(Preprint) AAS 11-519

MARS SAMPLE RETURN - LAUNCH AND DETECTION STRATEGIES FOR ORBITAL RENDEZVOUS

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This study sets forth conceptual mission design strategies for the ascent and rendezvous phase of the proposed NASA/ESA joint Mars Sample Return Campaign. The current notional mission architecture calls for the launch of an acquisition/caching rover in 2018, an Earth return orbiter in 2022, and a fetch rover with ascent vehicle in 2024. Strategies are presented to launch the sample into a nearly coplanar orbit with the Orbiter which would facilitate robust optical detection, orbit determination, and rendezvous. Repeating ground track orbits exist at 457 and 572 km which would provide multiple launch opportunities with similar geometries for detection and rendezvous.

INTRODUCTION

Potential Mars Sample Return (MSR) architectures have been studied for decades.[1] Scenarios range from single-launch, direct-entry, direct-return missions, to multiple-launch, multi-element campaigns spanning many opportunities and requiring multiple rendezvous. In light of recent budgetary constraints and the desire for international cooperation, a three-mission MSR campaign has been proposed as a joint venture between NASA and ESA.[2] The current notional mission architecture, depicted by Figure 1, baselines the launch of an acquisition/cache rover in 2018, an Orbiter with an Earth return vehicle in 2022, and a fetch rover and ascent vehicle in 2024.

Previous architectures baselined the two landed missions combined into one.[3] In either case, a transfer of the sample from the surface of Mars to Mars orbit, and then another transfer to a return vehicle would be needed. The samples would be packaged into an orbiting sample (OS) container for these transfers. Direct return to Earth from the surface of Mars has been postulated,[4] but would require landing a return vehicle on Mars, which would have a mass is well beyond the current entry/descent/landing technology. In addition, the MAV and orbiter would be kept separate from each other to facilitate breaking-the-chain of contact with Mars for Earth planetary protection, and risk/complexity reduction. This would require the release of the OS in orbit and then a rendezvous and capture of the OS by the orbiter. This critical transfer in orbit is at the heart of this study. This transfer scenario was first addressed when a MSR project was started in 1998 but cancelled a year later.[5] Further studies and technology development have ensued in the meantime, but the fundamental aspects of this transfer scenario have remained intact. While over the

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last decade numerous studies on the elements of the architecture have been performed, within the last year, two activities have been initiated that warranted a current re-look at the orbital rendezvous scenario. They were NASA industry studies on the MAV and ESA industry studies the Orbiter mission. The mission interface between these two mission elements drives the design of both.

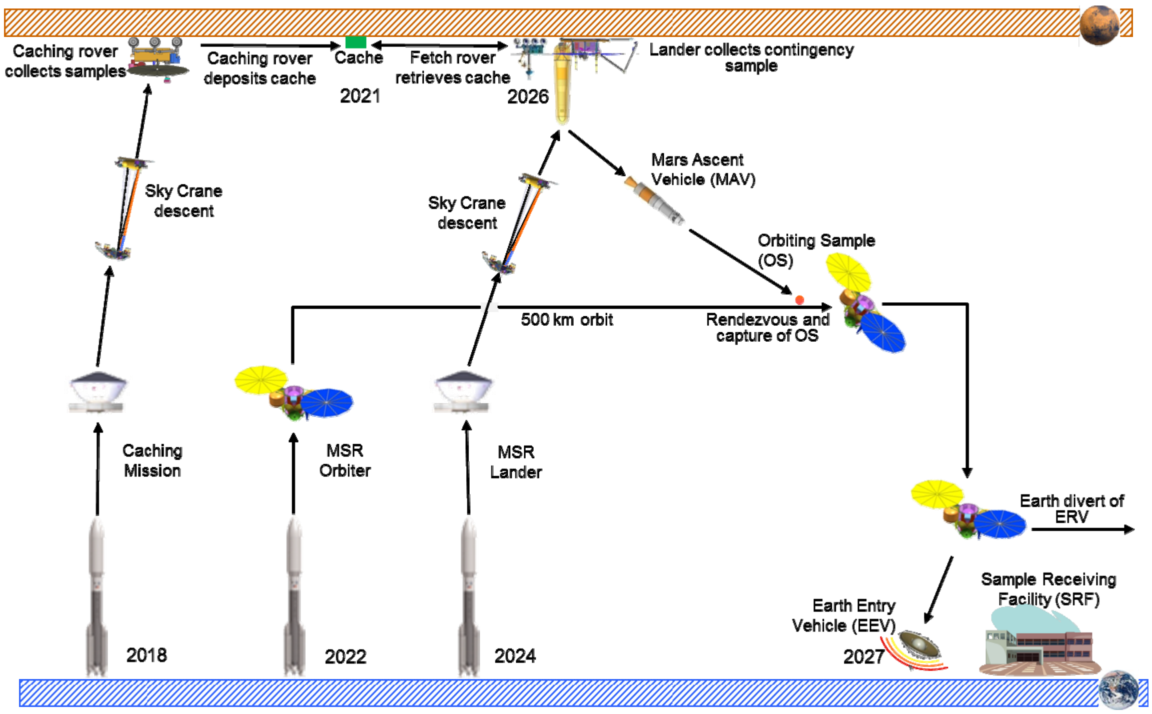

Figure 1. Conceptual Mars Sample Return campaign.

A critical element to this proposed architecture is the successful launch, detection, and rendezvous of the orbiting sample (OS). A feasibility study was conducted with a notional set of assumptions and requirements to develop a proof-of-concept and to determine the feasibility of optical detection. The notional set of assumptions for this study includes:

- The Orbiter shall be in a circular, 45° inclined orbit.
- The Mars Ascent Vehicle (MAV) shall have the capability to launch the OS to a circular orbit with an altitude between 400 – 600 km with an accuracy of +/-50 km.
- The launch shall occur between 9am and 3pm local solar time (LST), due to thermal constraints on the MAV.
- The Orbiter shall be available (i.e. clear Line-of-Sight, LOS) for critical event telemetry coverage during MAV launch through OS separation.
- The Orbiter shall provide at least 4 opportunities to launch over a 7-day period which also satisfy the previous two requirements.
- The Orbiter shall have the ability to detect the OS optically and to determine its orbit.
- The optical telescope is limited to searching in the forward, down-track direction only.

There are two key drivers that distinguish the current launch geometry design from those that have been done in the past.[5] The first is the requirement that the Orbiter be available for critical event coverage. This would require that the Orbiter have LOS visibility during MAV launch, thus restricting launch timing and driving the launch opportunity strategy. The second driver is that the MAV would be launching into a nearly coplanar orbit with the Orbiter with a small down-track separation so as to aid in optical detection and orbit determination (OD) of the OS. The combination of these two factors would place much larger restrictions on launch strategy than have been needed in past mission designs. However, they also provide a more robust and rapid detection scheme for the OS.

STUDY METHODS

The nominal mission timeline was broken into six phases between the lander's entry, descent, and landing (EDL) and the Orbiter's trans-Earth injection (TEI): surface operations/orbiter relay, MAV launch period, preliminary rendezvous (detection and OD), intermediate rendezvous (orbit matching), terminal rendezvous, and TEI phasing. This study focuses on mission design constraints to meet the notional requirements (set forth above) during MAV launch and preliminary rendezvous.

