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CIRCULATING TRANSPORTATION ORBITS BETWEEN EARTH AND MARS

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Abstract

This paper describes the basic characteristics of circulating (cyclical) orbit design as applied to round-trip transportation of crew and materials between Earth and Mars in support of a sustained manned Mars Surface Base. The two main types of non-stopover circulating trajectories are the so-called VISIT orbits and the Up/Down Escalator orbits. Access to the large transportation facilities placed in these orbits is by way of taxi vehicles using hyperbolic rendezvous techniques during the successive encounters with Earth and Mars. Specific examples of real trajectory data are presented in explanation of flight times, encounter frequency, hyperbolic velocities, closest approach distances, and ΔV maneuver requirements in both interplanetary and planetocentric space.

I. Introduction

The concepts and principles of planetary swingby or "gravity-assist" are now well-established in both theory and practice. A number of planetary science missions already flown have utilized gravity-assist swingbys of Venus and Mercury (Mariner 10), the Moon (ISEE-3/ICE), and the giant outer planets (Voyager). This energy-saving technique can be expected to see increased use in future automated and manned interplanetary travel. The potential application of interest in this paper is the transportation of crew and supplies in support of a sustained Manned Mars Surface Base sometime during the second quarter of the next century.

A circulating orbit may be defined as a multiple-arc trajectory between two or more planets which: (1) does not stop at the terminals but rather involves gravity-assist swingbys of each planet; (2) is repeatable or periodic in some sense; and (3) is continuous, i.e., the process can be carried on indefinitely. Different types of circulating orbits between Earth and Mars were identified in the 1960s literature.[1,2,3,4] Re-examination of this interesting problem during the past year has produced new solutions.[5,6,7] Some involve only these two bodies while others incorporate Venus encounters in the scenario. Some have more or less desirable characteristics as measured by flight times, frequency of encounters, hyperbolic approach velocities, closest approach distances, and the amount of midcourse propulsive ΔV needed to adjust and maintain the orbit continuously.

Circulating orbits share one potential advantage for manned transportation between Earth and Mars. They allow a large orbiting facility (herein called a "CASTLE") providing all power, living and work space, life support, gravity environment, and solar storm shelter to be "once-launched", thereby obviating the need to carry these massive elements repeatedly through large planetocentric ΔV maneuvers. Transportation to and from these CASTLEs is carried out by smaller Space Taxis using hyperbolic rendezvous techniques.

This paper will describe the basic characteristics of circulating orbit design and specific examples of real trajectory data that have been generated in a recent study of this problem.[8] The two main types of circulating orbits having desirable

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characteristics are the so-called VISIT orbits and the Up/Down Escalator orbits. Each of these candidate orbits will first be discussed in terms of their design principles in the approximate model world of circular and coplanar planetary motion. With this background, quantitative results are then presented and compared for the multi-orbit propagations in the actual case of eccentric and inclined planet orbits. Also covered are orbital analysis topics related to the use of the circulating transportation mode, e.g., Taxi vehicle maneuver requirements in launching to (orbit injection) and separating from (orbit capture) the circulating facilities. The reader is referred to a companion paper in the Conference Proceedings which describes the overall mass performance analysis of circulating orbits compared to traditional, minimum-energy stopover trajectories in support of a sustained manned Mars Base.[9]

II. Prelude to Circulating Orbit Design

Earth and Mars revolve about the Sun with orbit periods of 1.0 year and 1.8808 years, respectively. Earth travels in the ecliptic plane with an orbit eccentricity of 0.0168 while Mars travels in a plane inclined by 1.85° to the ecliptic with an eccentricity of 0.0934. As a help in understanding the properties of circulating orbits, ignore for the moment the non-circular, non-coplanar motion of the real world. Additionally, approximate the period of Mars (PM) by 1.875 years, so that every 15 years Earth makes 15 revolutions about the Sun while Mars makes exactly eight revolutions. Since the relative geometry between Earth and Mars repeats with the synodic period of 15/7 = 2.1429 years, trajectories connecting them will re-occur with this period also. The inertial geometry repeats every 15 years. These relationships have important implications in the design and repeatability of circulating orbits between these planets.

The VISIT type of circulating orbit, first proposed by Niehoff[5,6], evolved from consideration of a class of trajectories which might display low relative velocities at both Earth and Mars terminals. In order for this to occur it is necessary that the connecting heliocentric orbit be nearly tangent to the planetary orbits, i.e., the perihelion of the transfer orbit must be near 1.0 AU and the aphelion near 1.52 AU. The orbit which satisfies this exactly in the circular coplanar model has a semi-major axis of 1.26 AU and a period (P) of 1.415 years. If, in addition, it is required that the transfer orbit be resonant with both Earth and Mars, that is:

$$nP = m \quad \text{and} \quad jP = kPM \tag{1}$$

where n, m, j, and k are small integers, then there are only two possibilties. The first possibility (denoted VISIT-1) has a period of 1.25 years and a semi-major axis of 1.16 AU. This orbit completes four revolutions about the Sun while Earth completes five. It also completes three revolutions about the Sun while Mars completes two. Hence, the 4:5 resonance with Earth and 3:2 resonance with Mars means that Earth encounters will occur once every five years and Mars encounters once every 3.75 years. The second possibility (denoted VISIT-2) has a period of 1.5 years and a semi-major axis of 1.31 AU. This orbit completes two revolutions about the Sun while Earth completes three. It also completes five revolutions about the Sun while Mars completes four. The 2:3 resonance with Earth and 5:4 resonance with Mars means that Earth encounters occur once every three years while Mars encounters occur once every 7.5 years. In the circular coplanar world the VISIT-1 orbit must have a perihelion of less than 1.0 AU and the VISIT-2 orbit must have an aphelion of greater than 1.52 AU since their periods are respectively less than and greater than the value of 1.415 computed above. In the real world, the eccentricity of Mars' orbit makes the VISIT-1 orbit ideal for encountering Mars near its perihelion and the VISIT-2 orbit ideal for encountering Mars near its aphelion. These orbits are illustrated in Figure 1.

Due to the resonant characteristics of the VISIT orbits with their Earth and Mars encounters they remain fixed in inertial space in the circular coplanar world. The implication of this is that the planetary encounters must have only a negligible effect on the transfer trajectory, but this implies in turn that the encounters while close on a heliocentric scale must be distant on a planetocentric scale.

The Up/Down Escalator type of circulating orbit, first proposed by Aldrin[7], evolved from the desire to have more frequent and regular encounters with both Earth and Mars. Since encounter locations on a 15/7 synodic period orbit rotate 1/7 of a circle per revolution, there exists a synodic precession of the line of apsides equal to 51.4° per orbit which must be accommodated by either propulsive maneuvers (which are not desirable) or, to the extent possible, by gravity-assist swingbys of the planets (primarily Earth since it is more massive). Given this effective trajectory shaping, both Earth and Mars will be encountered sequentially every 2-1/7 years. The encounter speeds at both planets (but principally Mars), however, will be significantly higher than those of VISIT orbits because the 2-1/7 year period transfer orbit has an aphelion distance of about 2.32 AU, thereby crossing the orbit of Mars at steeper (non-tangential) angles.

The "Up" (Earth-to-Mars) and "Down" (Mars-to-Earth) Escalator orbits defined here are essentially mirror images of each other. The "Up" orbit will have a short transfer to Mars and a long transfer back, while the reverse is true for the "Down" orbit. Figure 2 illustrates the concept of rotating the orbit. The cycling facility leaves Earth at E1 and encounters Mars at M2 (for the "Up" Escalator). When the facility crosses the Earth's orbit again at 2-1/7 years later, Earth is not there, but is re-encountered at E3. At E3 Earth's gravity rotates the orbit so as to encounter Mars at M4 while maintaining heliocentric energy. Similarly, the "Down" Escalator is defined by the orbit from E1 to M2' to E3 to M4'. The advance of the perihelion per orbit is defined as $\Delta\Psi = 2\Pi/7$ radians.

Four orbital elements are required to specify an orbit in a plane. If the set (a, e, ω, and T) are chosen, then ω, the argument of periapsis, can be arbitrarily set to zero since the orbits of Earth and Mars are concentric circles. The semimajor axis, a, is determined by the synodic period, and the time of periapsis, T, will be specified by the requirement of encountering Earth and Mars. This leaves only the eccentricity, e, to be determined.

From Figure 2, it is seen that the magnitude of the true anomaly at Earth encounter, θ, is exactly one half of the required advance of perihelion, $|\theta| = \Delta\psi/2$. Thus, Earth is encountered at a true anomaly of 25.7° and the flyby changes the true anomaly to -25.7°. The net effect is to rotate the orbit by 51.4°. The value of true anomaly at Earth encounter specifies the final orbital element, e, through the conic equation:

$$r = a(1-e^2)/(1+e\cos\theta) \tag{2}$$

where

$$r = 1 \text{ AU}$$
$$a = (15/7)^{2/3} = 1.662 \text{ AU}$$
$$\theta = -25.7 \text{ degrees}$$

Solving the quadratic equation in e gives e = 0.416.

Having specified the heliocentric Escalator orbit, the characteristics of the Earth flyby can be determined. Figure 3 illustrates the rotation of the heliocentic velocity vector from $\overline{V}_{in}$ to $\overline{V}_{out}$ resulting in the change in heliocentric velocity, ΔV. The flight path angle, γ, is found as

$$\tan\gamma = (er/(a(1-e^2)))\sin\theta \tag{3}$$

Solving this equation gives $\gamma = 7.48$ degrees. From Figure 3 it is seen that:

$$\Delta V = 2V\sin\gamma \tag{4}$$

where $V = |\overline{V}_{in}| = |\overline{V}_{out}|$. The heliocentric velocity at Earth, V, is found from the energy equation:

$$\begin{aligned} V &= \mu^{1/2}\,((2/r)-(1/a))^{1/2} \\ &= (\mu/r)^{1/2}\,(2-r/a)^{1/2} \end{aligned} \tag{5}$$

