CURRENT AND FUTURE COMMUNICATIONS AROUND MARS

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On my honor as a University student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

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Abstract:

Human exploration of Mars will require advancements in the communication architecture located around Mars. While communication is currently possible with spacecraft around Mars, the bandwidth received is insufficient to what would be needed to support a crewed expedition. A Low Mars Orbit (LMO) and areostationary constellation both have benefits over the other, but an areostationary constellation would be the most logical choice to be launched first, with an LMO constellation being incorporated later when the need for reliable point-to-point ground communication or polar communication arises. Systems Tool Kit (STK) provides visualizations of some of the possible architecture configurations around Mars. While the main focus of this paper is on radio communication, it is explained that for future exploration of Mars, optical communication technology will need to be matured and implemented.

The past few years have seen a revival in interest in human exploration of Mars. Space has also become more open to private enterprises and investments. Companies such as SpaceX, Blue Origin, Rocket Lab, and others are hoping to secure significant profits and market share on humanity's future in space. Public investment in the space industry has also opened new opportunities, one of them being internet connectivity from space. Iridium, a company that specializes in global, space-based voice and low internet capability has been around for a few decades, but new players such as Starlink, OneWeb, and Kuiper are building constellations to provide high-speed internet from satellites placed in Low Earth Orbit (LEO). With the human exploration of Mars, a constellation of satellites will be essential to enable explorers to not only communicate with Earth but also to communicate across the surface of Mars. The question is, how would a satellite system around Mars compare to an Earth-based system, and how are we currently getting data back from Mars?

Current Communication with Mars

Scientific discovery would not be possible without the ability to relay information back to Earth after the discoveries are made on the surface or orbit of Mars. The National Aeronautics and Space Administration (NASA) has been working on building the Mars Relay Network to help send data back to Earth from Mars. Currently, there are five spacecraft that make up the network, including Mars Odyssey, Mars Express, Mars Reconnaissance Orbiter (MRO), Mars Atmosphere and Volatile EvolutioN (MAVEN), and Trace Gas Orbiter (TGO). Mars Express and Trace Gas Orbiter are both European Space Agency (ESA) missions, but they carry communication packages that allow them to communicate with NASA missions on the surface (Ho, n.d.-b). Mars Express and Mars Odyssey both use X-band to communicate with Earth. Mars Express is limited to 128 kbps and Mars Odyssey can get up to 230 kbps, which is an extremely low data rate compared to today's standards. On top of this, both spacecraft have their own science to perform, meaning the available bandwidth can't be used exclusively for missions on the Martian surface. To successfully receive standard definition video back to Earth, it requires about a 6 Mbps transmission rate, which is well above what the spacecraft can provide. NASA realized they needed to upgrade the architecture with new surface missions that could achieve higher throughput for their science missions to be taken full advantage of. The next step was the Mars Reconnaissance Orbiter, or MRO, which introduced speeds of up to 5 Mbps using Ka-band (Miranda, 2006). While 5 Mbps is the highest transmission rate back to Earth by the MRO, the Curiosity rover, for example, is only able to transmit to the MRO at 2 Mbps or only 256 kbps if transmitting to Odyssey. This might seem like an acceptable data rate, but it is important to keep in mind the Curiosity rover is only in the line of sight to "see" and transmit to the orbiters for about 8 minutes each per Martain day (sol). In that time, up to 250 Mb can be transferred to the orbiter (*Communications with Earth | Mission*, n.d.). That's not a lot of data for an entire day but is a large improvement over the previous orbiters. MRO can transmit at this higher rate through the use of Electra, which is a new telecommunications package used on NASA missions to the planet after 2007 (Ho, n.d.-a). Both MAVEN and TGO also have Electra radios which allow them to communicate with the rovers on the surface of Mars (Koktas & Basar, 2022). Since 2007, NASA has made great strides in expanding the fleet of available spacecraft around Mars with significant communications ability. The question now becomes how to increase the amount of time that the rovers or stations on the ground can communicate with the relay platforms in orbit. Having five operational spacecraft that can communicate for roughly eight minutes per sol each doesn't provide much coverage. That's less than an hour out of a Martian day when communication relay capability is available for relay to Earth or to communicate with vehicles beyond the horizon of a Mars-based location. A human settlement will need constant communication to ensure a wide range of functions, including data transmission, navigation, and safety, and that’s one aspect that hasn’t been addressed to this point.

Why isn’t this Sustainable?

A short-stay mission to Mars would require an average of 152.8 Mbps capacity back to Earth at any given point in time (Tai et al., 2018). The current architecture around Mars isn’t even close to being able to support that rate, with much of the day having a 0 Mbps rate or very low rate using onboard, direct-to-Earth communication for surface missions. Human expeditions may be able to bring larger antennas to the surface to help with communication rates when there is not a relay satellite overhead, but when Earth is on the opposite side of the expedition, meaning no line of sight, they would have no contact. These larger antennas would also not be able to be used when the astronauts go out in the rover or are otherwise out of line of sight with the base. The best course of action would be to deploy new satellites into orbit around Mars that could create a transmission and relay network, allowing for coverage of most of the surface at any time. Analysis to determine where the satellites should be located is an important consideration. Low Mars Orbit would mean a large constellation would be needed, but they could support higher throughput, while satellites in areostationary orbit would mean just a few satellites, but the throughput would be severely limited.