Sample Return Orbiter Orbit Selection

In order to facilitate optical detection and rendezvous with the OS, it would be desirable to launch the MAV into a nearly coplanar orbit with the Orbiter. Coplanar launch opportunities occur twice daily (one ascending and one descending) as the MAV launch site would pass through the orbit plane. However, these launch opportunities occur at varying local times and with the Orbiter in varying positions (true anomaly) within the orbit. Since launch is notionally required to occur during daylight hours (9am-3pm) with the Orbiter visible, the majority of these launch opportunities must be ruled out. Providing multiple launch opportunities (four in seven days) with suitable launch geometries would require that the Orbiter be placed in a ground track repeating (GTR) orbit.

Table 1. Ground-Track Repeat orbits at Mars between 400-600 km (i = 45º). Altitudes are approximate and were calculated using a J2 gravity model.

Altitude (km)	Repeat (sols)	Orbits to Repeat	Grid Sep. (deg)	Actual Repeat (sols)	Sun Cycle (sols)	ΔLST/ Repeat (hrs)
401.7	4	49	7.35	3.91	44.90	-2.09
412.5	5	61	5.90	4.89	45.34	-2.59
419.8	6	73	4.93	5.87	45.64	-3.09
456.6	**1**	**12**	**30.00**	**0.98**	**47.14**	**-0.50**
494.3	6	71	5.07	5.88	48.67	-2.90
501.9	5	59	6.10	4.90	48.98	-2.40
513.4	4	47	7.66	3.92	49.45	-1.90
532.8	3	35	10.29	2.94	50.24	-1.41
548.5	5	58	6.21	4.90	50.87	-2.31
572.2	**2**	**23**	**15.65**	**1.96**	**51.84**	**-0.91**
596.3	5	57	6.32	4.91	52.82	-2.23

Table 1 lists the possible GTR orbits between 400 and 600 km at 45º that repeat in 6 sols or less. Attractive orbits exist at 457 km and 572 km with 1- and 2-sol repeats, respectively. Due to the precession of the orbit plane with respect to the sun, the LST of the ascending node decreases by about 30 minutes per sol. This means that for a 2-day GTR, successive launch opportunities may occur at 3pm, ~2pm, ~1pm, and so on, spaced at two-sol intervals. This gives up to 7 launch attempts over 12 days with similar geometries and meeting the notional requirements. Figure 2 shows the progression of launch opportunities for a 572 km orbit with the LST's given for each launch azimuth (ascending or descending). If the MAV would be unable to launch during the north-east (NE) launch period, but would be capable of launching to either azimuth, it must wait another ~12 days for the south-east (SE) launch period to open, where 7 more opportunities exist. This also presupposes that the Orbiter's node could be adjusted slightly between periods in order to preserve the desired launch geometry.

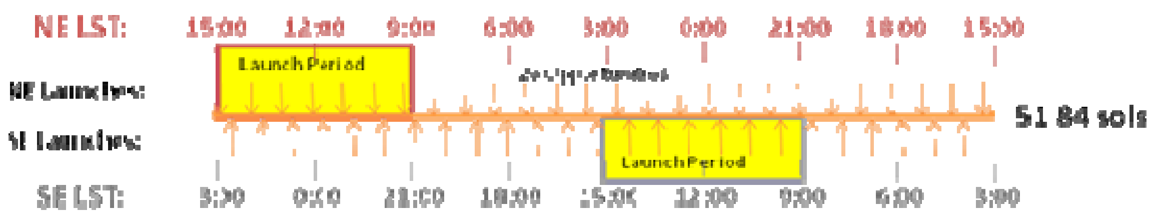

Figure 2. Launch window sequence for an Orbiter in a 2-sol GTR orbit. Each arrow represents an opportunity to launch with the specified geometry. The yellow boxes limit the launches to 9am - 3pm LST.

Mars Ascent Vehicle Launch Geometry

A nominal two-stage MAV ascent to orbit would take around 12 minutes and travel about 1000 km downrange. During this time the Orbiter would travel about 2300 km in its orbit. This means that the MAV must launch when the Orbiter is no higher than 10-15º above the horizon if the OS is to remain ahead of the Orbiter. Since the Orbiter would have forward-facing cameras, it would be necessary to place the OS into an orbit at or below the altitude of the Orbiter. Recall that the notional MAV for this study would have injection errors of +/- 50 km, which means that a nominal orbit 50 km below that of the Orbiter's should be targeted to ensure that the OS would not drift behind the camera's field-of-view (FOV).

Figure 3, below, shows the relative launch geometry for an orbiter at 572 km with the OS being injected into a 522 km orbit. When the Orbiter reaches 5º above the horizon, a signal would be sent giving a launch confirmation command. Thirty seconds later, the MAV would lift off in an optimized 2-burn launch profile. Almost 12 minutes later the OS would separate from the MAV 270 km in front of the observing Orbiter. The targeted offset in semimajor axes of 50 km would ensure that the OS would drift away from the Orbiter at a nominal rate of ~500 km per orbit. If the OS reaches the highest end of the dispersion range, equal to the Orbiter's altitude, it would remain "stationary" in front of the Orbiter. If it is sent to the low end of the dispersion range, 100 km below, it would move away at ~1000 km per orbit.

Detection and Orbit Determination

For this study a notional optical telescope was chosen with a 5º x 5º FOV. The choice of such a camera was based on a balance between the time needed to complete search mosaics and the reduced accuracy of the observations of a wider camera. Although the Optical Navigation Camera (ONC) was developed for the Mars Reconnaissance Orbiter (MRO) with the intention of its use for MSR OS detection[6], its FOV of 1.4° renders its use impractical for the MSR search scenario currently being considered. When the parameters of the ONC were chosen, the baseline scenario considered was one wherein the recovery craft arrived two years after the OS was lofted into Mars orbit, resulting in an OS orbit in which the only reasonably well known orbital parameters would be altitude and inclination. This search scenario required up to a month to complete, and was performed at ranges to the OS that were as large as 10,000 km. The proposed 5º optics would probably necessitate a new camera design, including refractive optics (as opposed to the Cassegrain design of the ONC). This wide-angle version of the ONC has not as yet been designed and built.

