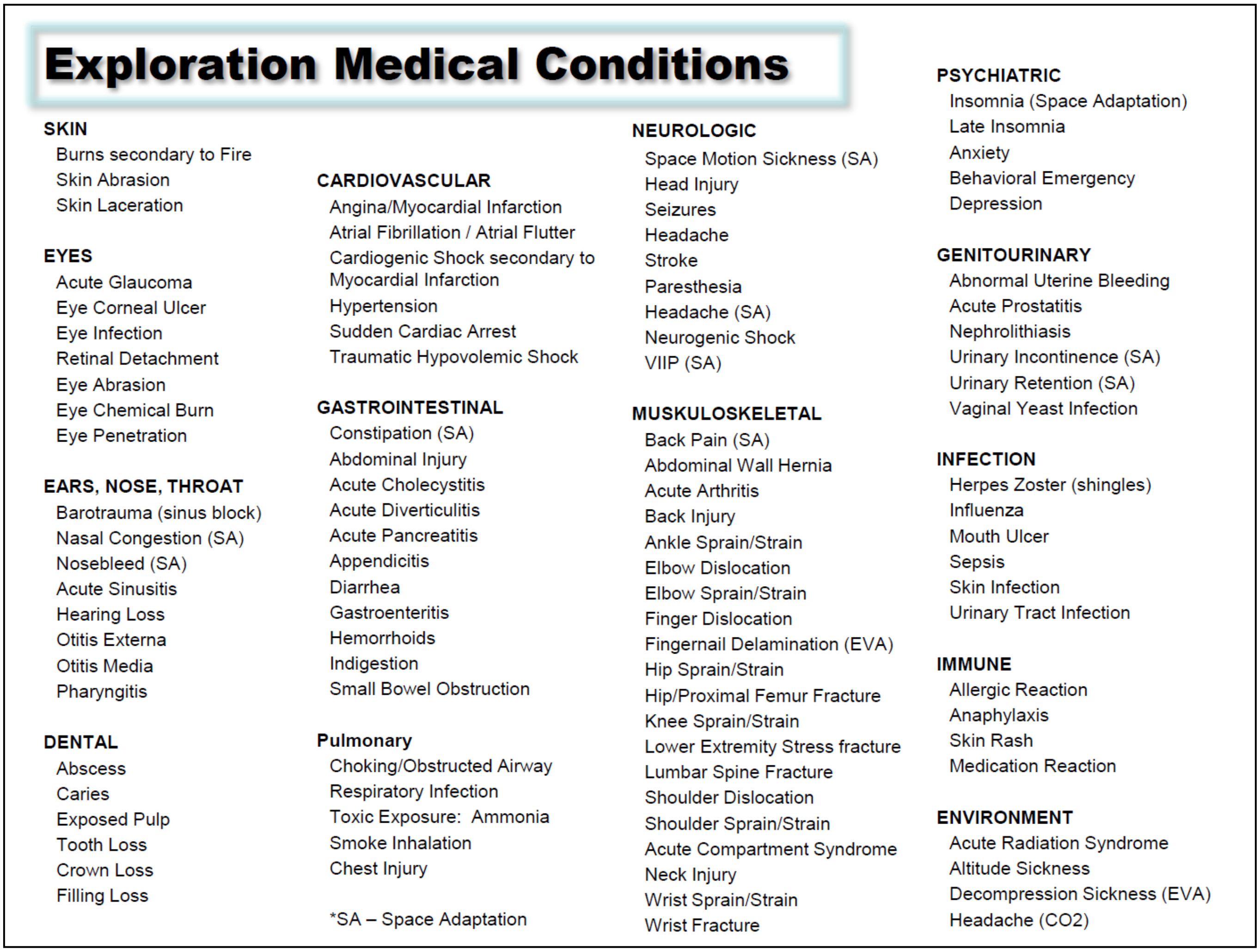
Outpost operations such as robotic site maintenance, cargo offloading and repositioning, in-situ resource utilization (ISRU) production, and other activities maintain greater schedule flexibility if SSCs do not constrain their activities.

However, the overriding question for this investigation is can an SSC communications outage lead to loss of life of a crew member? Such a concern would immediately elevate the priority of eliminating the communications outage during SSCs.

Dr. Erik Antonsen, Assistant Director Human System Risk Management at the NASA Johnson Space Center, predicts at least three key risks from SSC-based communications outages:

> *Behavioral Health and Performance Risk*
>
> The outage drives home the crew’s distance from Earth with impacts on crew mood, irritability, team/social cohesion, with potential decrements in performance as a result. It may magnify any pre-existing problems between crew members. There may be an increase in behavioral medical conditions such as depression, anxiety, and behavioral health emergencies. [6]
>
> *Medical Response Risk*

The crew is fully responsible for diagnosis, treatment, and secondary prevention (keeping small medical issues from becoming bigger ones) with no ground support. A complicated medical issue during this time will carry an increased risk of misdiagnosis or mistreat conditions, even if physicians are among the crew as no one (or even two) doctor(s) can be an expert in the wide range of possible medical conditions. NASA has identified over 100 medical conditions that may require treatment during an exploration mission [6], shown in Figure 2.



