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PRIMARY SCIENCE ORBIT DESIGN FOR THE MARS RECONNAISSANCE ORBITER MISSION

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This paper addresses the constraints, analysis, and design evolution of the Mars Reconnaissance Orbiter Primary Science Orbit. The discussion details the tradeoffs made to satisfy science objectives within the capability of the spacecraft and mission performance. Science objectives and the corresponding requirements levied on the orbit mission design are presented. Atmospheric effects on both the orbit itself and the spacecraft are discussed in terms of their impact on the final PSO selection. The decision rationale for the final selection of the orbital altitude and frozen orbit design is also presented.

INTRODUCTION

In 2005 NASA will launch the Mars Reconnaissance Orbiter (MRO) mission. The primary objective of the MRO mission is to deliver a single spacecraft in orbit around Mars in order to perform remote sensing science observations, conduct site characterization for future landers, and to provide telecom / navigation relay capability for follow-on missions.[1] After arrival at Mars in early 2006 and approximately six months of aerobraking, the orbiter will be delivered into the Primary Science Orbit (PSO) and will begin the collection of science data for the following two years.

The design of the PSO has evolved over the course of the MRO project. During the early phases of the mission planning process, an elliptical orbit with a periapsis altitude of 200 km and apoapsis altitude of 430 km was selected as the baseline PSO to balance the broad mission objectives of low altitude, high resolution imaging with higher altitude mapping and surveying. Once the science instrument suite had been selected for the project; however, a request was made by the principal investigators to re-examine the PSO design in order to increase the amount of time in the orbit below 300 km. The ensuing design trade study led to the selection of the MRO baseline PSO.

The PSO is designed to provide global access to Mars and to satisfy the science and mission objectives, while taking into account additional spacecraft considerations such as atmospheric drag effects. The orbital elements for the PSO produce the following characteristics: a Sun-synchronous ascending node at 3:00 pm local mean solar time (daylight equatorial crossing); a periapsis altitude near 250 km; an apoapsis altitude

near 320 km; a near-polar inclination of 92.6426 degrees; a near circular mean eccentricity of 0.008718, which, along with an argument of periapsis of –90.0 degrees, results in a frozen orbit.

This paper describes in detail the general characteristics of the MRO Primary Science Orbit outlined above, in the context of satisfying the science objectives within the capability of the spacecraft and mission cost. A brief discussion of the science objectives and the corresponding requirements levied on the orbit mission design is included. The decision rationale for the final selection of the orbital altitude and frozen orbit design is presented as well, including a description of the groundtrack characteristics and subsequent ground target observation opportunities. Conclusions are summarized in the final section.

SCIENCE OBJECTIVES

The main scientific objectives of the MRO mission, outlined in the MRO Mission Plan[2], are as follows:

1. Characterize Mars' seasonal cycles and diurnal variations of water, dust, and carbon dioxide.
2. Characterize Mars' global atmospheric structure, transport, and surface changes.
3. Search sites for evidence of aqueous and / or hydrothermal activity.
4. Observe and characterize the detailed stratigraphy, geologic structure, and composition of Mars surface features.
5. Probe the near-surface Martian crust to detect subsurface structure, including layering and potential reservoirs of water and / or water-ice.
6. Characterize the Martian gravity field in greater detail relative to previous Mars missions to improve knowledge of the Martian crust and lithosphere, and potentially of atmospheric mass variation.
7. Identify and characterize numerous globally distributed landing sites with a high potential for scientific discovery by future missions.

Eight different science investigations at Mars will be conducted over the course of the MRO two-year primary science period to accomplish the various scientific objectives. Each of these investigations utilizes various parts of the electromagnetic spectrum, including ultraviolet and visible imaging, visible to near-infrared imaging spectrometry, thermal infrared atmospheric sounding, and radar subsurface profiling. Functionally, the investigations are divided into three different observational modes:

1. Daily global mapping and profiling
2. Regional survey
3. Globally distributed targeting

These modes create additional complexity to the MRO spacecraft operations during the primary science period since some instruments have more than one observational mode, and the modes will be intermixed and sometimes overlapping. In addition to the instrumented investigations, there will also be science conducted using engineering subsystems onboard the orbiter.

ORBIT SELECTION TRADEOFFS

Each of the MRO scientific objectives points the PSO design towards an orbit at Mars with access to all latitudes. Choosing the inclination to be near 90° gives coverage to all latitudes other than precisely over the poles. Other factors can influence the choice in inclination as well. The mission objective to characterize both Mars' seasonal cycles and diurnal variations of water, dust, and carbon dioxide suggests a need to design an orbit which can eliminate daily variations in measured parameters.[3] A specialized orbit condition which maintains the orbit's line of nodes at a constant angular separation with respect to the Sun, thereby providing observations of the Martian surface at nearly constant lighting conditions, can aid in distinguishing between any daily variations on the ground and seasonal variations. This orbit is referred to as a Sun-synchronous orbit. It is designed by setting the semi-major axis, eccentricity, and inclination of the orbit such that the secular variations in the longitude of the ascending node are the same as the average rate of the Sun's motion projected on the equator of Mars. Sun-synchronous orbits are useful when consistent lighting conditions are desired on the planet surface for observation, or to maintain certain lighting conditions on the solar panels of a spacecraft.

Each of the MRO scientific objectives also points the PSO design towards a low altitude orbit at Mars. The sixth and seventh objectives especially provide impetus for the MRO PSO to have at least some altitudes lower than previous orbiter missions at Mars. Spacecraft instruments also gain a significant advantage in resolution as the orbital altitude is lower. Thus, orbits with periapsis altitudes below that of the Mars Global Surveyor (MGS) 372 km periapsis altitude and apoapsis altitudes below the MGS 433 km apoapsis altitude defined the upper altitude bounds that were initially considered in the design space for the PSO.

The tradeoff with a lower orbit; however, is the amount of fuel necessary to achieve, sustain, and exit the orbit. As the altitude of an orbit decreases, the amount of fuel required to establish the orbit increases. Although the atmosphere at Mars is much thinner than the Earth's at the surface, the Martian atmosphere diminishes slowly with altitude and therefore causes a small but persistent drag on the spacecraft which must be accommodated in the mass budget necessary to sustain an orbit at Mars. Finally, because orbiters at Mars are subject to NASA Planetary Protection requirements, it is typical to raise the orbit to a higher planetary quarantine orbit that is subject to less atmospheric drag once science operations are complete to ensure that the probability of spacecraft impact on Mars meets a minimum. Thus, additional fuel is required to exit the orbit to a safe altitude for the planetary quarantine orbit. Again, this fuel requirement increases as

the science orbital altitude is lower. Due to all of these mass budget considerations, orbits with periapsis altitudes at or above 200 km were initially considered as the lower altitude bounds in the design space for the PSO.

