Communication Delays, Disruptions, and Blackouts for Crewed Mars Missions

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As NASA continues to develop the Moon to Mars campaign, there are a number of challenges that must be addressed to execute a successful crewed mission to Mars. One of those challenges is delays, disruptions, and blackouts that crew will experience during their mission to Mars, and that is the challenge evaluated in this paper. This analysis showed that communication delays will vary from 0 to 22 minutes over the course of a mission, peaking while the crew is at or just departed from Mars. The disruptions occur in a similar time frame and can last for several days up to several months, depending on the solar disturbance sensitivity of the communication band being used. The delays and disruptions will have an impact on crewed Mars missions, and determining mitigations is future work to be informed by this analysis.

I. Background

NASA's Mars Architecture Team continues the Agency's efforts to study and refine the nation's plan to field a sustainable human Mars campaign as part of NASA's Moon to Mars directive. Building upon the success of the Design Reference Architecture [1], Evolvable Mars Campaign [2], and the Mars Study Capability Team [3, 4], the group is further developing capabilities to improve the fidelity of the Mars campaign and to continue exploring the design trade space to assess the impact of technology investments and architecture decisions for missions to Mars as early as the 2030s. While the team continues to investigate different mission and architecture options, several challenging areas have been identified as high priority assessment needs to help inform the mission and architecture planning process. One such area involves the communication between mission control on Earth and the crew during transit and while on the surface of Mars or in orbit around Mars.

Due to the long distance between Earth and Mars, any communication signals will take time to travel between the source and the destination. These communication delays will have significant impacts on how the crew operates and interacts with mission control throughout their mission. Additionally, the Sun is large enough to block or disrupt communication signals for a significant amount of time if it comes between the crew and Earth. To better inform mission planning and risk identification activities for human Mars missions, these communication delays, disruptions, and blackouts must be better understood.

A. Definition of Conjunction

Approximately every 26 months, Earth and Mars are on exact opposite sides of the Sun. This celestial phenomenon is known as conjunction, where all three celestial bodies are in a straight line and is a feature of the relative orbits of the planets. Conjunction presents a challenge to any Mars mission in that it results in a communication disruption. This is because communication signals cannot pass through the Sun directly, and any signals that come too close to the Sun become distorted from interference from solar energy. This can be seen in Fig. 1, where communication between Earth and Mars is disrupted in all three depicted positions, as well as all positions between them, due to the Sun blocking the line of sight between the two planets. For robotic missions, operations during these conjunction events are typically managed to reduce the impact on science objectives and increase spacecraft safety, utilizing planned safe mode of the robotic platforms and standdown of any operational activities [5]. The overall data output from the rovers to the relay satellites is also reduced to ensure enough data storage is available in the periods when no

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data can be sent back to Earth [6]. These stand-down options are not available to a mission that involves crew, however, as crew activities must continue even in the absence of direct communication with mission control.

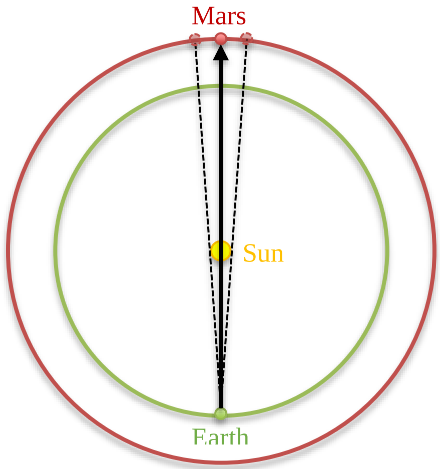

Fig. 1 Example of Earth-Sun-Mars conjunction.

B. Disruption Dependency on Radio Frequency

For this analysis, the angle that would lead to communication disruption was defined as the Sun-Earth-Mars angle, with Earth as the vertex. A graphical representation of that angle, θ, can be seen in Fig. 2. During superior solar conjunction periods, in which the Sun is between the Earth and Mars, direct communications from Earth to Mars deteriorate as the Sun-Earth-Mars and Sun-Mars-Earth angles decrease. Frequencies used for communication are disrupted due to the effects of solar charged particles, so communications degradations or blackouts can occur even when the signal does not pass directly through the disk of the Sun [7]. A primary cause of this is known as solar scintillation, where the apparent amplitude, phase, and angle of arrival of a radio signal is rapidly varied by passing through the Sun's coronal turbulence [8]. As higher radio frequencies are less affected by solar charged particles, Ka-band communications are more resilient for communications access during solar conjunction as compared to X-band, S-band, or optical communications. Additional considerations for the communications signal quality during solar conjunction include the location of the signal relative to the Sun's poles, the solar cycle conditions, which correlate to solar activity, and the encoding method used for the transmissions. However, as a basic guideline, S-band communications should be considered unreliable when θ is less than 4°, X-band when θ is less than 2.3°, and Ka-band when θ is less than 1° [7]. The Mars Reconnaissance Orbiter, for example, placed a communications moratorium for whenever θ is less than 3° and had restrictions on functions below 5° [9]. For this analysis an initial value of 2° was assumed to cause communication disruptions based on initial assessment of communication protocols and their susceptibility to signal disruption to define disruption period during Mars missions.

