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Interplanetary Round Trip Mission Design

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Agenda

- Summary
- What Determines Round Trip Travel Time
- Start and Stop Times Relative to Opposition
- The Ultimate Trip, W = 0
- Direct vs. Indirect Transfers
- The Interplanetary Train Schedule
- “Practical,” Rapid Round-Trips to Mars
- Conclusions

Summary

- Nearly all interplanetary round trip analysis to date has focused on minimum energy round trips or small deviations from minimum energy
  - Certainly a practical approach given the high cost of rocket travel
  - The result has been round trips to Mars on the order of 970 days (2.7 yrs) or longer
  - Increasing the energy does very little to change the round trip time
- An internally funded Microcosm study, begun in Sept. 2001, has focused on what drives the round trip time and what is required to dramatically reduce it
  - Increases delta V cost, but reduces "operations and maintenance" cost
  - May be important for human missions
  - Will be critical for extensive human travel
- Key results:
  - The fundamental constraint of Interplanetary Round Trip Travel is that the difference in the change in mission anomaly between the traveler and the home planet must be an integral number of orbits, W
    - By changing from W = 1 to W = 0, a round trip to Mars can drop from 2.7 years to 5 months, but at total delta V cost of nearly 60 km/s, about 5 times the delta V for a W = 1 Hohmann transfer mission
    - Some intermediate solutions also exist that are midway in terms of total trip time and required delta V

The goal is to understand the "basic physics" of Interplanetary Round Trip Travel.

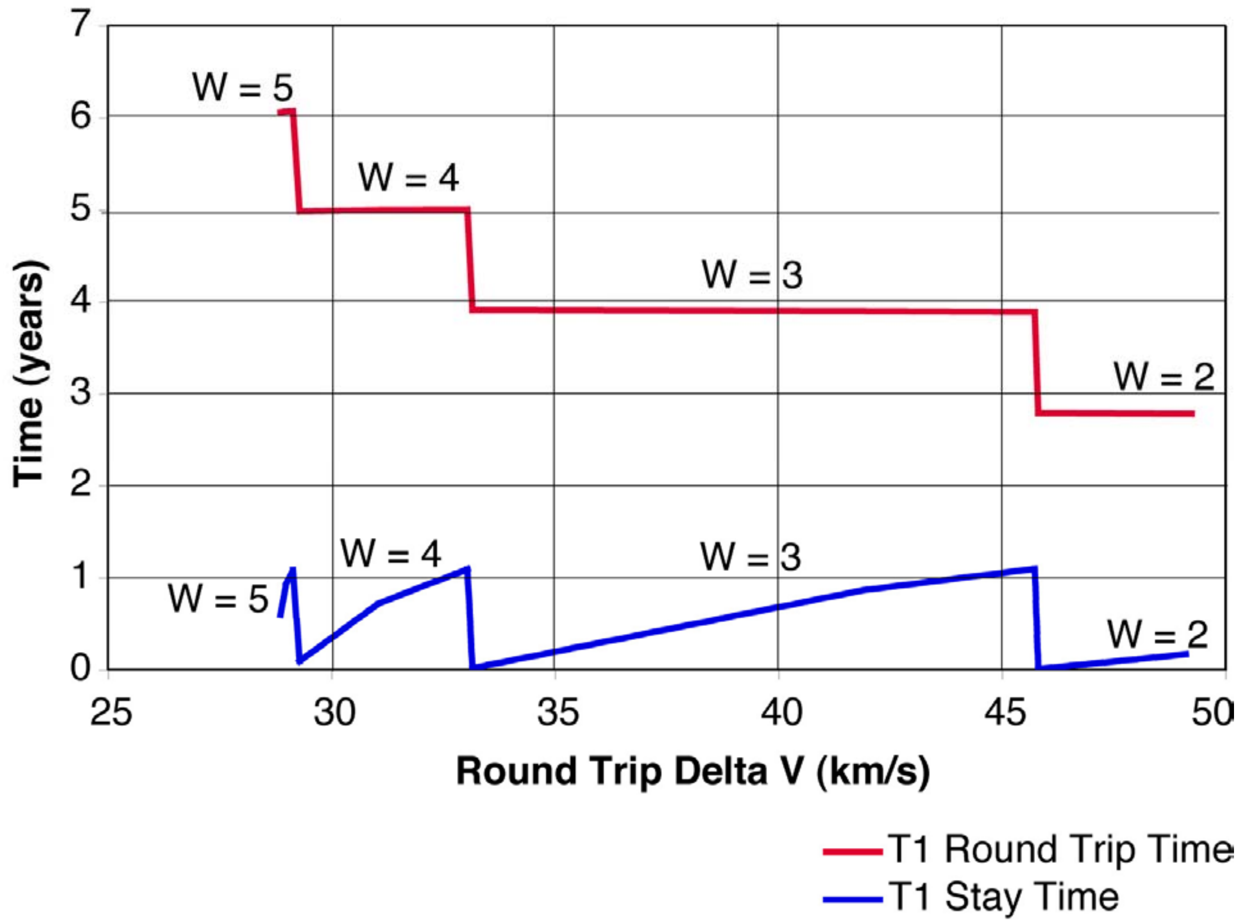
Summary (Continued)

- We define a new class of "*Rapid Round Trip*" interplanetary missions for which W is at least 1 less than for the traditional round trips using Hohmann transfers and, consequently, the total mission duration is 1 or more years shorter than traditional round trips
  - Rapid round trips reduce the time for all interplanetary travel at a delta V cost that depends on the specific trip
  - Rapid round trips are the only practical way to have round trips to Near-Earth Asteroids and other near-by interplanetary objects
- Representative results for Mars:

Example		A Hohmann (W=1)	B High Energy, W=1	C High Energy, Direct W=0	D Direct W=0 with Longer Stay	E Outbound and Return both Indirect	F Direct Outbound/ Indirect Return	G Direct Outbound/ Indirect Return	H Direct Outbound/ Indirect Return
Total Trip	(months)	32.0	30.7	5.0	5.0	19.9	14.4	15.4	16.9
Stay on Mars	(months)	14.9	25.6	0.1	0.4	2.0	3.0	4.7	7.3
Total Delta V	(km/sec)	11.2	57.2	59.1	65.2	35.3	43.4	49.3	59.1
Delta V 1/3	(km/sec)	5.6	28.6	29.5	32.6	17.7	14.5	16.8	20.7

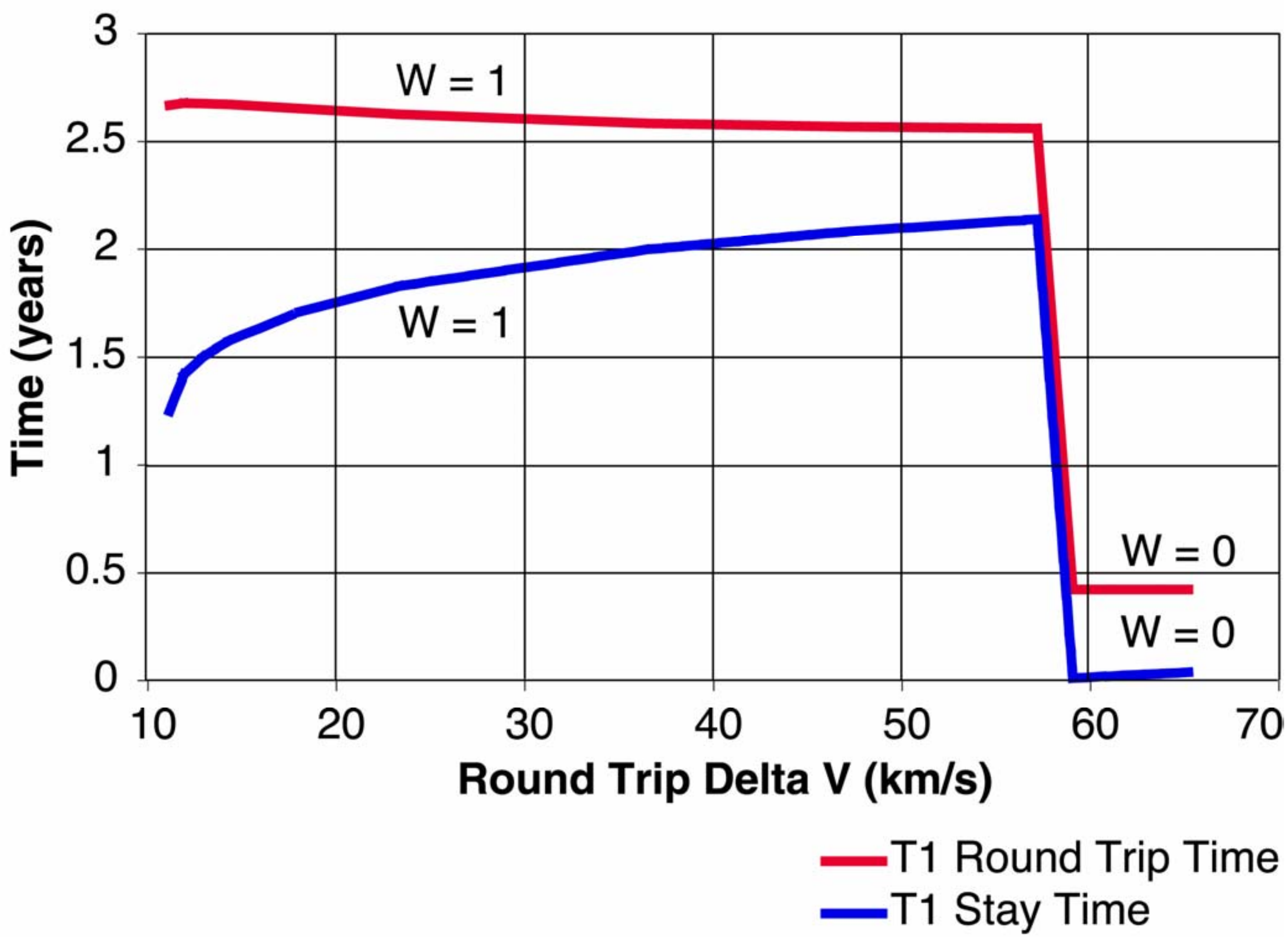
Intermediate Round Trips can provide a stay on Mars of 3 to 7 months with a total round trip time of 1.2 to 1.4 years and total delta V of 3 to 4 times the Hohmann delta V, or less if direct entry is used for planet arrival.