Three classes of orbits which describe the motion of periapsis exist within the 200 to 430 km altitude range considered for the PSO at Mars:

1. Frozen: Argument of periapse is frozen beneath the South Pole of Mars [$\dot{\omega} = 0$]
2. Librating: Argument of periapse oscillates back and forth over the South Pole of Mars [$\dot{\omega} = f(a, e, \sin \omega)$]
3. Circulating: Argument of periapse moves around the planet at a constant rate per day [$\dot{\omega} < 0$ or $\dot{\omega} > 0$]

In general, these classes of orbits exist because of secular and periodic variations in the orbital elements experienced due to perturbations on the orbit from the gravity field. While all orbital elements exhibit periodic variations, only the argument of periapse, longitude of the ascending node, and mean anomaly undergo secular changes. These secular changes are caused by the zonal harmonics of the gravity field, and can be used in orbit design to meet certain mission constraints. The motion of the argument of periapse and subsequent design tradeoffs are discussed here.

The secular variations in the argument of periapse can be made to be nearly zero by choosing the appropriate combination of eccentricity and argument of periapse at any inclination and altitude. When this occurs, the orbit is called frozen because the argument of periapse remains constant in time.[4] The frozen orbit arises because the effects of the odd and even zonal harmonics of the gravity field on eccentricity and argument of periapse nearly cancel, producing an orbit with virtually constant shape and apsidal orientation.[3] Two values are permissible for the location of periapsis in a frozen orbit with a near-polar inclination: $\omega_o = 90°$ or $270°$. The correct solution is dependent only on the second and third zonal harmonics. At Mars, the strong oblateness term (J_2) and north-south mass asymmetry (J_3) of the gravity field are of the same sign. Thus, they can only be balanced to produce a frozen orbit by placing the orbital periapsis near the South Pole ($\omega_o = 270°$). This is the case in the first orbit class listed above. For a more thorough discussion of frozen orbits, refer to Ref. 3 and Ref 4. listed at this end of this paper.

Increasing the eccentricity beyond that of the frozen eccentricity value for a given semi-major axis and inclination causes the orbit periapsis to librate near the frozen argument of periapse location. This is the case in the second orbit class listed above. Further increasing the eccentricity results in the natural secular changes in orbital periapsis occurring again. The third orbit class listed above is an example of the secular changes in the argument of periapse.

Figure 1 illustrates all three orbit classes for a near-polar inclination orbit. The frozen orbit in the figure is indicated by a single dot at the center of the curves. Closed

curves are representative of librating orbits, while the open curves indicate orbits with circulating apses. The motion of eccentricity and argument of periapse on these curves is in the counterclockwise direction.

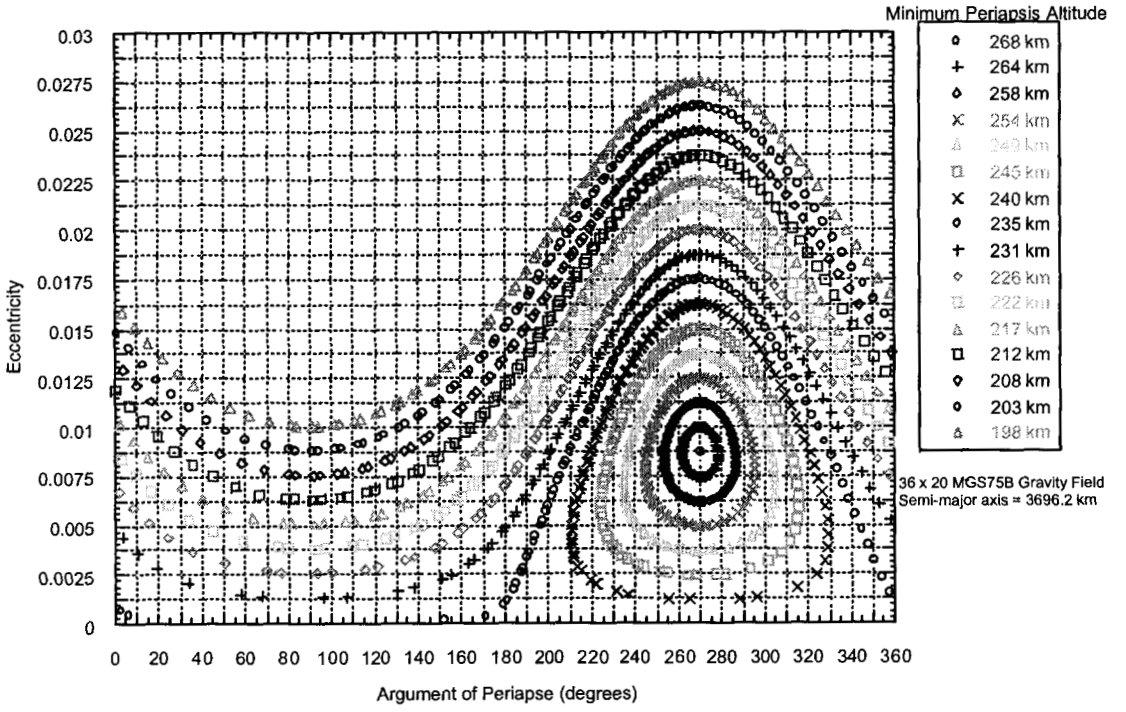

Figure 1: Orbital Periapsis Motion as a Function of Eccentricity

Frozen orbits offer an important design characteristic: the total altitude variation between orbital periapse and apoapse is reduced to 65-70 km because the variation of eccentricity across the orbit is lower than that of a non frozen orbit. The small variation in eccentricity that does occur in the frozen orbit is the short period variation produced by the specific shape of the Mars gravity field. Thus, a frozen orbit represents the most circular orbit that can be achieved at lower altitudes at Mars. The altitude range between apses is referred to as the 'S-curve', since the shape of the altitudinal variation with latitude across the Mars surface resembles a flattened letter S. Variations in the spacecraft altitude above the Mars surface at specific latitudes are limited to just a few kilometers for the frozen orbit, whereas variations at specific latitudes for non frozen orbits can exceed 150 km. Consequently, the frozen orbit uniform altitude profile is useful from an operational standpoint in that the complexity in sequence planning is greatly reduced.

Figure 2 shows the altitude variation with latitude for orbits representative of the three different types of orbits existing in the 200 to 430 km altitude range. Note that the maximum altitude variation at a given latitude for circulating apses orbits in this PSO altitude design space is 170 km. All altitudes are measured with respect to an ellipsoid based on the MOLA (Mars Orbiter Laser Altimeter) triaxial ellipsoid. As described in the MRO Planetary Constants Document[5], this simplified ellipsoid has an equatorial radius of 3396.19 km and a polar radius of 3376.2 km.