Exploration Medical Conditions

SKIN
- Burns secondary to Fire
- Skin Abrasion
- Skin Laceration

EYES
- Acute Glaucoma
- Eye Corneal Ulcer
- Eye Infection
- Retinal Detachment
- Eye Abrasion
- Eye Chemical Burn
- Eye Penetration

EARS, NOSE, THROAT
- Barotrauma (sinus block)
- Nasal Congestion (SA)
- Nosebleed (SA)
- Acute Sinusitis
- Hearing Loss
- Otitis Externa
- Otitis Media
- Pharyngitis

DENTAL
- Abscess
- Caries
- Exposed Pulp
- Tooth Loss
- Crown Loss
- Filling Loss

CARDIOVASCULAR
- Angina/Myocardial Infarction
- Atrial Fibrillation / Atrial Flutter
- Cardiogenic Shock secondary to Myocardial Infarction
- Hypertension
- Sudden Cardiac Arrest
- Traumatic Hypovolemic Shock

GASTROINTESTINAL
- Constipation (SA)
- Abdominal Injury
- Acute Cholecystitis
- Acute Diverticulitis
- Acute Pancreatitis
- Appendicitis
- Diarrhea
- Gastroenteritis
- Hemorrhoids
- Indigestion
- Small Bowel Obstruction

Pulmonary
- Choking/Obstructed Airway
- Respiratory Infection
- Toxic Exposure: Ammonia
- Smoke Inhalation
- Chest Injury

*SA – Space Adaptation

NEUROLOGIC
- Space Motion Sickness (SA)
- Head Injury
- Seizures
- Headache
- Stroke
- Paresthesia
- Headache (SA)
- Neurogenic Shock
- VIIP (SA)

MUSKULOSKELETAL
- Back Pain (SA)
- Abdominal Wall Hernia
- Acute Arthritis
- Back Injury
- Ankle Sprain/Strain
- Elbow Dislocation
- Elbow Sprain/Strain
- Finger Dislocation
- Fingernail Delamination (EVA)
- Hip Sprain/Strain
- Hip/Proximal Femur Fracture
- Knee Sprain/Strain
- Lower Extremity Stress fracture
- Lumbar Spine Fracture
- Shoulder Dislocation
- Shoulder Sprain/Strain
- Acute Compartment Syndrome
- Neck Injury
- Wrist Sprain/Strain
- Wrist Fracture

PSYCHIATRIC
- Insomnia (Space Adaptation)
- Late Insomnia
- Anxiety
- Behavioral Emergency
- Depression

GENITOURINARY
- Abnormal Uterine Bleeding
- Acute Prostatitis
- Nephrolithiasis
- Urinary Incontinence (SA)
- Urinary Retention (SA)
- Vaginal Yeast Infection

INFECTION
- Herpes Zoster (shingles)
- Influenza
- Mouth Ulcer
- Sepsis
- Skin Infection
- Urinary Tract Infection

IMMUNE
- Allergic Reaction
- Anaphylaxis
- Skin Rash
- Medication Reaction

ENVIRONMENT
- Acute Radiation Syndrome
- Altitude Sickness
- Decompression Sickness (EVA)
- Headache (CO2)

Figure 2. Exploration Medical Conditions [6]

Human System Integration Risk

Just as a medical issue can occur with a crew member at any time, a maintenance and repair issue may also occur with any element in the Mars vicinity. Regardless of the expertise of the crew, if the broader and deeper expertise of Mission Control cannot be brought to bear, there is an increased risk that the vehicle contingency may not be successfully resolved. [6]

Medical Response Test Cases

In addition to these high-level risks, NASA recently conducted two test cases [7] to identify bandwidths required for communications. The first case examined a physiological medical emergency: Impacted Renal Stone, Hydronephrosis, and Urosepsis with Septic Shock. The second case examined a behavioral health emergency: Death of Crew Family Member. Each test case is a medical narrative that is decomposed by a medical algorithm to communicate the diagnosis and treatment process. [7]

The renal stone scenario begins with an astronaut developing left-sided lower back pain that quickly escalates. The scenario considers a 14-day response period following the initial emergency, divided into the first three days, the next four days, and the following seven days. The communications required to provide treatment (inclusive of text, medical device measurements, and audio/video images) was estimated to be approximately 94 GB, almost all of which was during the first three days. [7]

The death of a family member scenario begins one month out from Martian orbital insertion, when a crewmember receives notice via spouse and flight surgeon that his/her 11-year-old child has been admitted to the hospital for difficulty breathing. The scenario proceeds from there over an 85-day period that leads to the child's death and involves continued support for the crew member.