Geostationary Satellites

Case Study: Tracking and Data Relay Satellite System (TDRSS)

This is not the first time NASA has had to develop a way to transport data in orbit around a planet. They've already done it with Earth and many lessons and technologies can be leveraged from the existing system. In the 1960s, NASA realized that they needed a way to stay in contact with spacecraft orbiting the Earth without having to blanket the Earth with ground stations. TDRSS was subsequently born. The Tracking and Data Relay Satellite System (TDRSS) is a constellation of satellites in geostationary orbit that provide the critical service of relaying data when a spacecraft can't connect with a ground station. A geostationary orbit means the satellites remain in the same geographic position with respect to the planet. In Mars orbit, this orbit is called areostationary, not Geostationary, but has the same reference meaning. Geostationary is good for having stationary antennas or receivers for targets on the ground but is further away from the planet than something like Low Earth Orbit meaning that the power and antenna size requirements are higher. Despite this fact, the true ability of the TDRSS is displayed by the fact that before TDRS satellites were launched, spacecraft like the space shuttle were only connected about 15% of the time, but that increased to 85% after just two spacecraft were placed into operation (Zaleski, 2016). The first generation was limited to speeds of about 300 Mbps, but the second and third generations have been able to increase speeds to 800 Mbps (*TDRS-K Tracking and Data Relay Satellite Media Kit*, n.d.)(Nguyen et al., 2002). While the exact architecture of the TDRSS wouldn't directly translate to a constellation around Mars, a constellation like TDRSS could be modified to serve a similar function. One of the main differences would be that instead of transmitting the data back down to Mars, in the same method that TDRSS uses for the Earth, most of the data would be transmitted to Earth from Mars for monitoring and control. Due to the large distance the data would have to travel, this would also mean that a higher power and/or a combination of larger antennas would be required.

LEO Satellites and Constellations

A geostationary/areostationary example has been discussed, but what about Low Earth Orbit or in our case Low Mars Orbit? In recent years, Earth has seen an explosion in the number of satellites in Low Earth Orbit (LEO). Launch costs and satellite production costs continue to decrease which has led to some exciting projects closer to home. Low Earth Orbit satellites have a much lower altitude than Geostationary ones which means the antenna size and power requirements can be reduced, but it also means that many more satellites must be present to cover the same geographic area. This is why very few constellations of this nature existed until very recently. One of the constellations in Low Earth Orbit that has been around for a few decades is Iridium.

Case Study: Iridium

Iridium is a satellite communications network that specializes in voice calls and low-data-rate transmissions through the use of a constellation of 66 satellites with global coverage. One issue the Iridium constellation can avoid by being in LEO is that it can cover the polar regions which is virtually impossible for geostationary satellites to provide coverage. Iridium's first constellation was able to provide data rates of up to 128 kbps with 2 million users while their newest constellation, called Iridium NEXT, can support L-band speeds up to 1.5 Mbps or Ka-band up to 8 Mbps with 3 million users (*Iridium NEXT Satellite Constellation*, n.d.). Now 8 Mbps is nowhere near the speed needed for a human mission to Mars, but it's important to understand that Iridium is designed to support millions of users. A constellation around Mars might be designed to support 100 connections or a few thousand if designed with future exploration and settlement in mind. This would allow engineers to design the satellites to have more throughput per user. One major difference would be, like the geostationary example, the data would be transmitted from Mars to Earth or vice versa and not Earth to Earth, the latter having much lower power requirements and requiring much smaller receiving dishes.

The Moon

There is some good news as creating relay networks has been considered and implemented in other places, albeit a little bit closer to home. The Moon is the only other body that humans have stepped foot on so it seems fitting the closest body to Earth would also be the one to have the most active history when it comes to transporting data. While it is not a perfect substitute for the distance experienced from Mars, looking into some of the past, current, and future ideas could help shed some light on what technologies could be applied to Mars.