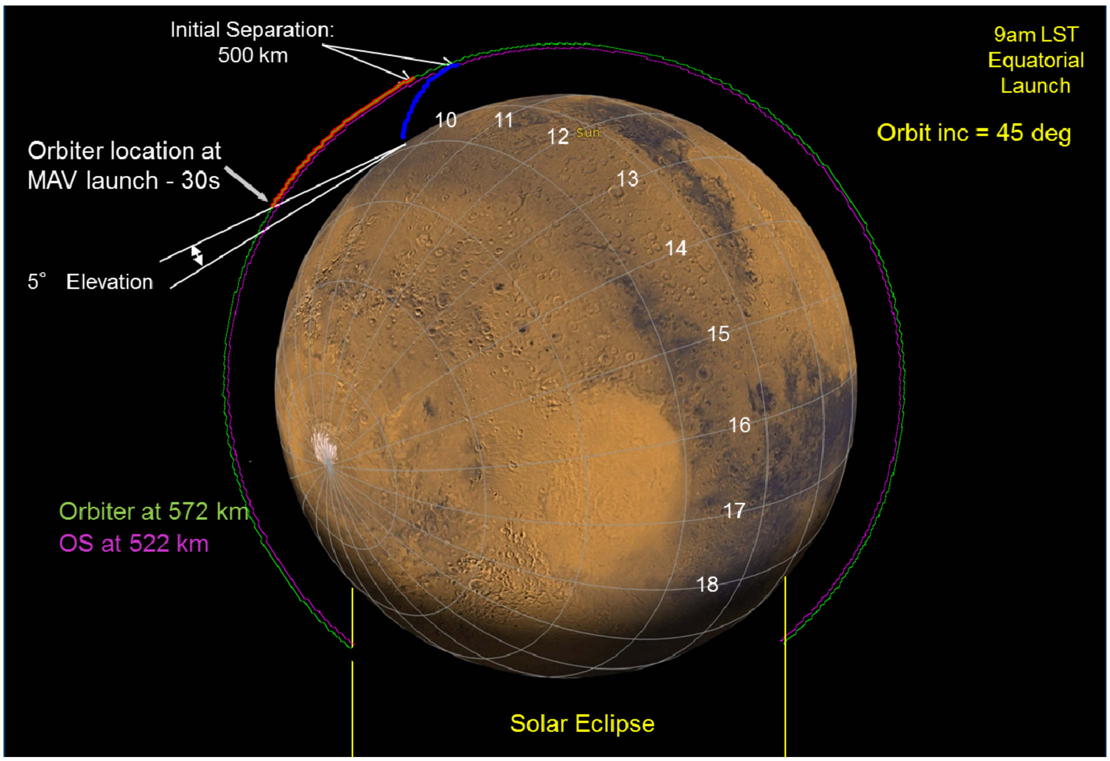

Figure 3. Projected launch geometry for a MAV injecting the OS into a 522 km circular orbit and the Orbiter at 572 km. Launch would occur when the Orbiter is 5º above the horizon, +30 seconds.

Camera photon sensitivity is integral to the robustness of the detection scenario. The ONC has proven itself to be a very powerful sensor, detecting 14th magnitude stars at Mars on approach. But with a high sensitivity comes the challenge of deflecting scattered light that enters the telescope from outside the FOV. The Mars environment represents a particular challenge, as the search for the OS would take place directly above the bright limb of Mars. It is assumed that there would be substantial scattered light signal. For the camera to be used on the capturing orbiter, much more extensive stray-light exclusion is anticipated to be necessary, as it was for the MRO context imager which is equipped with a formidable light-shade.

For the orbital characteristics of the Orbiter and OS assumed for this investigation, a repeating 6 X 2 mosaic pattern of frames is required to guarantee capture. Using 5-10 second exposure times and slew rates of 0.5 and 1°deg/s, the entire mosaic could be completed in less than 5 minutes. Figure 4 shows the mosaic pattern over the expected region to find the OS from the Orbiter's point of view.

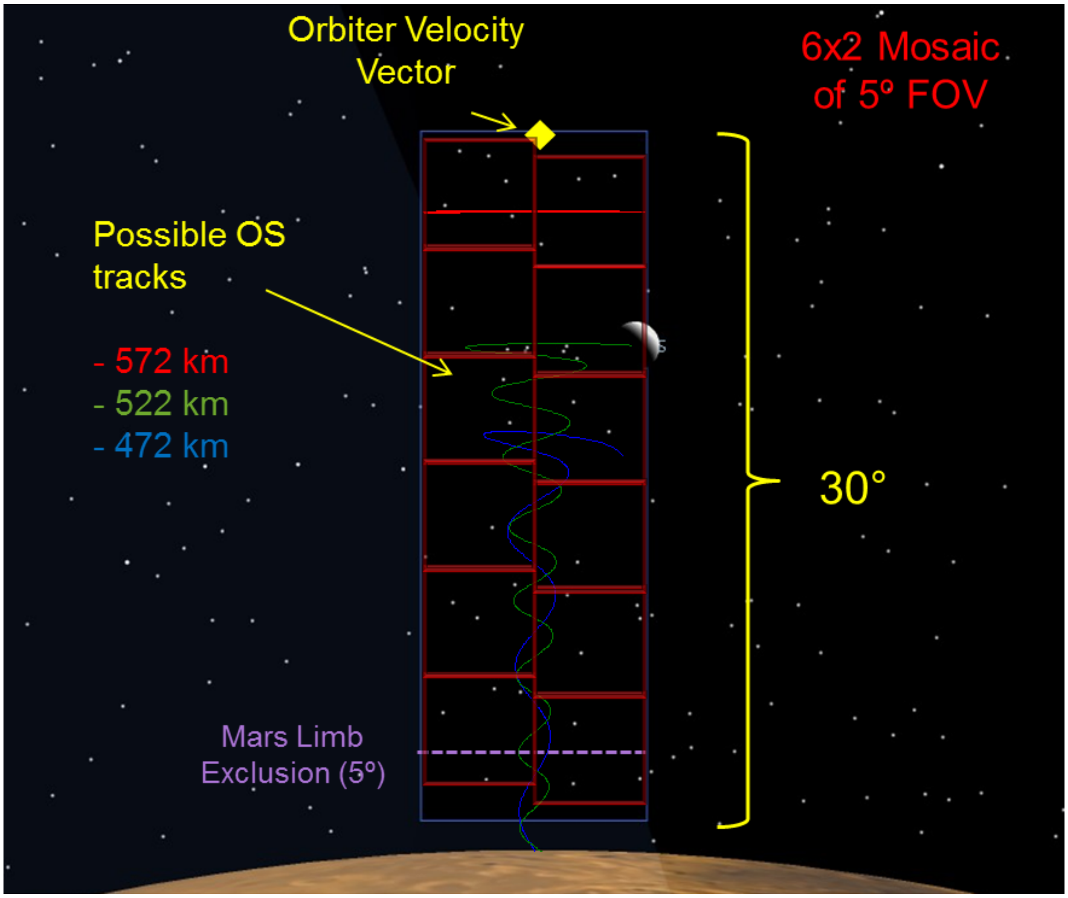

Figure 4. Modeled track of the OS as viewed from the Orbiter. A 6 x 2 mosaic of 5º images would be required to cover the 10º x 30º region where the OS may be located. Nominally the OS would be in front of and below the orbiter and therefore would gradually move away towards Mars' limb. The side-to-side wobble of the OS is due to small differences in node and inclination.

The method of analyzing the pictures to detect and subsequently to determine the orbit of the OS is one that would be completed by a navigation team. The detection process would entail comparison of corresponding elements of adjacent mosaics. Star images would be streaked much more than the OS image, as during the exposure the camera would be moved to remove the "most likely" motion of the OS. After a positive identification is made, an initial simple "Lambert's Method" solution would be performed using three observations of the OS. This is sufficient for a prediction of the OS location into the immediate future, and the spacecraft would be commanded to cease the search pattern and commence tracking the OS on this orbit.

With additional data, received within minutes or up to an hour later, a full solution for the OS orbit could be performed by the navigation team. Once a full solution is generated, a prediction for the location of the OS would be uplinked to the spacecraft which would begin tracking the OS until it drops below the horizon. The orbit determination quality of the estimate made with ten or more observations would be adequate to re-acquire the OS when it re-appears from behind Mars.

SIMULATIONS

Detailed simulations were performed to demonstrate the robustness of optical detection techniques under specified conditions. In order to do so, it is necessary to simulate a large range of the possible geometries of the ERV, OS, and Sun. Once these parameters were generated, it is possible to estimate the signal-to-noise ratio (SNR) vs. time to determine robustness of optical detection under a wide range of conditions that might be encountered on a sample return mission.

Note that no simulations were performed on the optical detection of the MAV upper stage as an aide to find the OS. In addition, no considerations were made for telemetry from the MAV or OS. It is likely that the MAV would send ascent data to the Orbiter for performance reconstruction. It is also probable that the OS be equipped with a simple transmitter beacon to aid in detection.

