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MARS MISSION CONCEPTS AND OPPORTUNITIES

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ABSTRACT

Trajectory and mission requirement data are presented for Earth - Mars opposition and conjunction class roundtrip flyby and stopover mission opportunities available between 1997 and 2045. The opposition class flyby 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.

INTRODUCTION

Ballistic mission profiles are convenient flight path approximations based on the use of instantaneous velocity impulses (ΔV) 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 propulsive systems were assumed with initial thrust acceleration > 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 missions, either at departure from or arrrival 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 2 year periodic orbit which may find use as an orbiting connecting node.

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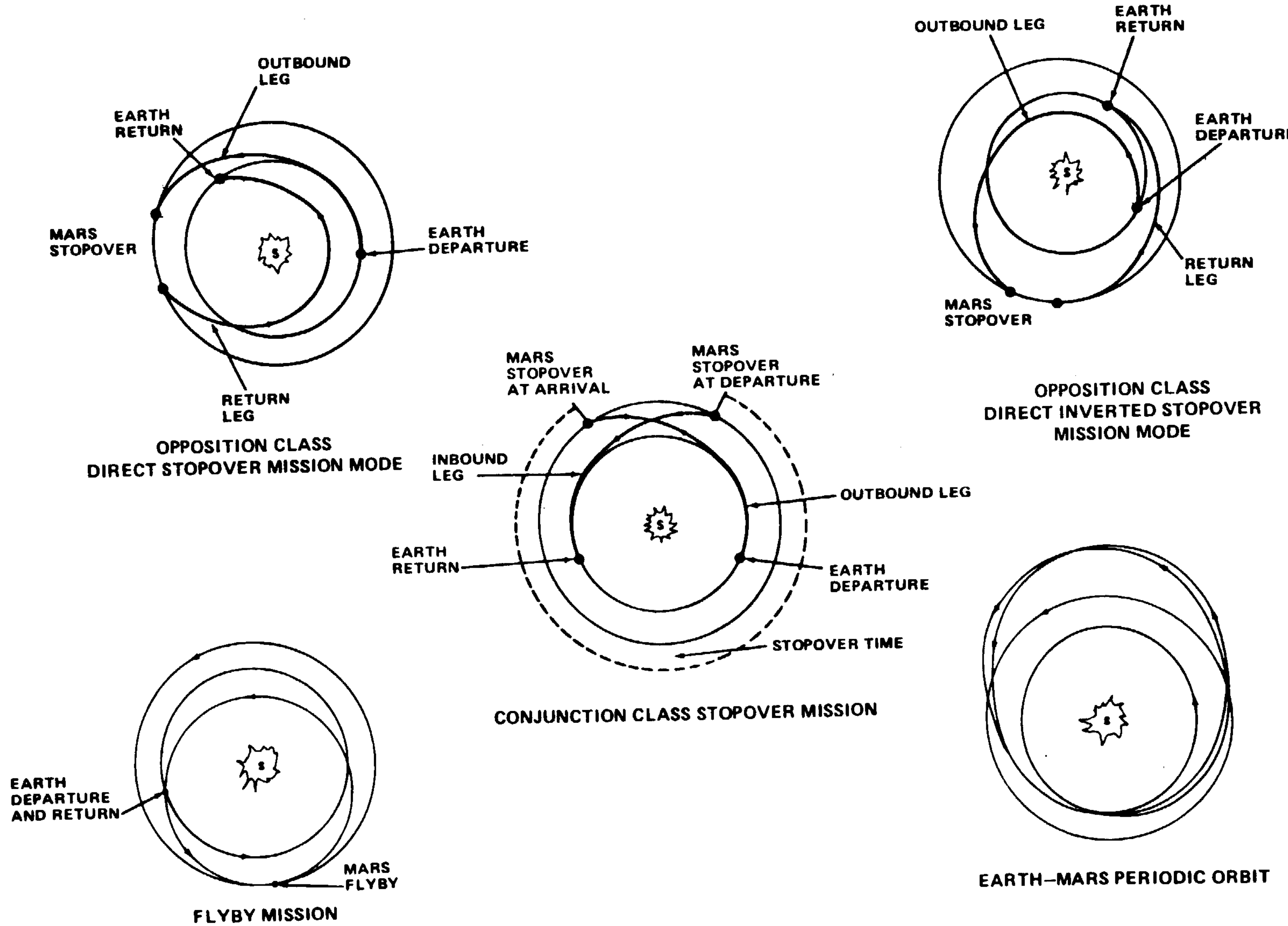

FIGURE 1. EXAMPLE MISSION PROFILES

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 2045.