Case Study: Apollo

During the Apollo missions, there was some interest in landing a mission on the far side of the moon. An added complexity would be the astronauts would be out of line-of-sight of the Earth meaning no communication resulting in much more work having to be done besides just picking a new landing site. Without a communications relay capability, mission control would have little to no contact except for what could be relayed from the command module when they regained contact with mission control after passing behind the moon. In 1968, P. E. Schmid of the Goddard Space Flight Center looked into two possibilities for what could be done to reduce the communication blackout that would be experienced from missions on the far side of the moon (Schmid, 1968). The orbits considered consisted of an orbit at the Libration Point, or in orbit around the Lagrange Point, at 65,000 km, and an orbit at 1,000 km around the moon. Schmid concluded that it would be possible to achieve voice and 1.6 kbps from the Libration Point satellite and the satellite placed in the 1,000 km orbit, but it would not be possible for 51.2 kbps of telemetry and a live video link. It was concluded based on these findings that the satellite placed at the Libration Point would be more beneficial as it could be used at all times with little to no antenna tracking and wouldn't require any modifications to the spacecraft. The issue with the satellite placed in the 1,000 km orbit was that it would require a tracking antenna which is heavier and more likely to fail (Schmid, 1968). Now 1.6 kbps is not even close to the 152.8 Mbps that would be required for a stay on Mars, but it's important to remember that this was our first stride into major communications and relay around another body in the solar system. While the satellite in the 1,000 km orbit wasn't feasible then, especially if only one were to be launched, constellations make a lot more sense now. Antenna technology has also advanced significantly since the days of Apollo with phased arrays becoming extremely popular. Phased array antennas are made up of many smaller antennas which allows for the antenna to be steered electronically, rather than having to move the dish or antenna itself (Giurgiutiu, 2014). Further analysis antennas will be covered later in the LMO and areostationary section.

Case Study: Chang'e-4

China has been making large strides in advancing its space exploration. One major area they have begun to focus on is the Moon. Like with the Apollo missions, China has been interested in exploring the far side of the moon. A recent mission, Chang'e-4 was launched to the far side of the moon and incorporated a relay satellite into the design. The question becomes whether the method that the Chinese mission used was any different from the methods proposed by Schmid and how advancements in technology have impacted the design. The relay satellite launched for this mission, Queqiao, was placed at the Earth-Moon libration point 2 (Zhang, 2021). Interestingly the Chinese mission used the same architecture that P. E. Schmid proposed over five decades earlier. This makes sense in that the constellation method is becoming much more prevalent, but there is still a large cost involved in deploying something on that scale. Queqiao uses X-band for communicating with the lander and can support up to 555 kbps and up to 10 Mbps back to Earth stations (Zhang, 2021). The high transmit rate back to Earth makes sense as Queqiao can store data from the lander and transmit it back to Earth in blocks to reduce the time ground stations on Earth have to be pointing at Queqiao. A large choke point in the communications framework has become the bandwidth and time availability of the ground stations on Earth. While this issue won’t be covered in this paper, it is an important aspect that should be further analyzed in conjunction with developments of relays around Mars.

LMO (Low Mars Orbit) and Areostationary

The question then becomes whether to go with a Low Mars Orbit constellation or to pick an areostationary constellation. The sections above give some context into the advantages and the disadvantages of both but don’t address the case around Mars specifically. The areostationary constellation can be created by using three satellites offset by 120 degrees. Figure 1 shows how this constellation would look around Mars. It can be seen that with this constellation there would be fairly large gaps near the poles, which could present a significant challenge. One way to get around this would be to have a few satellites in a polar or similar orbit which would allow the