Signal-to-Noise Ratio Estimation

In order to determine the detectability of the OS from the Orbiter it was necessary to devise a method to estimate the SNR for the OS's signature on the optical camera's detectors. The signal strength is a product of 1) the camera's optical properties and efficiency, 2) the physical size and reflectivity of the OS, 3) the time-varying geometric configuration of the OS-Orbiter range and line-of-sight (LOS) and Orbiter-OS-Sun phase angle, and 4) the solar irradiance at Mars. The signal was divided by an estimate of noise at the detector to obtain the SNR.

The SNR is approximated by

$$SNR(t) = \left(Aft_e\right) * \left(\pi \left(\frac{d}{2}\right)^2 \alpha\right) * \left(\delta \left(\frac{1}{r(t)^2}\right) 10^{-0.01\lambda(t)}\right) * (kE) * \left(\frac{1}{N}\right) \qquad (1)$$

where

- A Area of optical camera's aperture
- f Efficiency of the camera's electronics
- t_e Effective exposure length (varies with OS-Orbiter range)
- d OS diameter (assumed spherical)
- α OS albedo
- δ LOS visibility (δ=1 when OS is visible, δ=0 when occulted or in exclusion region)
- $r(t)$ OS-Orbiter range (time varying)
- $\lambda(t)$ Orbiter-OS-Sun phase angle (in degrees, time varying)
- k Power to signal (DN) conversion factor
- E Solar irradiance at Mars
- N Estimated system noise

Conservative estimates were made for the properties of the optical camera and OS canister. System noise was assumed to be constant and geometric inputs were simulated as described in the following section. The OS was assumed to be visible when it was illuminated (i.e. not in eclipse), greater than 5 degrees above the limb of Mars, and at least 20 degrees from the sun.

Simulation Parameters

When the OS is visible, the two geometric variables that drive the SNR function are the OS range and phase as observed by the Orbiter. The simulation trade space was derived from these two variables by first identifying the Orbiter and OS orbit parameters and the MAV launch parameters that affect them. Then the nominal value and bounds of possible values for each of the identified parameters were determined. Last, values within the range were chosen for simulation. Table 2 shows the resulting parameters trade space.

Table 2. Simulated Parameter Trade Space

Parameter	Nominal	Bounds	Simulated
Orbiter Altitude	572 km	(see Table 1)	572 km
OS Altitude (relative to Orbiter)	-50 km	-100 – 0 km	-100, -50, 0 km
Initial Range	539 km	-3000 – 800 km	596, 539, 481 km
MAV Launch Latitude	0°	-15° – 30°	0°, 30°
MAV Launch Time	9:00 LST	9:00 – 15:00 LST	9:00, 15:00 LST
MAV Launch Azimuth	SE	SE, NE	SE, NE
Mars Season	L_S 230°	L_S 150° – 275°	L_S 180°, 230°

The nominal values for the parameters are all based on a notional MSR design reference mission. The parameter bounds are determined from various system or geometric constraints. The values chosen for simulation were based on minimizing the number of simulation permutations while still capturing the trends and worst-case scenarios. All of the parameters in the table above can be grouped into one of two categories: those affecting range and those affecting illumination.

Range Affecting Parameters. The range affecting parameters influence the initial range at MAV-OS separation, the final range at OS occultation, and the rate at which the range changes (e.g. the time from MAV-OS separation to OS occultation by Mars).

- **Orbiter Altitude** – Variations in Orbiter altitude between 400 and 600 km have a small effect on the time to OS occultation and on eclipse duration. Only the two-day repeat altitude (572 km, see Table 1) was used for the simulations because the Orbiter altitude was deemed to have a much lesser effect on OS detection when compared to the other parameters.
- **OS Altitude[*] (relative to Orbiter) -** The OS altitude relative to the Orbiter determines how quickly the OS would "move away" from the Orbiter. The time to OS occultation and duration of the occultation are directly related to this parameter, as is the rate at which the Orbiter-OS range grows. The bounds of orbiter-relative, OS alti-

[*] Note that the OS is assumed to achieve a circular orbit for this study

tudes are derived from the MAV dispersions in the OS orbit injection, assumed to be ±50 km for this study. The nominal was chosen such that the high dispersion case would not exceed the Orbiter altitude, ensuring that the OS would always move away from, not toward, the Orbiter. The nominal and both the bounds were used in the simulations runs as this parameter greatly affects the time profile of the SNR function.

- **Initial Range –** This is the OS-Orbiter range at OS-MAV separation. The bounds are determined by MAV launches that occur just as the Orbiter rises or sets over the horizon. (Negative values for OS trailing the Orbiter). Since we chose to keep the OS in front, the simulated cases arise from a concept where the MAV launches 30 seconds after the Orbiter has risen 5° above the horizon (see Figure 3) for each of the three Orbiter altitudes. The initial range bounds are highly dependent on the MAV ascent time, assumed to be about 13 minutes for the notional MAV.

Illumination Affecting Parameters. The illumination affecting parameters influence the OS orbit beta angle (depicted in Figure 5), which is the angle from the OS orbit plane to the Sun. This beta angle determines the minimum and maximum phase angles of the OS and the duration of the eclipses.

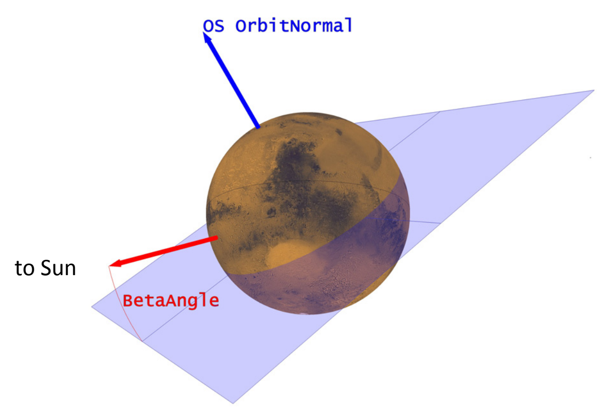

Figure 5. Definition of OS orbit beta angle. This is the angle from the OS orbit plane to the Sun vector (red).

- **MAV Launch Latitude -** The latitude bounds are set by the possible landing sites for the proposed MSR Lander (MSR-L) mission. The nominal and maximum latitude were chosen for simulation. The minimum latitude was left out because it is closer to the equator than the maximum and any trends between the nominal and maximum will be symmetric about the equator, when looked at with the launch time, azimuth, and Mars season.

- **MAV Launch Time (LST) -** The launch time bounds are soft and are based on the desire to launch the MAV during the day for thermal reasons. The earliest and latest launch times were chosen for simulation.

- **MAV Launch Azimuth -** The MAV could launch either North-East or South-East; however, only specific latitudes where the Orbiter ground tracks cross would allow it to do so within a single launch period within the launch time bounds. Otherwise, the MAV would have a launch period of North-East launches followed by a launch period of South-East launches, as shown in Figure 2. Both North-East and South-East azimuths were included in the simulation runs.

- **Mars Season** (L_s) **-** The Mars season is directly related to the declination of the Sun with respect to the Mars equatorial plane, and thus, varies with the solar longitude (L_s) The declination of the Sun sets the range of achievable OS orbit beta angles. The bounds on the Mars season are set by landing season of the proposed MSR-L mission, the duration of its surface operations, and the Orbiter Earth-return opportunities. The notional reference mission has the MSR-L mission landing at an L_s of 150° and the Earth-return opportunity at an L_s of 275°. The nominal MAV launch date has an L_s of 230°. The nominal and equinox (L_s 180°) values were included for simulation.

