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Mars Mission Profile Options and Opportunities

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Abstract

Mars Mission profile options and mission requirements data are presented for Earth-Mars opposition and conjunction class round-trip flyby and stopover mission opportunities. The opposition class flyby and sprint mission uses direct transfer trajectories to and on return from Mars. The opposition class stopover mission employs the gravitational field of Venus to accelerate the space vehicle on either the outbound or inbound leg in order to reduce the propulsion requirement associated with the opposition class mission. The conjunction class mission minimizes propulsion requirements by optimizing the stopover time at Mars. Representative interplanetary space vehicle systems are sized to compare and show sensitivity of the initial mass required in low Earth orbit to one mission profile option and mission opportunity to another.

Introduction

Ballistic mission profiles are convenient flight path approximations based on the use of instantaneous velocity impulses (AV) near the planetary bodies to enter free-fall (coasting) trajectory segments between the planets. The free-fall segments are represented by "two-body" equations that result from integration of the differential equations describing the motion of a space vehicle in the force field of a control gravitational body. To achieve the velocity impulse, high thrust chemical or nuclear propulsion systems were assumed with initial thrust acceleration greater than 0.1g.

Data are presented for the Mars opposition and conjunction class mission profiles. These profiles are pictorially described in Figure 1. Two categories of the opposition class profiles were considered: a Mars flyby with no landing or stay at Mars; and a Mars stopover mission with a short stay time of 60-80 days. These are relatively high energy mission, either at departure from or arrival at one of the planets. The conjunction class mission profile requires low Hohmann energy transfer trajectories which are achieved by optimizing the stay time, from 300 to 550 days, at Mars. Another type of Earth-Mars-Earth trajectory is the free-fall approximately 1 1/4 or 1 1/2 year periodic orbit which may find use as an orbiting connecting node.

Figure 1 Example Mission Profiles
For opposition-class missions, a Venus swingby utilizes the gravitational field of Venus to either accelerate or decelerate the space vehicle as it passes by the planet, thus reducing the high energy requirements. An acceleration effect is desired for an outbound Venus swingby enroute from Earth to Mars and a deceleration effect is desired for an inbound Venus swingby enroute from Mars to Earth. The time contained in this paper is year 1997 to year 2030.

Mars Mission Profiles
Mars round-trip flyby trajectories are the Martian counterpart of lunar flyby return flight paths. A round-trip flyby may be attractive as an early manned mission to Mars, which should reconnoiter the planet at close range. In order to construct a flyby trajectory, three requisite characteristics of the outbound and inbound transfer trajectories are as follows: (1) the outbound arrival and inbound departure dates at Mars must be the same, (2) the hyperbolic excess speed \( V_e \) at Mars on the inbound and outbound legs must be equal, and (3) the angle between the hyperbolic excess speed of the approach and departure must be less than a certain critical value in order not to require an excessive amount of powered flyby maneuver. The Venus swingby profile involves one or more gravitational encounters with Venus and often requires significantly less AVs than direct trajectories to Mars and return. The conjunction class mission employs a minimum energy transfer trajectory on both the outbound and inbound trajectories. This minimum trajectory is realized by optimizing the Mars stay time to allow near-Hohmann type transfer orbits. In order to achieve a short mission time, sprint mission. (420 to 500 days) with reasonable mass required in low Earth orbit, a direct opposition mission mode could be employed with a conjunction type mission mode for the outbound leg for a cargo vehicle. The manned interplanetary vehicle would use the short opposition mission profile. This type of mission profile is the split option trajectory as displayed in Figure 1.

Mission Opportunities
Mission opportunities for standard direct flights to Mars will occur near the Earth-Mars opposition, and precede by 90 to 180 days the opposition dates which will occur on the average every 26 months. Because of the eccentricity of Mars orbit, the mission trajectory profile changes from one opposition to the next. The cyclic pattern of mission profile variation repeats every 15 years or every 7 oppositions [1]. The relative positions of the Earth-Mars oppositions are indicated in Figure 2 for two periodic cycles of oppositions from year 1997 to 2031. The slight inclination of the Mars orbit, with respect to the ecliptic plane, causes an interplanetary transfer trajectory also to be inclined to the ecliptic, but this effect is small compared to the effect caused by the eccentricity. The relative position of Earth and Mars for an opposition class