This scenario is much more data intensive and ultimately transmits approximately 835 GB of data to Earth. [7] The most data-intensive periods were days 4-7 and 22-25, where the average daily data transmission was approximately 35 GB per day and 66 GB per day respectively. [7]

The approach traditionally taken for SSCs with robotic spacecraft – the flight control team goes on vacation – does not work for human spaceflight. Clearly, it would be unacceptable for the Mission Control Flight Surgeon to be on vacation during an SSC. If either of these medical scenarios occurred on Mars during an SSC with a communications outage there is a very real likelihood that an otherwise survivable (though tragic) event may have led to loss of a crew member. Consequently, there is a clear need to eliminate the communications outages during SSCs and it is further important to enable high data rate communication between Mars and Earth at all times.

5. USE OF SOLAR LAGRANGE POINTS TO ELIMINATE COMMUNICATIONS OUTAGES DURING SOLAR SUPERIOR CONJUNCTIONS

Despite the clear need presented by a medical emergency, it is physically impossible for a high data rate RF or optical signal to transmit through the sun during an SSC. (It is theorized by NASA Mars program engineers [8] that very low data rate messaging – on the order of one bit every three to six seconds – may be possible "through the sun" using a modified semaphore communication method similar to the method used to receive messages during the "7 minutes of terror" when Mars landers used to lose all communication with Earth due to landing plume ionization effects on signal degradation. [9] Such a method might only result in (at best) 14-28 KB per day, far below the medically necessary 66 GB per day.)

One solution to mitigate link availability issues and potentially maintain high data rates (Capacity) is through the use of a relay, located somewhere in the solar system to where it has a line of sight to both Mars and Earth during an SSC. While there are multiple options that may be considered for such a relay location between Mars and Earth an initial candidate is a solar Lagrange point. Relays placed at these locations both have the potential to completely resolve the Availability problem, while simultaneously maintaining the link Capacity required to keep the mission operations on schedule.

Each planet that orbits the Sun has a series of five Lagrange points, points of gravitational balance, shown in figure 3. A smaller object at a Lagrange point (or technically orbiting the point) maintains the same approximate position relative to the two larger orbiting bodies (e.g. the Sun and a planet).

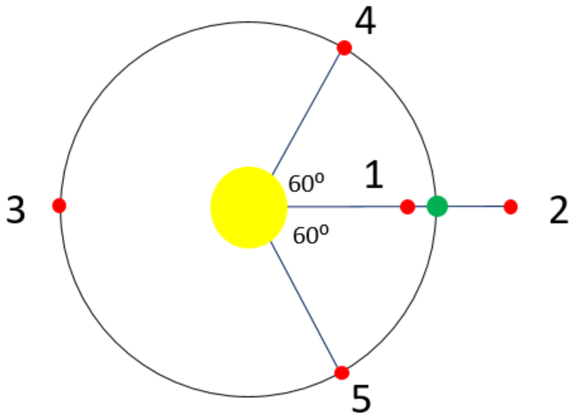


Figure 3. Lagrange Points

The L4 and L5 points are gravitationally stable and lead (L4) or follow (L5) the planet. A satellite placed in orbit of a L4 or L5 point can relay signals around the sun. Whenever an SSC blocks Earth and Mars from each other the L4 and L5 Lagrange points will have a line of sight. So, the question emerges, which Lagrange point?

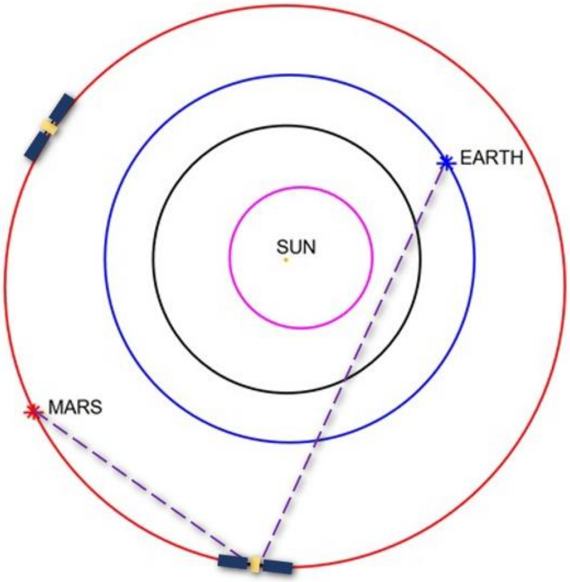


Figure 4. Relays at Mars-Sun Lagrange Points

Figures 4-7 show options for relay satellites at the L4 and L5 points for Mars, Earth, Venus, and Mercury. It is worth noting that the L4 and L5 points can capture Trojan asteroids. Mercury has no known Trojans. Venus has a temporary Trojan at its L4. [10] Earth has a single Trojan at its L4. [11] Mars has one Trojan at its L4 and eight at its L5. [12]