Simulation Tools

The simulations were run using Satellite Tool Kit (STK) by Analytical Graphics, Inc. (AGI), with the resulting geometry data post-processed in MATLAB by MathWorks.

The first step in setting up the STK scenarios was to set the date to achieve the desired Mars season. The nominal L_s of 230° corresponds to March 2026 and the equinox to December 2025. Translating the remaining trade space parameters into STK satellite object orbits was done using Target Sequences in STK's Astrogator module. The Target Sequences enabled the trade space parameters to be set by varying the Keplerian elements of the Orbiter and OS orbits.

The simulation cases were generated from all the possible permutations of the values in the *Simulated* column of Table 2. This resulted in only 48 cases since OS Altitude and Initial Range are not independent of each other. The cases were run using STK Analyzer, a module for trade space exploration developed by Phoenix Integration. A Design of Experiments was set up to run each of the parameter permutations and generate a report based on a custom template created with STK's Report & Graph Manager. The custom template recorded the Orbiter-OS range, the OS phase angle, the OS-to-Limb angle, the OS eclipse times, and OS occultation times. These reports were then post-processed in MATLAB. The geometric data generated in STK were used to calculate the SNR using eq. (1) for each case. The results could then be plotted and statistics accumulated.

RESULTS

The simulated geometric parameters from the nominal case are plotted in Figure 6. As expected, the range to the OS would grow steadily[*] from a few hundred km at MAV-OS separation up to 4000 km when it would go below the limb of Mars, which would occur in about 17 hours. Approximately 72 hours later the OS would emerge from the other side and proceeds to "lap" the orbiter about 4.5 days after the initial separation. For the 3σ low case of -100 km the pattern would be same with all the durations cut in half. For the 3σ high case the OS would be in the same orbit and remains stationary just ahead of the Orbiter.

The critical time to detect the OS would be before it disappears below the limb. For the nominal case this gives about 7 orbits, and 3-4 orbits for the fastest case. During these orbits the Orbiter would be "chasing" the OS in to and out of eclipse. As the OS emerges from the shadow the illumination would be poor at first, then gradually would increase until near full illumination just

[*] As a rule-of-thumb, the OS would move away from the Orbiter at the rate of 10 times the difference in semimajor axis per orbit. For the nominal case this would be 10 x 50km = 500 km/orbit (about 200 km/hr)

before eclipse again. Each orbit the range increases and the OS-to-Limb angle decreases (Figure 6). These parameters can be used to estimate a SNR of the optical detector using eq. (1).

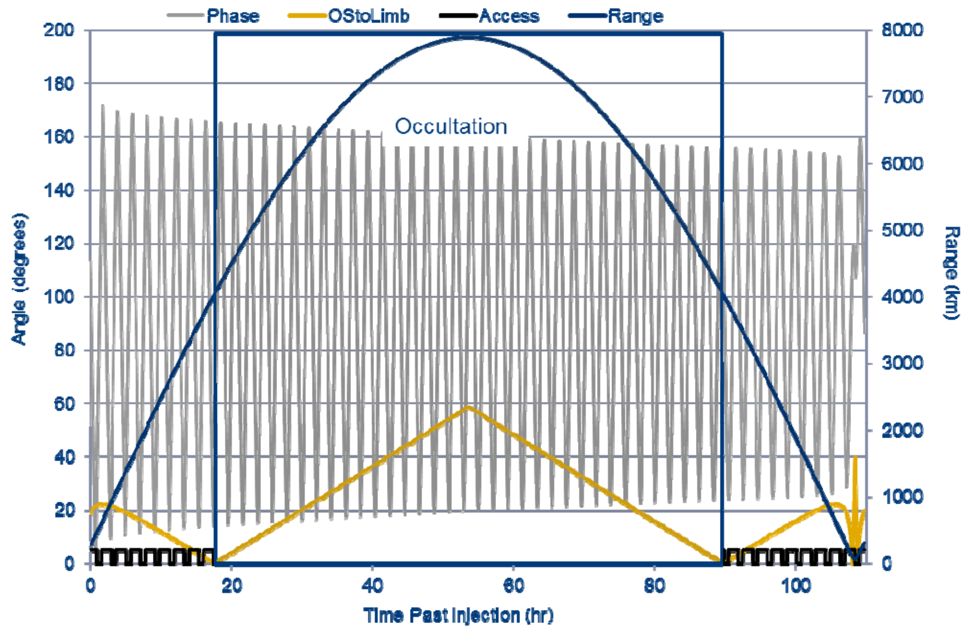

Figure 6. Simulated geometric parameters for the nominal case. Phase and OS-to-Limb angles are measured in degrees (left axis) and OS-Orbiter range is measured in km (right axis). Access is set to 1 when the illuminated OS is in view, otherwise it is 0. The Occultation region indicates where the OS would be blocked by Mars.

The temporal profile of the SNR function is wave-like, as can be seen in Figure 7, which shows the temporal profile of the nominal case. Each segment of the plot represents the portion of the orbit where the OS would be illuminated by the sun. The OS would get brighter as the phase angle increases. When near the maximum illumination, the Orbiter would follow the OS into eclipse. The peak SNR of each orbit would gradually decrease as the OS drifts away. At approximately 4000 km, the OS would be occulted by Mars and the Orbiter must wait three days for the OS to emerge from the other side.

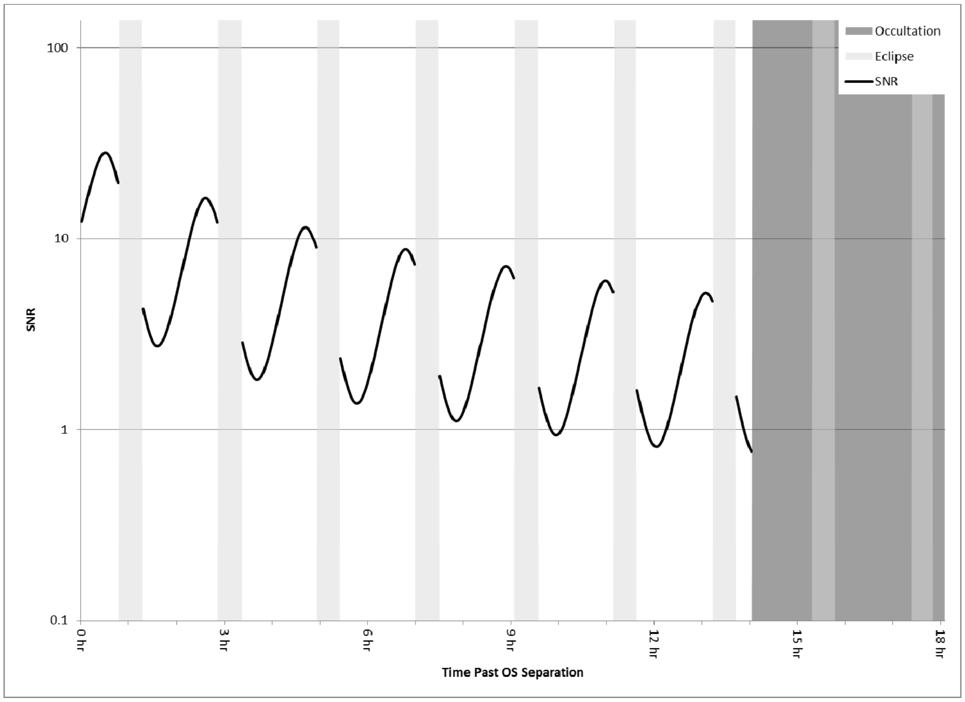

Figure 7. Signal-to-Noise ratio vs. time for the Orbiter tracking the OS. T = 0 corresponds to OS orbit injection. Each segment represents the illuminated part of one orbit. The light grey bars indicates that the OS would be in eclipse (with the Orbiter following). The sequence would end when the OS is occulted by the limb of Mars at ~14 hrs.