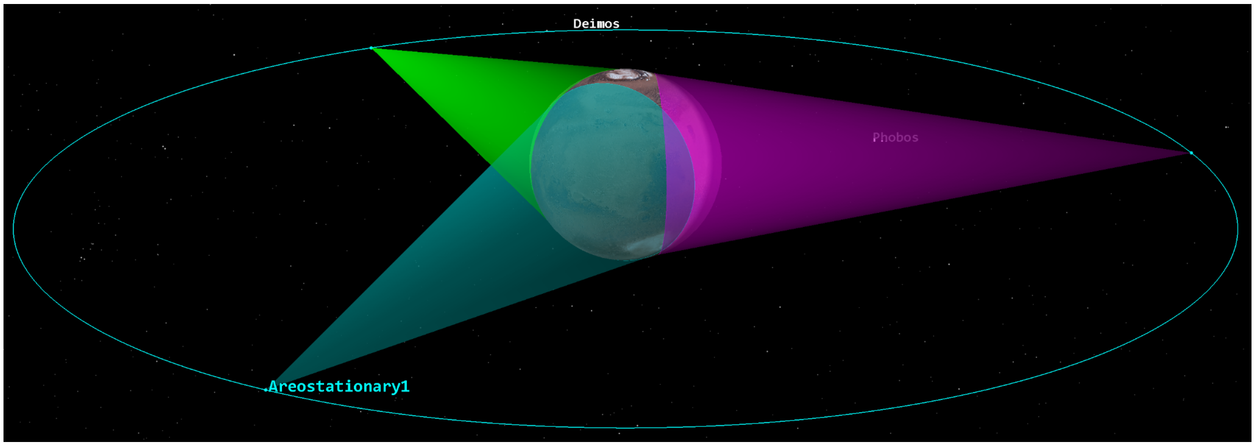
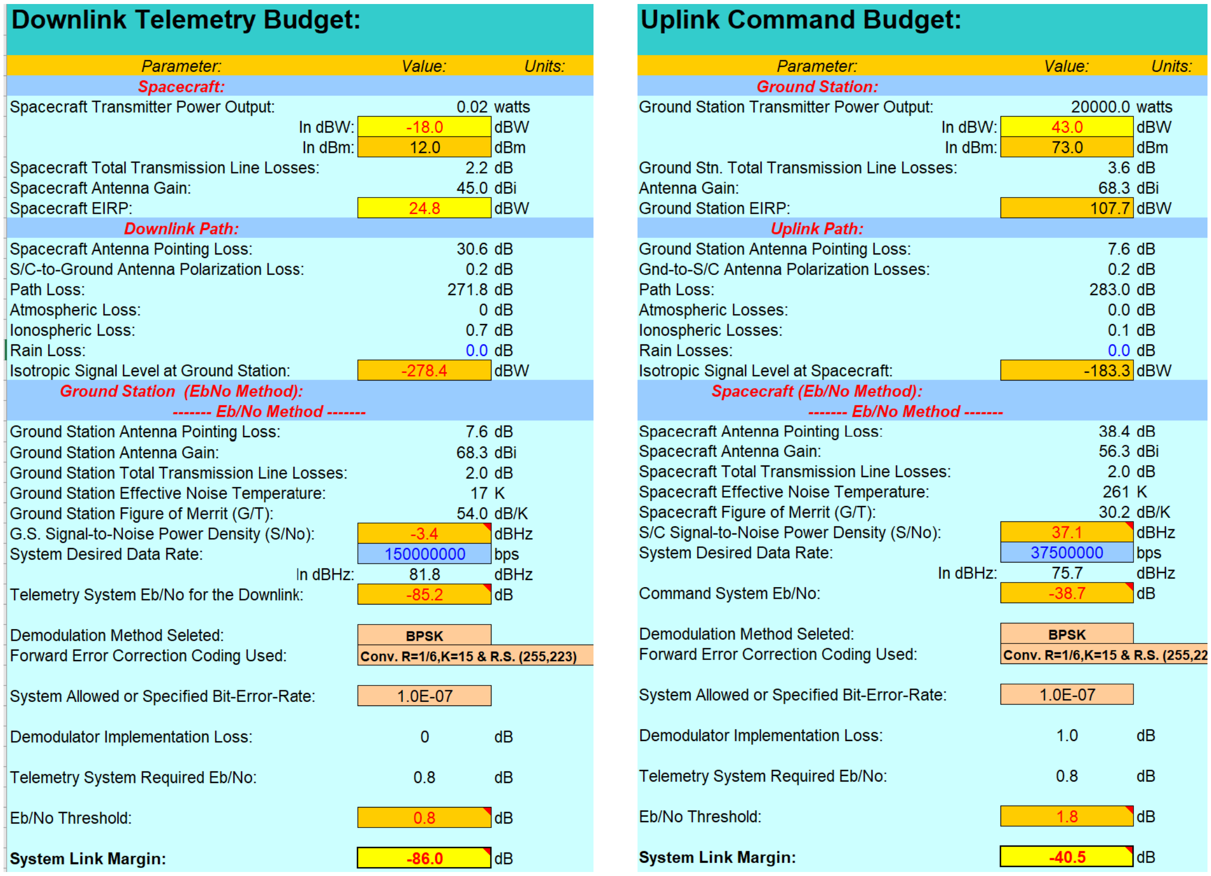


Figure 1: Systems Tool Kit depiction of Areostationary Constellation (Systems Tool Kit, 2021)