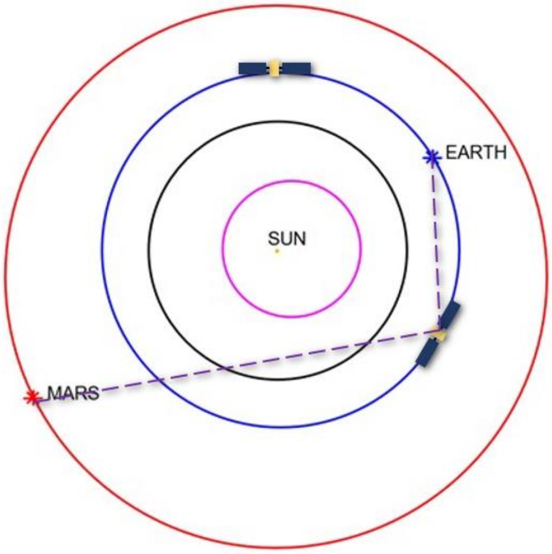


Figure 5. Relays at Earth-Sun Lagrange Points

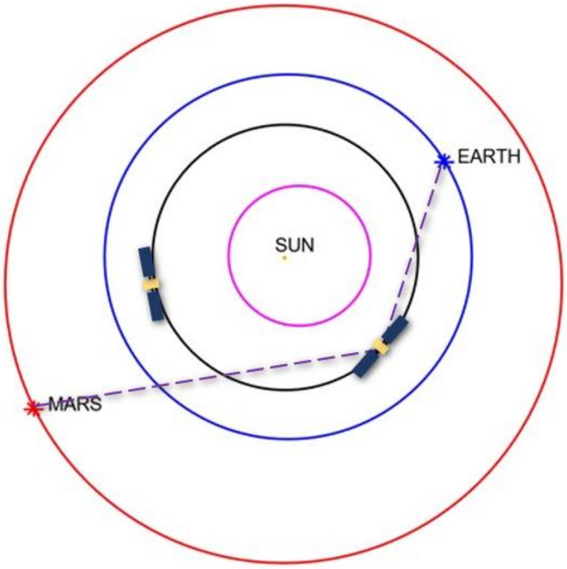


Figure 6. Relays at Venus-Sun Lagrange Points

A relay that shares a Lagrange point with one or more Trojan asteroids would need to be capable of maintaining a keep out sphere to prevent inadvertent contact with an asteroid. Further study is needed to determine if this requires any more complex guidance, navigation, and propulsion capability than would already be required for station keeping and antenna/transmitter pointing.

For Mars and Earth, a single satellite at either L4 or L5 is sufficient, though additional satellites could be added for redundancy. For Venus and Mercury, it is theoretically possible that either a L4 or L5 point could line up with the Sun, Earth, and Mars during an SSC, but analysis would need to be done to determine if this will occur during any foreseeable human Mars mission dates. (This is notionally indicated in Figure 7, where the Mercury L5 relay is in line with Mars, the Sun, and Earth, requiring use of the L4 relay.) If this is a potential occurrence, then a second satellite at the other stable Lagrange point would eliminate any possibility of communications outage.

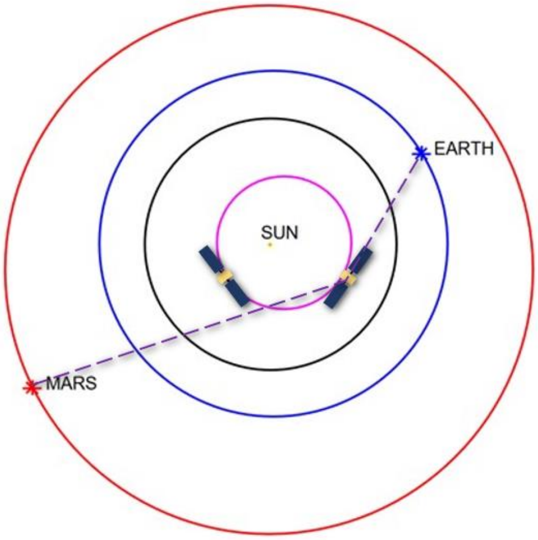


Figure 7. Relays at Mercury-Sun Lagrange Points

6. PERFORMANCE TARGET FOR A SATELLITE-BASED RELAY FROM SOLAR LAGRANGE POINTS

Estimated Communications Need

Presently, there are no established requirements that specify the communications needs of a Mars outpost. This is a challenge in that communications personnel cannot know what targets to aim for without guidance. Is the daily communications bandwidth best measured in kilobytes or petabytes?

The medical scenario in section four of this paper suggests a possible minimum communications need – 66 GB per day. If one is to assume continuous transmission 24 hours per day, then this translates into slightly about 764 KBps. However, if transmission times are restricted to 8 hours per day this translates into roughly 2.3 MBps.

However, this approach likely underestimates the actual communications need. Was the medical scenario selected actually the worst possible communications case? Is it possible that a medical case might be accompanied by a vehicle emergency that also requires high bandwidth telemaintenance support? What else should accompany the medical transmission and how high does that push the bandwidth above 66 GB per day?