The SNR temporal profile can be split out into its four contributing components: phase, eclipses, occultation, and range. Each of the simulation parameters affects these components in different ways and with varying degrees of magnitude. The following sections discuss each of the components of the SNR temporal profile and the simulation parameters that affect them.

OS-Orbiter Range. The range acts as a vertical offset function that shifts the phase sinusoidal function up or down based on the range from the Orbiter to the OS. The two main parameters that affect this function are the initial range and the OS altitude relative to the Orbiter. Figure 8 shows the inverse relationship between range and the estimated SNR for various phase angles.

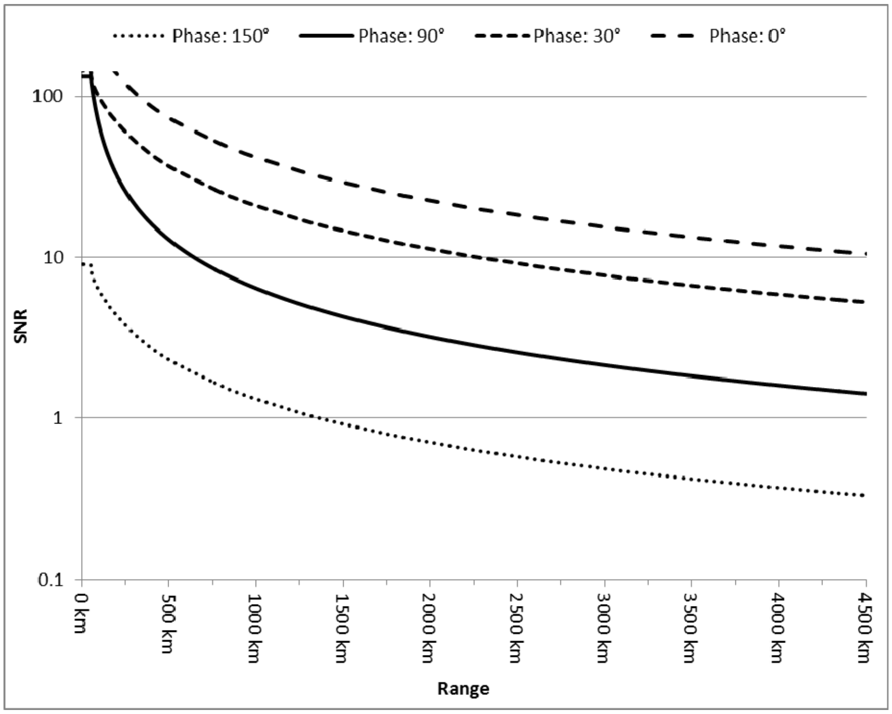

Figure 8. SNR vs. Orbiter-OS Range for various illumination angles (Phase).

Phase Function. Treating the phase component of the SNR function as a sinusoidal function results in three parameters of interest: the amplitude, the frequency, and the phase. The amplitude of the function is directly related to the range of phase angles at which the Orbiter observes the OS. This range is directly dependent on the OS orbit beta angle (see Figure 5). A beta angle of 0° results in the largest range of phase values, from 0° to 180°, where a beta angle of 90° would results in a constant phase of 90°. Figure 9 shows the sinusoidal function for several different beta angles. Along with the change in sinusoidal function amplitude, the beta angle changes the eclipse duration (as shown by the width of the gray bars).

Figure 9d is for a beta angle of 59°, which is the boundary between orbits with and without eclipses. The beta angle varies slightly with time in due to the precession of the orbit caused by the J2 perturbation. Thus, in Figure 9d, the beta angle starts just below 59° and slowly crosses above it, removing the OS orbit eclipses. Notice, however, that even though the eclipses are removed, the phase sinusoidal function value does not go as high as with lower beta angles due to the Orbiter observing the OS in a plane more perpendicular to the sun vector.

While Figure 9 conveys the importance of beta angle selection on the phase function, the range of achievable beta angles depends wholly on the Martian season (L_s) which is dictated by the mission arrival date(s). Figure 10a shows that beta angles less than 45° are achievable in any season, but beta angles that result in no eclipses are only achievable near the solstices. The actual beta angle achieved would depend on the longitude of the ascending node of the OS orbit, which is a function of the MAV launch latitude, time, and azimuth (see Figure 10b).

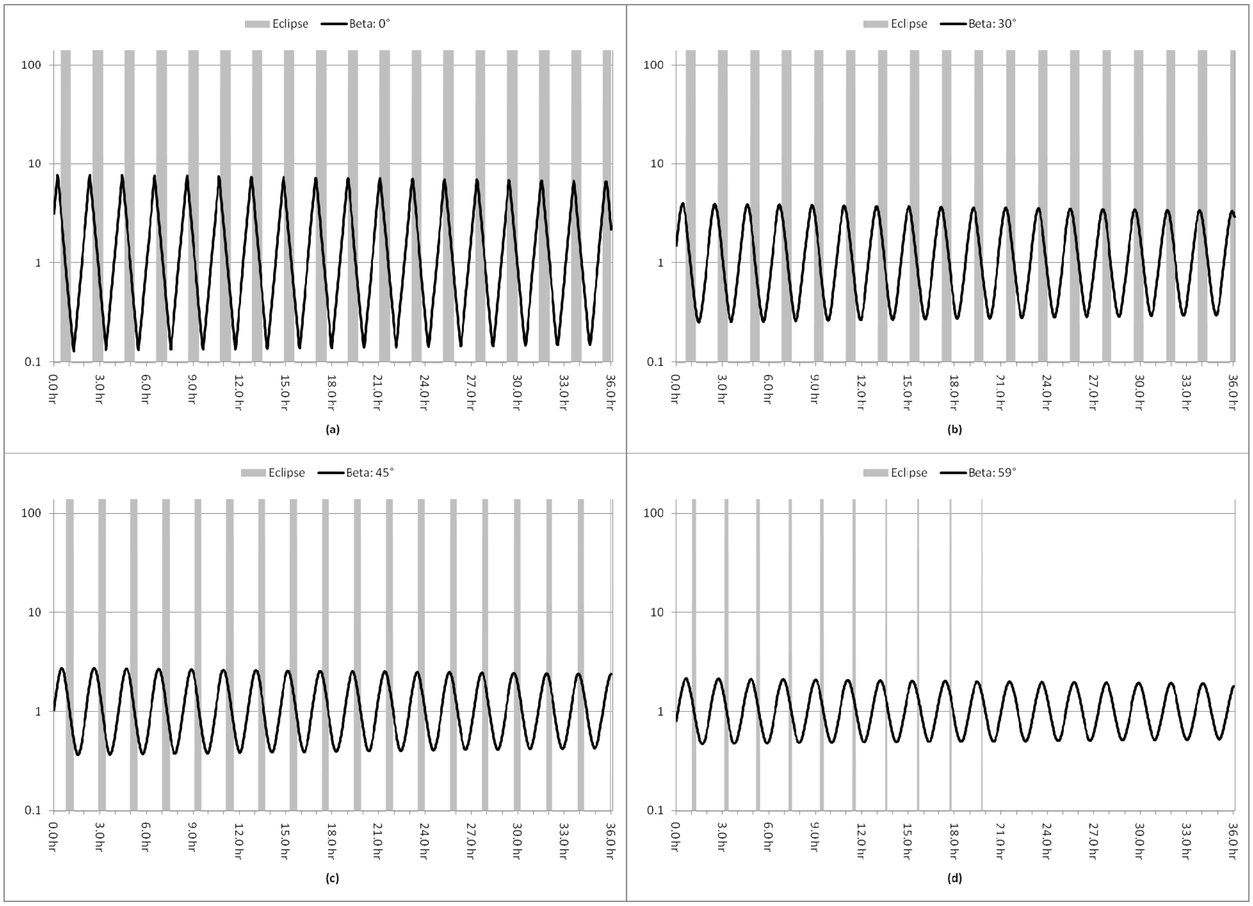

Figure 9. Phase Sinusoidal Function and Eclipse Duration for Various OS Orbit Beta Angles.