polar regions to be covered. A polar orbit has an inclination of 90 degrees and is useful for missions in which the polar region needs coverage (*Planetary Orbits - NASA Science*, n.d.). The other issue with an areostationary constellation is that the satellites would be farther away from Mars, but it would mean the antennas wouldn't have to track the satellite as discussed previously. In the analysis, some assumptions and Earth comparisons will be taken that make the analysis easier as it is difficult to get a perfect representation of how the constellation would perform. This is mainly because there has never been a constellation like this around Mars. The past few years on Earth have seen major advancements in satellite communication technology. One of the flagship satellite lines, Viasat-3, which is placed in geostationary orbit, can support 1 TBps onboard the satellite with solar panels that can produce 25 kW (Freeman, 2023). The initial requirements on Mars would be a low number of connections and the areostationary orbit is closer to the surface due to the smaller size of Mars, meaning higher performance, but the solar energy received, thus power generation potential, on the spacecraft around Mars wouldn't be nearly what it could get when compared to the same spacecraft around Earth. Around Mars, the solar radiance is about 43% of what is received on Earth (Gilbert, 2022), this means that Viasat-3 would only produce around 10.75 kW of power if located around Mars. Viasat-2, which was the precursor to Viasat-3, uses 8 kW of power to support a capacity of 260 Gbps and roughly 100 Mbps to each of the users (*How Fast Is the New ViaSat-2 Satellite, and Other Numbers*, 2017) (*ViaSat-2*, n.d.). Using the Viasat-2 architecture another antenna could then be added to the bus that would direct the signal back to Earth which would have a power budget of about 2.75 kW. For the link budget, we will assume that a 10-meter antenna can be added to a modified Viasat-2 bus. The top-of-the-line transceiver for sending signals back to NASA's Deep Space Network from the Mars environment is the Electra radio that was previously discussed. Electra has a maximum transmit rate of 12 Mbps which is far short of the 152.8 Mbps required for a mission to Mars (*Mars UHF Transceiver*, 2023). The Electra radio was NASA's first step into a new realm of software-defined radios, which means that many of the hardware components are sized down thanks to advancements in programming and can have their characteristics change just from a new software update. NASA quickly realized that while Electra was a step in the right direction, it wouldn't be sufficient for some of the future flagship missions to Mars. The Jet Propulsion Laboratory has been working on a new software-defined radio, called The Universal Space Transponder (UST), that can support "up to 37.5 Mbps RX and 300 Mbps TX" (Pugh et al., 2017). This is a large step up from the Electra radio and could prove to be a viable option for supporting a human mission to Mars. Incorporating the UST into the areostationary satellite provides for a communications network that could be a viable option for meeting the communication requirements. Using data available online for the UST and NASA's Deep Space Network, a link budget was performed, the results show that a connection is not possible with a 150 Mbps downlink and a 37.5 Mbps uplink with this architecture. For the connection to be possible the system link margin would need to be positive and it can be seen from Figure 2 that it



Downlink Telemetry Budget:

Parameter:	Value:	Units:
Spacecraft:		
Spacecraft Transmitter Power Output:	0.02	watts
In dBW:	-18.0	dBW
In dBm:	12.0	dBm
Spacecraft Total Transmission Line Losses:	2.2	dB
Spacecraft Antenna Gain:	45.0	dBi
Spacecraft EIRP:	24.8	dBW
Downlink Path:		
Spacecraft Antenna Pointing Loss:	30.6	dB
S/C-to-Ground Antenna Polarization Loss:	0.2	dB
Path Loss:	271.8	dB
Atmospheric Loss:	0	dB
Ionospheric Loss:	0.7	dB
Rain Loss:	0.0	dB
Isotropic Signal Level at Ground Station:	-278.4	dBW
Ground Station (EbNo Method):		
------- Eb/No Method -------		
Ground Station Antenna Pointing Loss:	7.6	dB
Ground Station Antenna Gain:	68.3	dBi
Ground Station Total Transmission Line Losses:	2.0	dB
Ground Station Effective Noise Temperature:	17	K
Ground Station Figure of Merrit (G/T):	54.0	dB/K
G.S. Signal-to-Noise Power Density (S/No):	-3.4	dBHz
System Desired Data Rate:	150000000	bps
In dBHz:	81.8	dBHz
Telemetry System Eb/No for the Downlink:	-85.2	dB
Demodulation Method Seleted:	BPSK	
Forward Error Correction Coding Used:	Conv. R=1/6,K=15 & R.S. (255,223)	
System Allowed or Specified Bit-Error-Rate:	1.0E-07	
Demodulator Implementation Loss:	0	dB
Telemetry System Required Eb/No:	0.8	dB
Eb/No Threshold:	0.8	dB
System Link Margin:	**-86.0**	dB

Uplink Command Budget:

Parameter:	Value:	Units:
Ground Station:		
Ground Station Transmitter Power Output:	20000.0	watts
In dBW:	43.0	dBW
In dBm:	73.0	dBm
Ground Stn. Total Transmission Line Losses:	3.6	dB
Antenna Gain:	68.3	dBi
Ground Station EIRP:	107.7	dBW
Uplink Path:		
Ground Station Antenna Pointing Loss:	7.6	dB
Gnd-to-S/C Antenna Polarization Losses:	0.2	dB
Path Loss:	283.0	dB
Atmospheric Losses:	0.0	dB
Ionospheric Losses:	0.1	dB
Rain Losses:	0.0	dB
Isotropic Signal Level at Spacecraft:	-183.3	dBW
Spacecraft (Eb/No Method):		
------- Eb/No Method -------		
Spacecraft Antenna Pointing Loss:	38.4	dB
Spacecraft Antenna Gain:	56.3	dBi
Spacecraft Total Transmission Line Losses:	2.0	dB
Spacecraft Effective Noise Temperature:	261	K
Spacecraft Figure of Merrit (G/T):	30.2	dB/K
S/C Signal-to-Noise Power Density (S/No):	37.1	dBHz
System Desired Data Rate:	37500000	bps
In dBHz:	75.7	dBHz
Command System Eb/No:	-38.7	dB
Demodulation Method Seleted:	BPSK	
Forward Error Correction Coding Used:	Conv. R=1/6,K=15 & R.S. (255,22	
System Allowed or Specified Bit-Error-Rate:	1.0E-07	
Demodulator Implementation Loss:	1.0	dB
Telemetry System Required Eb/No:	0.8	dB
Eb/No Threshold:	1.8	dB
System Link Margin:	**-40.5**	dB