For Earth $V_E = (\mu/r)^{1/2} = 29.785$ km/s, where μ is the gravitational parameter of the Sun, and so V = 35.2 km/s. Substituting these values gives ΔV = 9.17 km/s. Again from Figure 3 the asymptotic velocity magnitude is given by

$$V_\infty = (V^2 + V_E^2 - 2VV_E\cos\gamma)^{1/2} \tag{6}$$

Substituting gives V_∞ = 6.88 km/s. The flyby of Earth turns the asymptotic velocity vector by an angle 2δ. The equation relating this turn angle and the radius of closest approach r_p, is given by:

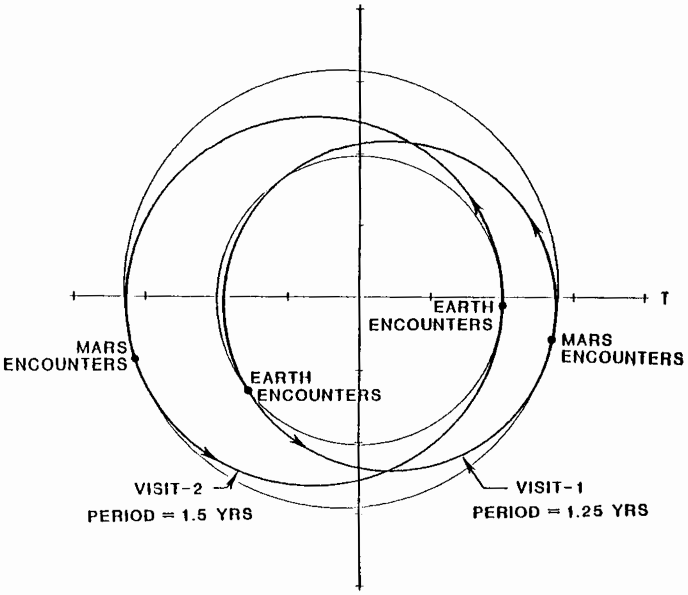

Fig. 1 VIST orbit diagram.

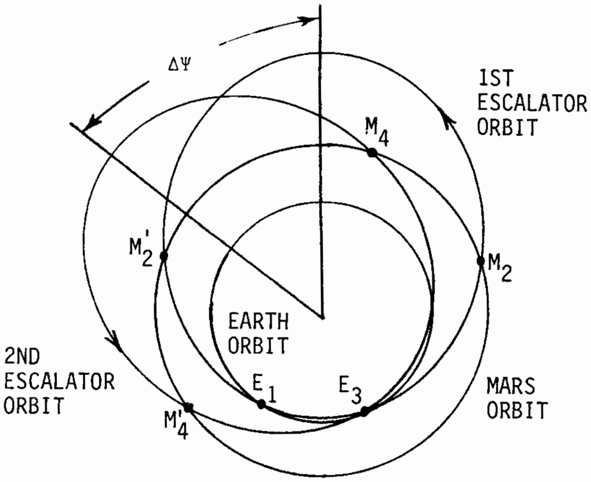

Fig. 2 Escalator orbit diagram.

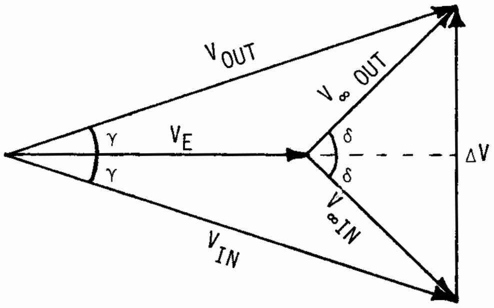

Fig. 3 Gravity-assist velocity diagram.

$$\sin \delta = 1/(1 + r_p V_\infty^2/\mu_E)) \qquad (7)$$

where μ_E is the gravitational parameter of Earth. Since from Figure 3

$$\Delta V = 2V_\infty \sin \delta \qquad (8)$$

solving gives r_p = 4,221 km, and the turn angle $2\delta = 83.4°$. Since the Earth's radius is 6,371 km, the value of r_p corresponds to a flyby of Earth beneath the surface. In order to have a physically realizable flyby, the cycling facility must therefore perform a propulsive maneuver somewhere on the orbit. A relatively small maneuver of about 230 m/sec performed at aphelion of the Escalator orbit can rotate the argument of periapsis by an amount sufficient to make the flyby of Earth occur at 1,000 km above the surface.

Although other types of circulating orbits have been identified, these typically have some major drawback such as much higher V_∞ values at Earth and/or Mars. This study has therefore focused on the VISIT and Escalator orbit concepts in taking the necessary next step of verifying their existence and characteristics in the real world of non-circular, non-coplanar planetary orbits.

III. VISIT Orbit Characteristics

Optimal trajectory searches using a point-to-point conic model were made for several successive launch opportunities near the end of this century. This is by way of example verification only, since it became clear that similar results would be obtained for a later time period in the 21st century when a sustained Mars Base may become a practical reality. Figure 4 shows a 20-year propagation of a VISIT-1 orbit launched in 1996. This is a "free orbit" meaning that no midcourse ΔV is required other than navigation targeting maneuvers which will be necessary to compensate for expected small errors. Table 1 lists the key parameters of this circulating orbit, namely, the hyberbolic approach approach speeds and the closest approach distances at Earth and Mars swingby. Note that perihelion and aphelion distances are maintained nearly constant at about 0.94 AU and 1.39 AU. Encounter speeds are also fairly constant; 4.2 to 4.5 km/sec at Earth and 3.7 to 3.9 km/sec at Mars. Closest approach distances tend to be fairly large, particularly at Earth, indicating relatively weak gravity-assist requirements for maintaining the VISIT type orbit resonances. This geometry characteristic has somewhat adverse implications on the hyperbolic rendezvous trajectory of the outgoing Taxi vehicles. That is, a rendezvous Δ V penalty of up to several hundred meters/sec (depending on the time allowed from Taxi launch to rendezvous) will have to be accounted for to compensate for the non-aligned asymptotes of the CASTLE and Taxi trajectories (see Section V).

