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INTERPLANETARY ROUND TRIP MISSION DESIGN*

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ABSTRACT

This paper defines the basic constraints for interplanetary round trip travel or, equivalently, for round trip travel from and to a natural or artificial satellite, such as round trips from the International Space Station to another satellite and back. While the constraints are straightforward, they do not seem to have been discussed previously in the literature, perhaps because round trip travel has not been a realistic option for most missions.

We call the location that we are leaving and returning to the *home planet* or satellite and the spacecraft which makes the round trip the *traveler*. In round trip space travel, the traveler and the home planet must begin and end at the same true anomaly. Consequently, the fundamental constraint for mission design is as follows:

> **Over the duration of the mission the difference in the change in true anomaly for the home planet and the change in true anomaly for the traveler must be an integral number of revolutions.**

This fundamental constraint implies a number of interesting properties for round trip travel to other locations in the solar system. For example:

- For Hohmann minimum energy transfers, going to nearby objects takes longer than going to some which are further.
- The shortest Hohmann round trip to a destination further from the Sun is a 2-year trip to a heliocentric distance of 2.2 AU, i.e., 1.2 AU outward from the Earth.
- Increasing the transfer velocity has only a very small effect on total trip time, except at discrete "jumps" where the total trip time can change by a year or more.
- One way to reduce the round trip time is to go beyond the target planet and visit the target "on the way back."
- Some scenarios that go above a ΔV threshold can dramatically reduce the total round trip time, i.e., a reduction in round trip time for a Mars mission from the traditional 2.5 years to less than 6 months.

This paper discusses the general constraint equations and the resulting implications for round trip mission design. These equations provide very fundamental constraints on solar system travel in which people or equipment want to visit another planet and return.

INTRODUCTION

Substantial work has been done to date on both Earth orbiting and interplanetary orbit and mission design — i.e., launch opportunities, transfer times, ΔVs, and optimization of mission timelines. (See, for example, the summary works by Brown [1998], Wertz [2001], and the references therein.) However, the bulk of this work has focused on 1-way travel, with relatively little work on round trip missions, largely because round trips have required too much energy and time to be realistic for most missions. Excellent summaries of the various round trip trajectories considered to date are given by Hoffman, et al. [1989] and Young [1988] for impulsive trajectories and by Polsgrove and Adams [2002] for low thrust trajectories. Among the options considered are "Sprint" missions [Hoffman, et al., 1989; Hoffman and Soldner, 1895] that reduce somewhat the total trip time, Cycler or VISIT orbits [Friedlander, et al., 1986] that make continuing round trips to the vicinity of a particular planet (typically Mars), a Cycler variant called the Escalator [Aldrin, 1985], and, of course, the usual set of direct transfers and planetary fly-bys [Brown, 1998; Hoffman, et al., 1989].

This paper focuses on a specific question for round-trip travel:

> **What are the fundamental constraints on the mission design and mission timeline created by the requirement to return "home" at the end of the mission.**

This problem was first addressed for electric propulsion missions by Microcosm in September, 2001, as part of the TRW-led[§] team for the Mars Sample Return electric propulsion study funded by JPL. The basic problem was that optimization codes gave correct numerical answers for electric propulsion transfer, but the results were particularly difficult to interpret physically. Although many parametric runs were done with a wide range of input parameters, these adjustments had only a very small impact on the overall mission timeline. This outcome led to consideration of whether there were very basic constraints on impulsive round-trip travel as well that would have an impact on our capacity to tour the solar system and return home, either robotically or with human crews[‡]. The purpose of this paper is to describe the "basic physics" of interplanetary round trip travel. Although the results are discussed entirely in terms of impulsive missions, the same constraints apply (and have similar results) to planetary fly-bys, electric propulsion missions, or other transfer trajectories.

The basic definitions we use are as follows:

Round Trip = a space mission which begins and ends on a single planet, satellite, or orbital location, called ***Home.***

We will be concerned primarily with interplanetary travel and will often use the terminology "*home planet;"* however, the fundamental rules apply to Earth orbits as well.

Target = the planet, satellite, or orbital location that we wish to visit.

Traveler = the spacecraft which makes the round trip.

Mission Anomaly = the angular position of any of the orbiting objects with respect to some reference that can be regarded as fixed in inertial space.

The key point is that we wish to talk about differences in angular positions among various objects and the changes in these angular positions over time. Therefore, we want to measure this angular position with respect to some common reference. This is somewhat different than the usual definition of *true anomaly* that is measured with respect to a potentially changing perigee location.

Synodic Period = the period of the target with respect to the home planet.

The synodic period measures how long it takes for the target and the home planet to return to the same positions <u>with respect to each other</u>. Assuming Earth is the home planet, the synodic period will be much longer than a year for planets or locations near the Earth and somewhat more than a year for more distant planets.

THE FUNDAMENTAL EQUATIONS OF ROUND TRIP TRAVEL

The following conditions are both necessary and sufficient for round trip travel:

1. **The difference in the change in mission anomaly between the traveler and the home planet must be an integral number of orbits.**
2. The total change in radial position must be the same for both the traveler and the home planet.
3. The change in cross-track position must be the same for both the traveler and the home planet.

In addition, if a rendezvous or soft landing is planned, then the velocity of the traveler at the end of the mission must match the velocity of the home planet.

Condition 1 is the primary driver of round trip mission design. Condition 2 is met as part of the orbit design process that addresses Condition 1. (The home planet may or may not change its radial position over the duration of the trip.) Condition 3 may impact the ΔV requirements, but is typically not a major design driver, unless the inclination of the target and the home planet are very different (i.e., landing on a high inclination comet and returning to Earth). Of course, for planetary trips the cross-track position does not normally change for the home planet. However, the "home satellite" cross-track position can change in the case of Earth or planetary orbiting missions.

So far as I am aware, these fundamental constraints have been recognized in a broad sense, but have not been explicitly stated previously or their implications explored. We begin by breaking down the total mission duration, T, into a series of transportation segments, t_i, and a stay on the target planet of duration t_S. (See Fig.

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§ TRW has since become a part of Northrop Grumman Space Technology.