This problem can be approached from the opposite direction, with the expectation of eventually meeting in the middle. Under the assumption that bandwidth is dominated by high resolution video (e.g. 4K, 8K and beyond) it is possible to estimate a "wish list" bandwidth.

First, cameras in space and on the surface of Mars must be estimated. Under most (not necessarily all) conjunction class mission concepts, during human Mars excursions there are essentially two primary outpost facilities – the transit spacecraft in Mars orbit and the surface outpost. The transit spacecraft consists of a habitat (modular or monolithic) and a propulsion element. The surface outpost includes a habitat (also modular or monolithic), airlock, two or more pressurized rovers (a single pressurized rover architecture carries either very short range with resultantly poor scientific usability, or a high risk for loss of crew and is excluded from consideration in this study), at least one active logistics module, and a lander/ascent vehicle. A notional camera lists, included in Appendix A, suggests up to 173 high definition cameras in the Mars system during a human Mars mission.

It will never be necessary for all 173 cameras to simultaneously transmit at 4K resolution. However, a mixture of purposes will drive high resolution needs, including telemedicine (as suggested in section four of this paper), telemaintenance, media activities, remote science, and mission operations.

A reasonably high camera utilization during a surface Small Pressurized Rover (SPR) excursion may involve 26 high resolution cameras. This notional allocation includes six cameras on the transit spacecraft – four providing imagery for autonomous internal payloads and two providing orbital imagery; four similar payload cameras on the surface hab; one suit mounted camera each for two crew members on EVA; and seven cameras on each SPR – four driving cameras, two science cameras, and one internal crew camera.

Assuming a data rate of 9 GBps for 4K resolution (compression techniques can likely reduce this data rate, but using it here as a worst case), 234 GBps is required for real-time downlink. A target bandwidth of 250 GBps is assumed, further assuming that the remaining bandwidth is allocated as far as possible among low resolution video from other cameras, audio, and data.

Herein lies the wide uncertainty of Mars communications. An ultra-minimalist assumption could drive a conclusion of only an 800 KBps data rate, whereas a lightly restrained idealistic assumption could drive a data rate of 250 GBps. The performance goal suggested in this example is therefore 250 GBps and the minimum success criteria is 800 KBps.

7. SURVEY OF EXISTING AND CONCEPTUAL TELECOMMUNICATIONS SATELLITES FOR USE AS A RELAY SYSTEM

If a relay satellite is to be designed from the ground up, it will add another architectural element to human Mars exploration and the resulting cost of standing up a program specifically for that satellite will add significant expense. Thus, it is worth exploring whether any alternative options exist to use existing or low-cost solutions.

Cubesats

Cubesats can likely be instantly eliminated from the trade space. It is highly unlikely that the transmitters and telescopes necessary to achieve the data rates described in the previous section will fit within the envelope of a cubesat platform, unless a breakthrough is made in the ability for hundreds if cubesats to combine their small-aperture/small transmitter resources together into a large phase-synchronized array, all focused together on a single distant link target (like Earth) and working cooperatively to transmit and receive signal energy like a single large satellite.

"Hosted Payload" Lagrangian relay

Instead of developing a satellite bus at all, the necessary communication relay hardware for a relay (and if necessary additional power generation) can be mounted onto an already-planned spacecraft headed to Mars, such as a robotic precursor mission or a cargo pre-deploy mission. Then, after the cargo mission has delivered its Mars payload, the spacecraft spirals itself out to and parks in a Lagrange point such as the Mars-Sun L4 or L5, and the relay hardware onboard powers up and for service. This, however, imposes substantial penalties on the host spacecraft to the point that the primary mission may be adversely impacted.

Telecommunications Satellites

A more likely near-term higher TRL/flight-ready candidate may be found among the large communications satellites currently used in geostationary orbits around Earth.

Boeing 702—The Boeing 702 family can provide payload power ranges from 3 kW to 25 kW [13] and more than 100 high power transponders. [14]

Lockheed Martin LM 2100—The Lockheed LM2100 provides up to 20 kW power [15] and data rates in excess of 100 MBps. [16]

Maxar SSL 1300—The SSL 1300 features solar electric propulsion [17] with broadcast power ranging from 5 kW to 25 kW and 12 to 150 transponders. [18] The SSL 1300 is especially worth noting in that it is currently being used in a mission that will demonstrate deep space communications.

The Psyche orbiter mission will visit the main belt asteroid 16 Psyche in the mid-2020s. As part of its mission, it will use an optical communications system as a concept demonstrator. The Psyche spacecraft is based on the Maxar SSL 1300 satellite and its solar panels provide approximately 20 kW of power at Earth and 2.3 kW of power at the asteroid Psyche. [19] It will demonstrate optical communications at 292 KBps at a distance of 0.4 AU. [20] Presumably this demonstration will occur during the outbound cruise to the asteroid.