The VISIT orbit solution is not totally unique in that other "free orbits" can be found for neighboring variational trajectories. Table 2 lists one such solution having slightly different encounter dates and encounter speeds, but very different closest approach distances. The aim here was to reduce the Earth swingby distance.

Another important point is noted with reference to Figure 4. There is a retrograde shift of both Earth and Mars encounter longitudes amounting to about 38° over 20 years. If left uncompensated, this drift away from the desired longitude (e.g., near perihelion at Mars) will eventually result in higher values of the encounter speed. Therefore, to maintain the VISIT orbit characteristic over extended times, it will be necessary to "reset" the orbit periodically (perhaps every 15 years or so) by utilizing the excess gravity-assist capability that is available from closer Earth swingbys. The nominal encounter time sequence may be interrupted briefly during this resetting revolution. Over extended times, the Mars encounter locations will be seen to oscillate or rock about Mars' perihelion longitude. Trajectory runs have been made to verify the ability to reset the orbit.

Table 1

VISIT-1 Orbit Encounter Conditions

Encounter	Date	Approach V_∞ km/sec	Closest approach distance planet radii
Earth-1	08 May 1996	4.50 (launch)	--
Mars-2	23 Jan 1998	3.69	9.3
Earth-3	30 Apr 2001	4.33	SOI[a]
Mars-4	01 Nov 2001	3.71	40.7
Mars-5	22 Jul 2005	3.70	5.4
Earth-6	16 Apr 2006	4.20	SOI
Mars-7	13 Apr 2009	3.72	6.7
Earth-8	06 Apr 2011	4.21	157.9
Mars-9	30 Dec 2012	3.85	22.5
Earth-10	01 Apr 2016	4.45	--

[a] Sphere-of-influence, 270 Earth radii

Table 2

VISIT-1 Orbit Encounter Conditions (variation)

Encounter	Date	Approach V_∞ km/sec	Closest approach distance planet radii
Earth-1	08 May 1996	4.76 (launch)	--
Mars-2	05 Jan 1998	4.04	2.4
Earth-3	21 Mar 2001	4.20	6.9
Mars-4	28 Oct 2001	4.07	1.5
Mars-5	20 Jun 2005	4.08	15.8
Earth-6	13 Apr 2006	4.45	148.4
Mars-7	18 Apr 2009	3.77	20.0
Earth-8	06 Apr 2011	4.24	111.6
Mars-9	30 Dec 2012	3.84	27.2
Earth-10	06 Apr 2016	4.45	--

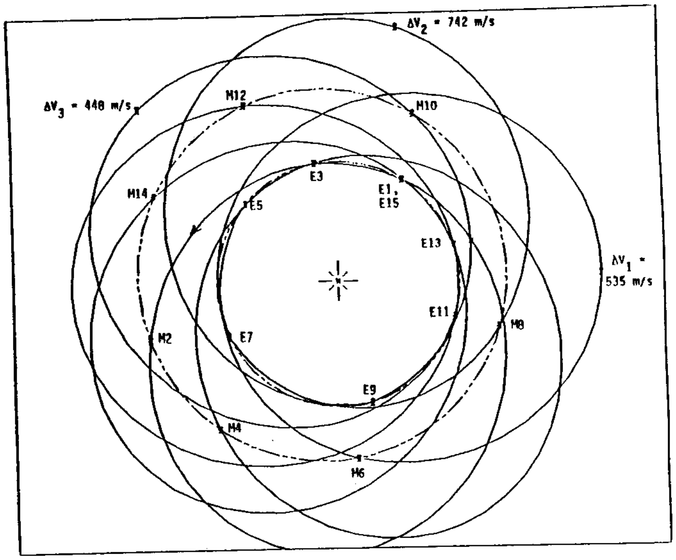

Fig. 5 15-year propagation of Up Escalator orbit.

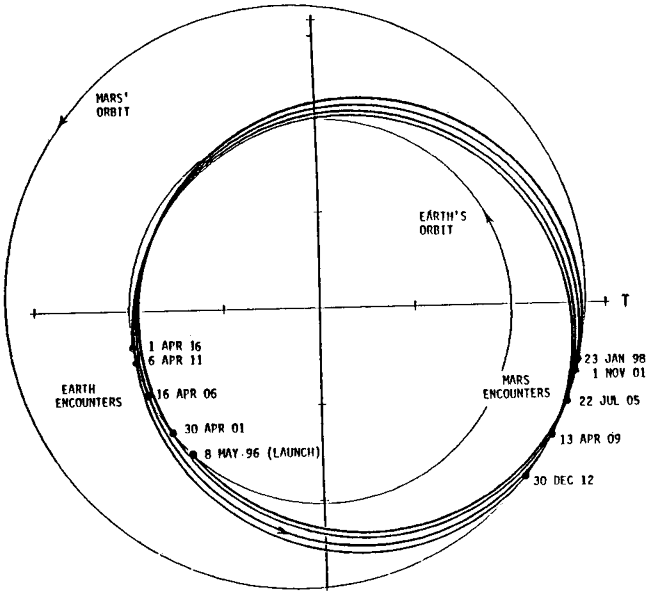

Fig. 4 20-year propagation of VISIT-1 orbit.