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 would 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_∞) 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 ΔV's than direct trajectories to Mars and return.

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 mission causes the energy requirement to be excessive because the flight time for a near-Hohmann outbound leg is such that, at Mars

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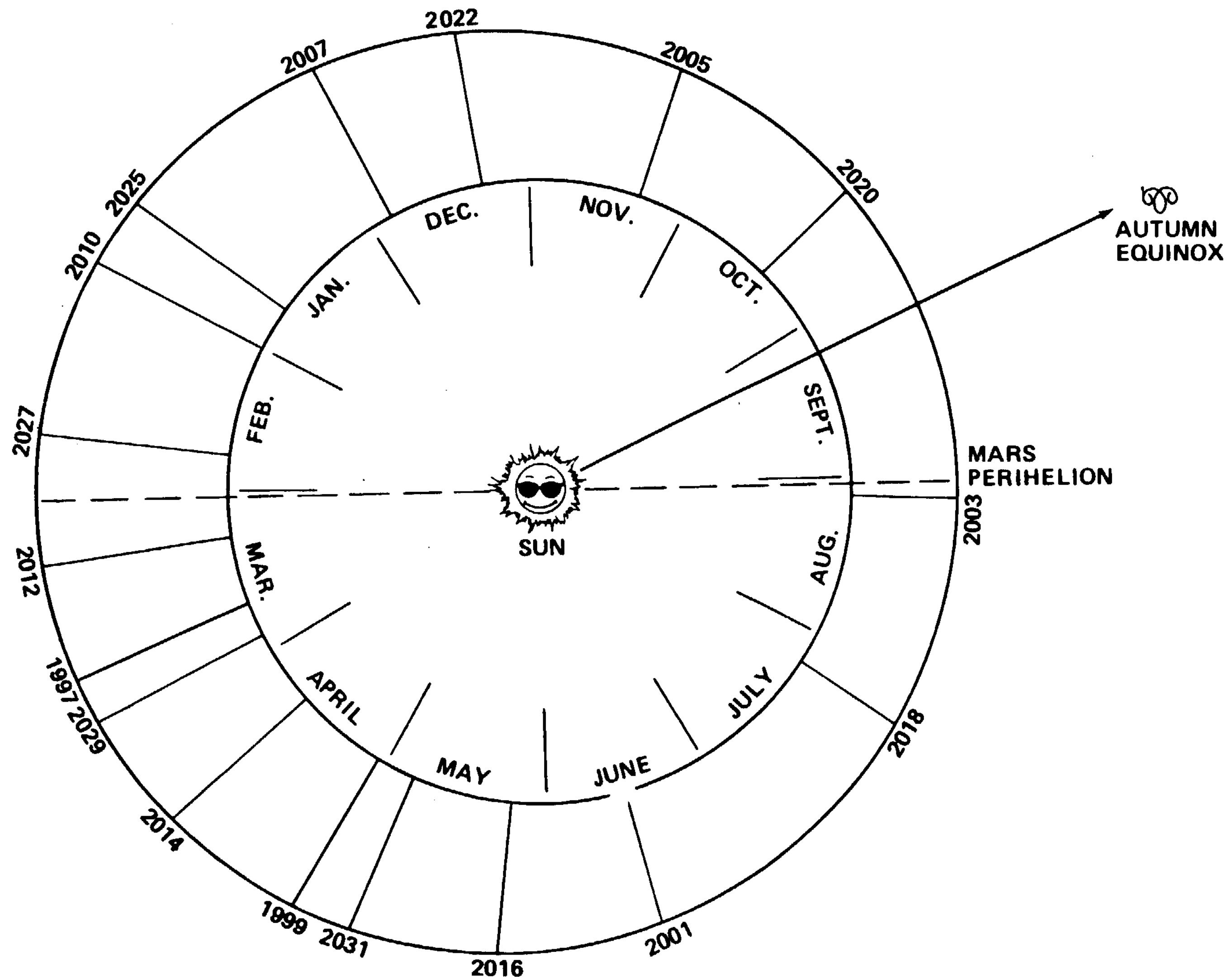