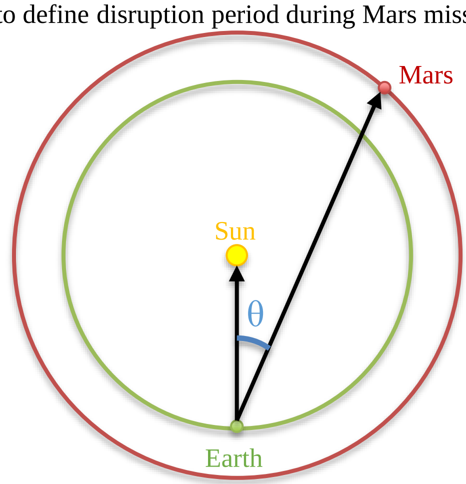

Fig. 2 Angle definition.

II. Approach

The majority of this analysis was done in either Systems Tool Kit (STK)* or Copernicus [10]. STK was used for the Earth-Mars communication impacts and Copernicus was used for the various spacecraft-Earth impacts. To determine the potential periods of disruption, the angle θ must be known for the entire period of interest. When it drops below the pre-determined value, a disruption can occur. Both tools are capable of generating time history data sets of pre-defined angles. STK by default uses the JPL DE430 database for planetary ephemeris and was used to output the sun-Earth-Mars θ. Copernicus decks with representative trajectories for various Mars crew mission options were used for the crewed Mars spacecraft and Copernicus was able to generate the sun-spacecraft-Earth θ history. Once the time histories of the θ were generated, they could be filtered to determine when θ was less than the desired limit and thus the body could be assumed to be in communication disruption.

To determine the one-way communication delays between the body (Mars or the spacecraft) and Earth, each tool output the time history of the straight-line distance from Earth to the body. This distance was then divided by the speed of light to calculate the light-speed delay in communications. The following sections describes the results from this analysis.

III. Disruption Analysis Results

For this paper, the analysis focused on the communication delays and disruptions as they pertain to NASA's 2022 Strategic Analysis Cycle's reference missions [3,4]. These communication challenges are directly related to the interplanetary trajectories that are associated with the mission, so this paper analyzed multiple trajectory options for the reference mission to help understand unique challenges associated with each. The following sections will detail the various periods of disruption and disruption between elements of potential Mars campaigns during different phases of the mission. The goal of the analysis is to determine when disruptions occur due to the planetary alignments, the duration of the communication disruptions, and the potential impact to a Mars crew.

A. Between Earth and Mars

First, analysis of the relative position of Earth, Mars, and the Sun across the entire Earth-Mars synodic cycle provided definition of the Earth-Mars conjunction. The angle between the Sun-Earth and Sun-Mars vectors was utilized as the primary mathematical representation of these conjunction events, which signifies potential communication disruption events. The variance of angle θ over that period is show in Fig. 3. As seen in the plot, the Sun-Earth-Mars angle follows a periodic pattern, varying from 0 to 180° every 26 months, following the periodic motion of the two planets as they revolve around the Sun.

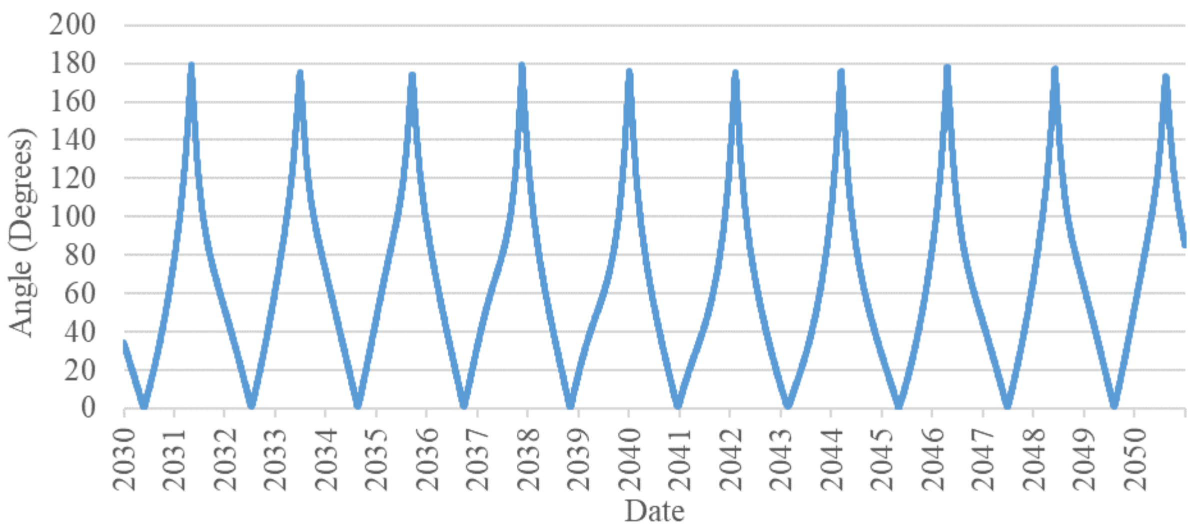

Fig. 3 Variance of Sun-Earth-Mars angle over time.

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* Reference to or appearance of any specific commercial products, processes, or services by trade name, trademark, manufacturer, or otherwise does not constitute or imply its endorsement, recommendation, or favoring by the U.S. Government or NASA

The duration of any potential communication disruption will be dependent on the communication protocol and the sensitivity of the communication signal to interference. This sensitivity was also evaluated. Through evaluating various communication protocols that could be utilized for a human Mars mission, the potential communication disruption for different protocols was analyzed and correlated to the conjunction angle previously defined. Based on the sensitivity of the communications frequency to solar energy, these disruptions could last anywhere on the order of days to months. The specific durations for 1°, 2°, 3°, and 10° are shown in Table 1. As seen in the table, 1° has an average disruption period of 2.9 days, 2° has an average of 11.8 days, 3° has an average of 19.6 days, and 10° has an average of 66.9 days.