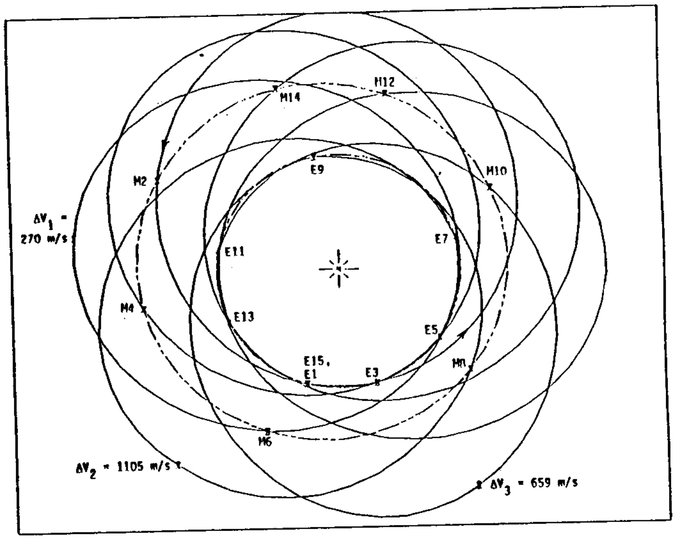

Fig. 6 15-year propagation of Down Escalator orbit

VISIT-2 circulating orbits have also been generated to verify the theoretical prediction, but these data are omitted due to space limitations in this paper. The main result in terms of encounter speeds compared to VISIT-1 is a slight reduction at Earth to the range 3.7 to 4.0 km/sec and a larger reduction at Mars to the range 2.6 to 2.8 km/sec. VISIT-2 orbits have the advantage of more frequent Earth encounters (every 3 years) but the significant disadvantage of infrequent Mars encounters (every 7.5 years). Thus, this type of circulating orbit does not appear to be very useful for transportation to Mars except, possibly, in combination with other cycling facilities having more frequent Mars encounters.

IV. Up/Down Escalator Orbit Characteristics

With an understanding of the Escalator orbit from the circulating coplanar problem, a search was made to find the existence of trajectories based upon actual planet ephemerides data. The trajectories were begun in the 1995/96 time period. Initially, a point-to-point conic model was used to identify the opportunities and verify their existance in the real world. In this model heliocentric conics connect the flybys of Earth and Mars with the times of flyby varied to obtain a match of V_∞ magnitude at each flyby. Thus a sequence of flybys similar to those of the circular coplanar model are obtained (E1-M2-E3-M4-...); the difference being that the real world geometry causes the pattern not to repeat exactly. These sequences over a 15 year period were then used as first guesses for a computer program which uses the more accurate Multi-Conic propagation technique along with optimization techniques[10] to generate a trajectory with minimum propulsive maneuvers subject to constraints on flyby altitudes.

Figures 5 and 6 illustrate the circulating orbits for both Escalators as they evolve over a complete 15 year cycle. Corresponding data on hyperbolic approach speed, closest approach distance, and propulsive ΔV requirements are listed in Tables 3 and 4. The orbit plots show the characteristic rotation of the encounter locations caused by the planetary flybys. Because the orbital motion of Mars is not constant along its real elliptical path (and similarly for Earth to a lesser extent), the longitudinal difference between encounters is likewise not constant nor are the Earth-Mars and Mars-Earth flight times. This variability is related to different bending requirements of the trajectory during the successive planetary swingbys. The flight time variation is not large: 147-170 days for Earth to Mars transits on the Up Escalator and for Mars to Earth transits on the Down Escalator.

Recall that in the circular coplanar problem, more bending is required of Earth than is available,

so a propulsive maneuver is required on each orbit. In the real world, the optimal trajectory covering this 15 year cycle requires propulsive maneuvers on only three of the seven orbits. Interestingly enough, the sum of these three maneuvers is approximately seven times the per orbit requirement in the circular coplanar problem. The propulsive maneuvers are made near aphelion of the circulating orbit, which occurs about eight months after Mars encounter on the "Up" orbit and about eight months before Mars encounter on the "Down" orbit. Note that these maneuvers occur on the orbits which encounter Mars in the general region of its perihelion passage when it is moving the fastest.