‡ Development of the original transfer equations and all work on non-electric propulsion missions has been done under Microcosm IR&D.

1.) The various transportation segments can represent multiple cruise and propulsive phases, such as planetary fly-bys, or several cruise phases with intermediate impulsive burns such as ascent and descent trajectories. Ordinarily at a minimum there will be a t_{out}, a t_s, and a t_{return}, representing the outbound, stay at the target, and return portions of the trip. For any mission,

$$T = \Sigma\, t_i + t_S \qquad (1)$$

During each segment, the spacecraft goes through a mission anomaly arc (i.e., angular position as measured from the Sun) of magnitude $\Delta\nu_i$ with an average angular rate of

$$\omega_i = \Delta\nu_i / t_i \qquad (2)$$

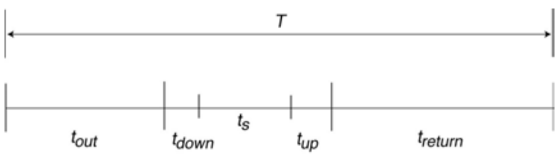

Fig. 1. The Total Mission, *T*, Time is Broken into Multiple Transportation Segments and a Stay, t_s, at the Target Planet.

The fundamental constraint for round trip interplanetary travel is that we must return to the planet where we started, i.e.

$$\Delta\nu_H = \Delta\nu_{spc} + 2\pi W \qquad (3)$$

where $\Delta\nu_H$ is the change in mission anomaly of the home planet, $\Delta\nu_{spc}$ is the change in mission anomaly of the traveler, and W is an integer (positive or 0 for outward trips, negative or 0 for inward trips), as illustrated for W = 1 in Fig. 2. While some other equations are approximations, Eq. (3) must be satisfied exactly.

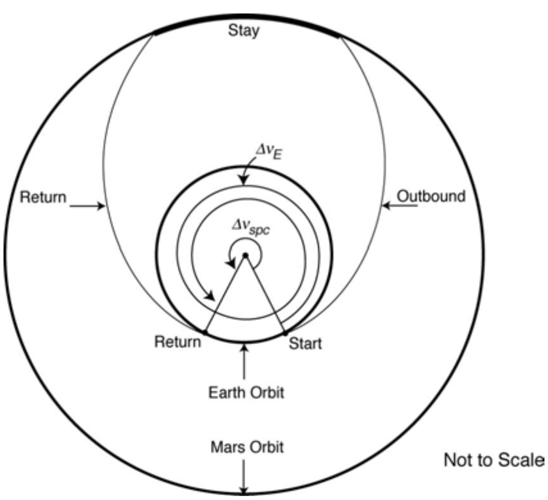

Fig. 2. The Fundamental Constraint is that the Difference in the Change in Mission Anomaly for the Traveler and the Home Planet Must be an Integer (Negative, 0, or Positive).

For the home planet

$$\Delta\nu_H \approx \omega_H\, T \qquad (4)$$

where ω_H is the orbital angular velocity of the home planet, ~ 0.986 deg/day for the Earth, and T is the total round trip travel time. For the traveler, we divide the trip into K segments, such that

$$\Delta\nu_{spc} \approx \omega_1 t_1 + \omega_2 t_2 + \ldots + \omega_K t_K = \Sigma\, \omega_i t_i + \omega_{Target}\, t_S \qquad (5)$$

$$T = t_1 + t_2 + \ldots + t_K = \Sigma\, t_i + t_S \qquad (6)$$

where ω_i and t_i are the average angular rates and time of each travel segment, ω_{Target} is the average angular rate of the target ~ 0.524 deg/day for Mars, and t_S is the stay time at the target. Typically (though not necessarily), the average angular rates for the various segments will fall in the following range:

$$\omega_{imax} = \omega_H \approx 0.986 \text{ deg/day for the Earth} \qquad (7a)$$

$$\omega_{imin} = \omega_{Target} \approx 0.524 \text{ deg/day for Mars} \qquad (7b)$$

For convenience, we define the dimensionless variable $\omega'_i = \omega_i / \omega_H$. Then the fundamental constraint of Eq. (3) can be rewritten as

$$T = \Delta\nu_H / \omega_H = \Delta\nu_{spc} / \omega_H + 2\pi\, W / \omega_H$$

$$= \Sigma\, \omega_i t_i / \omega_H + \omega_{Target}\, t_S / \omega_H + 2\pi\, W / \omega_H \qquad (8a)$$

$$T = \Sigma\, \omega'_i t_i + \omega'_{Target}\, t_S + W P_H \qquad (8b)$$

where P_H is the home planet sidereal period ~ 365.24 days for the Earth. For a typical outbound mission:

$$\omega'_{imax} = 1$$

$$\omega'_{imin} = \omega'_{Target} = \omega_{Target} / \omega_H \approx 0.531$$
for the Earth/Mars/Earth trip

We can solve Eqs. (6) and (7) for T and t_S in terms of the travel times and average angular rates:

$$T = (\Sigma\, \omega'_i t_i - \omega'_{Target}\, \Sigma\, t_i + W P_H) / (1 - \omega'_{Target}) \qquad (9)$$

$$t_S = T - \Sigma\, t_i \qquad (10)$$

We can define an "approximate minimum round trip travel time," T_{min}, as the minimum round trip time if we travel rapidly to the target, stay at the target long enough to allow the planets to again get in position for transfer, and then travel rapidly home. For W = 1,

$$T_{1min} = \omega'_{imin}(t_1 + t_2 + \ldots + t_K) + P_H = \omega'_{imin}\, T_{1min} + P_H \qquad (10a)$$

$$T_{1min} = P_H / (1 - \omega'_{imin}) \sim 2.13 \text{ yrs} = 779 \text{ days for Earth/Mars} \qquad (10b)$$

W = 1 means that the home planet makes one more trip around the Sun than the traveler does. (We will see shortly that there are several techniques that can lead to shorter round trip times.) For the Earth/Mars example with $W = 2$, we have

$$T_{2min} = 2\ P_H / (1 - \omega'_{imin}) \sim 4.26 \text{ yrs} = 1{,}558 \text{ days} \qquad (11)$$

Generally, the total travel time will be longer than the above minimum times. Thus, if $W = 1$, the approximate minimum total trip time to Mars and back will be over 2 years and the probable trip time will be 2.5 to 3 years. If $W = 2$, the approximate minimum total trip time to Mars and back will be over 4 years and the probable trip time will be over 5 years.