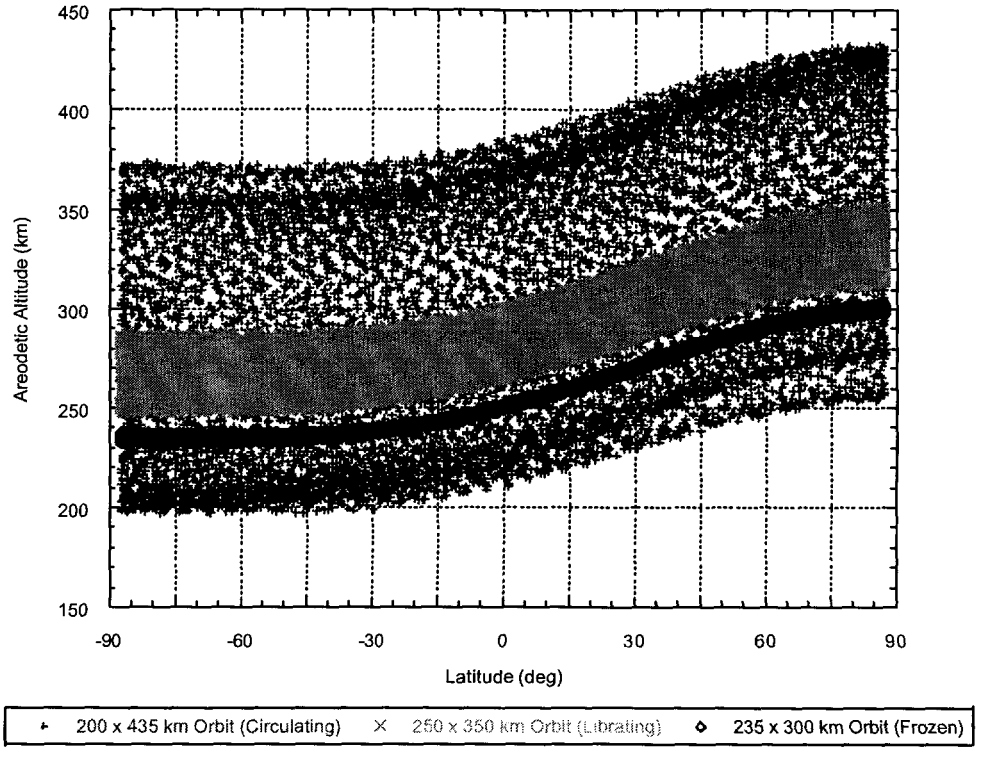

Figure 2: Altitudinal Variation with Latitude for Orbits at Mars with Frozen, Librating, and Circulating Apses

A frozen orbit within the 200 to 430 km altitude range considered for the PSO offers a few design tradeoffs. Because the MRO reference payload consists of instruments involved in targeted investigations, a frozen orbit helps to simplify the targeting planning and sequencing due to its predictability and small variation in altitude with latitude. The payload design is simplified in a frozen orbit, since the instruments do not have to accommodate large altitude and ground speed variations. The frozen orbit also offers the lowest altitudes across the entire planet of any type of orbit within the PSO altitude design space. However, non frozen orbits are better for the instruments when operating in the survey and mapping observational modes because of the variation in altitude across the planet and thus the ability to gain access to more of the planet at a

faster rate. For those reasons, some of the instruments explicitly desired an orbit with at least some altitudes higher than 300 km.

As was previously mentioned, another tradeoff in the orbit selection process is the amount of fuel necessary to achieve, maintain, and exit the orbit. Lower orbits exhibit a higher demand on the spacecraft resources to enter and exit the orbit than higher orbits do. Additionally, lower orbits at Mars require more fuel to maintain the orbit because they experience a higher drag perturbation overall due to the increased atmospheric density. Aerotorque and gravitational force management become more of a concern to the spacecraft attitude control at lower altitudes as well. To accommodate the increase in atmospheric and gravitational disturbances without significantly impacting the spacecraft design, spacecraft in lower orbits require angular momentum desaturation maneuvers more often. These maneuvers have the potential to corrupt science and navigation data by adding excess jitter to the spacecraft; thus introducing noise, or to even interrupt science operations altogether. Incorrect navigation data affects the validity of the long-term orbit predictions which are used in the targeting planning process in the timing sequences for image acquisition. Accordingly, a desire both from a fuel efficiency standpoint and a science and navigation perspective is to minimize the frequency and magnitude of desat maneuvers required to keep the spacecraft stable.

The final consideration in the PSO selection is the desired groundtrack pattern. The pattern is a function of the orbit semi-major axis, inclination, and eccentricity; however, a particular desired repeating ground trace pattern is defined mainly by the semi-major axis. In order to meet the science objectives of the mission, an orbit with a groundtrack that repeats within one to two weeks to provide repeated targeting opportunities is desired. An orbit with a groundtrack that provides uniform global coverage over the course of the two-year science period for global mapping is desired as well. Because the MRO spacecraft pointing capability crosstrack from nadir is limited to $\pm 30°$, a repeated targeting opportunity is defined such that a 20° off-nadir turn by the spacecraft at 300 km altitude can produce an opportunity to view a particular ground location a second time within a 7 to 21 day period of time. This corresponds to a groundtrack spacing at the equator of approximately 100 km. The exact groundtrack spacing achieved by an orbit is dependent on the number of days in which it is desired for the repeat to take place, the length of the Mars day, and the semi-major axis of the orbit.

The order in which the 100 km groundtrack spacings at the equator are built up is important in the desired PSO groundtrack pattern as well. Rapid and evenly distributed coverage is preferred so that the global groundtrack pattern does not have wide holes which take long periods of time to fill in. A complete discussion of groundtrack design including the equations for groundtrack spacing, and the secular changes in node and argument of periapse can be found in Ref. 6.

PRIMARY SCIENCE ORBIT ANALYSIS

It is clear in the discussion above that there are several design constraints and tradeoffs in the selection of the final PSO. Accordingly, studies were conducted using varied types of orbits within the desired PSO altitude range to determine the best orbit design which met the desired mission and science criteria within the spacecraft capability and mission performance.

Once the PSO altitude design space was characterized in terms of the types of orbits existing within it, the design process focused on the groundtrack characteristics of orbits within the PSO altitude design space. Because the groundtrack spacing over one repeat cycle is entirely dependent on the length of the repeat cycle and not the orbit type, analyses showed that the number of days required to achieve the desired 100 km groundtrack spacing at the equator for the PSO is 16-17 sols (Martian days), or 17-18 days. Figure 3 illustrates this correlation between groundtrack spacing and the number of sols to repeat.