V. Planetocentric Maneuvers

In traditional interplanetary flight, a spacecraft is injected from low Earth orbit onto a targeted hyperbolic departure trajectory having a perigee distance essentially equal to the low orbit injection point. A similar injection geometry might be effected at Mars for the return flight to Earth. The ideal (optimal) coplanar injection maneuver is given by

$$\Delta V_I = \left(V_\infty^2 + \frac{2\mu}{r_p}\right)^{1/2} - \left(\frac{\mu}{r_p}\right)^{1/2} \qquad (9)$$

in the case of departing from a circular orbit. The situation is somewhat different for circulating orbits since rendezvous must occur with a "real facility" flying by the launch planet on a speci-

Table 3

Up Escalator Encounter Conditions

Encounter	Date	Approach V_∞ km/sec	Closest approach distance planet radii
Earth-1	19 Nov 1996	6.19 (launch)	--
Mars-2	01 May 1997	10.69	5.8
Earth-3	01 Jan 1999	5.94	1.3
Mars-4	28 May 1999	11.74	29.1
Earth-5	08 Feb 2001	5.67	1.2
Mars-6	06 Jul 2001	10.22	1.3
Maneuver	13 Mar 2002	0.54 (ΔV_1)	--
Earth-7	16 Apr 2003	5.67	1.2
Mars-8	12 Sep 2003	7.28	1.3
Maneuver	17 May 2004	0.74 (ΔV_2)	--
Earth-9	07 Jul 2005	5.87	1.2
Mars-10	13 Dec 2005	6.05	3.4
Maneuver	23 Jul 2006	0.45 (ΔV_3)	--
Earth-11	06 Sep 2007	5.87	1.8
Mars-12	16 Feb 2008	7.43	6.4
Earth-13	10 Oct 2009	5.89	1.9
Mars-14	28 Mar 2010	8.66	5.0
Earth-15	13 Nov 2001	5.81	1.9

Table 4

Down Escalator Encounter Conditions

Encounter	Date	Approach V_∞ km/sec	Closest approach distance planet radii
Earth-1	05 Jun 1995	5.88 (launch)	--
Mars-2	20 Jan 1997	8.52	5.5
Earth-3	09 Jul 1997	5.95	1.8
Mars-4	07 Mar 1999	7.35	9.4
Earth-5	17 Aug 1999	6.01	1.4
Maneuver	28 Sep 2000	0.27 (ΔV_1)	--
Mars-6	15 May 2001	6.60	5.2
Earth-7	08 Oct 2001	5.88	1.2
Maneuver	04 Dec 2002	1.11 (ΔV_2)	--
Mars-8	07 Aug 2003	7.30	1.3
Earth-9	02 Jan 2004	5.39	1.4
Maneuver	02 Feb 2005	0.66 (ΔV_3)	--
Mars-10	10 Oct 2005	9.96	1.3
Earth-11	12 Mar 2006	5.48	1.5
Mars-12	19 Nov 2007	11.59	8.4
Earth-13	16 Apr 2008	5.96	1.5
Mars-14	13 Dec 2009	10.55	5.0
Earth-15	22 May 2010	5.93	1.8

fied hyperbolic trajectory at a specified time. Generally, the periapsis distance of this hyperbola may not be very close to the planet and certainly varies from encounter to encounter as discussed previously. This implies the necessity of a two-impulse maneuver sequence, at the least, requiring a finite amount of time to accomplish. Limiting the rendezvous transfer time is an important consideration since the crew in the small Taxi vehicles will not have the same environmental luxuries of the large transportation facility to which they are destined. Furthermore, the injection maneuvers will incur a ΔV penalty compared to the ideal value of equation (9) inasmuch as the two hyperbolic asymptotes (i.e., of the Taxi and CASTLE) will not be aligned but, rather, will cross at some angle depending on the time interval allowed. The longer the time, the smaller the angle and, therefore, the smaller the ΔV penalty.

This problem has been examined quantitatively in some detail using both an approximate two-body, Earth-centered model and an accurate N-body integration model. Suprisingly little error in the two-body results were found even for large swingby distance of the CASTLE and for rendezvous points outside the Earth's sphere-of-influence. Furthermore, a very simplified "guidance formula" also yields an accurate measure of the ΔV penalty:

$$\Delta V_{penalty} = \frac{\Delta B}{\Delta T} \tag{10}$$

where ΔT is the time allowed from injection to rendezvous and ΔB is the absolute magnitude difference between the two hyperbolic asymptotes, i.e., the traditional aim point or miss distance. The miss distance is calculated by the expression:

$$B = \left(r_p^2 + \frac{2\mu r_p}{V_\infty^2} \right)^{1/2} \tag{11}$$

where r_p is the periapsis or closest approach distance of the appropriate hyperbola. A typical periapsis injection point at either Earth or Mars encounter is 500 km altitude.

A graph of equation (10) shown in Figure 7 is a more convenient and generalized way to present the main characteristic rather than presenting tabular data for specific encounter conditions. For asymptotic displacement up to 10^6 km, the ΔV penalty could be as high as 1.65 km/sec if the rendezvous time is limited to 7 days. Allowing 21 days for rendezvous reduces the penalty correspondingly by a factor of three. This example with $\Delta B = 10^6$ km represents one of the worst cases of the VISIT-1 encounters with Earth (Earth-8 in Table 1). Another example is the Mars-4 encounter in Table 1: with ΔB = 135,000 km, the ΔV penalty is 0.223 km/sec for ΔT = 7 days or 0.074 km/sec for ΔT = 21 days.