Table 1 Days below the specified angle for each year opportunity of the Sun-Earth-Mars angle.

DISRUPTION DURATION	≤ 1°	≤ 2°	≤ 3°	≤ 10°	
2034	0	9	16	60	Days
2036	2	10	16	59	Days
2038	5	11	18	63	Days
2040	5	13	21	48	Days
2043	0	14	24	89	Days
2045	7	16	25	84	Days
2047	4	12	20	70	Days
2049	0	9	17	62	Days
AVERAGE	2.875	11.75	19.625	66.875	Days

The overall average sensitivity to the conjunction angle, from 0.5° to 10° for both Earth and Mars, can be seen in Fig. 4. The relationship is quite linear for both planets, with Mars having a steeper slope. That behavior is expected since Mars is farther from the sun and will spend more time within a given angle measurement than Earth. As a point of reference, the solar disk as seen from Earth is about 0.52°, and as seen from Mars is 0.36°. The angle constraint from Mars for when disruptions occur is different than that of Earth but is not part of the analysis. Determining that angle is future work and for now it is assumed that Mars cannot talk to Earth when Earth cannot communicate to assets at Mars.

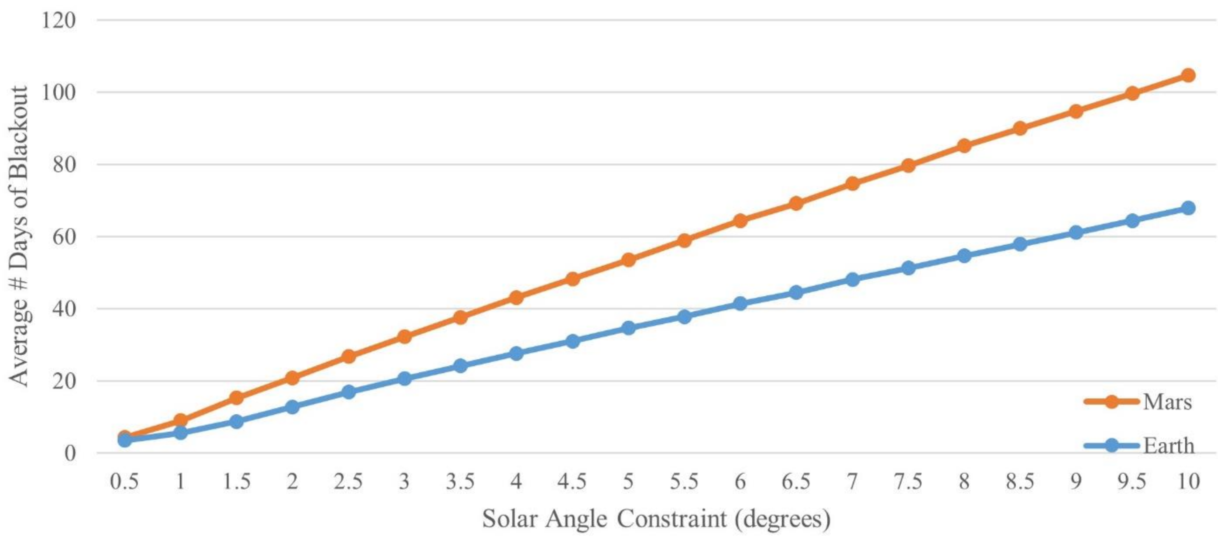

Fig. 4 Solar angle constraint impact on average disruption duration for both Earth and Mars.

B. Between Earth and Mars Transit Vehicle

The results from the previous section showed the potential communication disruption events when the crew is either in Mars orbit or on the surface of Mars. In order to correlate these potential disruptions to specific Mars mission opportunities, trajectory analysis is required to define potential mission options. Additionally, the Mars Transit Vehicle (MTV) may also experience disruptions along its trajectory, separate of when it is in Mars vicinity.

This next section of analysis examined the communication disruptions crew could potentially experience in their transit to and from Mars. In total, four mission options with two different mission types and two different propulsion systems, were analyzed to evaluate the impact of these disruptions. The two mission types were: minimum energy, long-stay missions and high energy, short-stay missions. Minimum energy, long-stay class trajectories rely on specific alignments between Earth and Mars to perform two optimal transfers between the planets. Depending on the specific trajectories, it can take between 180 and 360 days (6 to 12 months) to travel between planets. Some infrequent opportunities' transit times can be as short as 120 days (4 months). Once the spacecraft has arrived at Mars, it must wait for 300 to 600 days for the next minimum energy departure window (dictated by the alignment of Earth and Mars) to return back to Earth. High energy, short-stay style missions require significantly more energy compared to the minimum energy trajectory but provide substantially shorter missions. The one-way transit time is similar to the minimum-energy class mission (6 to 12 months), but instead of a long-stay of up to 600 days at Mars to wait for planetary alignment, the high energy missions spend only 30 to 50 days in Mars vicinity before beginning the return journey back to Earth. The two different propulsions systems are a hybrid propulsion system and a ballistic high thrust system. The hybrid propulsion system is comprised of both a high thrust system (for the large planetary arrival and departure burns) and a low thrust system (for use during interplanetary transit). The ballistic high thrust system does not get the benefits of the high efficiency low thrust propulsion system, but only perform major maneuvers around planetary bodies with minor maneuvers in deep space as needed. These options combined to constrain the four trajectories, shown in Fig. 5, used in this analysis to determine the potential communication disruptions. By utilizing the additional angle defined by the Spacecraft-Earth and Spacecraft-Sun vectors, communication disruption events for the end-to-end missions defined by these options were assessed.