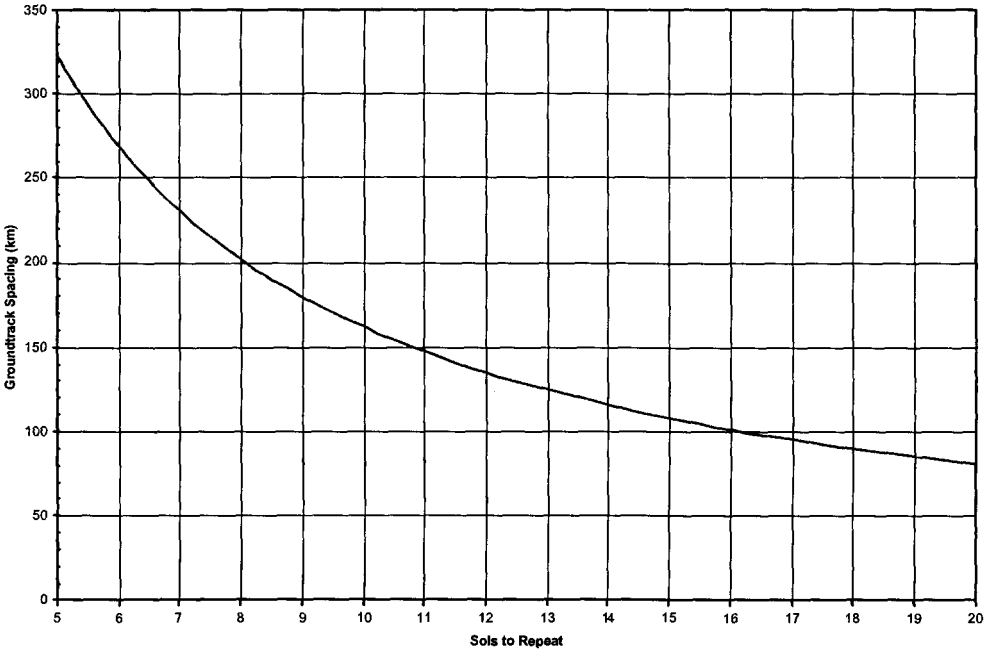

Figure 3: Groundtrack Spacing and Targeting Cycle Duration

Many possible orbits exist in the PSO altitude design space which exhibit the 16-17 sol repeat cycle. However, the order in which each of these candidate orbits build up the 100 km groundtrack spacings at the equator is varied. Some of the orbits in the PSO

altitude design space fit the desired pattern of rapid and evenly distributed coverage, while others build up coverage in slowly widening bands. The parameter Q can be used to reflect how the groundtracks fill in the gaps between successive orbits:[7]

(1) $$Q = \text{Orbits to exact repeat} / \text{Sols to exact repeat}$$

Candidate orbits in the PSO altitude design space meeting the 100 km groundtrack spacing have approximate Q values ranging from 12.93 to 13.35. At the beginning of each 16-17 sol repeat cycle, orbits with Q values closer to integer numbers have groundtracks which lie nearly on top of the groundtracks of the previous repeat cycle, whereas orbits with more fractional Q values have groundtracks that have shifted left or right of the previous repeat cycle's groundtracks by the fractional part of the Q value. Thus, an orbit with a Q value of 12.93 builds up coverage slowly and in clusters. An orbit with a Q value of 13.35 builds up coverage at a faster and more evenly distributed rate.

Figures 4 and 5 depict the required reference altitude (semi-major axis minus equatorial radius of Mars) and corresponding periapsis and apoapsis altitudes of frozen and non frozen orbits as a function of the Q parameter. It can be seen in the figures that orbits with Q values that produce the desired 100 km spacing all have reference altitudes in the 200 to 325 km range. Furthermore, as the Q values tend towards orbits which build up the preferred rapid and evenly distributed coverage, the periapsis altitudes of those orbits are decreasing. Non frozen orbits with Q values greater than 13.2 do not fit within the PSO altitude design space because their periapsis altitudes dip below 200 km.

Analyses conducted by the flight system showed that orbits at Mars spending more overall time at lower altitudes required more frequent desat maneuvers due to the accumulated momentum buildup. The amount of propellant necessary to accommodate these maneuvers proved to be too much to consider any orbits with reference altitudes below 250 km. Thus, the design space for the PSO was narrowed to those orbits with reference altitudes between 250 km and 275 km. Non frozen orbits within this reference altitude range are those with Q values greater than 13.2. Accordingly, the frozen orbit geometry was selected for the final PSO design. The details of the characteristics of the final PSO are presented in the next section.