Figure 2  Earth-Mars Opposition for Years 1997 - 2031
mission causes the energy requirements to be excessive because the flight time for a near-Hohman outbound leg is such that, at Mars arrival, Earth is ahead of Mars in heliocentric longitude, i.e., Mars arrival occurs after opposition. This makes it impossible to employ a near-Hohman transfer for the inbound leg; the required heliocentric transit angle must greatly exceed the Hohmann transfer angle of 180 degrees. Thus, it is never possible to leave Earth on a minimum energy inbound leg. The relative position of Earth at Mars arrival can be adjusted with a swingby of Venus enroute to Mars on an outbound leg or swingby of Venus enroute to Earth on an inbound leg. The major advantage of making a swingby of Venus is that the hyperbolic encounter with the planet changes the velocity of the space vehicle relative to the Sun. The magnitude of the velocity change can be large enough to make a significant desirable change in the heliocentric trajectory. The high energy level required can be avoided in the conjunction class mission mode where near-Hohmann transfers can be used on both the outbound and inbound leg by adjusting the stay time at Mars appropriately. 

The availability of a Venus swingby mode can be determined by the following facts [1]: (1) The space vehicle will normally pass inside near the orbit of Venus either on the outbound leg or on the inbound leg of a direct roundtrip mission to Mars. Figure 1 illustrates these conditions for an outbound leg and an inbound leg. (2) The gravity field of Venus is sufficiently powerful to significantly shape the interplanetary transfer trajectory in a desirable way. (3) The angular position of Venus is generally available either on the outbound leg or on the inbound leg. The initial step in determining a Venus swingby trajectory profile for a given mission opportunity is the determination of the relative heliocentric position of the three planets, Venus, Earth, and Mars.

**Interplanetary Trajectory Calculations**

The computer program used in this work to compute the interplanetary trajectory characteristics is based on the restricted two-body (patched conic) approximation of the interplanetary space vehicle trajectory. While the vehicle is within the sphere of influence of Venus or Mars, the swingby planet or flyby planet respectively, it is assumed to be on a free-flight hyperbolic trajectory about Venus or Mars, and gravitational effects of all other bodies are neglected. There is no change of energy with respect to the swingby or flyby planet, Venus or Mars. Conservation of energy requires that the magnitude of the vehicle's velocity, relative to Venus or Mars, as it leaves the sphere of influence of Venus or Mars must equal to the magnitude of its velocity as it enters the sphere of influence approaching Venus or Mars. If the required angle of deflection, bend angle, at Venus or Mars is too large to be achieved by constraining the periapsis altitude to one-tenth of the planet radii, a propulsive maneuver is effected in conjunction with the Venus or Mars gravity field to give the required bend angle.

Independent optimization of each leg is possible when the conjunction class roundtrip mission is considered. The outbound leg takes place near one opposition and by adjusting the stopover time at Mars appropriately, the inbound leg will take place near the following opposition. Examination of single leg trajectory data [2] indicates that if the outbound and inbound legs of a roundtrip mission could be optimized separately, then departure and arrival hyperbolic excess speeds at both Earth and Mars of less than 0.10 to 0.15 EMOS (Earth Mean Orbital Speed at 97,700 ft/sec) could be attained. The total mission time of conjunction class missions is greater than the mission time of the Venus swingby opposition class mission (950 to 1004 days for conjunction class compared to 558 to 737 days for Venus swingby).

**Assumptions for Trajectory and Mass Optimization**

Pertinent assumptions used in this study are given for the departure and capture orbit parameters, propulsion stages and planetary spacecraft elements (Figure 3). The interplanetary space vehicle was assumed to be assembled in, and depart from the 270 nm altitude, 28.5 degrees inclination, Space Station circular orbit. For the all propulsive flyby case, required interplanetary velocity increments are achieved by two propulsive stages. The first propulsion stage effects the Earth escape maneuver. The second propulsion stage brakes the Earth return capsule into a 24-hour elliptical orbit at Earth return. Each of the two propulsion stages' mass fractions were developed using scaling equations. For the Mars aerocapture and Earth return aerobraked case, the interplanetary velocity increments are achieved by two propulsive stages. The first and second stages were used to effect the Earth and Mars escape maneuvers, respectively.

Venus swingby, outbound, inbound, or double swingby, was used to lower the energy required for the Mars opposition class missions. The Venus closest approach distance was constrained to be equal to or greater than 0.1 planet radii (330 nm).

For the conjunctions class mission, type I (less than 180 degrees) or type II (greater than 180 degrees) Hohmann transfer trajectories were used. The Mars stopover time was optimized to achieve minimum initial weight to be assembled in the Space Station's orbit. The variable propulsion stages were sized using general scaling weight laws which are dependent upon propellant loading. These coefficients are input to the interplanetary trajectory shaping program. Up to six major interplanetary maneuvers can be optimized.