Jupiter “Reduced W” Missions



- Note that the first step (W = 5 to W = 4) requires only a very small increase in delta V

W = 1 and W = 0
Direct Transfer Missions to Mars



- For a Mars round trip, going from W=1 to W=0 has a major impact on round trip time, but at a high cost in delta V

What Determines Round Trip Travel Time?

The Jogging Analogy

The Fundamental Rules for Round Trip Travel

Basic Equations for Round Trip Travel

The Change in Mission Anomaly

What Causes the Large Step Function in Round Trip Time

Round Trip Interplanetary Travel — the Jogging Analogy

- My name is Marty. (It's not really, but it makes the story easier)
- Being both old and a tad "portly," I jog like a lethargic snail with a bandage on one foot
  - Let's assume that I can jog (crawl) around the outer edge of the track in 5.0 minutes
- My friend, Earthy, runs backward to keep from going too much faster than I, but still jogs around the inner edge of the track in 3.0 minutes
- Basic parameters:
  - Marty's speed = 5 min/lap = 72 deg/min
  - Earthy's speed = 3 min/lap = 120 deg/min
  - Relative speed = 120 – 72 = 48 deg/min
- If they start together, they will next be together after 360/48 = 7.5 minutes, this is called the *synodic period*
  - Marty will have gone 1.5 laps and Earthy will have gone 2.5 laps, i.e., exactly 1 lap more than Marty
- Suppose on a particular day, Marty has forgotten his water bottle and wishes to borrow Earthy's
  - Earthy hands the bottle to Marty at the first opportunity, 7.5 minutes after starting together
  - Marty hands it back at the next opportunity, 7.5 minutes later when they again return to being next to each other
  - Earthy will have made 5 laps when he gets the water bottle back, but the bottle (which will become our spacecraft) has made 2.5 + 1.5 = 4 laps, exactly 1 lap less than its owner (i.e., W = 1, Round Trip time = 7.5 min)

Jogging II — Faster Transfers

- Earthy is happy to help, but is a bit annoyed at not having his water bottle for an extended period. How can Marty return it more quickly?
- Solution 1 — Marty takes a drink and then sets the bottle on the ground and Earthy picks it up when he comes around next
  - The transfer has been speeded up by slowing the bottle, which increases the relative speed between the bottle and Earthy to Earthy's speed of 120 deg/min
  - Earthy picks up the bottle 3 minutes after he gave it to Marty; Earthy has gone a total of 3.5 laps and the bottle has gone 2.5 laps — again the magic difference of 1 lap
    - W = 1, Round Trip time = 3 min
- Solution 2 — Just as Earthy is about to pass Marty, he tosses the bottle forward to Marty. Marty takes a quick drink and hands it right back to Earthy. Now the elapsed time is very short
  - This is an example of an extremely short trip, with no difference in the number of laps for Earthy and the bottle
    - W = 0, Round Trip time = almost 0
- Solution 3 — Marty takes a drink and then begins cutting across the infield such that he meets Earthy again exactly opposite of where Marty took the drink
  - Earthy gets the bottle back in only 1.5 minutes from when he handed it off
  - Again Earthy and the bottle have both completed 3.5 laps (or at least 3.5 trips around the center), the difference between the two is now 0 laps and the transfer is quicker
    - W = 0, Round Trip time = 1.5 min

What Does the Analogy Show?

- Our analogy to interplanetary round trips certainly isn't perfect
  - In interplanetary travel the trip itself (i.e., the handoff) takes quite a bit of time
  - The outer planets both travel further and move slower than the inner ones
  - It takes just as much energy to slow a spacecraft as to speed it up — i.e., I can't "set down the spacecraft on the track" and wait for the Earth to swing by. (I can, however, go above the orbit of my target planet and travel more slowly than the target.)
- Nonetheless, it does illustrate a few points:
  - No matter what, the difference in the number of laps taken by the water bottle and by Earthy (the origin and final destination) must be an integer, W
  - Slowing down the spacecraft angular velocity can speed up the transfer, but only by a limited amount
- The real change in round trip time comes when we reduce the number of added trips the bottle takes from 1 to 0
  - This is what lets us do stuff quickly

Definitions

- ***Round Trip*** = a space mission which begins and ends on a single planet, satellite, or orbital location, called ***Home*** [**Earthy** in the analogy]
  - We will be concerned primarily with interplanetary travel, so 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 [**Marty**]
- ***Traveler*** = the spacecraft which makes the Round Trip [**the water bottle**]
- ***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 position between 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* as measured with respect to a potentially changing perigee location.
- ***Synodic Period*** = 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

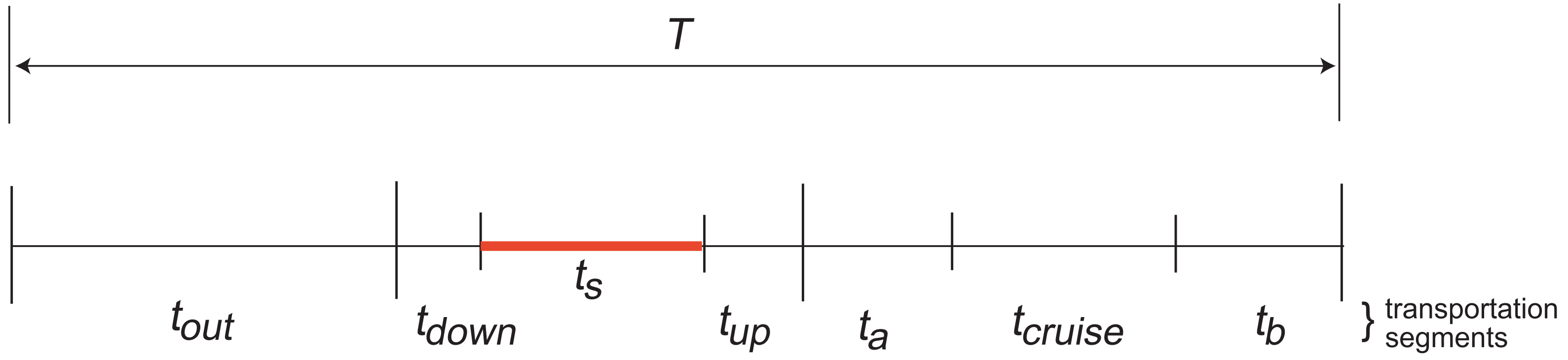
The Fundamental Rules for Round Trip Travel

- The following conditions are 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 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 which addresses Condition 1
- Condition 3 may impact the delta V 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)
  – For planetary trips the cross-track position does not normally change for the Home planet

So far as we know, these fundamental constraints have never been explicitly stated or their implications fully explored.

Mission Timeline

- The total mission time, T, can be broken down into a series of transportation segments of duration t_i, and a stay on the target planet of duration t_S
- For example, the following timeline might apply to an electric propulsion mission:



- 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

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

Fundamental Constraint Equation

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

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

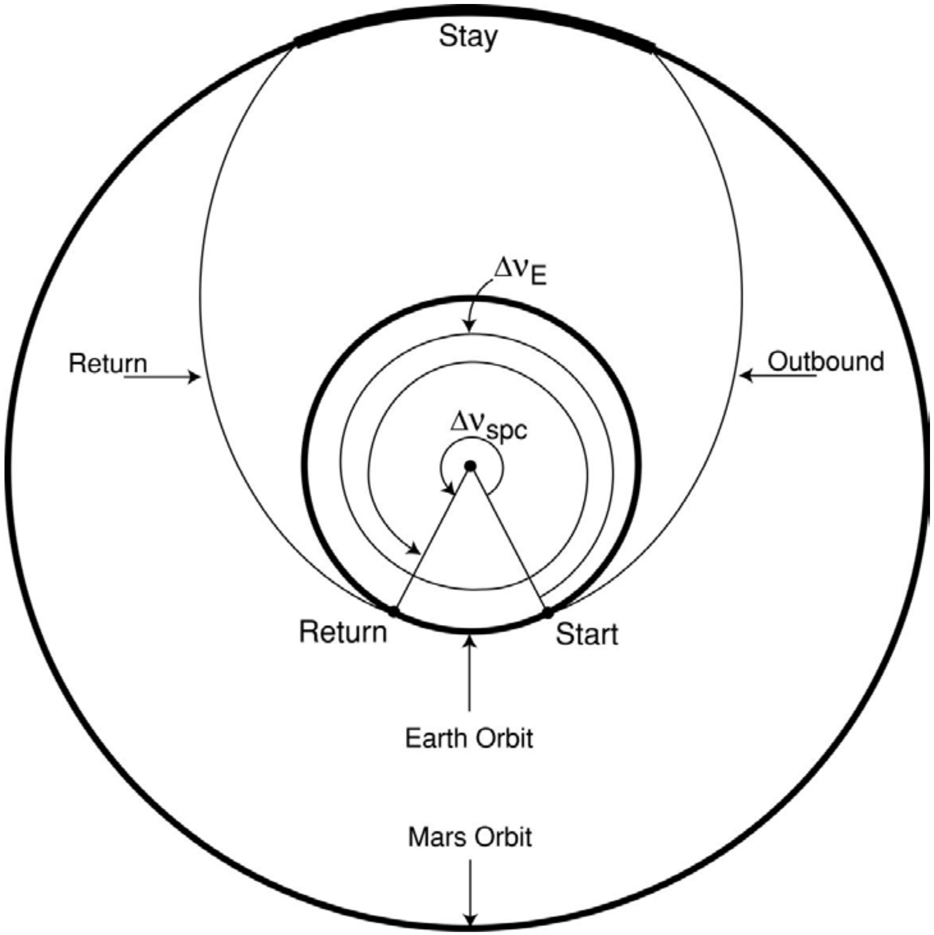
where

$\Delta\nu_H$ is the change in true anomaly of the home planet

$\Delta\nu_{spc}$ is the change in true anomaly of the traveler's spacecraft

W is an integer (positive or 0 for outward trips, negative or 0 for inward trips)

- While some other equations are approximations, Eq. (3) must be satisfied exactly



The key to conceptual round trip mission design is to work in terms of angular rates and angular positions in the orbit.