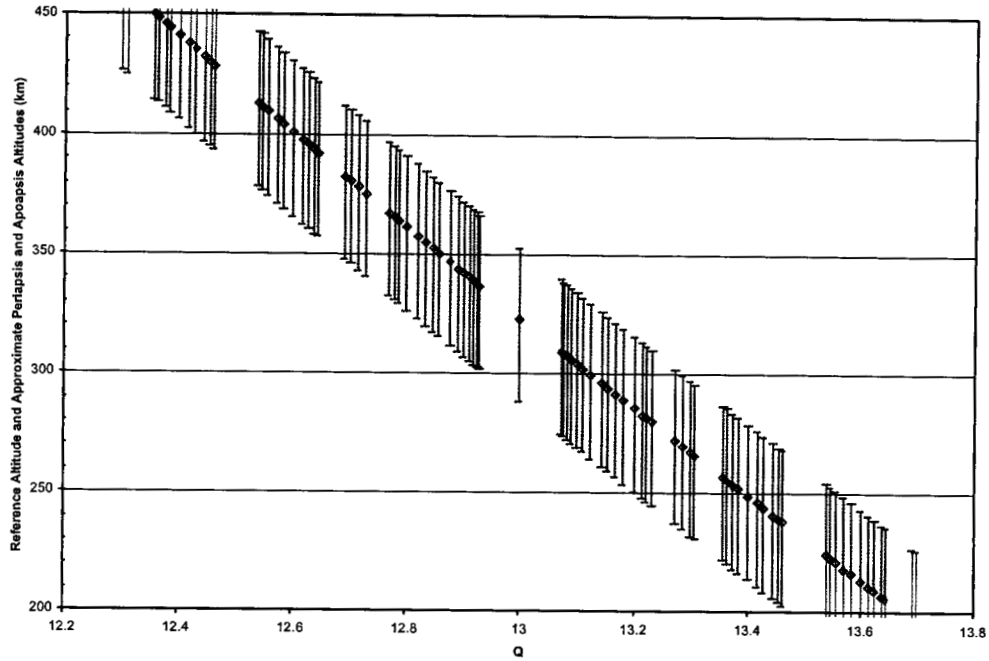

Figure 4: Required Frozen Orbit Altitudes for Desired Groundtrack Spacing

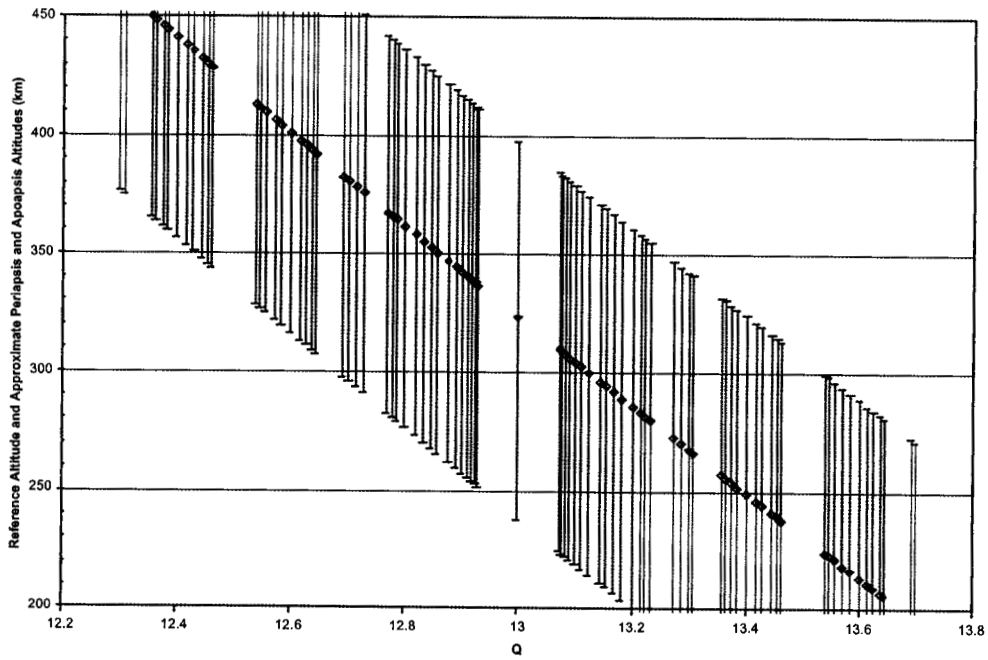

Figure 5: Required Non Frozen Orbit Altitudes for Desired Groundtrack Spacing

PSO CHARACTERISTICS

The PSO is designed to satisfy both science and mission requirements, as outlined in the previous sections. The exact semi-major axis of the PSO is chosen to be consistent with the desired groundtrack repeat cycle. The eccentricity is determined by the frozen orbit geometry; then the inclination is determined such that the orbit is Sun-synchronous. Reference primary science orbital elements are shown in Table 1. It should be emphasized that the elements in Table 1 are osculating, and so will change throughout the orbit (eccentricity in particular). Views of the PSO from Equatorial and Polar perspectives are shown in Figure 6.

Classical Orbital Elements at Apoapsis, Mars centered, equator and equinox of epoch (IAU)		
Orbit Epoch, t_0	**15-July-2006 01:00:00.00 ET**	
Parameter	**Value**	**Characteristic**
Semi-Major Axis, a	3648.5995 km	Consistent with: 16 sol target cycle
Eccentricity, e	0.01218	Consistent with: Frozen Periapsis f(e, ?)
Inclination, i	92.6426 deg	Consistent with: Sun-synchronous f(Ra, Rp, i)
Ascending Node, Ω	-10.7004 deg	Consistent with: 3:00 PM ± 15 minutes LMST
Argument of Periapse, ω	-90.0 deg	Frozen: Over South Pole
Mean Anomaly of Epoch	180.0 deg	Variable: 0 to 360 deg
Periapsis Altitude, Hp	251.7529 km	Average: 255 ± 5 km
Apoapsis Altitude, Ha	316.7893 km	Average: 320 ± 5 km
Nodal Period	6732.4251 secs	Consistent with: 16 sol target cycle

Table 1: Primary Science Orbit Reference Elements

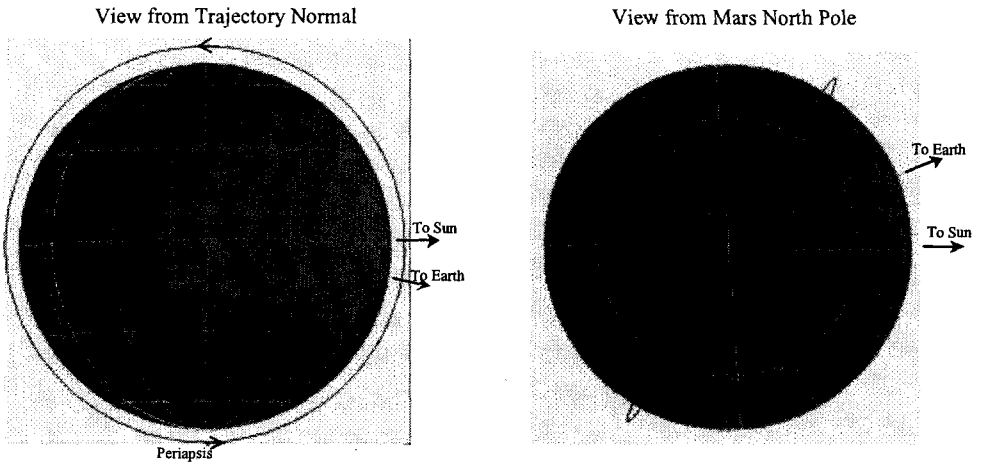

Figure 6: Views of the Primary Science Orbit

Figure 7 illustrates the variation of the Local Mean Solar Time and Local True Solar Time of the node over the two-year science phase of the MRO mission. Note that while the Local Mean Solar Time of the node does drift by a few minutes, it essentially remains constant as is desired with the Sun-synchronous PSO design. The selection of the 3 p.m. Local Mean Solar Time orientation of the node is chosen as a compromise between the conflicting desires of two of the instruments onboard the MRO spacecraft: the high resolution camera and the spectrometer. Images acquired with a camera show better distinction of surface characteristics when the surface lighting conditions at image acquisition are such that objects have shadows. Conversely, images acquired with the use of a spectrometer prefer lighting conditions at the surface to be earlier in the day.