It is worth noting that optical communication is not the primary payload of the Psyche spacecraft. It carries a multi-spectral imager, gamma ray and neutron spectrometer, fluxgate magnetometer, and an X-band radio science instrument. Thus, it does not utilize the bulk of the spacecraft's onboard power.

Northrop Grumman GEOStar—The GEOStar-3 is comparatively small, with payload power of only 8 kW [21] but is worth mentioning because Northrop Grumman manufactures the UltraFlex solar array, scalable from 0.5 kW to 20 kW [22] and the MegaFlex solar array, scalable from 30 kW to 300 kW. [23]

Thales Alenia Spacebus Neo—The Spacebus Neo is a modular spacecraft providing payload power up to 20 kW. [24]

Conceptual Dedicated Satellite Solution

All the previously discussed commercial satellites, with the possible exception of the GEOStar, are capable of providing primary power in the 20-kW scale used by the Psyche spacecraft. If higher levels are necessary, Northrop Grumman appears to offer options to increase onboard power by a factor of fifteen.

Thus, the spacecraft bus and the primary power system appear to be available as high TRL commercial acquisitions. The optical communications payload will, of course, have to be a custom solution.

The optical communications payload system consists of two parts – the transmitter and the receiver. Phase II NASA Small Business Innovation Research (SBIR) program [25] research is currently developing a prototype, space-qualifiable, high-efficiency, high power (50W), 1.5-µm wavelength-division-multiplexed (WDM) space lasercom transmitter. If progressed to TRL 9, such a transmitter could be used in the relay satellite.

Based on discussions with JPL researchers, a 50-watt transmitter will likely require approximately 500 watts from the spacecraft power system, plus perhaps as much as an additional 100 watts to power other components of the payload. Forward work will determine the data rate this transmitter can achieve at Earth-Relay-Mars distances.

There is no expectation that one transmitter will be able to achieve the performance goal of 250 GBps, so multiple transmitters will be needed. An upper limit will be driven based on available satellite power and demuxing limits of the receiver.

It is additionally important to note that because the satellite is a relay, the number of transmitters needed is actually doubled. In order to be capable of transmitting and receiving (in both directions) at the same time, there must be transmitter pairs – one for uplink and one for downlink.

The receiver itself is a telescope with cryocooled detectors. The detectors on the receiver will need to operate at temperatures in the vicinity of 1-3 K and may require a combination of active cryocooling and sun shields, such as those employed on the James Webb Space Telescope. Just like the transmitter pairs, there will need to be both an uplink and a downlink receiver.

A starting point for the telescope aperture is 4.6 meters in diameter. This would enable a single mirror, launched by any commercial launch vehicle (CLV) with no need for a post-launch assembly process. If future analysis shows this to be insufficient, then deployable mirrors like those used on James Webb could enable larger telescopes, potentially increasing diameter by a factor of ten.

The cryocooler for the James Webb's Mid InfraRed Instrument (MIRI) cools the MIRI focal plane arrays to the operating temperature of 6.7 K and requires a maximum power draw of 475 Watts. [MIRI] Until actual sizing can be performed, it will be conservatively assumed that the lower operating temperature needed by the receiver's detectors will require slightly more than double this power and 1 kW will be assumed as needed to power each of the two receivers.

Based on the above analysis, Table 1 predicts the number of transmitters that could be accommodated on a relay satellite – based on a given solar array power. It also indicates the data rate each transmitter would need to support in order to achieve an overall 250 GBps system bandwidth. In all likelihood, the demuxing limit will fall somewhere within this table, preventing the theoretical number of transmitters indicated below.

Table 1. Transmitter Accommodation Limits

Satellite Power (kW)	Transmitter Limit	GBps per Transmitter
20	12	20.833
40	29	8.621
80	62	4.032
150	120	2.083
250	204	1.225
300	245	1.020

The complete satellite solution will require one or two Lagrange-based relays as previously described. (As noted in section five of this paper, if the relay is based in the Mars-Sun or Earth-Sun Lagrange system then only one relay is needed. But if it is based in the Venus-Sun or Mercury-Sun system then two relay satellites are needed.

In addition, this paper assumes locally based relays in the gravitational influences of Earth and Mars. These relay satellites are the hub for all local signals and serve as the connection to the Lagrange relay.

For the Earth system relay, this satellite – potentially in a high

Earth orbit or Cislunar space – would receive any Mars-bound signals from Mission Control, other science investigators, lunar and Cislunar platforms, aggregate and/or multiplex them, and transmit them to the Lagrange relay or directly to Mars, while simultaneously receiving inbound signals from the Lagrange relay or Mars and forwarding them to the appropriate destination.

For the Mars system relay, this satellite – presumably in a high Mars orbit – would similarly multiplex signals from the transit hab, surface hab, rovers, and other assets on Mars, in orbit, or on the Martian moons and transmit them to the Lagrange relay or directly to Earth, while simultaneously distributing signals received from the Lagrange relay or Earth.