Up/Down Escalator encounter conditions listed in Tables 3 and 4 show generally smaller closest approach distances which translates to smaller penalties. The worst case is the Mars-4 encounter of the Up Escalator which has ΔB = 95,000 km for a penalty of 0.157 km/sec with rendezvous in 7 days. A more typical case is the Earth-11 encounter of Table 3 which has ΔB = 5,400 km and a 7-day penalty of only 9 m/sec. The clear implication is that shorter Taxi rides could easily be afforded in the Escalator transportation mode. Recall, however, that the ideal injection ΔV's are much larger for the Escalator mode than the VISIT mode because of the higher values of V_∞, particularly at Mars. The performance tradeoff measured in terms of total propellant requirement is therefore not so simplistic but must be subject to careful analysis.

There are other penalties in planetocentric maneuvers related to plane changes, time-phasing, and launch delays. These problems have been examined but only in a very cursory manner to date. Specific results or characteristics of the plane change and time-phasing penalties depend very much on the particular staging "spaceport" in planetocentric space that is assumed. Also, appropriate software to obtain optimal solutions has yet to be developed. Some preliminary calculations assuming an Earth-Moon L_1 point staging base have indicated that plane change/timing penalties could possibly be limited to 250 m/sec but may require elaborate and lengthly maneuver strategies.

Figures 8 and 9 illustrate Taxi maneuvers made at the Mars terminal assuming a staging spaceport in the vicinity of Phobos (cryogenic propellant

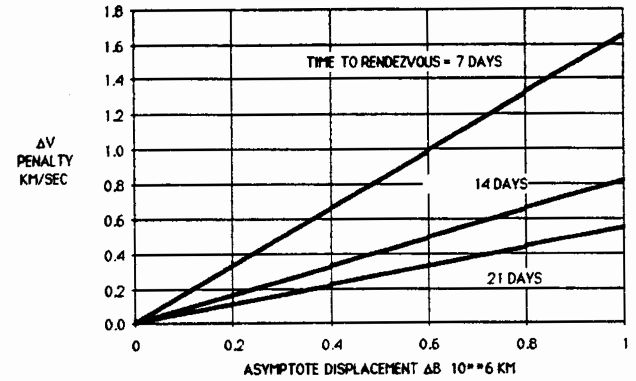

Fig. 7 Hyberbolic rendezvous requirements.

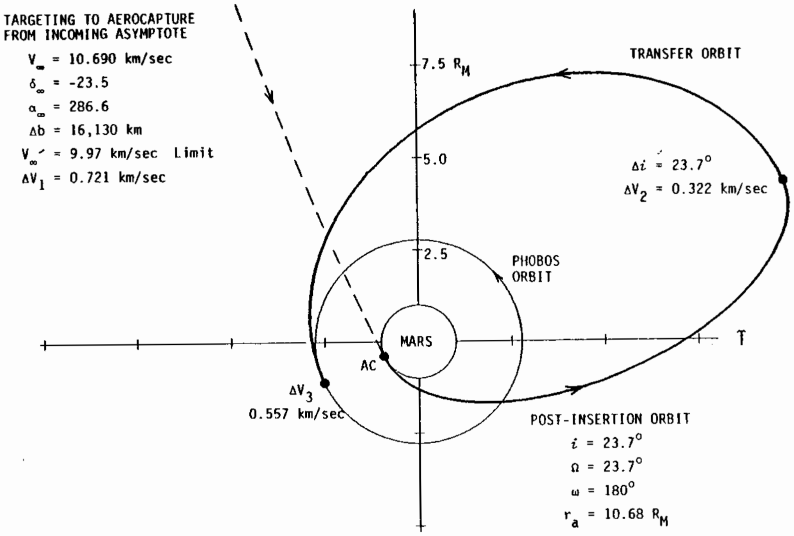

Fig. 8 Taxi manuevers to Phobos - Up Escalator Mars encounter at $t_0 + 0.45^y$

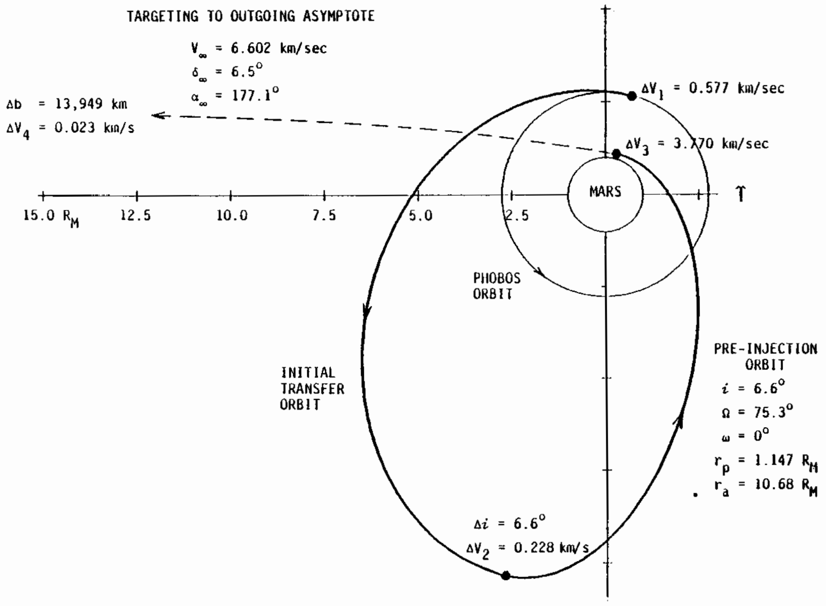

Fig. 9 Taxi maneuvers from Phobos - Down Escalator Mars encounter at $t_o + 4.49^y$.