Figures 8 and 9 show the spacecraft altitude variation with latitude throughout the primary science phase and as a function of time since periapsis for one revolution of the PSO. Note the characteristic frozen orbit 65-70 km altitude range between periapsis and apoapsis due to the shape of the Mars gravity field. Also note that the altitude variation at specific latitudes is only 5-6 km. Figure 10 shows the MRO, MGS, and Odyssey spacecraft altitude variation with latitude. The MRO PSO is approximately 120 km below the lowest orbiter (MGS) currently at Mars.

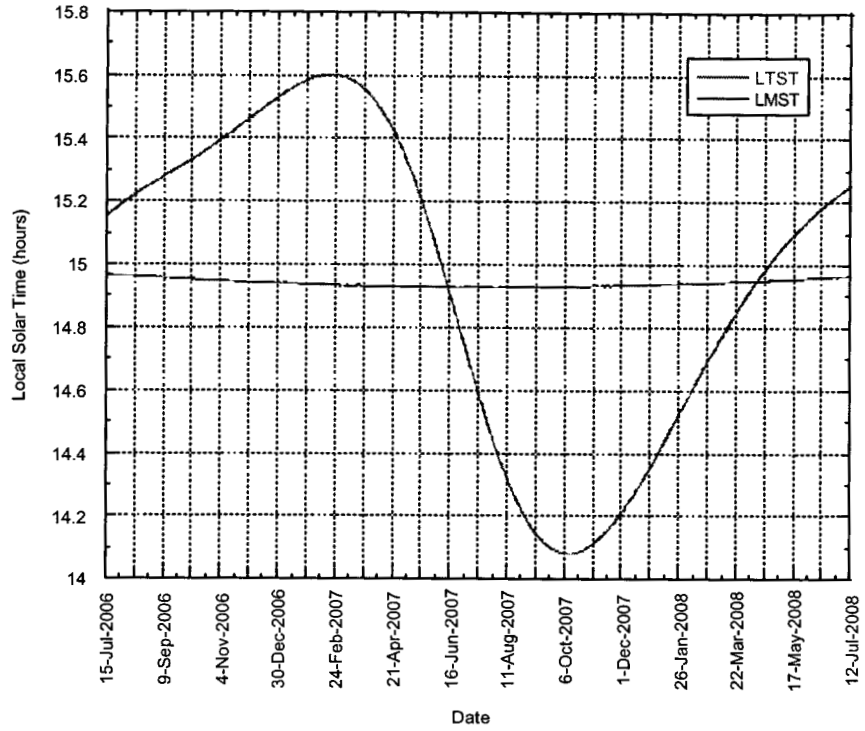

Figure 7: PSO Local Mean and True Solar Times

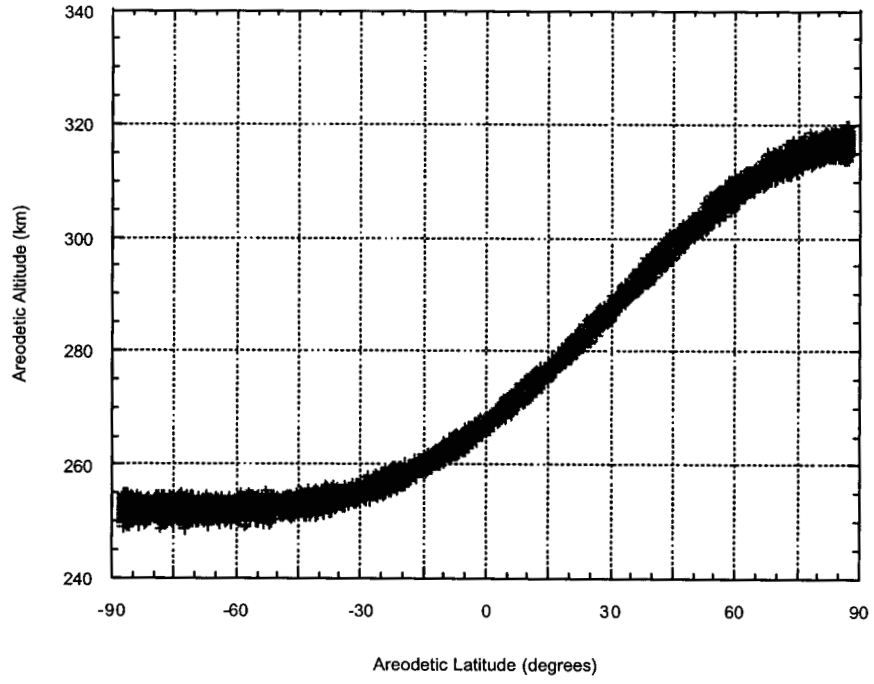

Figure 8: PSO Altitude Variation with Latitude

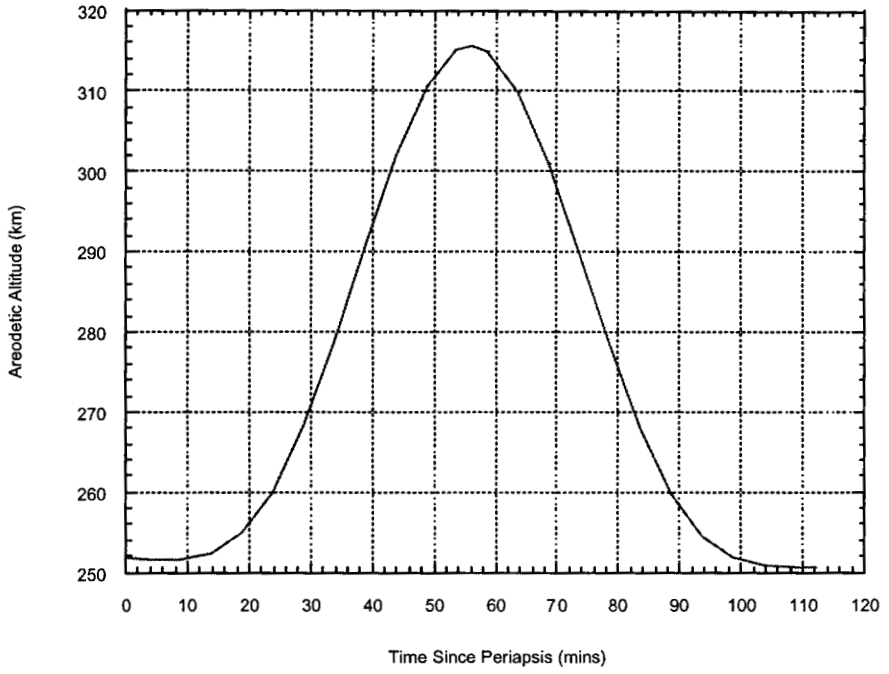

Figure 9: PSO Altitude Variation Over One Orbit

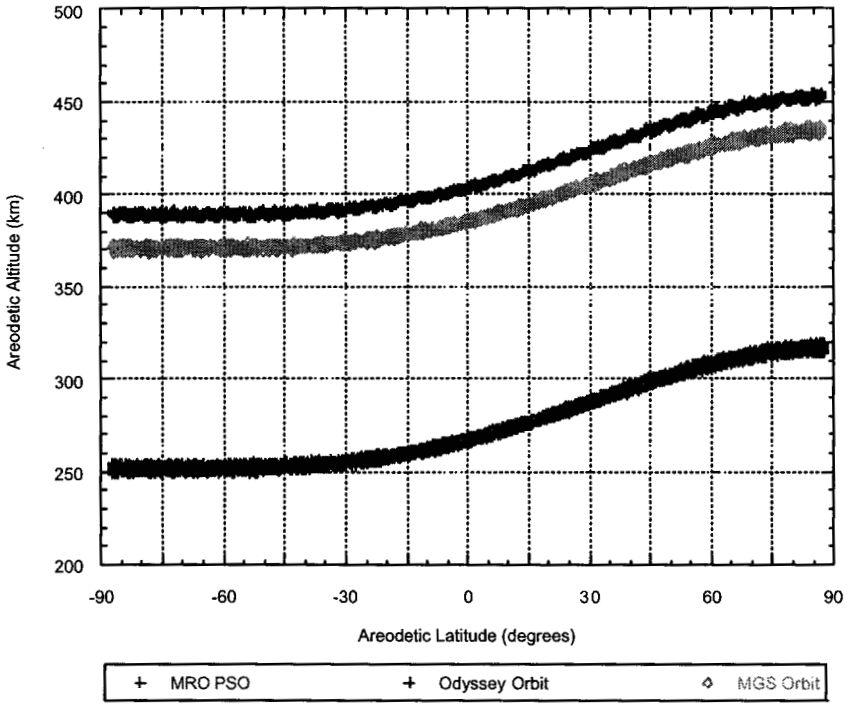

Figure 10: MRO, MGS, and Odyssey Altitude Variation with Latitude

As stated previously, the PSO groundtrack is designed to repeat on a short-term basis to provide global access and repeated targeting opportunities, as well as to provide uniform global coverage of Mars over approximately half a Martian year. The PSO groundtrack short-term repeat cycle is 16 sols (17 days) in order to be consistent with the desired 100 km spacing at the equator. This short-term repeat occurs in 211 revs, and is called the targeting cycle. Thus, the Q value for the PSO is (211 orbits) / (16 sols) = 13 3/16. This Q value builds up the desired 100 km separation rapidly and evenly. After 16 sols, rev 212 of the PSO is 3/16 of the distance between rev numbers 1 and 2. Over the course of the 17 day targeting cycle, 300 km separation at the equator is achieved on the order of 5 to 6 days.