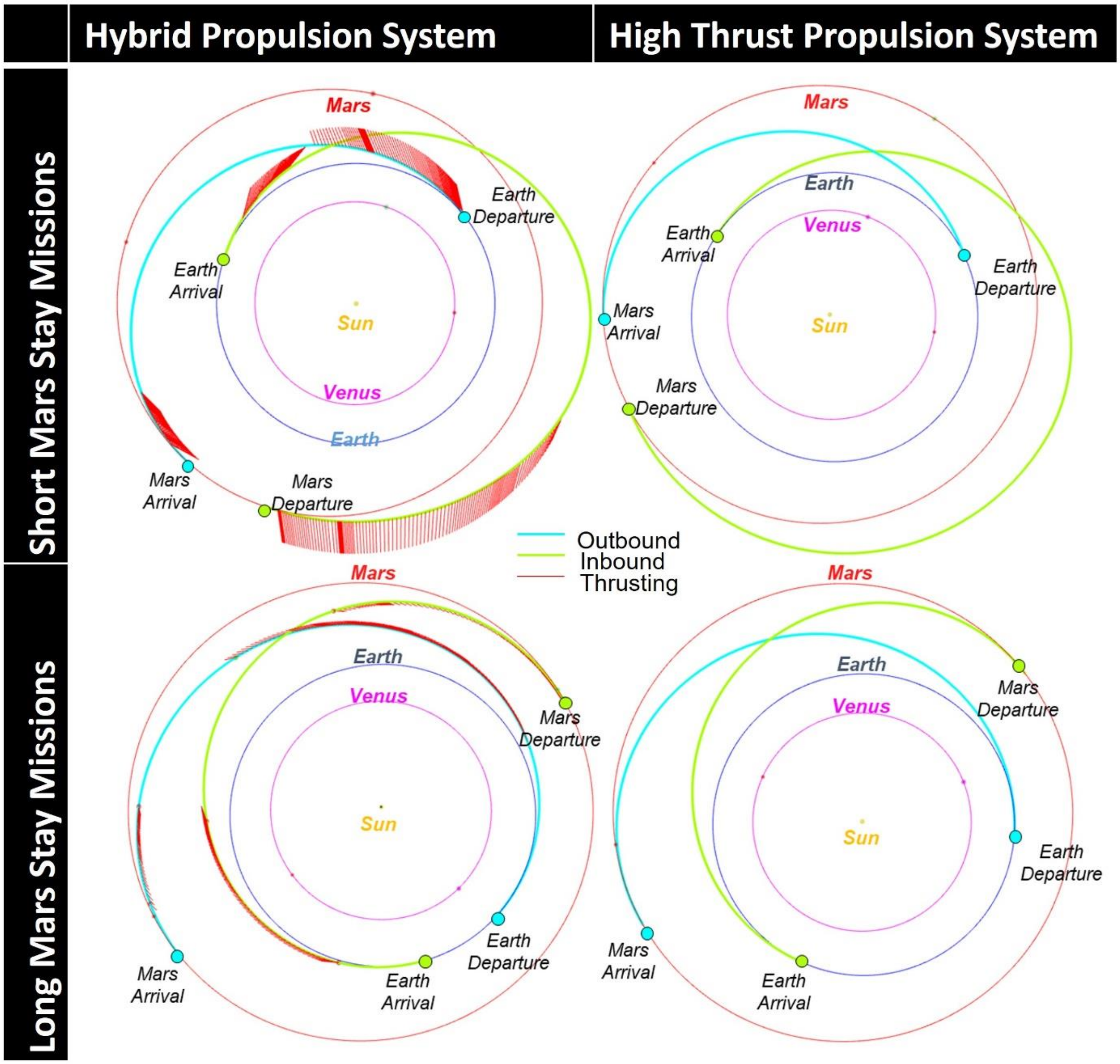

Fig. 5 Four trajectory options, departing Earth in 2039.

The analysis showed that every representative human mission to Mars will experience some communications disruption, either at Mars for the long-stay, minimum energy missions, or shortly after Mars departure for the short-stay, higher energy missions. The time histories of the spacecraft conjunction angle in terms of mission days for representative missions starting in 2039 can be seen in Fig. 6. The potential disruption durations are listed in the blue circles in each plot. The short-Mars-stay hybrid propulsion system mission has three durations marked while the other mission options only have one. The shorter identified durations near the beginning at the end of the mission do not correspond to disruptions but do have angles less than 2°. This is because if Earth is between the MTV and the Sun, the measured angle will also be small, but the vehicle still has an unobstructed view of Earth. Based on the distance of the spacecraft from Earth at that point, that is the case during the early and late mission small-angle values.