HOHMANN ROUND TRIP TRAVEL

For most cases, a Hohmann transfer represents the minimum energy transfer between two circular, coplanar orbits. (See, for example, Vallado [2001].) Thus, assume that a minimum energy mission consists of 2 Hohmann transfers + a stay of length t_S.* Then

$$T = 2\ \omega'_{transfer}\ t_{transfer} + \omega'_{Target}\ t_S + W\ P_H \qquad (12)$$

$$t_S = T - 2\ t_{transfer} \qquad (13)$$

Therefore,

$$T = (W\ P_H + 2\ t_{transfer}\ (\omega'_{transfer} - \omega'_{Target}))/(1 - \omega'_{Target}) \qquad (14)$$

For an Earth-Mars Hohmann transfer** and $W = 1$, we have

$$\Delta\nu_{transfer} = 180 \text{ deg} \qquad (15a)$$

$$t_{transfer} \sim 259 \text{ days} \qquad (15b)$$

$$\omega_{transfer} = 0.695 \text{ deg/day} \qquad (15c)$$

$$\omega'_{transfer} = 0.705 \qquad (15d)$$

$$\text{Total Trip: } T \approx 971 \text{ days} = 2.66 \text{ yrs} \qquad (15e)$$

$$\text{Stay at Mars: } t_S \approx 453 \text{ days} = 1.24 \text{ yrs} \qquad (15f)$$

Thus, the traditional round trip approach involves an extended stay on Mars. The key point is that this time is not easily influenced by changing the transfer speed. If we travel more quickly, then we have to spend more time at Mars waiting for the Earth to make its one extra trip. Decreasing the travel time increases the duration of the stay on Mars, but has very little effect on the total trip time. Recall from Eq. (10) that if we make a very rapid trip to Mars, we would still have to spend 779 days on Mars just to allow the Earth time to again catch up.

For Earth/Mars Hohmann round trips with $W = 0$, the stay time is –326 days, i.e., we need to leave Mars about a year before we arrive. For $W = 2$, the total trip is 1,750 days (4.8 years) and the stay time is 1,232 days (3.4 years).

We can use Eqs. (13) and (14) to determine the total trip time and stay time for Hohmann round trips to various distances. The results are shown in Fig. 3 for trips to the vicinity of Mars and the asteroid belt, in Fig. 4 for trips to the vicinity of Jupiter, and in Fig. 5 for trips toward the Sun, i.e., in the direction of Venus or Mercury.

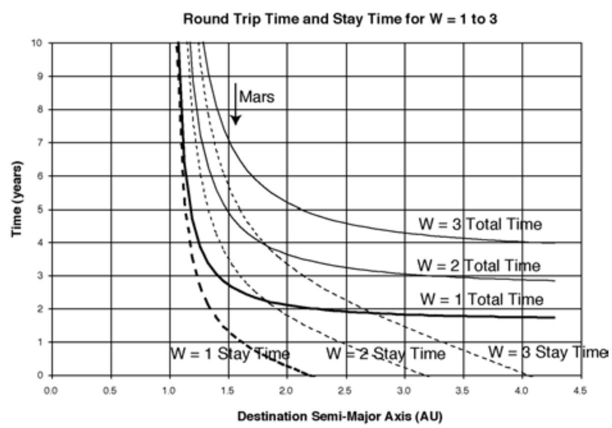

Fig. 3. Total Trip Time and Stay Time for Hohmann Round Trip Travel Outbound from the Earth to the Vicinity of Mars and the Asteroid Belt.

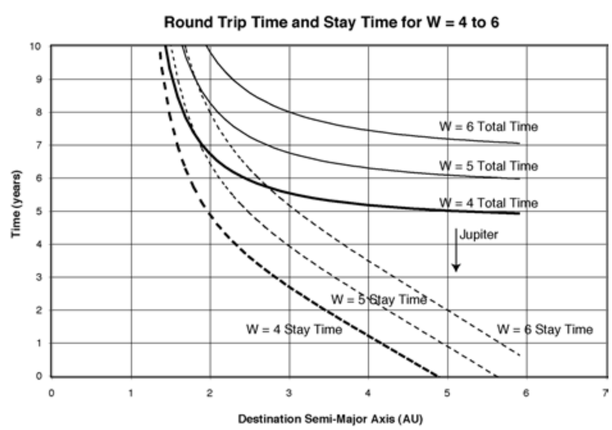

Fig. 4. Total Trip Time and Stay Time for Hohmann Round Trip Travel to the Vicinity of Jupiter.

* Depending on the application, the descent and ascent times at the destination can be included either in the stay time, t_S, or in the transfer times. For the remainder of this paper, we include any required ascent and descent times in the stay time and exclude the descent and ascent ΔV's from the total transfer ΔV because these will vary, depending on the nature of the mission and whether the target is a planet, an asteroid, or an empty point in space.

**We assume throughout that Mars and the Earth are in circular, coplanar orbits. The actual non-circular, non-coplanar nature of the orbits changes the numerical values somewhat, but does not effect the basic process or mission analysis technique.

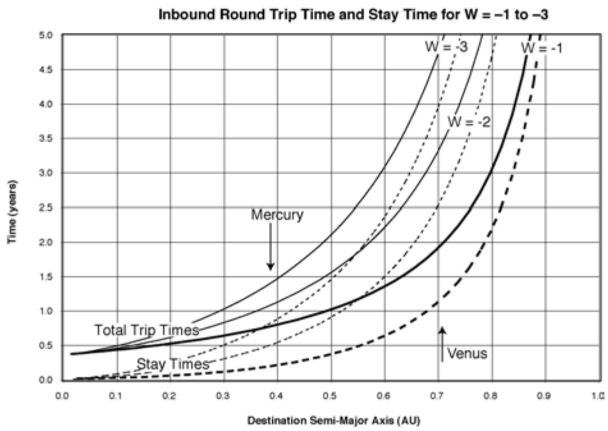

Fig. 5. Total Trip Time and Stay Time for Hohmann Round Trip Travel Inbound from the Earth, I.E., Toward Venus or Mercury.