Figure 11 illustrates the PSO short-term 17 day targeting cycle. The figure shows that the separation between any two successive equatorial groundtrack PSO crossings is 27.3 degrees in longitude. Orbit rev number 2 falls 1618.2 km west of rev number 1. Figure 11 also illustrates the targeting cycle walk. Orbit rev number 212 falls 30.6 km west of rev number 1. This westward walk every 17 days provides an overlapping buildup of coverage and is referred to as the superwalk.

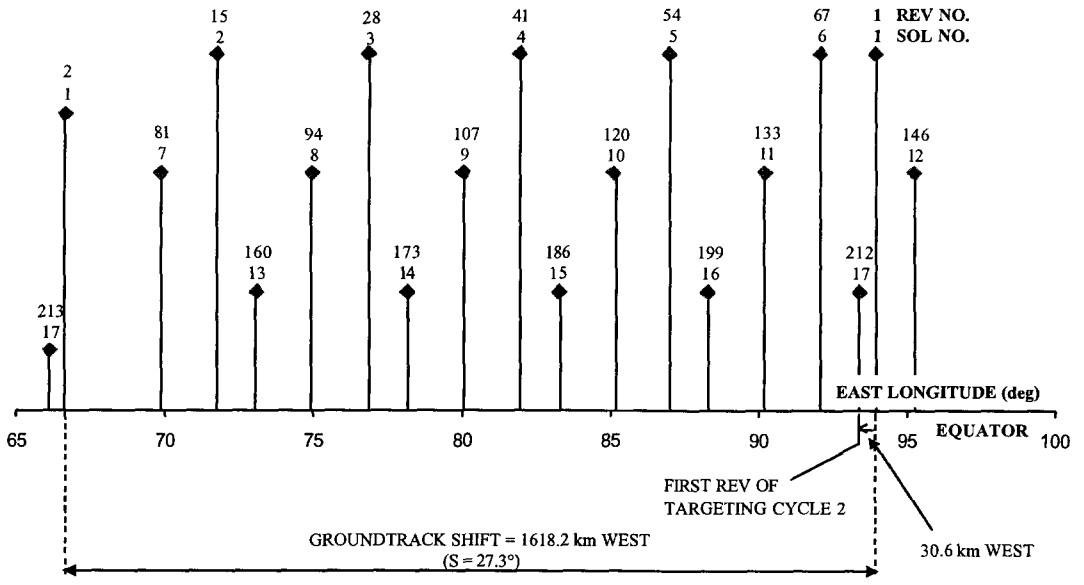

Figure 11: PSO Short-Term Groundtrack Repeat Cycle (Targeting Cycle)

With the 30.6 km targeting cycle superwalk, the PSO groundtrack would provide uniform coverage of Mars and exactly repeat after 4602 revs and 359 days (349 sols) if the orbit could be perfectly maintained. This 359 day period is referred to as the orbit

supercycle. The ultimate interval at the equator between adjacent groundtracks after 359 days would be 0.078 degrees, or 4.64 km. Figure 12 demonstrates the ideal PSO repeat cycle. In Figure 12, orbit rev number 4603 falls exactly over rev number 1, and there is exactly 4.64 km separating adjacent groundtracks.

Due to gravity field perturbations and orbit control uncertainties; however, the very fine orbit groundtrack spacing will not be achieved exactly. The intervals between adjacent groundtracks will not be evenly spaced, although the intervals will still be small. The orbit supercycle will not exactly repeat, but instead will exhibit a small walk similar to the targeting cycle superwalk. Further analysis is necessary to determine if orbit control will keep the groundtracks more evenly spaced throughout the repeat cycle.