**Representative Mission Profiles**

Tables 1, 2, and 3 present summary data for the Mars flyby, opposition class stopover mission with Venus swingby, and conjunction class missions for missions
STUDY ASSUMPTIONS

TIME PERIOD OF CONSIDERATION: YEAR 1997 TO 2045

PLANET DEPARTURE AND CAPTURE ORBIT PARAMETERS

EARTH DEPARTURE
- CIRCULAR ORBIT ALTITUDE = 270 N.MI

MARS CAPTURE
- 24 HR ELLIPTIC ORBIT PERIAPSIS ALTITUDE = 270 N.MI

MARS ESCAPE
- 24 HR ELLIPTIC ORBIT PERIAPSIS ALTITUDE = 270 N.MI

EARTH CAPTURE
- 24 HR ELLIPTIC ORBIT PERIAPSIS ALTITUDE = 270 N.MI

HELIODYNAMIC PROFILE

SPLIT OPTION USES DIRECT INVERTED STOPOVER MISSION MODE (SEE FIGURE 1)
VENUS SWINGBY MODE (OUTBOUND, INBOUND OR DOUBLE SWINGBY)
VENUS MINIMUM CLOSEST APPROACH EQUAL 0.1 PLANET RADIUS (330 N.MI)
CONJUNCTION CLASS MISSION USES TYPE I OR TYPE II TRAJECTORIES

INTERPLANETARY SPACE VEHICLE

SPACECRAFT: MISSION MODULE WEIGHT = 88,500 (1)
MARS EXCURSION MODULE WEIGHT = N/A
PROBES WEIGHT = 20,000

PROPELLANT STAGES
- FIRST STAGE
  - MASS FRACTION (\(x\)) = 482
  - Isp (SEC) = LOX/LH2

- SECOND STAGE
  - MASS FRACTION (\(x\)) = 482
  - Isp (SEC) = LOX/LH2

- THIRD STAGE
  - MASS FRACTION (\(x\)) = 482
  - Isp (SEC) = LOX/LH2

(1) INCLUDES A 7,500 LB EARTH RETURN MODULE

* SPLIT MISSION OPTION IS A 540 N.MI. CIRCULAR CAPTURE ORBIT

Figure 3 Mars Explorations Post Space Station Missions

MARS 1-YR ROUND-TRIP MISSIONS (OPPOSITION CLASS)*

<table>
<thead>
<tr>
<th>LAUNCH DATE</th>
<th>C3 (km/SEC)^2</th>
<th>ΔV@MARS (km/SEC)</th>
<th>C3 @ EARTH RETURN (km/SEC)^2</th>
<th>ΔVTOT (km/SEC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/28/97</td>
<td>159.6</td>
<td>0.802</td>
<td>237</td>
<td>18.239</td>
</tr>
<tr>
<td>4/2/99</td>
<td>99.5</td>
<td>0.406</td>
<td>156</td>
<td>13.639</td>
</tr>
<tr>
<td>5/22/01</td>
<td>63.5</td>
<td>0.425</td>
<td>108</td>
<td>10.846</td>
</tr>
<tr>
<td>6/8/03</td>
<td>71.6</td>
<td>1.723</td>
<td>134</td>
<td>13.299</td>
</tr>
<tr>
<td>10/15/05</td>
<td>122.6</td>
<td>3.806</td>
<td>253</td>
<td>20.518</td>
</tr>
</tbody>
</table>

* DATA FROM REFERENCE 6

Table 1 Mars Flyby Mission
### Table 2  Mars Stopover Mission with Venus Swingby

<table>
<thead>
<tr>
<th>Mission</th>
<th>Earth Launch Date</th>
<th>Total Trip Time (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Double Swingby</td>
<td>March 1996</td>
<td>733</td>
</tr>
<tr>
<td>Outbound Swingby</td>
<td>January 1998</td>
<td>666</td>
</tr>
<tr>
<td>Inbound Swingby</td>
<td>January 2001</td>
<td>708</td>
</tr>
<tr>
<td>Outbound Swingby</td>
<td>August 2002</td>
<td>610</td>
</tr>
<tr>
<td>Outbound Swingby</td>
<td>June 2004</td>
<td>659</td>
</tr>
<tr>
<td>Inbound Swingby</td>
<td>September 2007</td>
<td>558</td>
</tr>
<tr>
<td>Double Swingby</td>
<td>January 2009</td>
<td>736</td>
</tr>
<tr>
<td>Outbound Swingby</td>
<td>November 2010</td>
<td>650</td>
</tr>
<tr>
<td>Inbound Swingby</td>
<td>November 2013</td>
<td>634</td>
</tr>
<tr>
<td>Inbound Swingby</td>
<td>November 2015</td>
<td>577</td>
</tr>
<tr>
<td>Outbound Swingby</td>
<td>April 2017</td>
<td>638</td>
</tr>
<tr>
<td>Inbound Swingby</td>
<td>June 2020</td>
<td>594</td>
</tr>
<tr>
<td>Outbound Swingby</td>
<td>October 2021</td>
<td>636</td>
</tr>
<tr>
<td>Outbound Swingby</td>
<td>September 2023</td>
<td>614</td>
</tr>
<tr>
<td>Inbound Swingby</td>
<td>November 2026</td>
<td>570</td>
</tr>
<tr>
<td>Double Swingby</td>
<td>March 2028</td>
<td>737</td>
</tr>
<tr>
<td>Outbound Swingby</td>
<td>January 2030</td>
<td>694</td>
</tr>
</tbody>
</table>