For most practical interplanetary travel, the Hohmann transfer round trip is the lowest energy approach. Using Hohmann transfers to any destination fixes both the round trip time and stay time. The quickest outbound Hohmann round trip is 2 years in duration with $W = 1$. It goes to a distance of 2.2 AU with 0 stay time. Hohmann round trips to less than 2.2 AU take more than 2 years and increase rapidly in total trip time at less than 1.5 AU (i.e., the distance of Mars). Hohmann round trips to further than 2.2 AU require $W > 1$ to have a non-negative stay time and, therefore, require a total trip time greater than 3 years (See Fig. 3). Hohmann round trips to Jupiter require $W = 5$ or greater and a total trip time greater than 6 years to achieve a non-negative stay time (See Fig. 4). With $W = 1$, or any odd value, the stay time is centered when the home planet and the target are 180 deg apart, thus making communications challenging. With $W = 2$, or any even value, the stay time is centered when the target and the Earth are in conjunction, i.e., lined up on the same side of the Sun. In this case, communications during the stay is much easier.

The quickest inbound Hohmann round trip is 0.36 years (133 days) in duration with any negative value of W. This corresponds to dropping into a grazing orbit about the Sun and returning, not a particularly practical trip for most purposes. $W = -1$ trips to Venus at 0.72 AU take 2.04 years (747 days) with a stay time of 1.2 years (455 days). A summary of the Hohmann round trip baseline parameters for nearby destinations is as follows:

	Mean Orbit Radius	Round Trip ΔV	Round Trip Time	Stay Time
Venus	0.72 AU	10.4 km/sec	2.08 yrs	1.28 yrs
Mars	1.52 AU	11.2 km/sec	2.66 yrs	1.24 yrs
Jupiter	5.20 AU	28.9 km/sec	6.05 yrs	0.59 yrs

Here and elsewhere "round trip ΔV" is the transfer plus velocity matching ΔV for both the transfer to the target and the return trip to Earth, i.e., a total of 4 impulsive thruster firings. It does not include the ΔV to leave or land on the Earth or the target.

FASTER ROUND TRIPS

Hohmann transfer round trips minimize the total energy, but take a long time. However, the transfer time is a major driver of cost, risk, and utility for human spaceflight. For example, radiation exposure becomes a significant problem in long duration human missions. While radiation exposure can be solved with sufficient shielding, it's hard to envision thriving Martian tourism and commerce with a 2.7 year minimum round trip time. If we are going to truly settle and use the solar system, we need significantly faster round trip travel options.

Because the Hohmann transfer trajectory is tangent to the target orbit, we can significantly reduce the 1-way trip time and mission anomaly angle with a relatively small increase in ΔV. For the Mars Hohmann trip, increasing the total ΔV by 0.112 km/s (1%) reduces the 1-way transfer time by 11 days (4.3%) and the transfer change in mission anomaly by 5.3 deg (3.0%). Unfortunately, this ΔV reduces the total trip time by only 2 days (0.2%).

The fundamental problem with round trip travel is that the total time is driven by the constraint to have the home planet make an integral number of additional orbits around the Sun than the traveler makes. The more we slow down the traveler, the faster the Earth can "lap" the traveler and the sooner they can return home. Therefore, for outbound trips, slowing the traveler speeds up the round trip time, so long as we remain with the same value of W.

This effect is illustrated in Fig. 6. A Hohmann transfer has a mission anomaly change of 180 deg with the transfer trajectory tangent to the orbit of the target planet. A ***T1 Transfer*** (also called Type 1 in JPL terminology) occurs on the first half of a transfer trajectory which goes beyond the Target planet and has a mission anomaly change of less than 180 deg. This reduces the 1-way transfer time and increases the stay time, but has little impact on the round trip time. In contrast, a ***T2 Transfer*** (or Type 2) occurs on the second half of the transfer trajectory with a mission anomaly change of more than 180 deg. This increases the 1-way transfer time, but reduces the round trip time by adding a low angular velocity arc at aphelion. Unfortunately, the stay time is significantly reduced because the traveler spends much of its time in the aphelion arc.

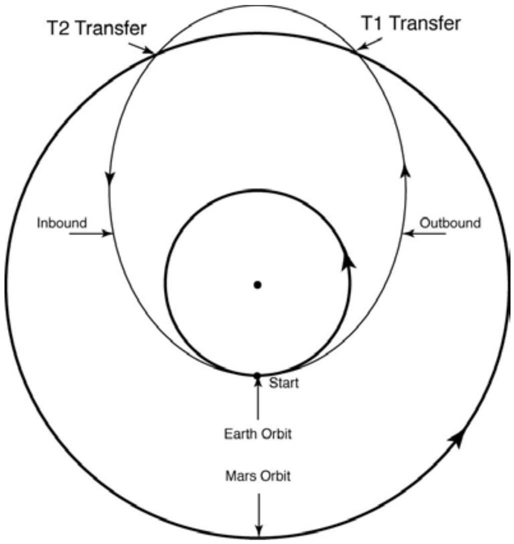

Fig. 6. T1 and T2 Transfers. T2 transfers can reduce the total trip time by allowing the spacecraft to spend time at the low angular velocity arc at aphelion.

The stay time and round trip time for alternative Mars round trips with W = 1 are shown in Fig. 7 and for Jupiter round trips with W = 5 in Fig. 8. (Note that the horizontal coordinate in these and subsequent figures is the round trip ΔV as defined above. The curves converge on the left at the minimum energy Hohmann ΔV point.) Unfortunately, the mission duration effects are small for both Mars and Jupiter. For Mars, using a T2 transfer to reduce the total trip time to 2.3 years drops the stay time to 0. In the case of Jupiter, the T2 stay time drops to 0 almost immediately such that a T2 transfer for W = 5 is not an effective alternative. Speeding up the normal T1 transfer has virtually no effect on round trip travel time. Using a T2 transfer approach provides a greater reduction in total trip time than a T1 transfer, but is applicable in only some circumstances and greatly reduces the stay time.