FIGURE 2. EARTH–MARS OPPOSITION FOR YEARS 1997–2031

arrival, Earth is ahead of Mars in heliocentric longitude, i.e., Mars arrival occurs after opposition. This makes it impossible to employ a near-Hohmann transfer for the inbound leg; the required heliocentric transit angle must greatly exceed the Hohmann transfer angle of 180 deg. 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 or near the orbit of Venus either on the outbound leg or on the inbound leg of a direct roundtrip mission to Mars. Figure 3 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 rate of Venus orbit is large compared to that of Mars, so that 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

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MARS FLYBY FOR 1999 OPPOSITION
ONE YEAR MISSION

1 EARTH DEPARTURE, APRIL 2, 1999
2 MARS PASSAGE, AUGUST 8, 1999
3 EARTH ARRIVAL, APRIL 2, 2000

OUTBOUND VENUS SWINGBY 1999 OPPOSITION

1 EARTH DEPARTURE, JAN. 26, 1998
2 VENUS PASSAGE, JULY 9, 1998
3 MARS ARRIVAL, JAN. 16, 1999
4 MARS DEPARTURE, MARCH 17, 1999
5 EARTH ARRIVAL, NOV. 18, 1999

CONJUNCTION CLASS MISSION 1999 OPPOSITION

1 EARTH DEPARTURE, DEC. 17, 1998
2 MARS ARRIVAL, SEP. 28, 1999
3 MARS DEPARTURE, JAN. 25, 2001
4 EARTH ARRIVAL, SEP. 2, 2001

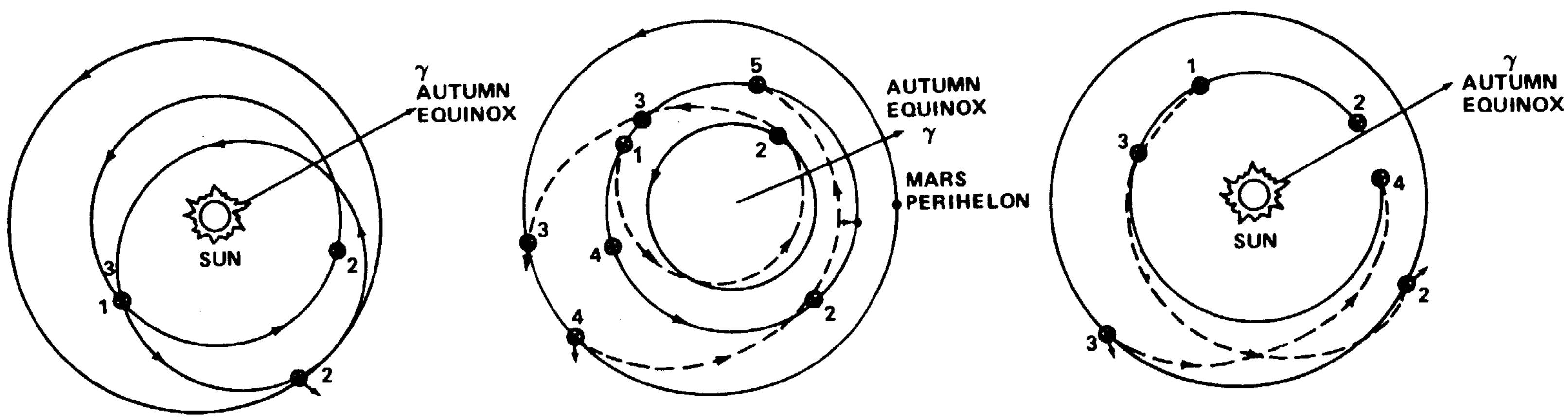

FIGURE 3. REPRESENTATIVE MISSION PROFILES FOR 1999 OPPOSITION

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 of 97,700 ft/sec) could be attained. The total mission time for 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).