Basic Equations

- For the Home Planet

$$\Delta v_H \approx \omega_H T \quad (4)$$

Where ω_H is the orbital angular velocity of the Home Planet ~ 0.986 deg/day for the Earth

T is the total round trip travel time

- For the traveler's spacecraft, we divide the trip into K segments, and

$$\Delta v_{spc} \approx \omega_1 t_1 + \omega_2 t_2 + ... + \omega_K t_K = \Sigma \omega_i t_i + \omega_{Target} t_S \quad (5)$$

$$T = t_1 + t_2 + ... + t_K = \Sigma t_i + t_S \quad (6)$$

where

ω_i and t_i are the average angular rates and time of each travel segment

ω_{Target} is the average angular rates of the Target ~ 0.524 deg/day for Mars

t_S is the Stay Time at the Target

- Typically (though not necessarily)

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

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

General Solution for Interplanetary Round Trip

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

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

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

where P_H is the Home planet sidereal period ~ 365.24 days for Earth

- For a typical outbound mission:

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

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

- We can solve Eqs. (6) and (8b) for T and t_S in terms of the travel times and average angular rates:

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

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

Equations (9) and (10) <u>must be satisfied in order to return Home at the end of the trip.</u> <u>The type of transfer doesn't matter</u> — impulsive or electric propulsion, chemical or nuclear, direct or via planetary fly-bys. To make a round trip, I have to return home.

Round Trip Travel Using Hohmann Transfer Orbits

- Assume the mission consists of 2 Hohmann transfers + a stay of length t_S. Then

$$T = 2\,\omega'_{transfer}\, t_{transfer} + \omega'_{Target}\, t_S + W\, P_H \qquad (11)$$

$$t_S = T - 2\, t_{transfer} \qquad (12)$$

- Therefore,

$$T = (WP_H + 2\, t_{transfer}\, (\omega'_{transfer} - \omega'_{Target}))\,/(1 - \omega'_{Target}) \qquad (13)$$

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

$$\Delta\nu_{transfer} = 180 \text{ deg} \qquad (14a)$$

$$t_{transfer} \sim 259 \text{ days} \qquad (14b)$$

$$\omega_{transfer} = 0.695 \text{ deg/day} \qquad (14c)$$

$$\omega'_{transfer} = 0.705 \qquad (14d)$$

Total Trip: $T \approx 971 \text{ days} = 2.66 \text{ yrs}$ (14e)

Stay at Mars: $t_S \approx 453 \text{ days} = 1.24 \text{ yrs}$ (14f)

- For Hohmann transfers to Mars and back with W = 0, the stay time = –326 days (i.e., we need to leave about a year before we arrive), and for W = 2, the total trip is 1750 days (4.8 years) and the stay time is 1232 days (3.4 years)

The Change in Mission Anomaly

- In Round Trip Interplanetary Travel the traveler and the home planet begin and end together and, therefore, have the same mission anomaly before and after the trip
- That they must start and end together implies that the difference in the change in mission anomaly between the traveler and the home planet must be an integral number of orbits, W
  - W = 0 or a positive integer for trips outward from the Earth
  - W = 0 or a negative integer for trips inward from the Earth
  - Using Hohmann transfer minimum energy transfer orbits, W = 1 for round trips to Mars, 5 for round trips to Jupiter, and -1 for round trips to Venus
  - The change in mission anomaly for the target doesn't matter
- The round trip time is dominated by the value of W, with very little change caused by the applied delta V, until the value of W changes
  - Implies a series of step changes as the applied delta V increases
  - Steps will result in about a 1 year reduction in round trip time for distant trips and an even greater reduction for nearby trips
  - We define a ***Rapid Round Trip (RRT)*** as one with a value of W lower in absolute magnitude than for a minimum energy Hohmann round trip to the same destination
- The ***Quickest Round Trips (QRT)*** occur for W = 0
  - For these trips, the average angular velocity about the Sun must be the same for the traveler and for the home planet over the full duration of the trip, including time spent at the target planet
  - For W = 0, a round trip to Mars can drop from 2.7 years to 5 months, but at total delta V cost of nearly 60 km/s, about 5 times the delta V for a Hohmann transfer mission

What Causes the Large Step Function in Round Trip Time?

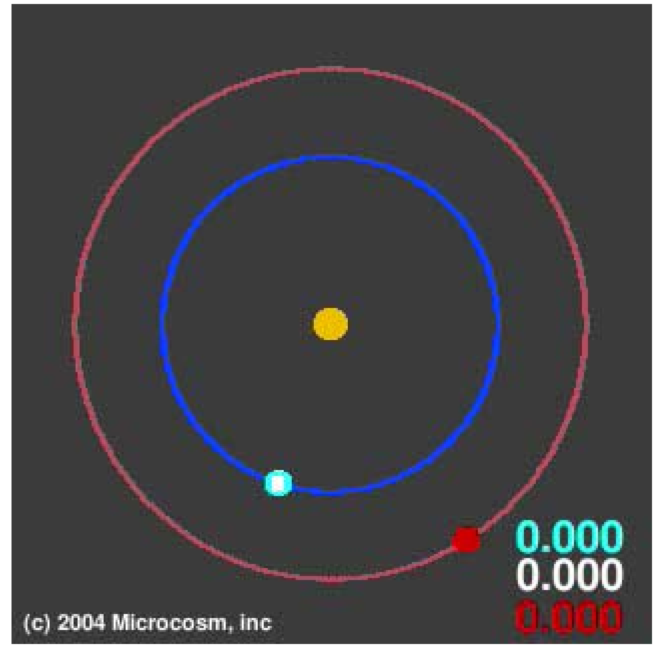
- To begin, assume symmetric trips out and back
- In a Hohmann transfer round trip to Mars, the traveler leaves before opposition and arrives at Mars quite a while after opposition
  - The traveler must wait until before the next opposition to begin the return trip, arriving back at Earth somewhat after the second opposition
  - In this trip, the Earth “laps” the spacecraft, making one more trip around the Sun than the traveler, i.e., W = 1
- As we add energy, we get to Mars sooner, but still have to wait until the second opposition to return home
  - We spend more time on Mars, but the total trip time changes very little
- If we put in enough delta V to arrive at Mars before opposition, then things change dramatically
  - We can stay on Mars for a short time, <u>leave just after the same opposition at which we arrived</u>, and get back to Earth far sooner than before
  - This is a W = 0 trip
- There are significant advantages to an asymmetric trip, but the basic idea remains the same
  - Leaving the target in the general time frame of the same opposition at which you arrived is the <u>**only**</u> way to dramatically reduce the round trip time to Mars

Hohmann Mission Simulation

- All simulations are available on the web at

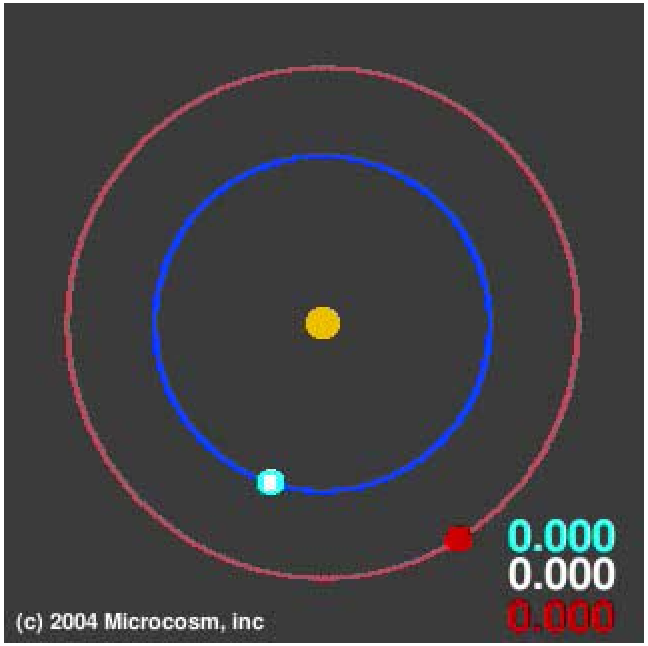
  http://www.smad.com/Interplanetary_Round_Trip/simulations

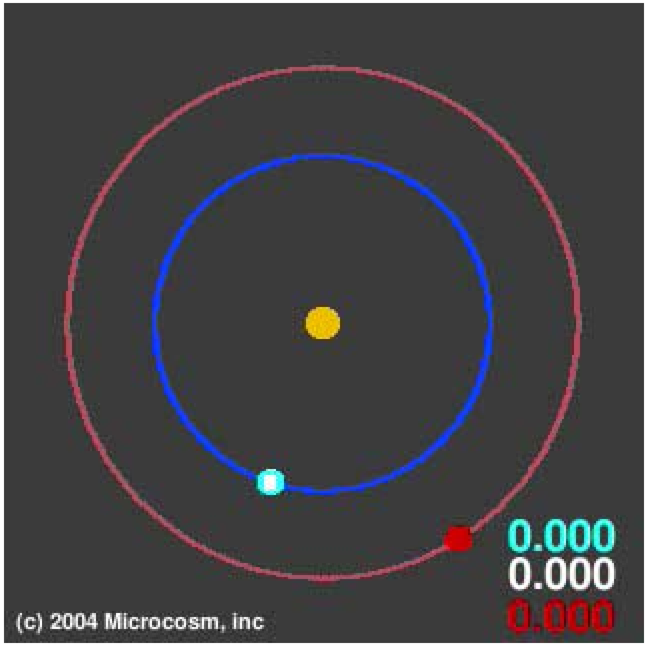
- Synodic period for Mars = time between successive oppositions = 2.13 years
  - Largely responsible for determining the round trip time
- In all of the simulations
  - The first opposition occurs on the X-axis
  - "Lap counter" in the lower right starts at the beginning of the simulation
    - Blue = Earth
    - White = Spacecraft
    - Red = Mars