These two local relays may use either RF, optical, or a combination for the local signals. They may or may not carry the same number, fewer, or a greater number of the transmitters and receivers in the Lagrange relay.

The Lagrange relay is always locked onto the Earth and Mars system relays. The local relays will generally lock onto each other. They have the option to lock onto the Lagrange relay when an SSC is imminent, or any time solar or other considerations make transmission through the Lagrange relay favorable.

8. RELAY PLACEMENT CONSIDERATIONS FOR A ZERO OUTAGE EARTH-MARS COMMUNICATIONS RELAY SYSTEM

It is evident that the only way to eliminate communications outrages is to deploy a relay in some location. However, several factors, some of which have already been directly or indirectly suggested, can influence which location is ultimately the best solution.

Communications Delay

The maximum one-way communications delay (based solely on signal distance traveled, not including hardware/software processing delays) is approximately 25.5 minutes for the Mars-Sun L5 relay, 23.5 minutes for the Earth-Sun L5 relay, 23 minutes for the Venus-Sun L5 relay, and 21 minutes for the Mercury-Sun L5 relay.

Solar Environment

The closer the satellite orbit is to the sun the higher the power generated by its solar arrays will be, but also the more solar radiation its electronics will experience. NASA has deployed spacecraft to all the inner planets, so while there are performance impacts related to the location of the relay none of them are outside of NASA's design experience with respect to the solar environment.

Another concern with respect to the solar environment is that the closer the satellite orbit is to the sun the more the sun will be in the field of view of the telescope optics, which is an undesirable factor.

Deployment Cost

A Lagrange-based solution will require a propulsion system to deliver it to the selected Lagrange point.

For the Mars-Sun Lagrange points it is possible that a communications relay could ride as a secondary payload for a Mars transfer spacecraft, separating at some point prior to Mars orbital insertion. This would, of course, come at the expense of payload delivered to Mars for the primary transfer mission and would have to be weighed against the cost of a dedicated mission.

If the relay is launched sufficiently in advance of human Mars exploration it may be possible to leverage low energy transfers to deliver it to the Earth-Sun L5 point.

Mercury and Venus Lagrange destinations will require dedicated missions with significant delta-v costs. This is readily achievable but does tie up one of the more powerful commercial CLVs.

Alternative Solutions

A Lagrange-based relay might not be the only option to achieve zero communications outage. The Mars transfer spacecraft used to deliver surface cargo may serve as a relay during its return flight to Earth. Also, logistics modules delivered to Cislunar space (for Gateway or crewed Mars transfer spacecraft resupply) could potentially be used as relays after their logistics mission is complete. If a Mars human exploration program is developed in conjunction with other human or robotic exploration of the inner solar system, there may be assets associated with other programs that might be in reasonable locations to serve as relays, if properly equipped with optical communications systems.

However, further analysis would be needed to determine if any of these spacecraft (a) have a sufficient communications system to handle the necessary bandwidth; or (b) are in (or can be placed in) an orbit or trajectory with line of sight to both Earth and Mars, and are thus able to serve as a relay. If these existing spacecraft can be repurposed to serve as a relay the total program cost is likely to be lower than using a dedicated telecommunications satellite.

Initial Starting Point Description

An initial starting point is proposed using the assumption that a dedicated relay system is necessary and using the conceptual satellite solution discussed in section seven of this paper. Any specific Mars architecture would, of course, need to identify a solution in light of the specific resources and constraints of that architecture.

A three-satellite solution is explored, including a local Earth relay, local Mars relay, and a Lagrange relay.

The Earth-Sun L5 point is used in this analysis for the Lagrange relay. An advantage of L5 over L4 is that a satellite at L5 will not have to consider the presence of asteroid 2010 TK_7, a known Trojan asteroid orbiting the Earth-Sun L4 point. [11] Also, launch to the Earth-Sun L5 will be considerably cheaper than launch to Mercury or Venus L5 points with the cost of only a few additional minutes of communications delay.

This drives placement of the Earth relay to a High Earth Orbit or Cislunar orbit that receives constant sunlight and has constant line of sight to the Earth-Sun L5 point and to Mars.

Finally, the Mars relay will need to be in an orbit that receives constant sunlight and has constant line of sight to the Earth-Sun L5 point and to Earth.

9. SUMMARY

Until recently – and even today in some circles – it was a commonly held assumption that due to SSCs it was physically impossible to avoid communications outages between Earth and Mars during conjunction class missions. They were perceived as an inescapable reality of physics and long duration human Mars missions would simply have to learn how to live with them. Reality is significantly more complex.

While some human Mars exploration architectures may choose to embrace a communications outage – whether as a driver for Earth autonomy, as a resource vs. risk trade, or for some other reason(s), this paper does establish that it is physically possible to completely eliminate Earth-Mars communications outages during SSCs.