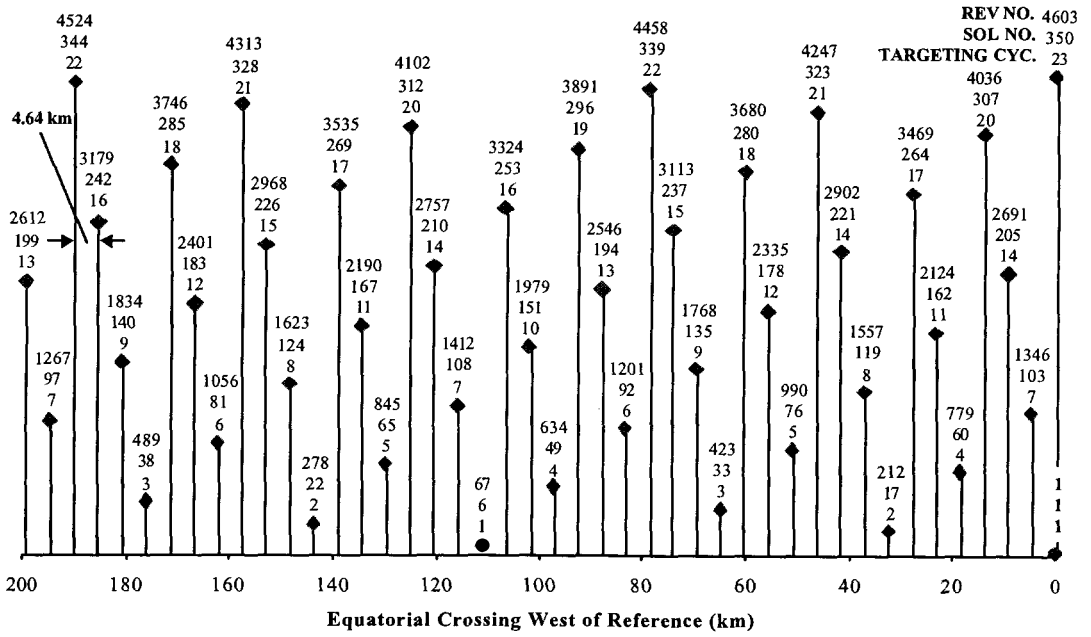

Figure 12: PSO Ideal 349 Sol Repeat Cycle Pattern

The design of the PSO groundtrack pattern provides repeated opportunities to observe particular Martian surface sites. The spacecraft is capable of scanning ±30 degrees crosstrack of nadir, which is equivalent to approximately 145 to 185 km on the surface for the altitude range of the PSO. The number of opportunities to revisit a particular site in daylight (Sun elevation ≥ 15°) is dependent on the latitude of the site and the roll angle needed to view it. For instance, a location on Mars between the equator and ±30 degrees latitude will be viewable at least once every two 17-day targeting cycles at roll angles of less than 10 degrees off-nadir. Locations in the 30-45 degree latitude range will be viewable one to two times during every two 17-day targeting cycles at the

same roll angles, while locations at higher latitudes will be viewable at least once during any 17-day targeting cycle with roll angles of less than 10 degrees. Opportunities to view the poles only occur when the roll angle is at 30 degrees. Higher latitudes do not have opportunities during certain periods of the Martian year due to the seasonal changes in Sun elevation.

Opportunities are evenly distributed between pointing to the left or right of the groundtrack except at the poles. When viewing the North Pole, the spacecraft will always be pointing to the right of the groundtrack; when viewing the South Pole the spacecraft will always be pointing to the left of the groundtrack. Increasing the roll angle increases the number of opportunities during any particular targeting cycle; however, because of impacts to global mapping investigations, targeted observations with roll angles less than 10 degrees will be preferred.

Figure 13 shows the nadir point groundspeed as a function of areodetic latitude. The date chosen for this plot is November 8, 2006, which is the start of the Primary Science Phase and very close to Northern mid-summer. The figure helps to determine the duration of viewing opportunities for sites at various latitudes.

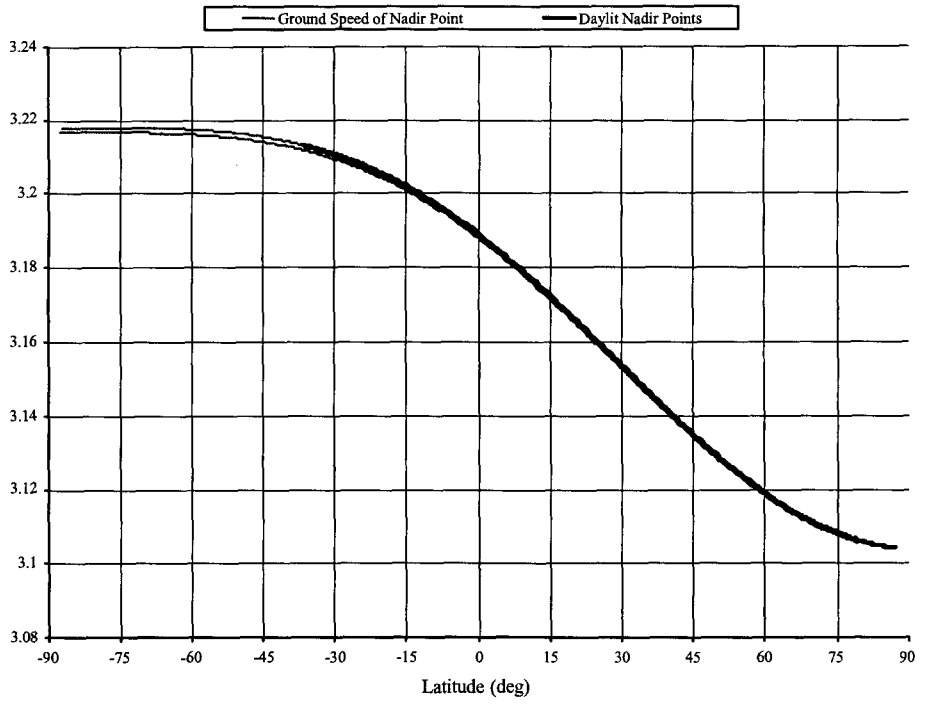

Figure 13: Nadir Point Groundspeed (km / sec) and Latitude (8-Nov-2006)

CONCLUSION

This paper has presented the baseline Primary Science Orbit design for the 2005 Mars Reconnaissance Orbiter mission. The final PSO design satisfies the scientific objectives of the mission within the capability of the spacecraft and mission performance. Furthermore, the final PSO design offers improved viewing characteristics over the original baseline PSO design: Both the amount of time below 300 km altitude and above sunlit surfaces is greater than in the initially considered 200 x 430 km elliptical orbit. The Mars Reconnaissance Orbiter will become the lowest orbiter ever at Mars, and thus will greatly enhance the understanding of Mars by returning new scientific observations at spatial resolutions better than any other preceding Mars orbiter.

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