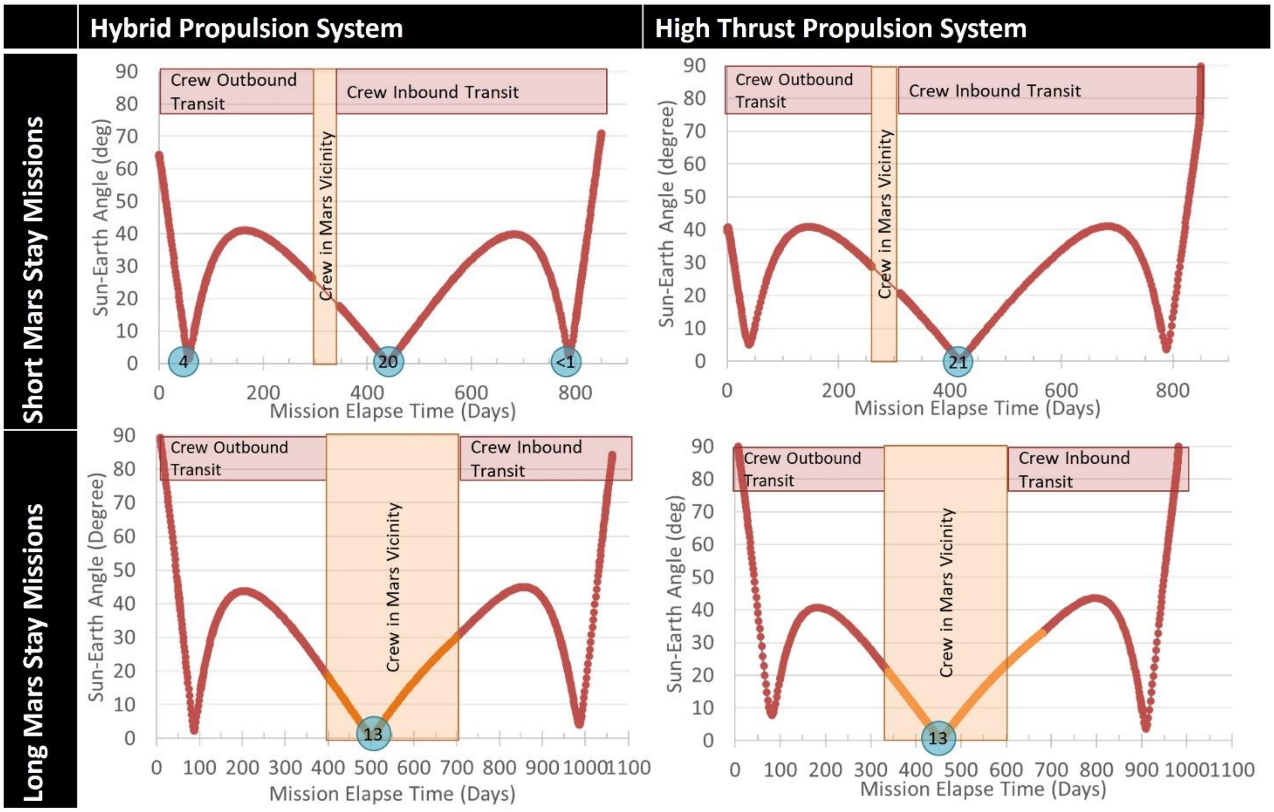

Fig. 6 Time history of the sun-spacecraft-Mars angle for the four reference trajectories including potential durations.

For the short stay missions, the hybrid propulsion system experiences 20 days of disruption and the high thrust system experiences 21 days. Both of these disruptions occur a couple of months after departing from Mars, and there is no disruption while the vehicle is in Mars vicinity. However, comparing these disruptions to when Mars is undergoing disruption reveals that both Mars and the spacecraft will be undergoing disruptions at the same time. This means that satellites around Mars are unavailable to act as a relay for the spacecraft during its time of communication disruption.

For the long stay missions, both propulsion systems experience approximately 13 days of disruptions. This is because both of these disruptions occur while the crew vehicle is at Mars, so the disruption the vehicle experiences matches the disruption duration that the planet experiences. This duration matches the Mars disruption duration for 2039 as seen in Table 1. While the disruptions do occur while the crew is at Mars, it is possible to plan the mission such that these disruptions do not occur during key mission segments such as surface landing or launch of the crew.

C. Between Mars Surface and a Mars 5-sol Orbit

The current assumption for a study reference Mars architecture calls for a minimum 4 crew mission [11]. While the crew is at Mars, two members will descend to the Martian surface for a 30-day surface mission while the other two remain in orbit. The assumed orbit is a 5-sol orbit around Mars with a 35° inclination and periapsis over the northern hemisphere. The assumed parking orbit will also occasionally experience disruptions when trying to communicate directly with the crew on the Martian surface. To analyze what this disruption period could be, a sample landing site was chosen. The current assumption is that the landing site is at 35°N. A longitude of 0° was chosen for simplicity and is not indicative of any site selection on the part of NASA. The landing site can be seen in red in Fig. 7 with respect to the MTV (in blue). Over the 50-sol stay in Mars vicinity, the vehicle can see the landing site on average for 7 hours 50 minutes at a time with gaps at an average of 16 hours 46 minutes in fairly regular intervals. This corresponds approximately to a third of every sol allowing direct communication from the landing site to the orbiting vehicle. There will be other satellites around Mars that may be able to act as relays to help mitigate these disruptions.