The phase of the sinusoidal function is determined by the combination of MAV launch latitude, local time, and azimuth used to achieve a given beta angle. The curves in Figure 9 are all from OS orbits with the same beta angle. The only difference between them is where and when the MAV would be launched.

Eclipse and Occultation Black-out Periods. The black-out periods in the SNR function profile are caused by solar eclipses of the OS and Mars occultations of the OS. The eclipse durations would be highly dependent on the OS orbit beta angle. A beta angle of zero results in the longest eclipses as the OS passes directly through the middle of the shadow of Mars. As the beta angle increases, eclipse durations would shrink and for high beta angles, disappear altogether. Figure 11 shows how the eclipsed portions of an OS orbit change with its beta angle. The four orbits in each of the portions of the figure represent the extremes of the beta angle, shown as the minima and local maxima in Figure 10a for the given Mars Season (L_s).

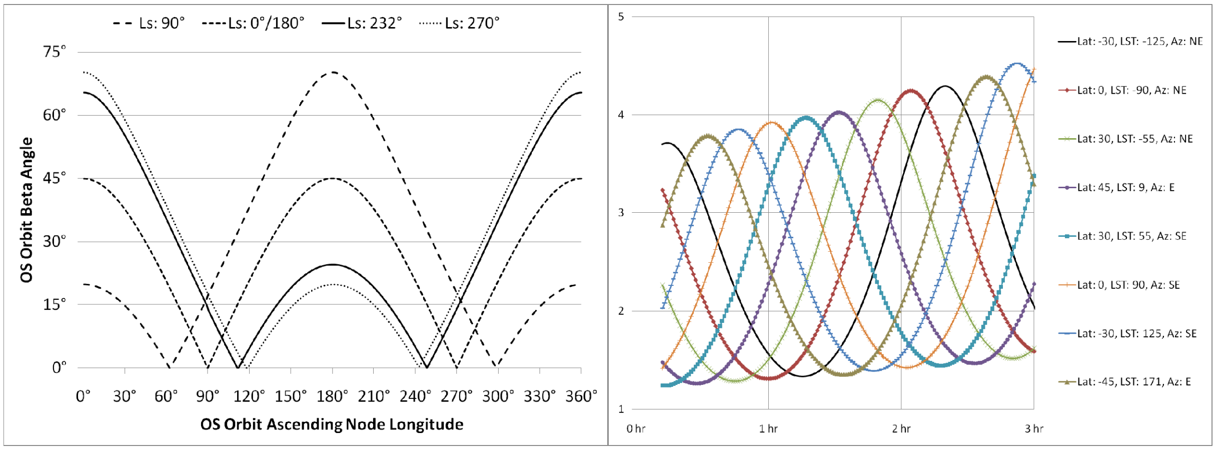

Figure 10. (a) Achievable OS Orbit Beta Angles by Martian Season. (b) Sinusoidal Function Variation with MAV Launch Latitude, Local Time, & Azimuth for a Constant Beta Angle

Near an equinox (L_s of 0° or 180°), as shown in Figure 11b, it would not be possible to achieve a beta angle that results in no eclipses. Orbits 3 and 4 are the minimum eclipse cases as they would follow the shortest path through the umbra (shaded region). Near the solstices (L_s of 90° or 270, there are beta angles that would have no eclipses, as shown in Figure 11a, orbit 3 and Figure 11c, orbit 4.

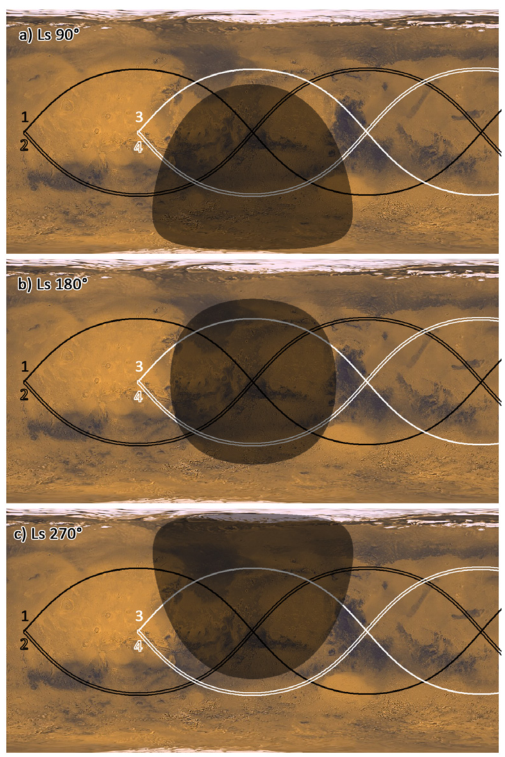

Figure 11. Eclipse Variation with OS Orbit Beta Angle and Ls.

The eclipse durations are also dependent on the OS altitude, but to a much lesser extent. As the OS altitude increases, the eclipse times decrease and vice-versa. Figure 12 shows how the area of Mars' shadow changes with altitude.

The occultation period happens when the OS drops below 5° to the Mars limb. The time from the MAV-OS separation to the first occultation is highly dependent on the initial range and orbiter-relative, OS altitude. The farther in front of the Orbiter the OS would start, the quicker it would reach the limb. The greater the difference between the Orbiter and OS altitudes, the faster the range between them would grow and the sooner the OS would reach the limb.