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 between 1998 and 2045. Representative profiles are presented for the three missions described in Figure 3.

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 ΔV 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.

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

LAUNCH DATE	C_3 (km/SEC)^2	$\Delta V_{@}$ MARS (km/SEC)	C_3 @ EARTH RETURN (km/SEC)^2	ΔV_{TOT} (km/SEC)
2/28/97	159.6	0.802	237	18.239
4/2/99	99.5	0.406	156	13.639
5/22/01	63.5	0.425	108	10.846
6/8/03	71.6	1.723	134	13.299
10/15/05	122.6	3.806	253	20.518

* DATA FROM REFERENCE 6

TABLE 1. MARS FLYBY MISSION

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STOPOVER TIME EQUAL 60 DAYS
TIME PERIOD 1996 TO 2031

MISSION	EARTH LAUNCH DATE	TOTAL TRIP TIME (DAYS)
DOUBLE SWINGBY	MARCH 1996	733
OUTBOUND SWINGBY	JANUARY 1998	666
INBOUND SWINGBY	JANUARY 2001	708
OUTBOUND SWINGBY	AUGUST 2002	610
OUTBOUND SWINGBY	JUNE 2004	659
INBOUND SWINGBY	SEPTEMBER 2007	558
DOUBLE SWINGBY	JANUARY 2009	736
OUTBOUND SWINGBY	NOVEMBER 2010	650
INBOUND SWINGBY	NOVEMBER 2013	634
INBOUND SWINGBY	NOVEMBER 2015	577
OUTBOUND SWINGBY	APRIL 2017	638
INBOUND SWINGBY	JUNE 2020	594
OUTBOUND SWINGBY	OCTOBER 2021	636
OUTBOUND SWINGBY	SEPTEMBER 2023	614
INBOUND SWINGBY	NOVEMBER 2026	570
DOUBLE SWINGBY	MARCH 2028	737
OUTBOUND SWINGBY	JANUARY 2030	654

TABLE 2. MARS STOPOVER MISSION WITH VENUS SWINGBY.

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MARS STOPOVER TIME OPTIMIZED FOR MINIMUM ENERGY

DATE OF OPPOSITION		EARTH LAUNCH DATE		MARS STOPOVER TIME (DAYS)	TOTAL MISSION TIME (DAYS)
MARCH	1997	NOVEMBER	1996	485	1025
APRIL	1999	DECEMBER	1998	485	1005
JUNE	2001	JANUARY	2001	530	1020
MAY	2031	DECEMBER	2030	500	998
JUNE	2033	APRIL	2033	550	950
SEPTEMBER	2035	JUNE	2035	530	1004
NOVEMBER	2037	AUGUST	2037	340	986
JANUARY	2040	SEPTEMBER	2039	340	984
FEBRUARY	2042	OCTOBER	2041	340	990
MARCH	2044	NOVEMBER	2043	340	996

TABLE 3. MARS CONJUNCTION CLASS STOPOVER MISSION.

The 1999 opposition outbound Venus swingby is characterized by a hyperbolic transfer angle between Earth and Venus of over 180 deg, with the transfer angle between Venus and Mars of less than 180 deg. The total transfer angle of the two trajectory transfers is slightly greater than 360 deg. 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 asserted to be 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 the g-load constraint.

CONCLUSION

Optimum trajectory transfers for opposition class mission to Mars for flyby and stopover missions have been computed for attractive launch and arrival dates between years 1997 and 2031. Also, Optimum transfer for conjunction class missions to Mars have been computed for attractive opportunities for years 1997, 1999, 2001, and 2030 to 2045.

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, thus reducing the required propulsive maneuver energy requirement. 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. Data have been developed for years 1997, 1999, 2001 and one Earth-Mars synodic period between years 2030 and 2045 which consists of seven launch opportunities associated with the oppositions occuring during this time period.

Free-fall periodic orbits which travel back and forth between Earth and Mars on a scheduled interval may be attractive for use as a regularly scheduled transportation system between Earth and Mars.

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