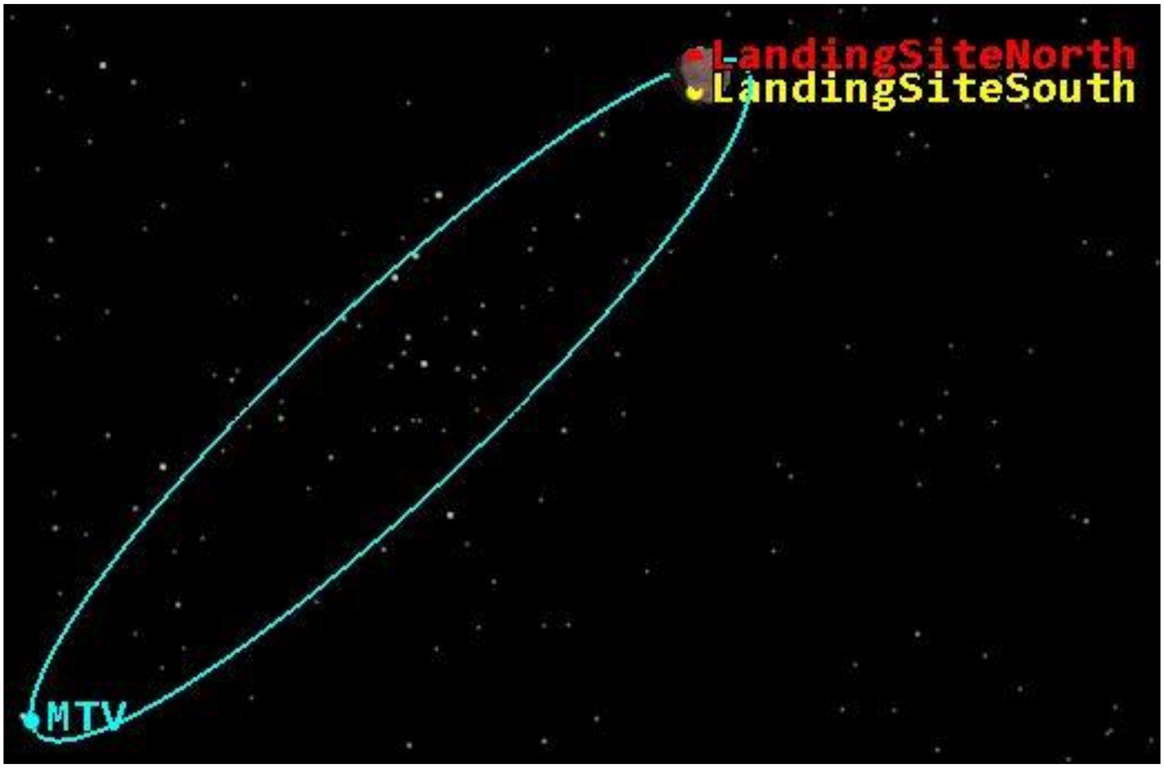

Fig. 7 MTV in its orbit relative to the proposed landing sites.

Since the orbit in question has its periapsis over the northern hemisphere of Mars, it spends the majority of its time over the southern hemisphere, where apoapsis is. To see what the impact on communication availability is if the landing site was instead in the same hemisphere as apoapsis, a secondary landing site was evaluated, this time at 35°S, 0°E as shown in yellow in Fig. 7. At that site, the vehicle can see the landing site on average for 14 hours 56 minutes at a time with gaps at an average of 9 hours 36 minutes. This corresponds approximately to two thirds of every sol allowing direct communication from the landing site to the orbiting vehicle. Similar results would be expected for the northern site if the MTV orbit had its periapsis over the southern hemisphere.

D. Potential Mitigations

While the purpose of this paper is not to present solutions to the communication disruption problem, several mitigations have been proposed and their feasibility evaluated at a high level. Any proposed mitigation will have costs associated to the architecture that must also be considered. The current timeline for cargo and crew missions do not allow for the proper positioning of the cargo stage to act as a relay for the crew during communication disruption. One potential option proposed was to place a relay spacecraft at the Earth-Sun L4 or L5 Lagrange Point [12]. As seen in Fig. 8, L4 presents a path around the Sun during conjunction. To further analyze this option, the Mars-Earth-Sun and Mars-L4-Sun angles were plotted together in Fig. 9. These two angles cross at ~18° so there is never a time where both are below the 2° threshold simultaneously, meaning it is possible to use L4 or L5, which has very similar geometry as L4 on the opposite side of Earth, as a location to place a relay spacecraft. However, as Fig. 8 shows, the distance to travel from Earth to L4 to Mars is significantly longer than straight from Earth to Mars. This results in an approximately five-minute increase in the one-way communication delay between the planets.

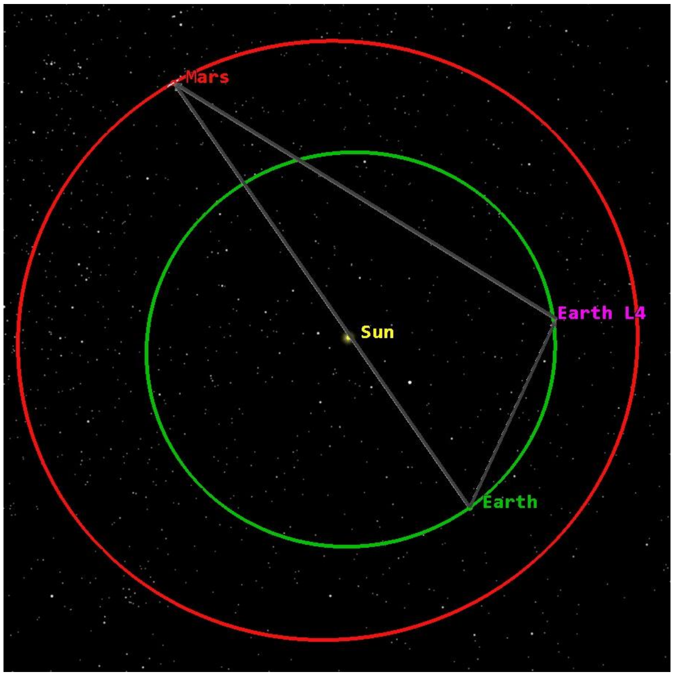

Fig. 8 Location of Earth-Sun L4 with vectors showing a communication path available during Earth-Mars conjunction.