Figure 2: Downlink and Uplink Budget (King, n.d.)

is not. The link budget was completed using *AMSAT_IARU_Link_Model_Rev2.5.3* Excel spreadsheet created by Jan King. One factor that the spreadsheet does not take into account is that the UST can transmit in both S and X bands at the same time. Within the link budget performed, only the single X-band case was analyzed. While the paper explains that this communication rate is possible with the UST, more analysis should be completed into what kind of antenna would be required on the Mars side where the UST is located (Pugh et al., 2017). Another case that could be analyzed is having multiple USTs transmitting back to Earth at the same time. This would reduce the amount of data required for each UST to transmit and it would be feasible to have one on each of the areostationary satellites. The following sources were used for the data used within the link budget along with the areostationary architecture discussed above (Taylor, 2016) (Lazio, 2021).

What about a Low Mars Orbit (LMO) constellation? Is there any reason to consider it? An LMO would mean that the satellites would be closer to the surface than the areostationary satellites resulting in lower response times, but it would also mean that more satellites would be needed. One issue that arises with having just a Low Mars Orbit (LMO) constellation is how would the data be transmitted back to Earth? It isn’t feasible for every satellite to have a UST and antenna pointed back at Earth and that would create major complexities back on Earth for receiving those signals. A solution to this would be to have a constellation that is a mix of both systems. The Low Mars Orbit (LMO) constellation would allow for lower latency and the areostationary constellation would allow a streamlined path for transmission back to Earth.

An important distinction within the Mars Communication network will be whether the data is being transmitted back to Earth or whether the data is being transmitted to another site on Mars. In the beginning phases of the network, most of the data would likely be relayed to or from Earth as there wouldn’t be many other landing sites for data to be relayed to. As exploration and the number of missions to Mars increase, the percentage of data being transported between two sites on Mars will likely increase. It’s important to keep this in mind with the design of the system to ensure the two modes of transmission can be supported. The LMO constellation would also be extremely important once humanity needs out-of-line-of-sight communication. The areostationary satellites would be optimized for communication between Earth and Mars and would have limited capability in supporting Mars’ local traffic. Having a mix of both systems would allow for the LMO satellites to receive all the data from the surface and either transfer it to the areostationary satellites for relay back to Earth or to other LMO satellites for relay somewhere else on the surface. Data from the surface could also be transmitted straight to the areostationary relays if it is Earth-bound traffic. The LMO satellites would also ensure that the polar regions of Mars would have coverage as well.

While we looked at Iridium for the LEO example above, a better comparison to the system that would be needed around Mars is OneWeb, which is a network of 648 satellites that is optimized more for data than voice. The service area of each satellite is 1080 km x 1080 km from an orbit of 1200 km (Azzarelli, 2016). OneWeb can support download speeds of up to 195 Mbps and upload speeds of up to 32 Mbps per user and each satellite can support around 1.1 Tbps (Griffin, 2022) ("Eutelsat OneWeb," n.d). While that upload speed is not as high as the data rate that would be needed for a human settlement, the architecture of the constellation could be modified so that higher speeds could be reached. Also, multiple connections could be used between the same LMO satellite or a connection between the LMO satellite and a satellite in areostationary orbit. Running an analysis based on the OneWeb architecture shows that it would take roughly 162 satellites placed in orbit around Mars to give near-global coverage. This would consist of 9 planes with 18 satellites in each plane. It can be seen in Figure 3 below that there are some small gaps between the regions the antenna on each of the satellites would be able to see, this could be corrected by adding another plane or increasing the beam coverage slightly. The satellites within the LMO constellation would have to be a fair amount larger than those around Earth due to the decreased solar radiance discussed above and the need to have an antenna pointed up towards the areostationary satellites as well.

Earlier in the paper we discussed that about 150 Mbps would be needed for a mission to Mars and may be possible with the radio communication architecture if multiple USTs are being used. It is also likely that the spacecraft orbiting Mars during the mission would also have data relay