### Table 3  Mars Conjunction Class Stopover Mission

<table>
<thead>
<tr>
<th>Date of Opposition</th>
<th>Earth Launch Date</th>
<th>Mars Stopover Time (Days)</th>
<th>Total Mission Time (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>March 1997</td>
<td>November 1996</td>
<td>485</td>
<td>1025</td>
</tr>
<tr>
<td>April 1999</td>
<td>December 1998</td>
<td>485</td>
<td>1005</td>
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<tr>
<td>June 2001</td>
<td>January 2001</td>
<td>530</td>
<td>1020</td>
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<td>August 2003</td>
<td>June 2003</td>
<td>550</td>
<td>952</td>
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<td>November 2005</td>
<td>August 2005</td>
<td>374</td>
<td>944</td>
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<td>December 2007</td>
<td>September 2007</td>
<td>340</td>
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<td>February 2010</td>
<td>October 2009</td>
<td>340</td>
<td>982</td>
</tr>
<tr>
<td>March 2012</td>
<td>November 2012</td>
<td>340</td>
<td>992</td>
</tr>
<tr>
<td>April 2014</td>
<td>January 2014</td>
<td>484</td>
<td>942</td>
</tr>
<tr>
<td>May 2016</td>
<td>January 2016</td>
<td>520</td>
<td>1010</td>
</tr>
<tr>
<td>July 2018</td>
<td>June 2018</td>
<td>540</td>
<td>928</td>
</tr>
</tbody>
</table>
between 1997 and 2030 [9]. Representative profiles are presented for the three missions described in Figure 4.

The one year flyby mission departs Earth April 2, 1999 with excess hyperbolic velocity, \( C_3 \), of 99.5 km\(^2\)/sec\(^2\). A flight time of 128 days brings it to a Mars flyby date on August 8, 1999. A propulsive maneuver, requiring a \( \Delta V \) of 0.406 km/sec, is made at Mars to achieve the necessary turn angle at Mars for the Earth return trajectory. The Earth return date is April 2, 2000 with the interplanetary trajectory having a hyperbolic energy of 156 km\(^2\)/sec\(^2\). The Earth departure and return \( C_3 \)'s of 99.5 and 156 km\(^2\)/sec\(^2\) respectively, are very high for a Mars mission. However, these \( C_3 \) values can be reduced by optimizing the total mission time and by making efficient midcourse maneuvers.

The 1999 opposition outbound Venus swingby is characterized by a transfer angle between Earth and Venus of over 180 degrees, with the transfer angle between Venus and Mars of less than 180 degrees. The total transfer angle of the two trajectory transfers is slightly greater than 360 degrees. Of paramount importance is the fact that the average angular rate of the outbound leg is much greater than that of Earth in its orbit. Thus, Earth is behind Mars at Mars arrival, i.e., Mars arrival occurs much sooner than oppositions. This situation permits, as shown, a near-Hohmann type Mars-Earth trajectory to be utilized on the inbound leg. However, the Earth return hyperbolic energy, \( C_3 \), is slightly high with a value of 81.52 km\(^2\)/sec\(^2\). This \( C_3 \) level could be lowered by effectively applying a propulsive midcourse maneuver on the Mars-Earth transfer leg. The total mission time for the year 1999 outbound Venus swingby opposition opportunity is 661 days.

Aerobraking is commonly used as a means of reducing propulsion requirements for Mars missions. Earth return with aerobrake entry has been analyzed and results show that with an Earth return \( C_3 \) greater than 25 km\(^2\)/sec\(^2\) the g-load will be in excess of 5 g's. This high g-load cannot be tolerated by the astronauts. Earth return with \( C_3 \) greater than 25 km\(^2\)/sec\(^2\) will require propulsive braking in order to stay within g-load constraint.