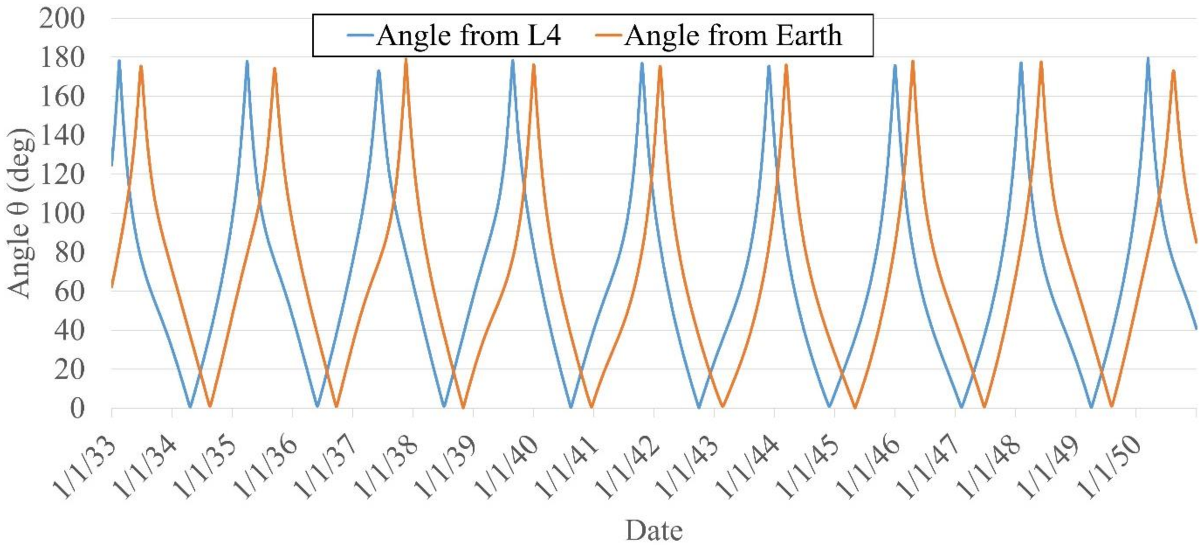

Fig. 9 Solar disruption constraint angle for both Earth-based and L4 based communications.

IV. Communication Delays

In addition to the communication disruption periods each crew will experience; another communication challenge is the light speed delay between the crew vehicle and Earth. Communication delays will have significant impacts on how the crew operates and interacts with mission control throughout their mission. To gain an idea of what these challenges could be, the one-way communication delay for the four different vehicle trajectories shown in Fig. 5 was evaluated. The results can be seen in Fig. 10. As seen in the plots, all four trajectories have a similar maximum one way communications delay of 21-22 minutes that occurs between 400 and 500 days into the mission. The short-stay-at-Mars missions have 17-to-20-minute delays while in the Mars vicinity, with the duration increasing the entire stay. The long-stay-at-Mars missions have 15-to-21-minute delays while in the Mars vicinity, starting around 19 minutes, peaking at 21 minutes a few months later and then declining for the rest of the Mars stay, to 15 minutes. Note that all times are one-way, so the time it would take a crew member to ask a question and receive an answer would be at minimum twice the duration.