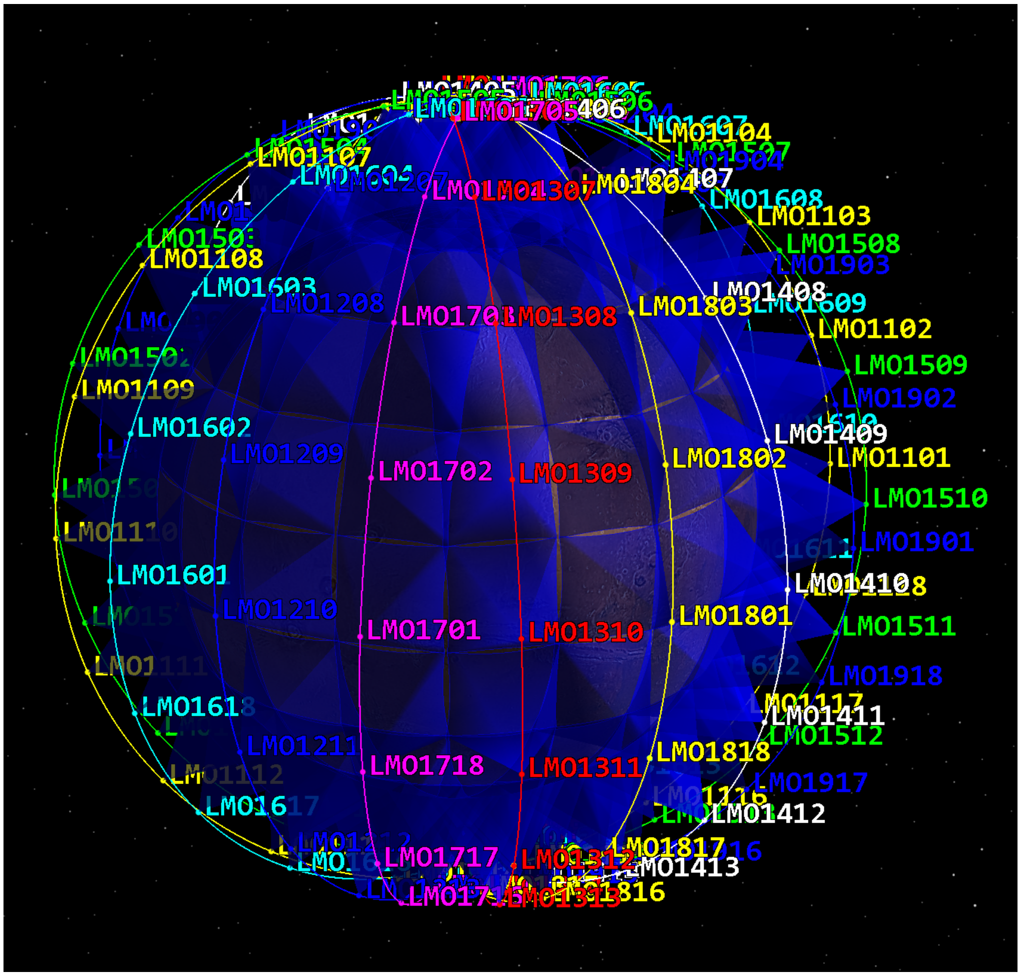


Figure 3: Systems Tool Kit depiction of Low Mars Orbit Constellation (Systems Tool Kit, 2021)

capability which could lessen the burden on the areostationary satellites. As humanity expands its presence on Mars, it would make sense to deploy a more efficient LMO constellation to support Mars's local traffic. This architecture is shown in Figure 4 below. An important technology that would need to be incorporated into these LMO satellites would be crosslinks.

Crosslinks would allow the constellation to communicate and transmit data between other satellites within the constellation. Two main uses of this would be for relaying data that is acquired by a satellite over the polar regions to another LMO satellite that could then relay that information to one of the areostationary satellites for relay back to Earth. Another use of the crosslinks would be for transmitting data between two ground sites on Mars. Instead of having to send the information up to an LMO satellite, relay it to an areostationary satellite, send it back to an LMO satellite over the recipient, and then transmit it to the surface, the data could simply be transferred through crosslinks from one LMO satellite to the other and transmitted to the surface.