A conjunction class mission mode for the 1999 opposition is also given in Figure 4. This mission mode uses a near-Hohmann type orbit transfer where the Mars stay time is optimized to be 485 days and the total mission duration is 990 days.

A low thrust nuclear electric propulsion trajectory using aerobraking for capture at Mars arrival and Earth return is given in Figure 5. The combined total heliocentric transfer time for the outbound and inbound leg is 500 days. The stay time at Mars plus Mars low thrust spiral time to a \( C_3 \) of zero is 100 days. This results in a total mission time of 600 days for a manned interplanetary vehicle. The total mass required in low Earth orbit is 958,300 pounds [8] for this low thrust mission profile.

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**Figure 4** Representative Mission Profiles of 1999 Opposition
Initial Mass Required in Low Earth Orbit

The initial mass required in low Earth orbit for each mission opportunity is given in Figure 6. The initial mass required ranges from 850,000 to 6,800,000 pounds for LOX/LH propellant. This range of weight for LOX/LH propellant compares to 958,000 pounds for an opposition class mission with approximately 60 days stay time at Mars using nuclear electric propulsion and aerobrake capture at Mars arrival and Earth return.

Conclusion

Optimum trajectory transfers for opposition class mission to Mars for flyby and stopover mission have been computed for attractive launch and arrival dates between years 1997 and 2018. Also, Optimum transfer for conjunction class missions to Mars have been computed for attractive opportunities for years between 1999 and 2018.

It is possible to employ an outbound or inbound Venus swingby for every Earth-Mars opposition; oppositions occur approximately every 26 months. Venus swingby permits the heliocentric transfer trajectory to be nearly tangential relative to Earth and Mars orbit upon planet departure and arrival. The mission time is increased from 20 to 50 percent employing the Venus swingby mode over the direct flights to Mars.

Optimum roundtrip trajectories for the conjunction class mission to Mars and return can be achieved by adjusting the stopover time at Mars. Near-Hohmann type trajectories can be employed both on the outbound and inbound leg with the conjunctions class mission.

Free-fall periodic orbits which travel back and forth between Earth and Mars on a scheduled interval may be

Figure 5  Low Thrust Trajectory Profile

Figure 6  Mars Exploration Mass in Earth Orbit Requirements
Chemical Propulsion (LOX/LH2)
• MISSION OPPORTUNITIES TO MARS OCCUR APPROXIMATELY EVERY 26 MONTHS; SOME VARIATION TO THIS TIME WITH SPRINT, VENUS SWINGBY AND LOW THRUST TRAJECTORIES

• OPTIMUM TRAJECTORIES FOR OPPOSITION CLASS MISSIONS TO MARS FOR FLYBY AND STOPOVER MISSIONS HAVE BEEN DETERMINED

• OPTIMUM TRANSFER FOR CONJUNCTION CLASS MISSIONS HAVE BEEN DETERMINED

• IT IS POSSIBLE TO EMPLOY AN OUTBOUND OR INBOUND VENUS SWINGBY FOR EVERY EARTH-MARS OPPOSITION

• MARS MISSIONS USING LOW THRUST TRAJECTORIES AND AEROBRAKE CAPTURE CAN BE ACHIEVED WITH TOTAL MISSION DURATION BETWEEN 500 AND 600 DAYS

• MASS REQUIRED IN EARTH ORBIT FOR MISSIONS AND OPPORTUNITIES CONSIDERED:
  
  FLYBACK 0.85 TO 4.70M LBS
  SPRINT 2.65 TO 6.80M LBS
  SWINGBY 1.60 TO 2.50M LBS
  CONJUNCTION 1.50 TO 1.70M LBS
  LOW THRUST W/AEROBRAKE ~ 1M LBS

Figure 7 Mars Mission Profile Options and Opportunities Conclusions

attractive for use as a regularly scheduled transportation system between Earth and Mars.

There is a great variation in initial mass required in low Earth orbit for the interplanetary space vehicles over a number of mission opportunities. This variation is due to the eccentricity of Mars orbit which has a perihelion distance of 1.38 A.U. and an aphelion distance of 1.66 A.U. The wide variation in initial mass may be reduced by aerocapture at Mars arrival and Earth return for the Venus swingby and conjunction class mission mode. The variation in initial mass for the conjunction class mission over a number of mission opportunities is relatively small because there is more freedom to optimize the outbound transfer to Mars and the return transfer to Earth. Concluding remarks are given in Figure 7.

References