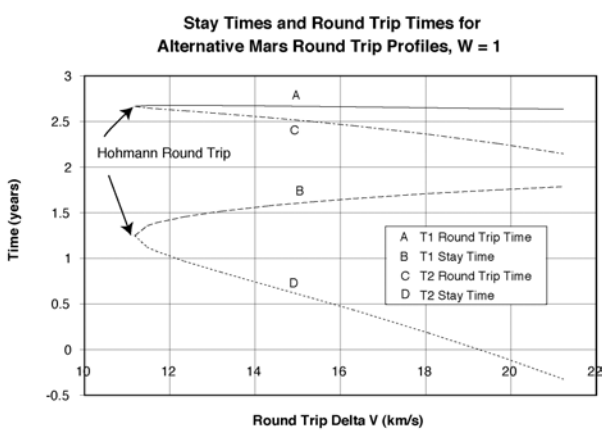

Fig. 7. Mission Duration Vs. Round Trip ΔV for Alternative Mars Round Trip Profiles with W = 1.

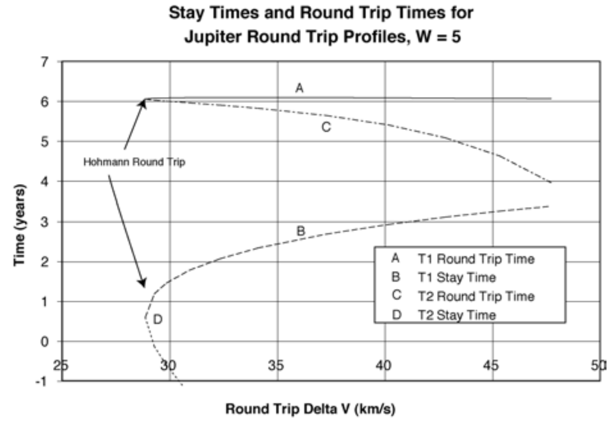

Fig. 8. Mission Duration Vs. Round Trip ΔV for Alternative Jupiter Round Trip Profiles with W = 5.

Figure 9 shows a similar process for an inbound round trip to Venus with W = –1. Decreasing the T1 transfer time does very little to reduce the total trip time, as was the case with the outbound trips. T2 transfers can have a greater impact on mission duration than for the outbound missions, but comes at a very high cost in terms of much larger ΔVs.

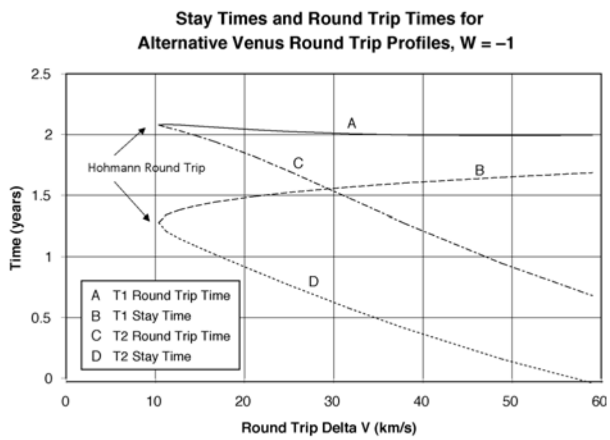

Fig. 9. Mission Duration Vs. Round Trip ΔV for Alternative Venus Round Trip Profiles with W = –1.

“REDUCED W” ROUND TRIPS

The round trip time is driven by the need for the difference in the number of revolutions for the Earth and the traveler to be an integer, W. With Hohmann transfers the minimum value of W is 1 for Mars, 5 for Jupiter, and –1 for Venus. As we have seen above, **so long as the value of W doesn't change, changing the 1-way travel time by adding energy has almost no impact on the total round trip time.** However, if the energy is increased sufficiently, it is possible to reduce the value of W and, consequently, make a large step reduction in the total mission duration. The additional ΔV required to reach the first step will depend entirely on where the baseline mission falls in the Hohmann transfer charts presented previously. These "Reduced *W*" missions can have a major impact on mission design. T1 transfer total mission duration will have a series of discrete jumps of somewhat more than 1 year with very little change in mission duration between the jumps. T2 transfers are not applicable since the "slow down and kill time" approach is counter productive when trying to obtain a reduced value of *W*.

This process is illustrated for T1 round trip missions to Jupiter in Fig. 10. It takes relatively little added ΔV to drop from $W = 5$ to $W = 4$, with a resulting reduction of more than a year in the total trip time. This effect comes about because the Earth is now required to "lap" Jupiter only 4 times, rather than 5 as for the traditional Hohmann round trip transfer. By approximately doubling the Hohmann ΔV, we can reduce W to 2 and reduce the total round trip time from more than 6 years to less than 3 years. "Reduced *W*" trips can enable missions that are not otherwise practical by allowing a major reduction in the total mission duration. The ΔV cost may be modest or very high, depending on the baseline Hohmann mission and the value of ΔW.

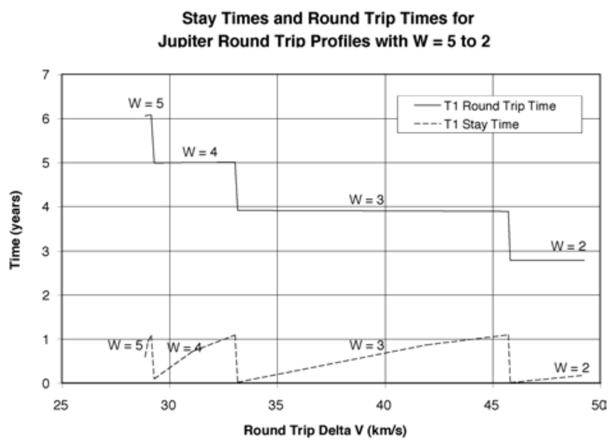

Fig. 10. Jupiter "Reduced *W*" Missions using T1 Transfers. Adding sufficient ΔV to reduce the value of W can have a dramatic impact on the total round trip time.