There are many potential solutions to establish uninterrupted communication. This paper has explored options for the use of solar Lagrange points, specifically exploring the use of a relay satellite at the Earth-Sun L5 point. Such a system can not only mitigate loss of life risks, but will also enable additional mission capability, providing greater utilization of mission assets at Mars.

Many details remain as forward work to clearly scope the costs and capability of this satellite relay system. Commercial telecommunications satellite buses from a variety of providers are all generally suitable for use as a relay.

Additional optical communications research is needed to flesh out the configuration of the 50-watt laser transmitter based on the current NASA SBIR research, as well as to define a 4.6-meter diameter receiver, and to determine the total number of transmitters that can be packaged together in a relay satellite and resulting bandwidth in the Earth-Mars communications link. If this system is unable to deliver the desired bandwidth then additional techniques may be explored, such as a larger diameter, deployable telescope aperture or incorporating MegaFlex solar arrays.

Once it is clear where current capabilities lie with respect to the minimum medically necessary bandwidth and the idealized “wish list” bandwidth, Mars architectures can be refined to adjust to the resulting communications capability. Exact bandwidth needs and desirements will invariably be a concept-specific quantity that could vary widely from one architecture to another – and even within the same architecture at varying stages of design maturity.

It does appear very likely that the medically necessary capability identified in this paper of 66 GB per day can be easily met – and exceeded – with an optical relay system. However, the door may be open to explore whether an RF system can meet this need and if so, is it a more minimal option (from a cost and schedule perspective) than an optical system. It is not an immediate conclusion that an RF solution will be less expensive or more readily available than an optical one.

Research is also needed to develop the local Earth and Mars system networks. In the case of the Earth relay, this involves the communications link between the satellite and the ground, which may or may not make use of TDRSS, commercial satellite networks, the Deep Space Network, and other ground terminals. In the case of the Mars relay, this involves links to the transit spacecraft, surface habitat, SPRs (including when on traverse), and other local and distributed surface assets.

When applied to any specific Mars architecture or Design Reference Mission, or in the context of other inner solar system exploration, it will also be prudent to consider other spacecraft that could serve as communications relays, as either supplements or replacements to a Lagrange-based relay, or for their potential contribution to local Earth system or Mars system communications networks. Each architecture may well have a unique solution, driven by its specific goals, objectives, resources, and constraints.

Finally, as there is a current interest in opposition class missions, it is important to determine whether SSCs will occur during the surface phase of a crewed mission or if the transit spacecraft will experience a communications outage during any point in the mission. Additionally, it is important to determine the impact of SSCs on uncrewed assets in orbit or on the surface between crew visits.

APPENDICES

A. NOTIONAL CAMERA LIST

No Mars campaign has been designed in enough detail to identify the number of cameras that will be placed in the Mars system and there are no NASA standards that prescribe the outfitting of cameras to habitable spacecraft. This camera list of notional internal and external cameras is suggested as a wag based on experience with prototype landers, rovers, robots, and habitats developed at NASA Johnson Space Center and the Jet Propulsion Laboratory, some of which were field tested in the Arizona desert.

Habitat (Identical camera allocation for transit and surface)

1. Science 1
2. Science 2
3. Payload 1
4. Payload 2
5. Payload 3
6. Payload 4
7. Med 1
8. Med 2
9. Wardroom
10. Ops 1
11. Ops 2
12. Maintenance 1
13. Maintenance 2
14. Maintenance 3
15. Crew Quarters 1 Private Comm Cam
16. Crew Quarters 2 Private Comm Cam
17. Crew Quarters 3 Private Comm Cam
18. Crew Quarters 4 Private Comm Cam
19. External 1
20. External 2
21. External 3
22. External 4
23. External 5
24. External 6
25. Robot Arm 1
26. Robot Arm 2
27. Robot Arm 3

Small Pressurized Rover

1. Fwd Driving
2. Stbd Driving
3. Port Driving
4. Aft Driving
5. SciCam 1
6. SciCam 2
7. BubbleCam
8. Suitport Cam
9. Internal 1
10. Internal 2
11. Internal 3
12. Internal 4

Lander

1. DE 1
2. DE 2
3. DE 3
4. DE 4
5. AE MPS Cam
6. AE 1
7. AE 2
8. AE 3
9. AE 4
10. Porch 1
11. Porch 2

Airlock

1. Internal 1
2. Internal 2
3. External 1
4. External 2

Logistics Module

1. Internal 1
2. Internal 2
3. Internal 3

EVA Suits

1. EV1
2. EV2
3. EV3
4. EV4

Multi-Legged Robotic Cargo Offloader and Transporter

1. Leg Cameras (1-24)

ISRU

1. ISRU Element 1 Camera
2. ISRU Element 2 Camera

Surface Power Units

1. Unit 1 Camera
2. Unit 2 Camera
3. Unit 3 Camera
4. Unit 4 Camera

Propulsion Element

1. Solar 1
2. Solar 2
3. Truss 1
4. Truss 2
5. MPS

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