- Illustration of traditional Hohmann transfer round trip
  - Traveler leaves Earth before opposition and arrives at Mars after opposition
  - Needs to wait for the next opposition for an opportunity to return

High Energy Mission Simulations





- W = 1 high energy transfer
  - Substantial increase in delta V
  - Traveler arrives just after opposition
  - Needs to wait for next opposition to return
  - Spends more time on Mars, but total round trip time nearly the same as Hohmann trip
- W=0 high energy transfer
  - Slightly more ΔV than the case on the left
  - Traveler arrives just before opposition
  - Leaves right after opposition to return home
  - Total trip time now reduced to about 5 months with very short stay on Mars

W = 1 and W = 0 Direct Transfer Missions to Near-Earth Asteroid (1.1 AU)

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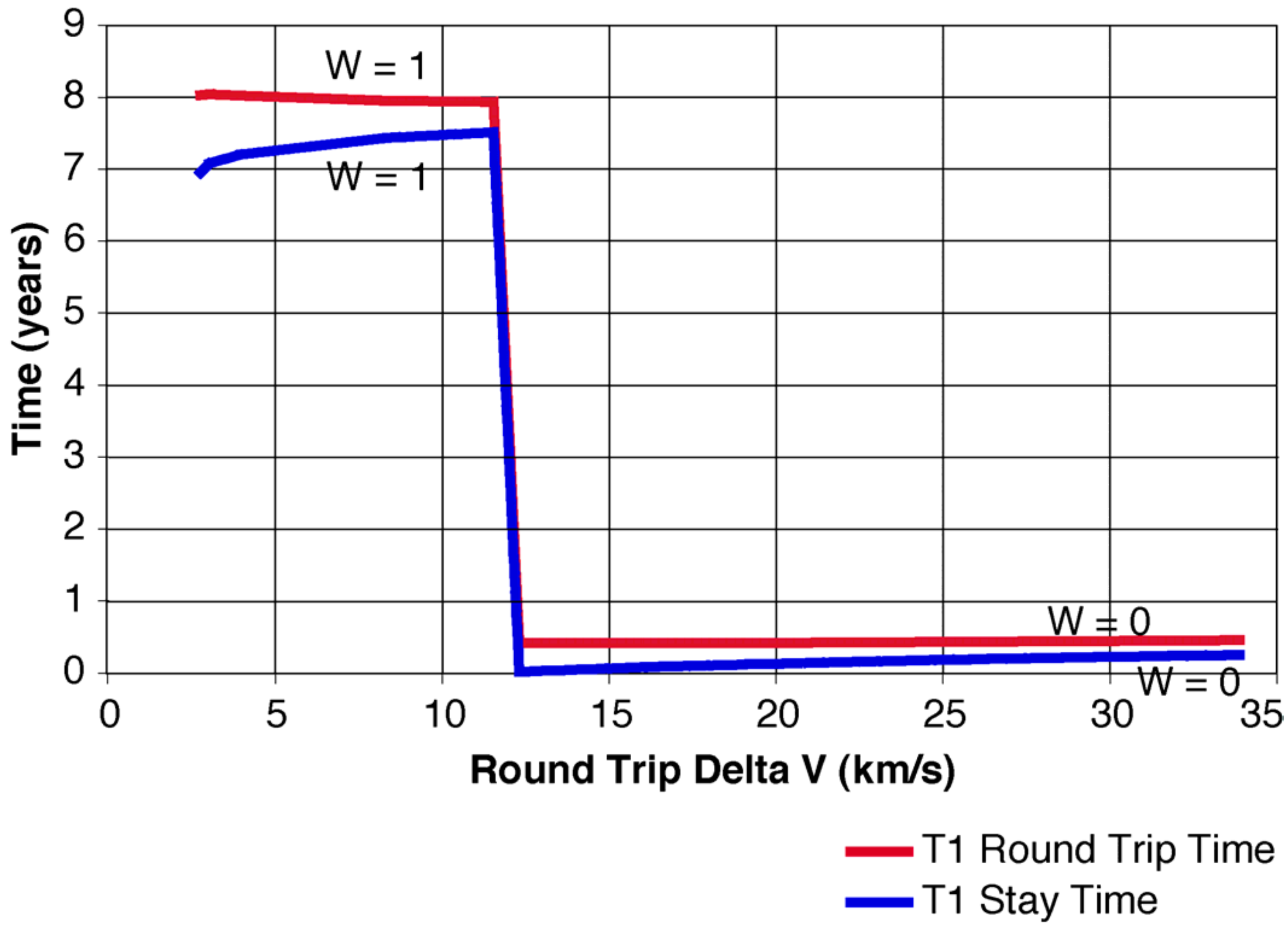
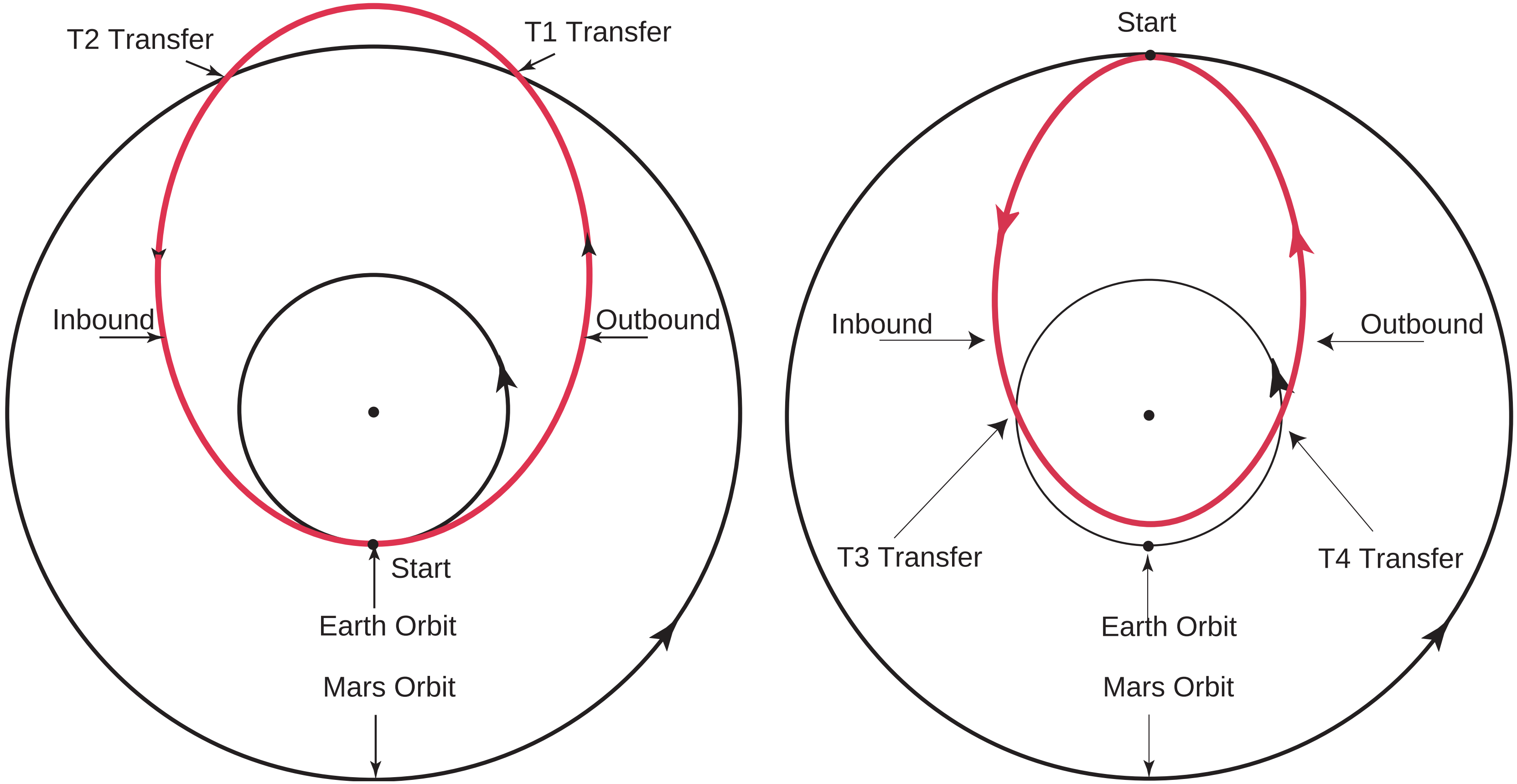


- In this case, going from W=1 to W=0 costs a moderate delta V, but is effectively required to complete the trip in a reasonable time

Direct vs. Indirect Transfers

The Jogging Analogy Revisited

Alternative Transfer Options



- For a non-Hohmann trip to an outer planet, the transfer trajectory can go beyond the target orbit (T1 and T2) or inside the Earth's orbit (T3 and T4)
  - We could do both, but there doesn't seem to be any advantage
  - Appears best to leave a planet tangent to it's orbit, but worth more exploration