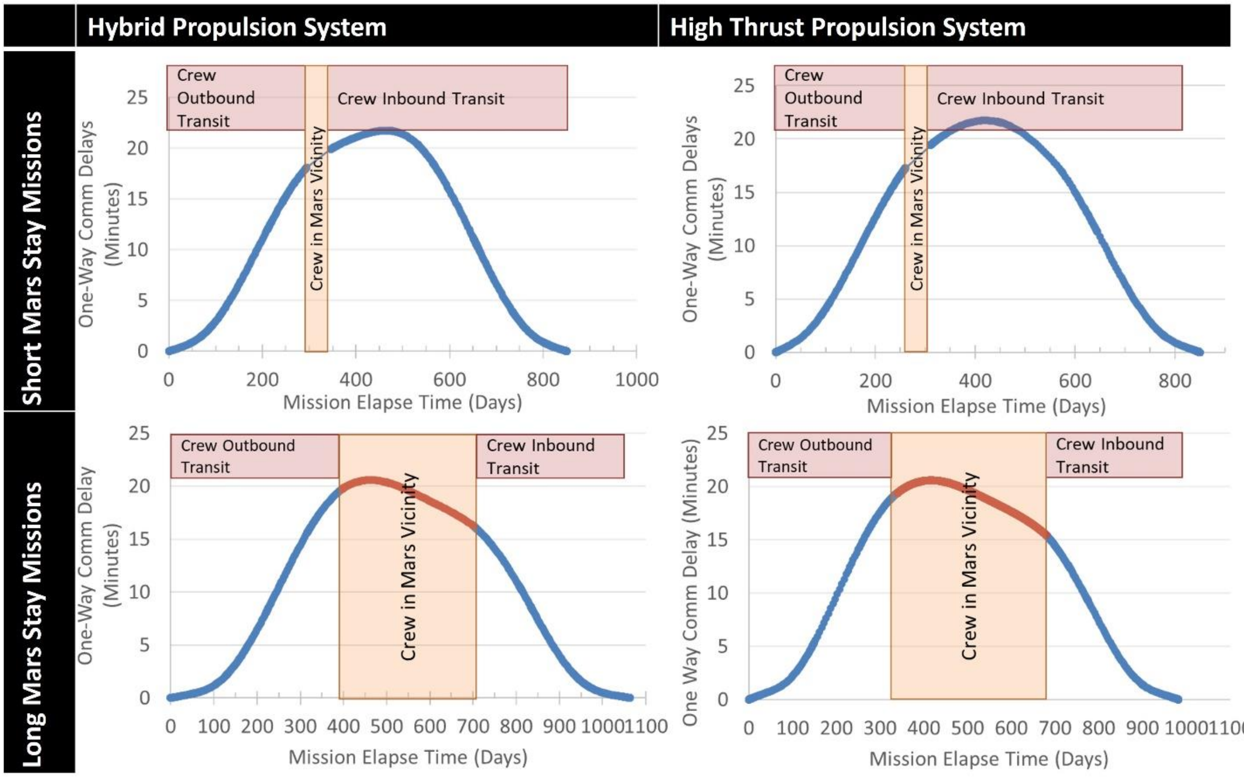

Fig. 10 One-way communication delays for the four reference trajectories in 2039.

V. Conclusion

As seen in the analysis, all Mars missions will experience, a single, two-to-three-week disruption at some point in their duration. Missions with long stays at Mars, regardless of the vehicle trajectory, will experience this disruption while in Mars vicinity. Missions with short stays at Mars will experience this disruption after departing Mars, about 2 months after the trans-Earth injection maneuver. At that point, the vehicle is still close enough to Mars that any assets in Mars orbit are also experiencing the same disruption and are unavailable as a relay. In terms of communication delays, the maximum one-way communication delay is about 22 minutes for any mission and can range from 15 to 20 minutes while crew is at Mars. Based on all the trajectories shown and their respective data, disruptions and delays are not discriminating factors between transportation options.

Based on the disruptions and delays discussed in the previous sections, it is clear that crew will face communication challenges while executing a Mars mission. The farthest humanity has ever been from Earth is just beyond the Moon, with missions experiencing few-second maximum communication delays and no significant periods of communication disruption. Any Mars mission will be pushing these bounds significantly, with minutes of delays and disruptions lasting on the order of weeks. Understanding these impacts is vital to a successful mission. Future work will be to characterize these impacts and develop mitigation strategies to reduce the risk presented by such communication delays and disruptions.

References

[1] Bobskill, M., Lupisella, M., Mueller, R., Sibille., L., Vangen., S., and Williams-Byrd, J., "Preparation for Mars: Evolvable Mars Campaign 'Proving Ground' Approach," IEEE Aerospace Conference, Institute of Electronics and Electrical Engineers, 2015.

[2] Drake, B., Hoffman, S., and Beaty, D., "Human Exploration of Mars Design Reference Architecture 5.0," IEEE Aerospace Conference, Institute of Electronics and Electrical Engineers, 2009.

[3] Chai, P. R., McBrayer, K. T., McCrea, A. C., Merrill, R. G., Prasad, A., and Qu, M., "Crewed Mars Mission Mode Options for Nuclear Electric/Chemical Hybrid Transportation Systems," ASCEND 2021, American Institute of Aeronautics and Astronautics, 2021.

[4] Chai, Patrick R., and Qu, Min. “Human Mars Mission Transit Abort Options for Ballistic High Thrust and Hybrid Transportation Systems.” ASCEND 2022, American Institute of Aeronautics and Astronautics, 2022.
[5] “Mars in Our Night Sky: Solar Conjunction,” *NASA Science Mars Exploration Program* [informational website], URL: https://mars.nasa.gov/all-about-mars/night-sky/solar-conjunction/ [retrieved 29 August 2022].
[6] Quade, J., Anabtawi, A., Thomas, S., and Laubach, S., “Communications with Curiosity during Solar Conjunction,” 2020 IEEE Aerospace Conference (AERO), Institute of Electronics and Electrical Engineers, 2020.
[7] Morabito, D., and Hastrup, R., "Communicating with Mars during periods of solar conjunction," *IEEE Aerospace Conference*, 2002, Big Sky, MT, pp. 3-1271-3-1281.
[8] Xu, G., and Song, Z., “Effects of Solar Scintillations on Deep Space Communications: Challenges and Prediction Techniques,” *IEEE Wireless Communications*¸ Vol. 26, No. 2, 26 April 2019, pp. 10-16. doi: https://doi.org/10.1109/MWC.2019.1800271
[9] Zurek, R., and Smrekar, S., “An overview of the Mars Reconnaissance Orbiter (MRO) science mission,” *Journal of Geophysical Research: Planets,* Vol. 112, No. E5, published online 12 May 2007. doi: https://doi.org/10.1029/2006JE002701
[10] Ocampo, C. A., and Senent, J. “The Design and Development of Copernicus: A Comprehensive Trajectory Design and Optimization System.” 2006 International Astronautical Congress, Valencia, Spain.
[11] Rucker, M. A., Craig, D. A., Burke, L. M., Chai, P. R., Chappell, M. B., Drake, B. G., Edwards, S. J., Hoffman, S., McCrea, A. C., Trent, D. J., and Troutman, P. A., “NASAs Strategic Analysis Cycle 2021 (SAC21) Human Mars Architecture,” 2022 IEEE Aerospace Conference (AERO), Institute of Electronics and Electrical Engineers, 2022.
[12] Howard, R., and Seibert, M., “Earth-Mars Communication Outages During Solar Superior Conjunctions,” ASCEND 2020, American Institute of Aeronautics and Astronautics, 2021.