production facility). The example cases correspond to the Mars-2 encounter of the Up Escalator and the Mars-6 encounter of the Down Escalator. Mars orbit capture is assumed to be accomplished by a combination of aerocapture and propulsive maneuvers effected by the Taxi vehicle departing the CASTLE. The low-to-moderate L/D aeroshield is assumed to have an upper limit on entry velocity of 11.1 km/sec (V_∞ less than 9.97 km/sec). Figure 8 shows that the first propulsive maneuver of 0.721 km/sec provides the velocity reduction in combination with the ΔB targeting. Since the approach declination is -23.5°, the post-insertion orbit has this value of inclination which must then be adjusted to the Mars equatorial plane in which Phobos moves. The second maneuver of 0.322 km/sec provides the combination of plane change and periapsis raising to Phobos orbit distance. The third and final maneuver of 0.557 km/sec achieves rendezvous at the Phobos spaceport. Figure 9 describes the reversal of this process for the crew departing for Earth on the Down Escalator four years later. The Mars surface-to-Phobos spaceport shuttle maneuvers are not shown here, but the round trip ΔV of the aero-propulsive shuttle is about 7.5.

VI. Comparison of Results and Conclusions

This final section of the paper consolidates the study results by comparing the main characteristics of the two types of circulating orbits between Earth and Mars. Table 5 summarizes the key parameters of the VISIT and Escalator orbits. In addition to the midcourse propulsive ΔV requirement, two key differences of Escalator orbits compared to VISIT orbits are higher values of encounter approach speed at Earth but mainly at Mars, and much lower values of closest approach distance at both planets but mainly at Earth. The velocity characteristic is a clear disadvantage in terms of the Taxi propulsion requirements for launch to the circulating CASTLEs. The distance characteristic is an advantage (but not necessarily an offsetting one) in terms of the Taxi rendezvous time and ΔV requirement. Of course, the Escalator-type orbit offers more regular, more frequent encounters with Earth and Mars than does VISIT orbits. Also they have the desirable characteristic of short transits (150-170 days) to Mars on the Up Escalator and returns to Earth on the Down Escalator. Use of VISIT orbits would require at least twice as many operating CASTLEs to achieve comparable encounter frequencies and crew transit times. Thus, there is the making of an interesting performance tradeoff problem between these two types of circulating orbits and, for that matter, between the circulating mode of transportation compared to the more traditional minimum-energy round-trip missions with lengthy stopovers. As mentioned earlier, this tradeoff is the subject of the companion paper by Hoffman, et al appearing in this Proceedings.

The potential application of circulating orbits in support of a sustained, manned Mars exploration program appears to have promise but clearly requires much more extensive study. In the area of orbital mechanics, the main problem not yet addressed thoroughly is the analysis (and optimization) of planetocentric maneuver strategies for injection to and departure from the interplanetary stations. This is a fertile area of investigation since there are a number of possible options for locating the planeocentric staging base. As just one example, Aldrin has proposed an Earth-Moon cycler as the appropriate stepping off base for interplanetary travel due to its proximity to both sources of propellant and its high-energy, low-perigee orbit. Others have proposed the Earth-Sun L_1 point and the Earth-Moon L_2 point, and similar variations on the theme apply to the Mars terminal. It is hoped that this paper will inspire much interesting new work.

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Table 5

Key Parameter Comparison of VISIT and Escalator Orbits

Parameter	VISIT-1	VISIT-2	Up Escalator	Down Escalator
Frequency of Earth encounters (yrs)	5.0	3.0	2.14	2.14
Frequency of Mars encounters (yrs)	3.75	7.5	2.14	2.14
Earth-to-Mars flight time (yrs)	0.5-3.0	1.0-2.4	0.43	1.71
Mars-to-Earth flight time (yrs)	0.7-3.3	0.6-2.1	1.71	0.43
Earth encounter V_∞ (km/sec)	4.2-4.8	3.7-4.0	5.7-6.2	5.4-6.0
Mars encounter V_∞ (km/sec)	3.7-4.1	2.6-2.8	6.1-11.7	6.6-11.6
Earth encounter distance (R_E)	6.9-SOI	8.3-SOI	1.2-1.9	1.2-1.8
Mars encounter distance (R_M)	1.5-40.7	2.0-18.5	1.3-29.1	1.3-9.4
Midcourse adjustment, 15 years (km/sec)	0	0	1.7	2.0
Max. Earth access ΔV, 14 days (km/sec)*	5.5	5.2	4.8	4.7
Max. Mars access ΔV, 14 days (km/sec)*	2.9	2.2	9.4	9.2

* Sum of ideal injection and rendezvous maneuvers