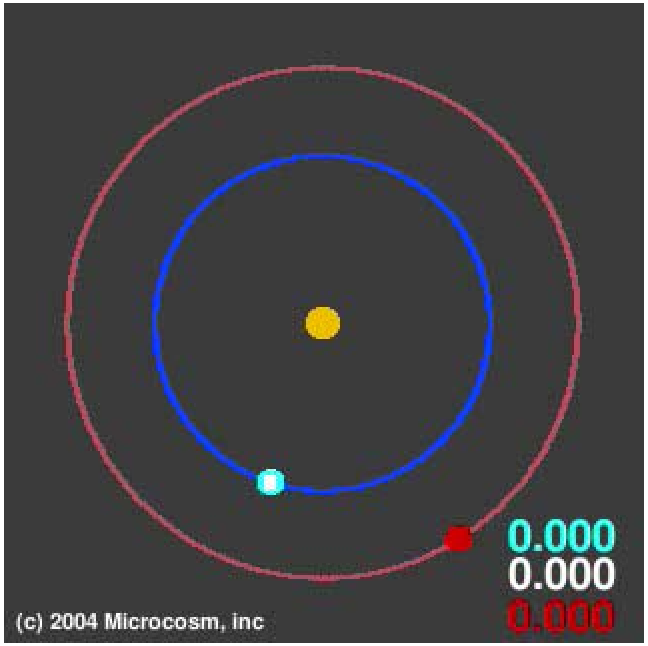
Direct vs. Indirect Transfer Missions

- ***Direct Transfer*** occurs when the traveler doesn't go inside the Earth's orbit or outside the orbit of the target
  - T1 or T4 outbound, T2 or T3 inbound
  - Minimizes the transfer time for the expended delta V
- ***Indirect Transfer*** occurs when the traveler goes inside the Earth's orbit or outside the orbit of the target (i.e., arrives at the target on the 2nd opportunity)
  - T2 or T3 outbound, T1 or T4 inbound
  - Going outside the orbit of the target
    - Slows the traveler to allow the Earth to catch up quicker on W = 1 missions
    - Equivalent to "setting the water bottle on the ground" in the jogging analogy
      - Unlike the analogy, the traveler can't just "stop and sit on the side of the road"
  - Going inside the orbit of the Earth
    - Allows the traveler to go faster and to catch up with the Earth on W = 0 missions
    - Equivalent to"cutting across the infield" in the jogging analogy

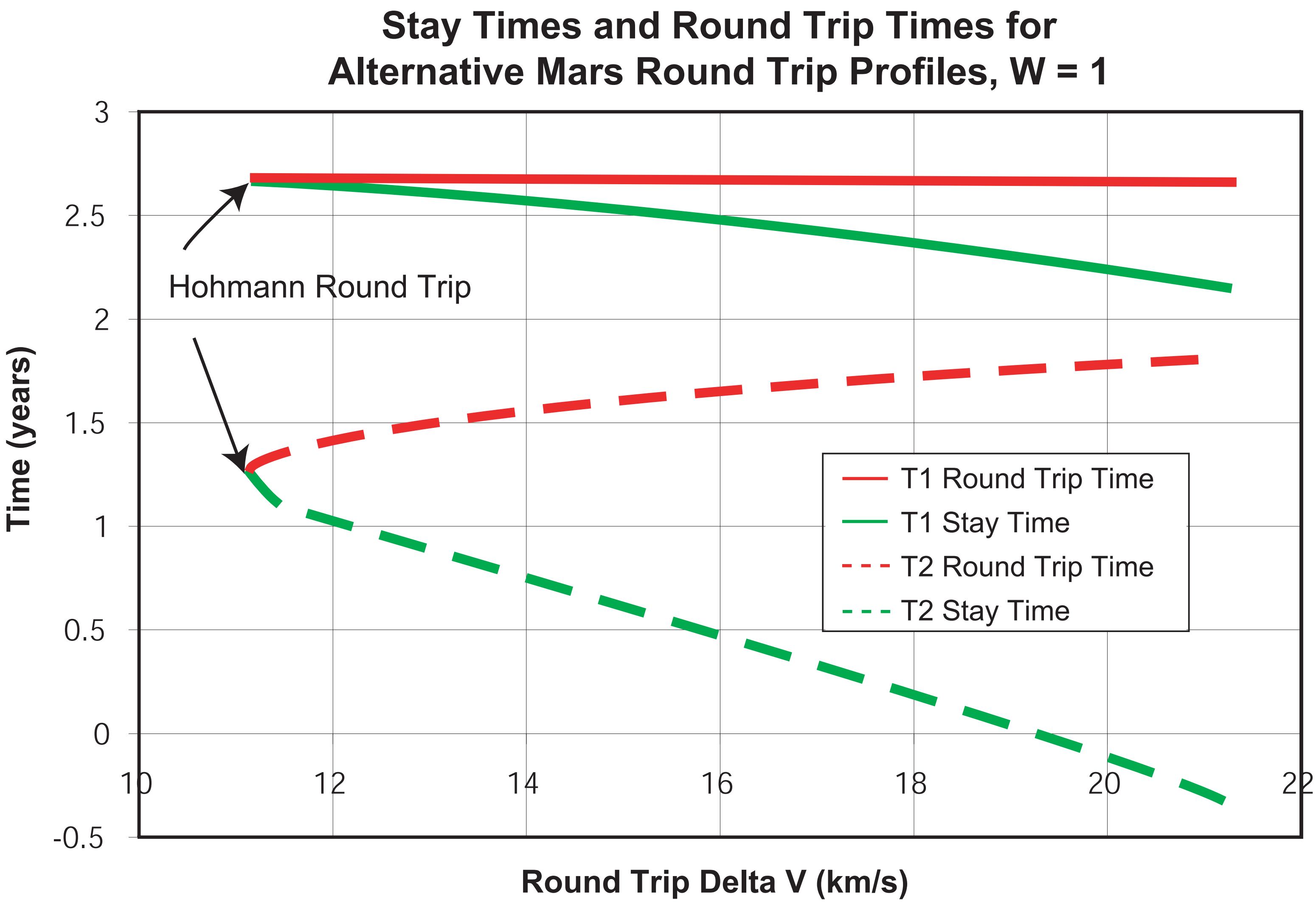
Indirect transfer extends the transfer time, but offers substantially increased flexibility to <u>reduce</u> total round trip time at the expense of more travel time.

Mission Simulation Going Outside the Orbit of Mars on Both Legs

- This simulation uses an indirect outbound leg, and a symmetric indirect return
- W = 1
- Slows down the traveler to allow the Earth to catch up
- Reduces total travel time somewhat (but not greatly) at the expense of longer time in transit
  - Substantially less time at the target
- Not helpful in most missions, but could be useful in some circumstances

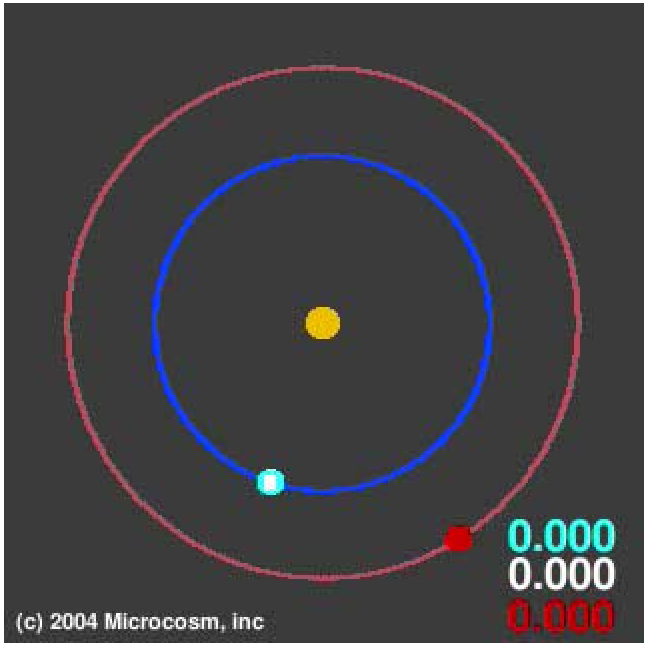


Mission Duration vs. Round Trip Delta V for Mars Round Trip Missions with W = 1



Direct Outbound, Indirect Return Mission Simulation

- This simulation uses a direct outbound leg, and an indirect return
- Cuts inside the orbit of the Earth in order to “catch up” with the Earth on the way home
- W = 0
- Mission duration, delta V, and stay on Mars are all intermediate between W=1 missions and the high speed W=0 mission



This type of mission is a compromise in both performance (short overall trip time and moderate duration stay on Mars) and cost (moderate total round trip delta V).