THE ULTIMATE ROUND TRIP, *W* = 0

From the above results it is clear that round trip times are driven almost entirely by the value of W. Round trips to nearby orbits (e.g., 1.1 AU) are exceptionally difficult. For example, a Hohmann transfer round trip to a near-Earth asteroid 10 million km (0.07 AU) beyond the Earth would require a total mission duration of 11.3 years and a stay time of 10.3 years. Recall that the shortest possible Hohmann outbound round trip is 2 years and that adding energy does very little to reduce that time.

To significantly reduce the round trip travel time to "nearby" locations, we need trips for which $W = 0$. In this case, the following must be true:

> **For $W = 0$ round trips, the average angular speed of the home planet and the traveler must be the same over the full duration of the mission (including the stay at the destination).**

As shown in Fig. 11, any periods of slower angular speed on the part of the traveler, including stay time at the target, must be compensated by periods of faster angular speed in order to get back home. Similarly, periods of higher angular speed on the part of the traveler must be compensated by lower angular speed to allow the home planet to catch up. This problem is workable, but requires a different time history (and considerably more energy) than the usual Hohmann transfer process.

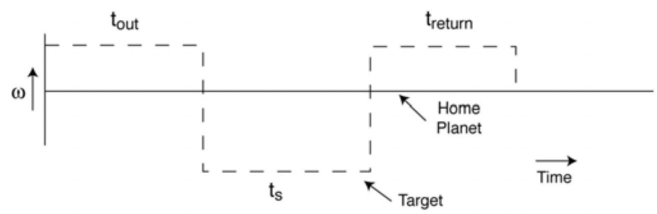

Fig. 11. For *W* = 0 Missions, the Total Area Under the Curve Below the Horizontal Axis must be Equal to the Total Area Under the Curve Above the Axis.

W=0 transfers enable short, flexible round trip missions. Mission durations and stay times will be determined primarily by the amount of ΔV that we are willing to use. These missions are easiest near the home planet and would be the only realistic alternative for round trips to, for example, near-Earth asteroids. For practical purposes, $W = 0$ missions are potentially applicable in the approximate region from Venus on the inner side to Mars on the outer side.

Figure 12 shows how the $W = 0$ missions work in practical terms. The figure shows the angular rates during a Hohmann transfer mission to Mars and the assumed constant angular rates for the Earth (the home planet) and Mars. The transfer begins by adding velocity such that the initial angular rate is higher than the Earth's rate. By the time the traveler gets to Mars, it has converted sufficient kinetic energy into potential energy that it is now going more slowly than Mars and must again speed up to rendezvous with the target. In the $W = 0$ missions, we will use only the left portion of Fig. 12 such that the average angular velocity for the trip out, the stay at the destination, and the return, all taken together, is just equal to the angular velocity of the Earth. We first speed ahead of the Earth, arrive at our destination, then wait for the Earth to catch up, and transfer back. While this can take a large ΔV, it can dramatically reduce the round trip time, which is particularly important for any human missions beyond initial exploration.

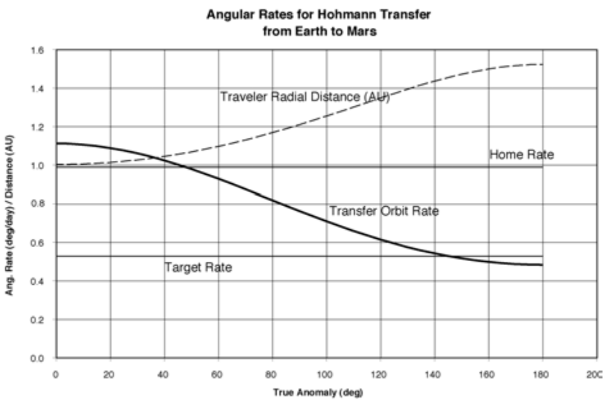

Fig. 12. Angular Rates for a Hohmann Transfer from the Earth to Mars. *W* = 0 missions will use only the left portion of the plot.

Much like the T1 and T2 missions described above, there are two classes of $W = 0$ missions. ***W = 0 Direct Transfer Missions*** are those that use only the early segment of the transfer trajectory, use a T1 transfer to the target orbit, remain there for some period, and then transfer back on a trajectory basically equivalent to the outbound leg. Typical performance for missions to a near-Earth asteroid, Mars, and Venus are shown in Figs. 13 to 15. This type of transfer requires a total ΔV of 5 to 10 times that of a Hohmann transfer round trip. Nonetheless, it can reduce the total round trip time for a Mars mission from about 2.6 years to less than 6 months, or, in the near-Earth asteroid case, from 8 years to less than 6 months. Note that the $W = 0$ near-Earth asteroid mission requires approximately the same ΔV as the Hohmann round trip to Mars. At the boundary between $W = 1$ (or -1) and $W = 0$, these missions have short stay times, which increase slightly with increased ΔV.

Because we need to balance the differential velocity between Earth and the target planet with high (or low) velocity segments during travel, the ΔV required for $W = 0$ missions increases substantially as we get further from the Earth where the Target velocity is very different from the Earth's rate. Conversely, it is much easier to use $W = 0$ missions near the Earth. $W = 0$ transfers must be used to achieve realistic mission timelines for "near-by" missions such as a round-trip to a near-Earth asteroid.

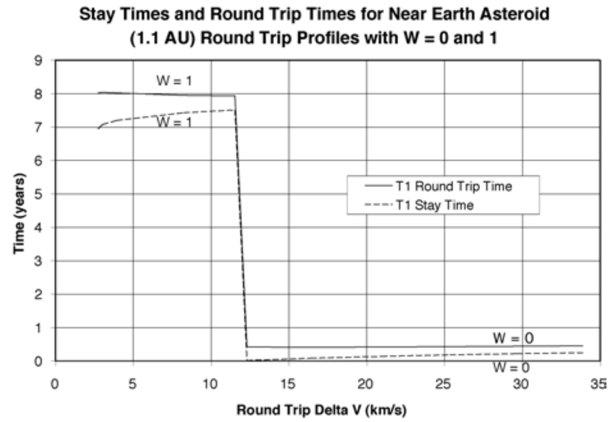

Fig. 13. *W* = 0 and 1 Direct Transfer Missions to a Near-Earth Asteroid at 1.1 AU.