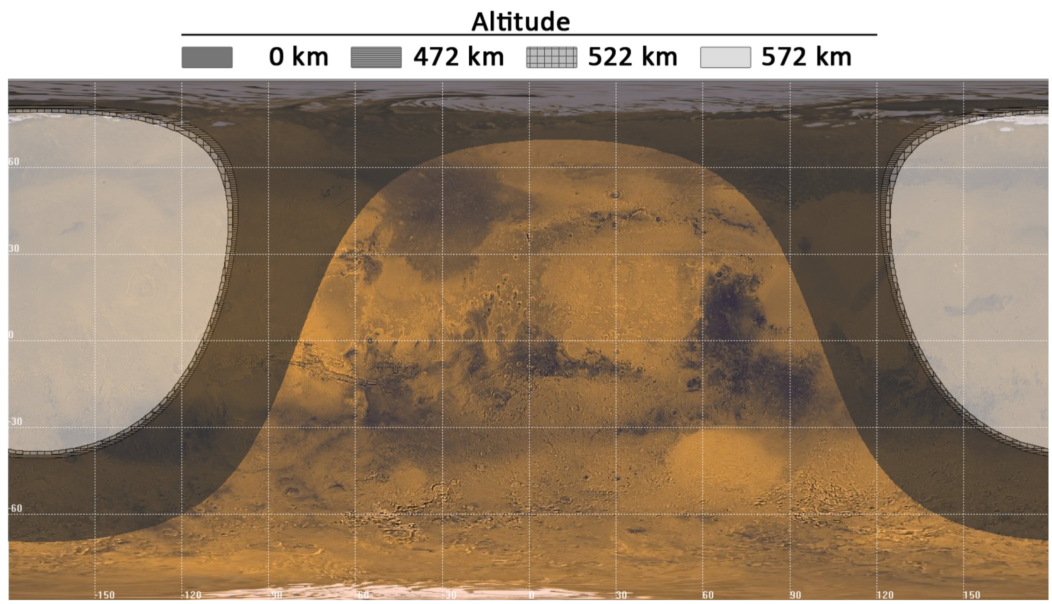

Figure 12. Mars Umbra Size at Several Altitudes

OS Detectability

For this study it was assumed that the OS would be detectable with a SNR above 5. This means that for every 5 minutes (one complete mosaic) that the OS remained above a SNR of 5, one observation would be recorded. Three observations would be needed for a crude estimation of the orbit and it was deemed that 10 observations would be sufficient to declare satisfactory knowledge of the OS's orbit. Each case permutation was run and statistics were collected on the total amount of time the SNR of the OS remained above the threshold of detectability. Figure 13 shows this data for the nominal case.

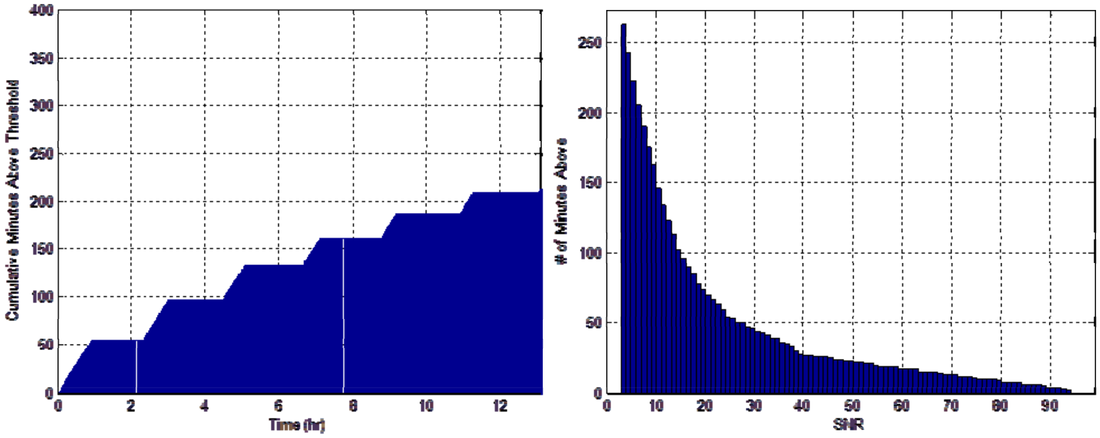

Figure 13. SNR statistics above threshold (SNR > 5) for the nominal case simulation. The left plot shows the cumulative time above the threshold while the right plot shows a histogram of the total number of minutes above a given SNR.

Table 3 shows the results from the cases that gave the lowest number of completed mosaics before OS occultation. The worst case for detection occurs when the MAV would be launched at the equinox (L_s = 180º) on the equator at 3pm LST and would achieve a 3σ low altitude of 100 km below the Orbiter (case #16). Even in this case the ONC would observe the OS ten times before the first eclipse and 30 times before the OS would go below the limb of Mars three orbits later.

Table 3. Trade space simulation results. Each mosaic completed represents one observation of the OS. The count for the 1st orbit is before the OS would be eclipsed and the total count is the number of observations before the OS would be occulted by Mars.

Case #	OS Altitude	Ls (Season)	Launch Latitude	Launch LST	Mosaics 1st Orbit	Mosaics Total
1	522	230	30 N	9am	18	66
2	522	180	30 N	9am	18	64
4	522	180	30 N	3pm	12	64
5	522	230	0	9am	18	68
6	522	180	0	9am	18	70
7	522	230	0	3pm	13	75
8	522	180	0	3pm	10	71
9	472	230	30 N	9am	17	34
10	472	180	30 N	9am	17	34
11	472	230	30 N	3pm	18	31
12	472	180	30 N	3pm	12	31
13	472	230	0	9am	16	32
14	472	180	0	9am	18	35
15	472	230	0	3pm	13	33
16	472	180	0	3pm	**10**	**30**

CONCLUSION

Retrieving samples from the surface of Mars using a single launch incorporating all the necessary elements to land, collect, launch, and return them to Earth would not be feasible with today's launch capabilities and financial constraints. A three-launch campaign is proposed to collect the samples, launch them into Mars orbit, and then return them Earth. The interfaces to hand off the samples, particularly in orbit, represent areas of risk and uncertainty. This study puts forth a potential scenario for launching and detecting the OS in a robust manner.

Analyses show that an Orbiter in a GTR orbit would provide many opportunities to launch the MAV into a nearly coplanar orbit, while maintaining a clear LOS and setting up a favorable geometry for optical detection. Our simulations show that a modified ONC camera would be able to robustly detect the OS under a wide variety of potential launch conditions. A minimum of 10 observations would be made before the OS enters into eclipse during the 1st orbit, and at least 30 observations before the OS would be occulted by Mars. This should be more than sufficient to detect and determine the orbit of the OS within a few hours of launch for a mission operating within nominal bounds.

ACKNOWLEDGMENTS

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. A special thanks to the members of the MSR architecture study team at JPL, who contributed significantly to this research. The team includes Robert Gershman, Stuart Kerridge, Eric Klein, Charles Kohlhase, Jim Lux, Dan Lyons, Erik Nilsen, Carl Sauer, Ted Sweetser, Stephen Synnott, Charles Whetsel and Shawn Holcomb (MSFC).

REFERENCES

[1] R. Mattingly, S. Matousek, and R. Gershman, "Mars Sample Return—Studies for a Fresh Look," Paper #384, *2002 IEEE Aerospace Conference*, Mar. 9–16, 2002.

[2] R. Mattingly, and L. May, "Mars Sample Return as a Campaign," Paper #1805, *2011 IEEE Aerospace Conference*, Mar. 5–12, 2011.

[3] R. Mattingly, S. Hayati, and G. Udomkesmalee, "Technology Development Plans for the Mars Sample Return Mission," Paper #1518, *2005 IEEE Aerospace Conference*, Mar. 2005.

[4] D. Thunnissen, D. Rapp, C. Voorhees, S. Dawson, and C. Guernsey, "A 2007 Mars Sample Return Mission Utilizing In-Situ Propellant Production," AIAA 99-0851, *37th AIAA Aerospace Sciences Meeting and Exhibit,* Reno, NV, January 11 -14, 1999.

[5] L. A. DAmario, W. E. Bollman, W. J. Lee, R. B. Roncoli, and J. C. Smith, "Mars Orbit Rendezvous Strategy for the Mars 2003/2005 Sample Return Mission," *AAS/AIAA Astrodynamics Specialist Conference*, Girdwood, Alaska, August 16-19, 1999.

[6] J. L. Stauder, A. E. Lowman, D. Thiessen, D. Day, and D. O. Miles, "Off-Axis Scatter Measurement of the Mars Reconnaissance Orbiter (MRO) Optical Navigation Camera (ONC)", *Proc. SPIE* 5874, 58740L (2005). doi:10.1117/12.619857

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