W = 0 Indirect Transfer Missions to Mars

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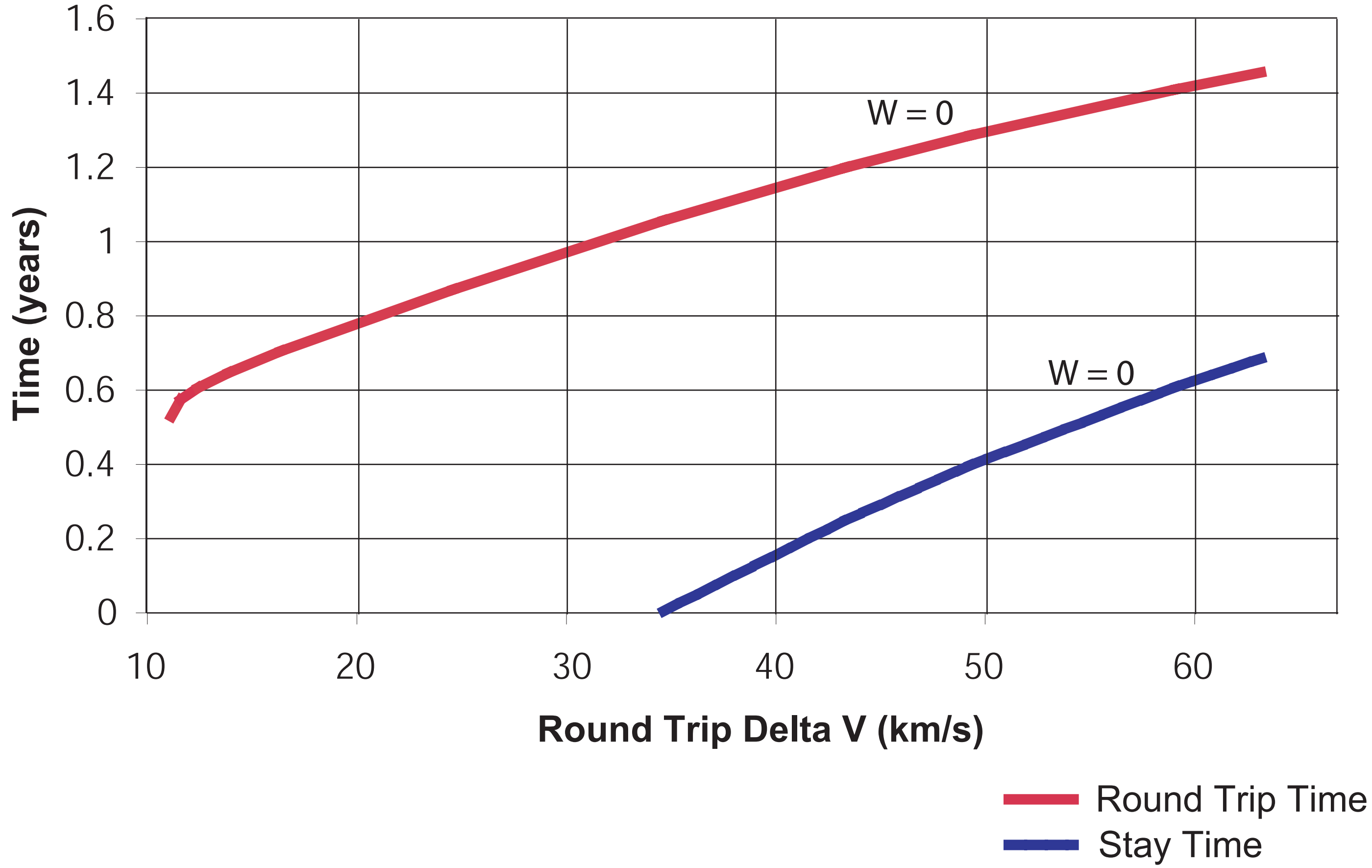
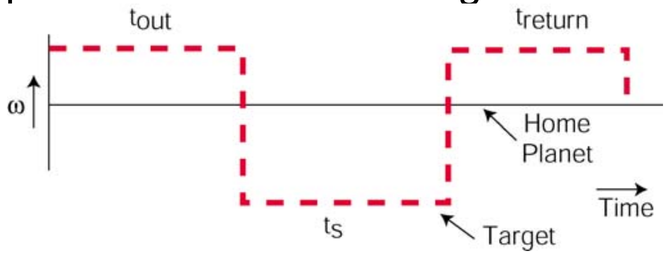


The direct outbound/indirect return approach provides a good compromise of moderate delta V, short round trip time, and reasonable stay time centered on opposition. The delta V is significantly reduced if direct entry can be used.

W = 0
The Quickest Round Trip

W = 0, the Ultimate Round Trip

- From the preceding 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
    - 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 good at reducing that time
- To solve this problem, we need W = 0 trips for which the following must be true:
  - **Over the mission duration, the average angular speed of the Home planet and the traveler must be the same**



  - 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 regime (and more energy) than the usual Hohmann transfer process

W = 0 transfers enable short, flexible round trip missions. Mission durations and stay times will be limited primarily by the amount of delta V that we are willing to use. W = 0 missions are applicable in the approximate region from Venus on the inner edge to Mars on the outer edge.

Angular Rates for a Hohmann Transfer from the Earth to Mars

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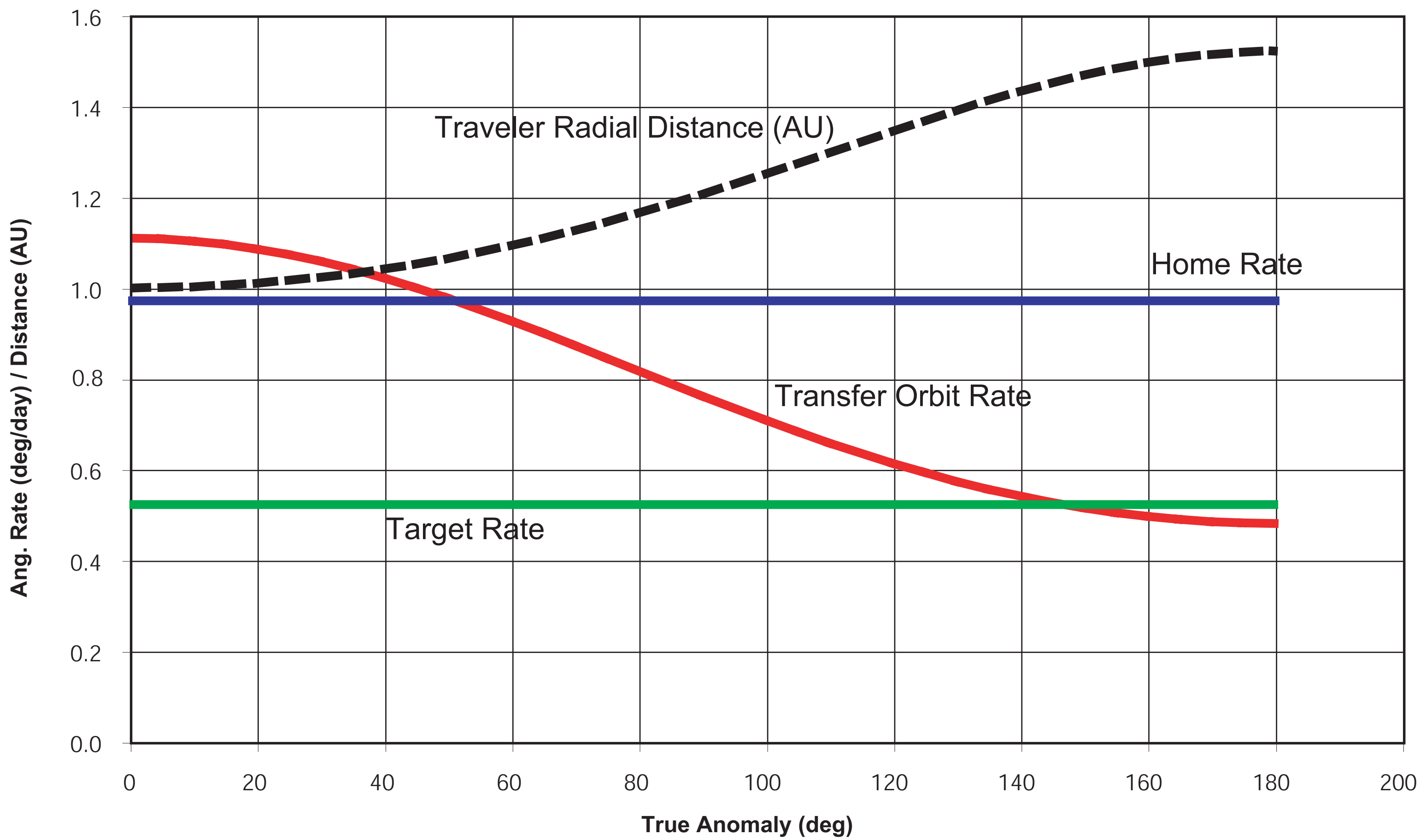

For W = 0 we have to work only in the left half of this plot where the average value of the Transfer Orbit rate = the Home Planet rate.

N = 0 Direct Transfer Missions

- ***N = 0 Direct Transfer Missions*** are those that use only the early segment of a transfer trajectory, use a T1or T4 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 (shown in the next charts)
  - Requires total delta V of 5 to 10 times that of a Hohmann transfer round trip
  - Can reduce the total round trip time from 2 or more years to less than 6 months
  - Initially short stay times which increase with increased delta V
- Can be applied to distances out to Venus inbound or Mars outbound
- Must be used to achieve realistic mission timelines for “near-by” missions such as a round-trip to a Near-Earth Asteroid

W = 0 Direct Transfer Missions to Venus

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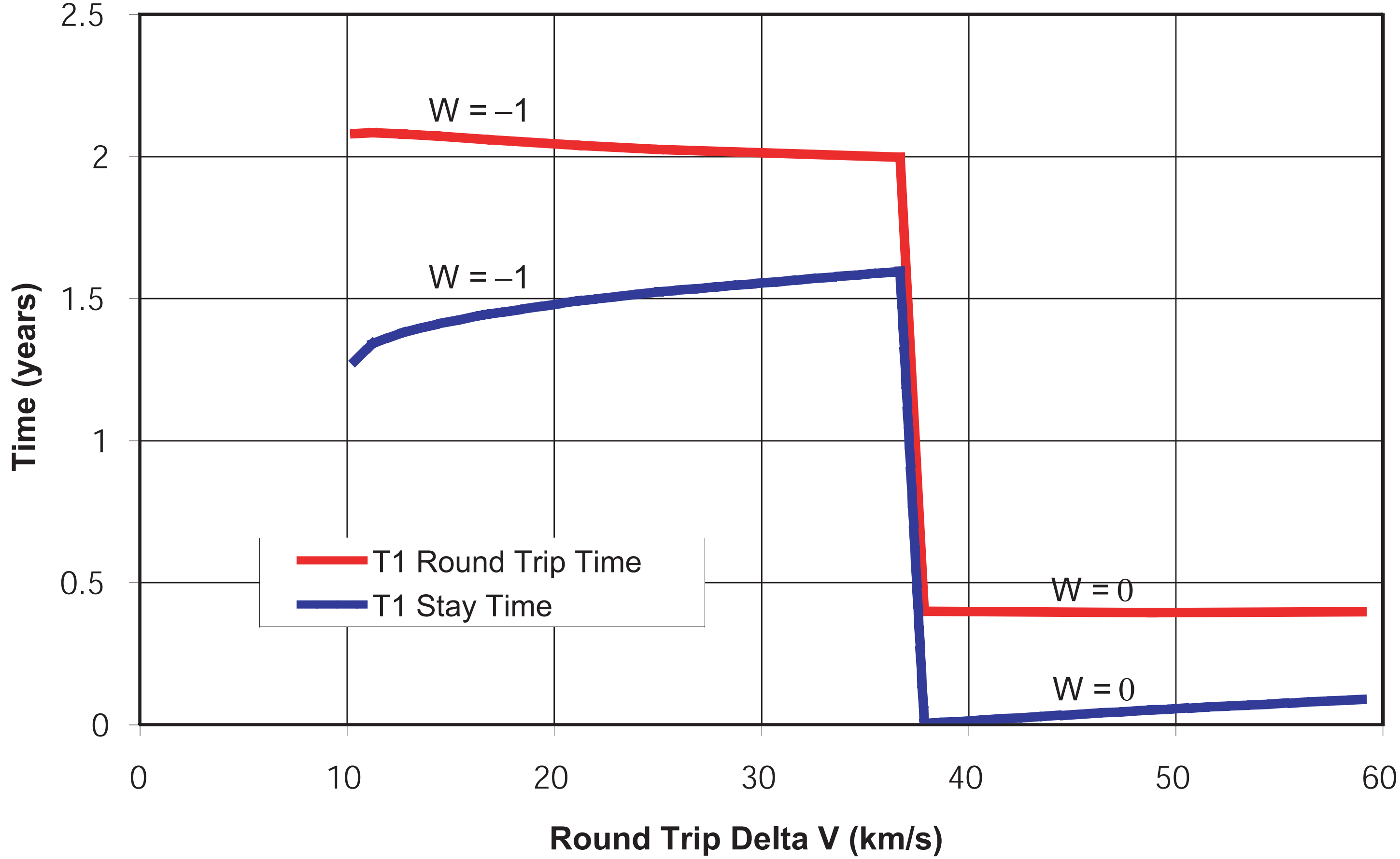
Stay Times and Round Trip Times for Venus Round Trip Profiles with W = 0 and –1