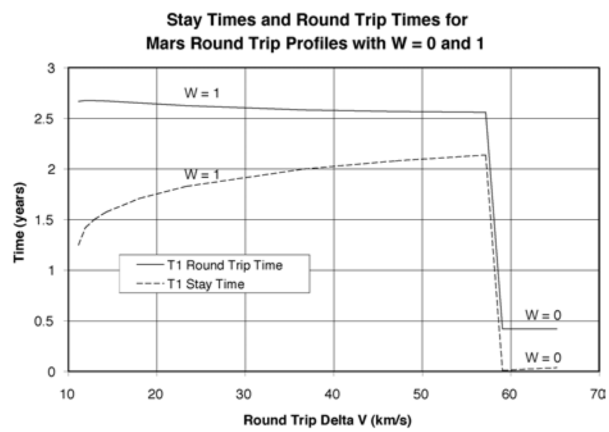

Fig. 14. *W* = 0 and 1 Direct Transfer Missions to Mars.

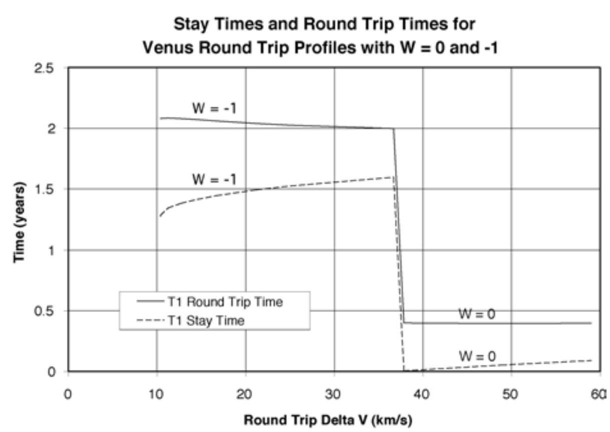

Fig. 15. *W* = 0 and –1 Direct Transfer Missions to Venus.

The $W = 0$ Direct Transfer missions can provide a very short total mission duration, but require high ΔV's and have a short stay time. This can be mitigated to some degree by having one or both transfer legs go inside the Earth's orbit (for outbound missions) to provide a high angular velocity segment to offset the lower angular velocity at the target. ***W = 0 Indirect Transfer Missions*** are those that, for outbound missions, drop inside the orbit of the home planet on either or both the outbound and inbound leg. Having one leg with rapid, direct transfer and one leg with a T2 transfer can provide good results as shown in Fig. 16. Typically this transfer method requires a total ΔV of 3 to 5 times that of a Hohmann transfer round trip, significantly less than that for direct $W = 0$ transfers. Indirect transfer provides intermediate round trip times of somewhat more than 1 year with stay times of reasonable duration. As is the case with direct $W = 0$ transfers, indirect transfers can be applied to distances out to approximately Venus inbound or Mars outbound.

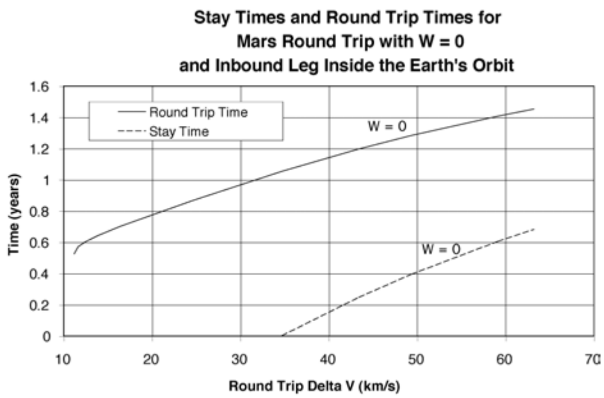

Fig. 16. ***W*** **= 0 Indirect Transfer Round Trip to Mars.**

ROUND TRIPS IN EARTH ORBIT

The fundamental constraints and constraint equations derived above for interplanetary missions apply equally to Earth-orbiting missions. For example, the same round trip rules apply to missions from the International Space Station (ISS) to other satellites in either low-Earth orbit or geosynchronous orbit that require returning "home" to the ISS.

However, the basic driver of the mission timeline is the period of the home planet or satellite. For interplanetary missions with Earth as home, this fundamental period is 1 year. One extra orbit can make a critical difference to mission cost and risk. For Earth-orbiting missions with the ISS as home, the fundamental period is 90 minutes. A few extra orbits make very little difference to mission cost and risk. For Earth-orbiting missions, round trip mission design is likely to be driven more by differences in inclination or nodal drift rates than by a few more periods in orbit transfer. The rules for returning home apply, but simply add one more constraint among many.

Synodic periods are a good way to measure the likely impact of the fundamental constraints on round-trip travel. (See, for example, Wertz [2001].) Thus, for the Earth and Mars, the synodic period is 2.135 years, and minimizing mission duration is important. For a near-Earth asteroid at 1.1 AU, the synodic period is 7.5 years and a $W = 0$ mission is generally required. For a satellite at 600 km altitude, the synodic period relative to the ISS at 350 km is 29 hours. While the round trip time may need to be taken into account, it is unlikely to be a key driver for round trip mission design in Earth orbit.