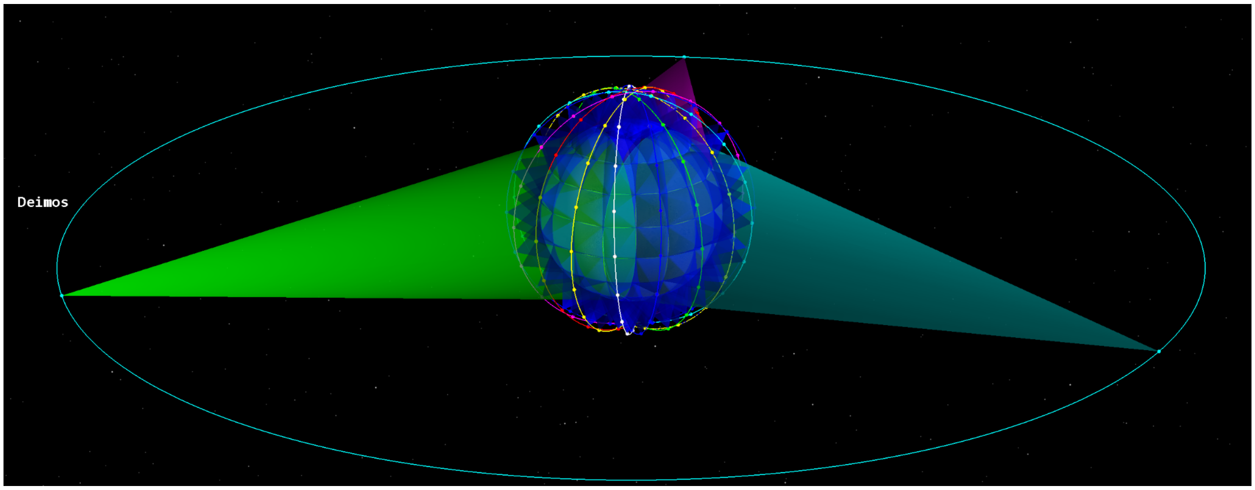


Figure 4: Systems Tool Kit depiction of Areostationary and Low Mars Orbit Constellation (Systems Tool Kit, 2021)

Storms

Communication is not the only reason to deploy satellites in orbit around Mars before large settlement development. Small cameras on board the satellites could be used for weather and dust storm monitoring to help astronauts and for scientific modeling. The Mars Reconnaissance Orbiter (MRO), for example, has the Mars Color Imager (MARCI) onboard which is used for gaining a better understanding of the weather on Mars (Malin et al., 2008). Having a constellation of satellites with MARCI-like instruments would provide a much clearer understanding of the weather around Mars through current conditions. They would also be extremely useful once a human settlement is established as a better understanding of the approaching weather conditions would provide safety to ensure work isn't being completed outside in poor conditions or to ensure necessary precautions are taken to prepare the settlement.

Location Determination

Another technology of satellites here on Earth that can be applied to Mars is location determination. The Global Positioning System is a constellation of satellites used for determining a user's location here on Earth. The technology works through the method of triangulation. Each of the satellites knows its exact location and the exact time. The satellites can then use the time that it takes between a signal being sent and a signal being received to find the distance to the user. If you have enough satellites (three is the minimum) the location of the user can be found (Dixon, 1991). While location accuracy is important, the accuracy of the satellites wouldn't have to be as good as those around the Earth, as long as the user can get a good understanding of where they are. During the development of the Low Mars Orbit constellation, it would be adapted to incorporate this technology into it. This would be useful during crewed and uncrewed exploration missions away from the base on Mars to assist in navigation and also for compiling location information for data collected.

The Future - Optical Communication

While radio communication has been at the forefront of space communication since the first satellite was launched, its days for deep space missions might be numbered. Optical communication, or laser-based communication, has become increasingly popular as more money is poured into developing it. Some advantages that optical communication has over radio communication are that it has “high bandwidth”, “less power and mass requirements”, “high directivity”, and “high security” (Kaushal & Kaddoum, 2017). High bandwidth is important as humans going to Mars will require much more data to be transmitted as discussed above and high directivity is also of high importance for future missions as there are only a limited number of frequencies that can be used. Having higher directivity means less interference will occur, helping to preserve the already scarce frequency resources. The communication network described above might be a reasonable design if launched within the next few years, but the optical communication technology continues to accelerate. Using optical communications will give a 10 to 100 times increase in the data rate over the current radio architectures being used on deep space missions. The Psyche mission, which launched in October 2023, carries an important secondary mission, the Deep Space Optical Communications experiment. “NASA’s Deep Space Optical Communications (DSOC) experiment is the agency’s first demonstration of optical communications beyond the Moon” (*DSOC (Deep Space Optical Communications) Technology Demonstration*, 2023). Optical communication technology will be an important step toward enabling expanded communication throughout the solar system as limitations in radio communication are reached.

Conclusion

Each mission sent to Mars is increasingly data relay-reliant. Human exploration of Mars is also looking more and more likely, with initial logistic support missions possible within the next decade. For future missions, including human exploration to be achievable, advancements must be made to the current communications architecture. NASA has started experimenting with optical communication technology as it has realized that radio communication is not a long-term solution for exploring and sending humans out into the solar system. The initial results are exciting, but the technology has not developed sufficiently to support deployment as the main communication architecture around Mars. As shown above, radio communications provide our current connection with Mars, but will not be sufficient for the ever-increasing bandwidth requirements as more missions and eventually human exploration is planned. While optical communication will be needed for the settlement and exploration of Mars, the areostationary and Low Mars Orbit architecture discussed with radio communication as the baseline would be extremely similar. An areostationary constellation incorporating optical communication is a logical first step, but the future of communications on Mars will likely require a mix of an areostationary constellation and a Low Mars Orbit constellation. Rockets under development including Starship will need to play a key role in the development and deployment of constellations such as this, as the payload that needs to be sent to Mars will be significantly higher than anything sent before even with optical communication payloads which allow for a reduced mass requirement. The coming years will need to see further funding put forth into the Mars communication architecture if humans are ever to reach and establish a presence on Mars.

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