W = 0 missions have a similar effect going to Venus as they do to Mars.

The Interplanetary Train Schedule

Start and Stop Times Relative to Opposition

The Tabular Train Schedule

The Graphical Train Schedule

Mission Start and Stop Times Relative to Opposition

- For the outbound segment, the traveler must begin at the home planet and arrive at the target. Therefore, the start time, T_{start}, and mission anomaly, ν_{start}, and the arrival time, T_{arrive}, and mission anomaly, ν_{arrive}, relative to opposition, are related by

$$\nu_{start} = T_{start}\ \omega_H \qquad (1)$$

$$\nu_{arrive} = T_{arrive}\ \omega_T \qquad (2)$$

- For the traveler to start at the home planet and arrive at the target, we have

$$\Delta\nu = \nu_{arrive} - \nu_{start} = \omega_{transfer}\ t_{transfer} \qquad (3)$$

- Given the transfer parameters, the start and arrival times relative to opposition are:

$$T_{start} = t_{transfer}\ (\omega_T - \omega_{transfer}) / (\omega_H - \omega_T) \qquad (4)$$

$$T_{arrive} = T_{start} + t_{transfer} \qquad (5)$$

The start and arrival mission anomalies are then given by Eqs (1) and (2)

- Given a transfer scenario, we use Equations (1) through (5) to determine the start and stop times of the various mission segments relative to opposition
  - Small corrections will be needed to account for the non-zero eccentricity of real orbits
    - Relative to a perfectly circular orbit, the Earth can be as much as 2 days ahead or behind and Mars can be as much as 20 days ahead or behind
- While the above formulas 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 delta V

Mars Train Schedules

- Sample schedule built around the Mars opposition of Jan. 29, 2010

Example		A Hohmann (W=1)	B High Energy, W=1	C High Energy, Direct W=0	D Direct W=0 with Lon-ger Stay	E Outbound and Return both Indirect	F Direct Outbound/ Indirect Return	G Direct Outbound/ Indirect Return	H Direct Outbound/ Indirect Return
Outbound									
Depart	**(date)**	24-Oct-09	13-Nov-09	13-Nov-09	13-Nov-09	1-Apr-09	11-Nov-09	12-Nov-09	13-Nov-09
Transfer	**(days)**	259	78	75	70	272	95	87	76
Arrive	**(date)**	10-Jul-10	30-Jan-10	27-Jan-10	22-Jan-10	28-Dec-09	14-Feb-10	7-Feb-10	28-Jan-10
Delta V1	**(km/sec)**	2.94	10.60	11.00	12.33	12.22	7.66	8.83	10.90
Delta V2	**(km/sec)**	2.65	18.01	18.55	20.30	5.43	13.73	15.51	18.41
Mars Stay									
Duration	**(days)**	454	778	2	13	62	90	144	221
Duration	**(months)**	14.9	25.6	0.1	0.4	2.0	3.0	4.7	7.3
Return									
Depart	**(date)**	8-Oct-11	18-Mar-12	30-Jan-10	4-Feb-10	1-Mar-10	15-May-10	1-Jul-10	6-Sep-10
Transfer	**(days)**	259	78	75	70	272	251	238	217
Arrive	**(date)**	23-Jun-12	4-Jun-12	15-Apr-10	15-Apr-10	27-Nov-10	22-Jan-11	23-Feb-11	11-Apr-11
Delta V3	**(km/sec)**	2.65	18.01	18.55	20.30	5.43	6.89	7.95	9.80
Delta V4	**(km/sec)**	2.94	10.60	11.00	12.33	12.22	15.14	17.03	20.04
Perhelion	**(AU)**	1.00	1.00	1.00	1.00	0.65	0.52	0.44	0.33
Total Mission									
Total Trip	**(days)**	972	934	153	152	606	437	468	514
Total Trip	**(yrs)**	2.66	2.56	0.42	0.42	1.66	1.20	1.28	1.41
Tot DV1-4	**(km/sec)**	11.19	57.21	59.10	65.24	35.30	43.41	49.32	59.15
Tot DV1/3	**(km/sec)**	5.59	28.61	29.55	32.62	17.65	14.54	16.78	20.70

- Direct trips both inbound and outbound provide the shortest round trip time (0.4 yrs = 5 months), but very short stays on Mars and a high delta V cost
- A moderate cost vs. performance alternative is a direct outbound mission with an “inward swing” on the return leg
  - Round trip times of 1.2 to 1.4 years with stays on Mars of 3 to 7 months

Train Schedule to Mars with Transition from W = 1 to W = 0

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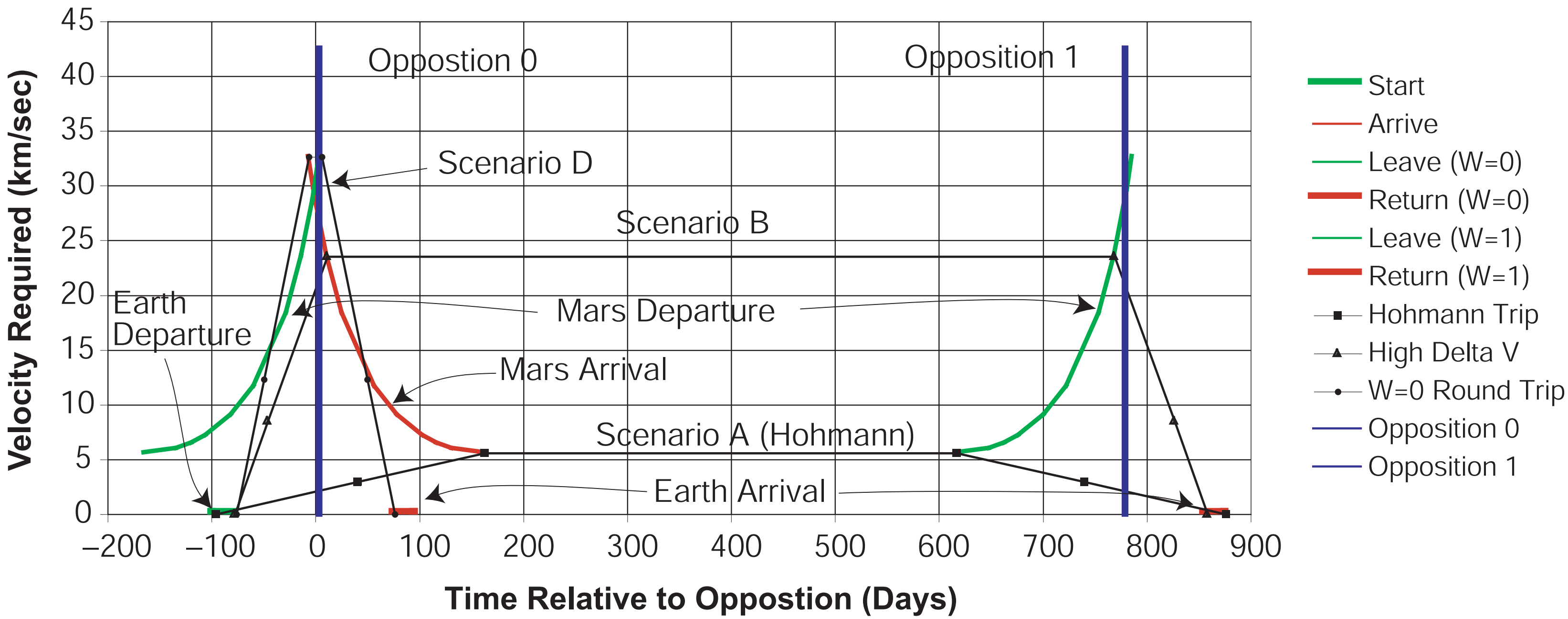
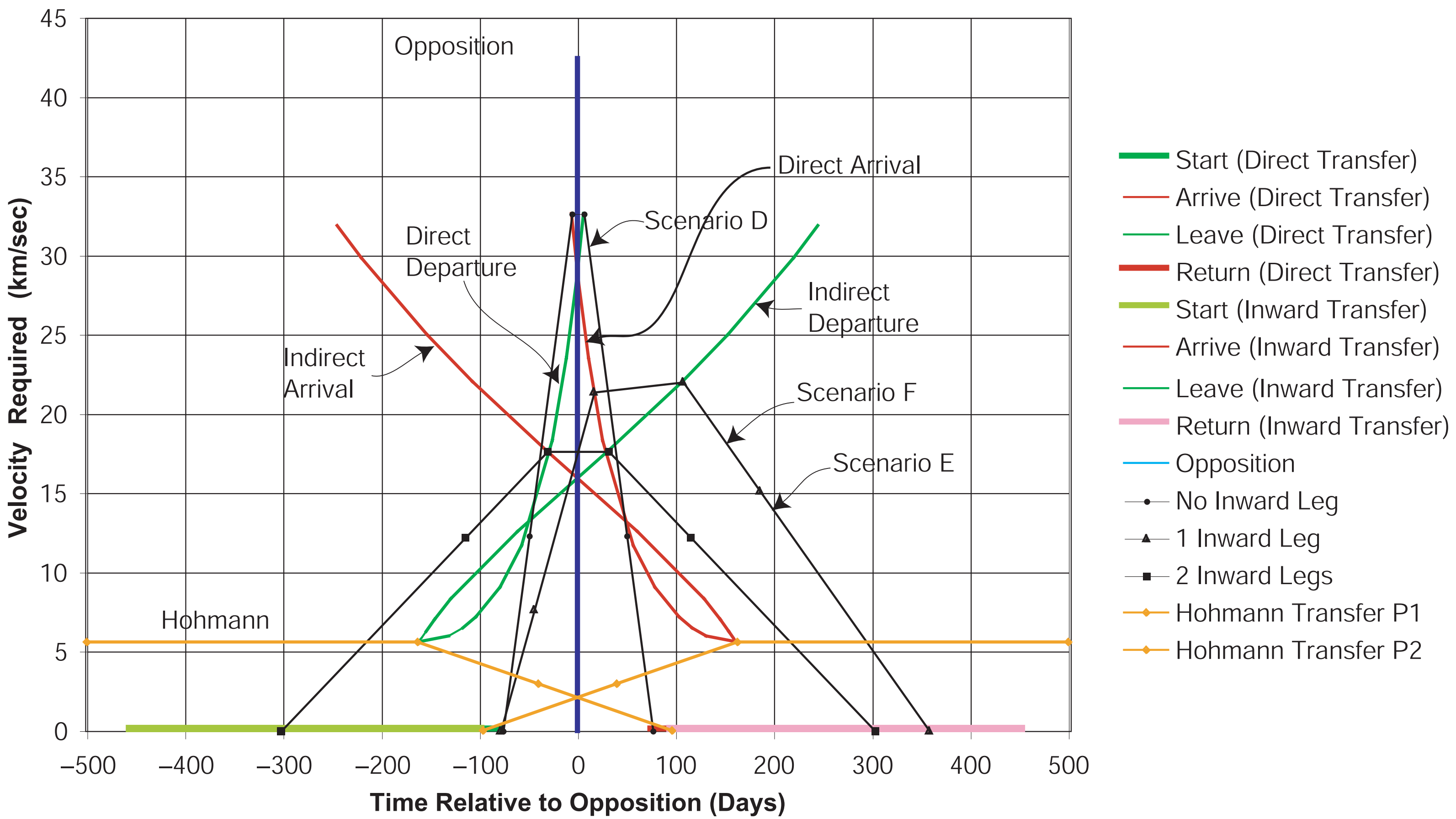