THE "INTERPLANETARY TRAIN SCHEDULE"

For the mission segment going from home to the target, the traveler must start at the home planet and arrive at the target. Therefore, the start time, T_{start}, and start mission anomaly, ν_{start}, and arrival time, T_{arrive}, and arrival mission anomaly, ν_{arrive}, relative to when the home planet and the target are both at the same mission anomaly are given by:

$$\nu_{start} = T_{start}\,\omega_H \tag{16}$$

$$\nu_{arrive} = T_{arrive}\,\omega_T \tag{17}$$

where ω_H and ω_T are the angular velocities of the home and target, respectively. For the Earth as the home planet, "the same mission anomaly" means that the target and Earth are on the same side of the Sun and the Sun, Earth, and target are in a straight line. This is opposition for Mars or inferior conjunction for Venus. For the traveler to start at the home planet and end at the target, we must have:

$$\Delta\nu_{transfer} = \nu_{arrive} - \nu_{start} = \omega_{transfer}\ t_{transfer} \tag{18}$$

where the "transfer" subscript refers to the travel segment between home and the target. Therefore, given a transfer time, $t_{transfer}$, and transfer arc, $\Delta\nu_{transfer}$, we can determine the required start and arrival times, relative to opposition, as:

$$T_{start} = t_{transfer}\ (\omega_T - \omega_{transfer}) / (\omega_H - \omega_T) \tag{19}$$

$$T_{arrive} = T_{start} + t_{transfer} \tag{20}$$

Equations (16) and (17) then provide the start and arrival mission anomalies.

Given a transfer scenario, we can use Equations (16) through (20) to determine the start and arrival times of the various mission segments relative to opposition. Small corrections will be needed to account for the non-zero eccentricity of real planetary orbits. While the above approximations are well known, they have been applied largely in the vicinity of minimum energy transfers. For higher energy missions we can construct a "train schedule" of transfer times to the planets as a function of phase in the synodic period and total transfer ΔV. Thus, the general mission design process lets us look at the total round trip time, the stay time, and the mission start and end times relative to the synodic period — all as a function of the total ΔV that is available for the mission.

EXAMPLE: CREATING A LOW-COST, NEAR-TERM HUMAN MISSION TO MARS

A key problem with human Mars missions is the need for life support for a 2.5 year mission duration. Reducing the mission to 6 months by using a $W = 0$ round trip would take dramatically high ΔV's and require shorter stays on Mars than are desirable for exploration.

As an alternative, we can consider a "two-phase" human mission to Mars. We send the descent module, exploration equipment, extra life-support equipment and supplies, and Earth-return equipment to Mars on a Hohmann low-energy, $W = 2$ transfer. All of the equipment is deployed and tested after arrival in Mars orbit. For the astronauts, we use a 70-day transfer, 2 to 3 week stay on Mars, and 70-day return. Most of the mass, including the mass required for the return trip, is transferred at minimum energy and, therefore, minimum cost. On the other hand, people are transferred on a minimum time trajectory. The total duration of human life support is reduced from 975 days to 160 days, a factor of 6 reduction. In addition, the astronauts are at Mars around opposition, when communication with Earth is the easiest and Mars would be brightly visible in the night sky.

This suggests a different paradigm for future low-cost, rapid human exploration of the solar system. Equipment moves slowly and economically. People move more rapidly and, consequently, more safely and economically as well. This alternative should be given serious consideration as we attempt to understand the potential, the limitations, and the technology needs of human exploration of the solar system.

CONCLUSIONS

The design of interplanetary round trip missions is driven primarily by the fundamental constraint that the difference in the change in mission anomaly between the traveler and the Home planet must be an integral number of orbits. For $W = 1$, the total trip time is driven by the need to allow the Earth to make one extra revolution during the trip. This constraint is needed to get the traveler back to Earth. Slowing the angular velocity of the traveler, by taking it to a larger distance from the Sun for example, can reduce the total trip time, although the impact is typically modest. A similar constraint applies to other non-0 values of W.

Some of the statements in this paper at first appear almost paradoxical, but on closer analysis they fall into a logical, if unfamiliar, pattern. Note that it does not matter how we go about getting from home to the destination. It could be via direct transfer, low-trust spirals, or multiple planetary fly-bys. All of these can change the required ΔV for any mission. However, the fundamental restrictions on total mission duration arise only from the requirement to return home, not on how we go about arranging the trip.

The most effective approach for reducing the total mission duration is to reduce the value of W, i.e., the number of extra times the home planet must go around the Sun before the traveler returns. For $W = 0$, there are much faster round trip missions with greater timeline flexibility at a cost of 3 to 10 times the ΔV of minimum energy missions. These missions can bring round trip times down to 6 months or less, whereas minimum energy outbound round trip missions are at least two years in duration and often substantially longer. Thus, realistic human spaceflight on a regular basis may require ΔV's that are 3 to 10 times that of minimum energy missions. Interplanetary Round Trip Mission Design is a relatively new field with interesting possibilities. While the general rules are now known, there are many detailed design elements yet to be discovered.

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REFERENCES

[1] Aldrin, E. E., 1985. "Cyclic Trajectory Concepts," SAIC Presentation to the Interplanetary Rapid Transit Study Meeting, JPL.

[2] Brown, C., 1998. *Spacecraft Mission Design*, 2nd ed.; Washington, DC; AIAA, 210 pg.

[3] Friedlander, A. L., J. C. Niehoff, D. V. Byrnes, and J. M. Longuski, 1986. "Circulating Transportation Orbits Between Earth and Mars," AIAA paper No. 86-2009-CP, AIAA/AAS Astrodynamics Conference, Williamsburg, VA, Aug., 1986.

[4] Hoffman, S. J. and J. K. Soldner, 1985. "Concepts for the Early Realization of a Manned Mission to Mars," AAS Science and Technology Series, Vol. 62, pp. 377-390.

[5] Hoffman, S. J., J. V. McAdams, and J. C. Niehoff, 1989. "Round Trip Trajectory Options for Human Exploration of Mars," Paper No. AAS 89-201.

[6] Polsgrove, T. and R. B. Adams, 2002. "Trajectories for High Specific Impulse High Specific Power Deep Space Exploration," Paper No. AIAA 2002-4233; 38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, July 7-10, 2002, Indianapolis, IN.

[7] Vallado, D. A., 2001. *Fundamentals of Astrodynamics and Applications*, 2nd ed.; Dordrecht, the Netherlands, and El Segundo, CA; Kluwer Academic and Microcosm Press, 958 pg.

[8] Wertz, J. R., 2001. *Mission Geometry; Orbit and Constellation Design and Management*; Dordrecht, the Netherlands, and El Segundo, CA; Kluwer Academic and Microcosm Press, 934 pg.

[9] Young, A. C., 1988. "Ballistic Trajectory Options for Manned Mars Missions," Paper No. AAS 88-189.