- To have a W=0 mission, we must arrive on a red line before having to leave on a green line
- Where the red line is to the right of the green line, we will need to wait for the next opposition to return
  - The mission will be much longer and will be centered on conjunction when communications is difficult
- Black lines show representative trip schedules and associated delta Vs

W = 0 Train Schedule to Mars



- For W = 0, we need to arrive on any red line and leave on a green line to the right
  - The markers on the representative trip lines (in black) are at the V1/V2 split and the V3/V4 split

Conclusions

Comparison with NASA Mars Reference Missions

"Practical" Rapid Round Trips to Mars

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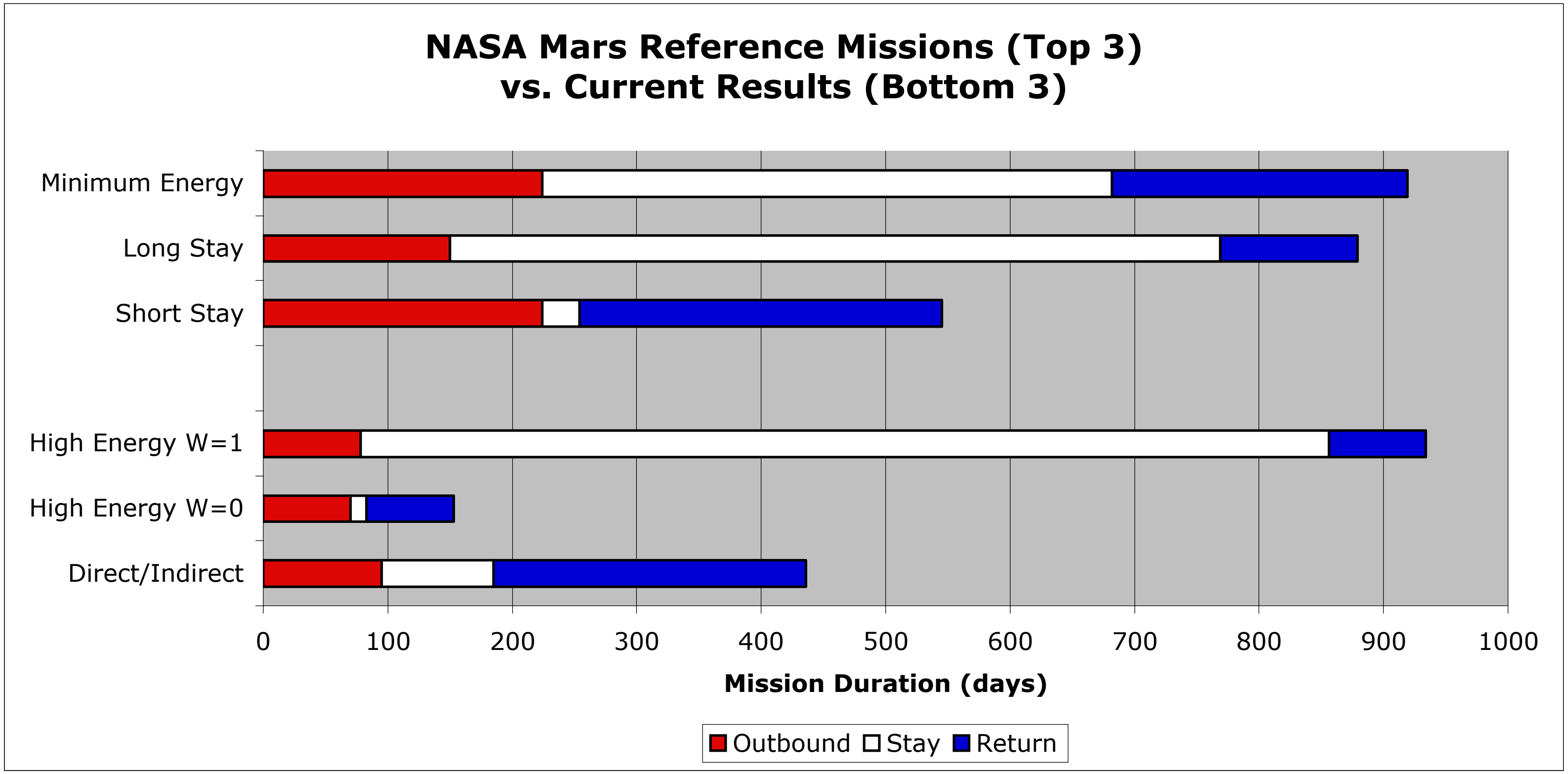
Comparison with NASA Mars Reference Missions



- NASA data from Hoffman and Kaplan, eds., "Human Exploration of Mars: The Reference Mission of the NASA Mars Exploration Team," 1997; available at http://www.spaceflight.nasa.gov/reference/hem/hem1.html
  - Emphasis of NASA work is on the "first human missions to Mars"
  - Emphasis of current work is on the general rules for human exploration

Example Scenario: Low-Cost, Near-Term Human Mission to Mars

- A key problem with human Mars missions is the need for life support for a 2.7 year (970 day) mission duration
  - Reducing the mission to 5 months would take dramatically high delta V's
- Consider the alternative of possible "two-phase" human missions to Mars
  - Send descent module, exploration equipment, extra life-support equipment and supplies, and return equipment to Mars on a Hohmann low-energy transfer
    - Test all of the equipment after it's arrival in Mars orbit
  - For the astronauts, use one of two possible scenarios:
    - **A (150 days)**: 70 day transfer, 13 to 20 day stay on Mars, and 70 day return
    - **B (435 to 515 days)**: 75 to 95 day direct transfer, 90 to 220 days stay on Mars, and 215 to 250 day indirect return
  - Most of the mass transferred at minimum energy, people transferred on a minimum time trajectory
  - Total amount of human life support reduced from 970 days to range of 150 to 435 days (factor of 2 to 6 reduction)
- Suggests a new paradigm for future low-cost, rapid manned exploration of the Solar System that should be given sufficient consideration to understand the potential, the limitations, and the technology needs

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.**
  - This constraint holds irrespective of the transfer method — i.e., direct transfer, electric propulsion spiral, or multiple planetary fly-bys
- All minimum energy round trip missions are two years in duration or longer
  - **Realistic manned flight on a regular basis may require delta V's that are 2 to 10 times that of minimum energy (Hohmann transfer) missions**
- For W = 0, there are much faster round trip missions with greater timeline flexibility at a cost of 2 to 10 times the delta V of minimum energy missions
  - Can bring Mars round trip times down to 5 months or less, at a high delta V cost
  - Intermediate round trips exist that provide 3 to 7 months on Mars with a total round trip time of 14 to 17 months

While the general rules of Interplanetary Mission Design are now known, many detailed design elements are yet to be discovered.
For those who want to contribute to human exploration, a great deal of interesting work still needs to be done.