A Survey of Earth-Mars Transfer Orbits Suitable for Human Passengers

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This paper presents a parametric study of time optimal Earth-Mars transfers assuming high thrust engines that are comparable to those studies on the research front. The departure and arrival orbits are assumed to be near the Lagrange points of the Earth-Moon-Sun and Mars-Sun systems, and time optimal paths are investigated. Historically, what is considered reasonable by the design engineer is rarely considered reasonable by the passenger(s)[1] and it is foreseeable that time will become a more important parameter than energy consumption in future space travel. For our purposes, travel times reasonable for passengers to Mars are defined as those comparable to the longest journeys that settlers, colonists, business travelers, and commodity brokers were willing to purchase and endure during the well-documented historical era of America colonization[2]. To achieve such travel times, current cutting-edge propulsion technology as well as reasonable projections of what thrusts we hope to achieve in the near future (i.e. the next few decades) are considered. The results of this study should thus be of interest to propulsion technology development and mission planning for the next era of space travel.

I. Introduction

In the beginning of the 21st Century with the advent of commercial space flight, we have the option to become a multi-planet species. As such we should consider plans for manned interplanetary commerce, human colonization of the planets, interplanetary shipping, emergency services, defense, business travel, and even a tourism industry among the potential colonies of Luna, Mars, the Asteroids, Venus, Mercury, the outer planets, and beyond.

When evaluating travel time among the planets, one must consider ΔV's - i.e. acceleration - not velocity. With a suitable power plant and consequent acceleration, the transfer times between Earth and Mars can come within the acceptable parameters for commercial clients and business travelers. In the next section we will explore those acceptable parameters, and what may be acceptable to the human passenger.

If future research shows that an acceleration of one gravity does not adversely affect a traveler's health, or in fact shows that one g could be quite comfortable due to its familiarity to the passenger, or conversely shows that subgravity[a] as opposed to microgravity[b] is beneficial to the health of passengers of certain ages or physical conditions, then the subgravity travel solution becomes preferable.

Furthermore, consider the possibility that some commodity or condition is discovered on Mars comparable to the era when gold was discovered at Potter's Mill in California. The commercial implications of a California Gold Rush type event on Mars in the 21st Century will be discussed in a future paper.

A. Interplanetary Colonization - An Historical Perspective

Less than 150 years ago it could take more than a month for a family of colonists or a business traveler to sail, or for an expensive piece of industrial equipment to be shipped from the old world to the new, and considerably longer for the journey from Europe to California. The transatlantic crossing that takes six days by steam today, took months by sail a few generations ago. Neither this travel nor unsavory conditions below decks prevented colonists from settling the "New World". We will explore these travel times in the next section.

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[a] ***subgravity*** - an acceleration less than one gravity. For this paper we consider 0.01g up to 1.0g

[b] ***microgravity*** - acceleration near 0.0 gravities or 0g - near weightlessness

1. Transit Time is Money

It is well known that a shorter exposure to the harsh interplanetary environment is preferable for equipment as well as travelers. Also, a quicker trip is less costly than a longer trip due to the fewer resources required (food, water, air, power), less wear & tear on equipment and on the spacecraft itself, a shorter delay in delivering cargo, and a quicker investment recovery. On the engineering side, there is less redundancy required of equipment, shorter MTBF required, and less exposure to adverse conditions thus requiring less robustness in the design of the hardware. The negative tradeoff is the design of the higher energy power plant and the engine's continual operation for the duration of the voyage. This economic tradeoff will be evaluated for each class of voyage in a subsequent paper.

We will draw parallels between the proposed colonization of the planets, and the well-documented colonization of the Americas in the last few centuries. We propose that commercial travel to the planets must operate under similar constraints of delivery dates on cargo, and travel time for passengers in the era of American colonization as described below.

2. Transit Time and Passenger Health

As described in the literature, prolonged exposure to weightlessness (microgravity) causes certain physiological changes in the human body.[1] At the time of this writing, NASA is reporting detrimental physiological changes in deep space crew affecting their life expectancy.[2] This raises a whole new problem with respect to the traveler's environment. Whereas there is as yet no definitive research on the effects of subgravity vs. microgravity on human physiology, one can surmise that it must be less detrimental than microgravity. If so, a high subgravity voyage may be less detrimental than a long duration microgravity trip.

Furthermore, by adjusting the acceleration to 0.376 gravities, it would be possible to gradually transition the passengers to Mars surface gravity during the voyage.

But it is also important to reduce the duration of exposure to solar and other interplanetary radiation.

3. Historical Dates & Transit Times

Consider the repetition of the travel domain of two centuries ago, but rather than continent to continent across an ocean, we are sailing planet to planet across interplanetary space. In this paper we will explore travel times, accelerations, and potential interplanetary transfer orbits. Power plant technology, engine size, and thrust will be relegated to a future paper.

1490's: 41 to 68 days Christopher Columbus' voyages took 41 to 68 days to complete from departure to first landing,[3,4] while the Pilgrim Fathers traveled for 65 days.[5]

1700's: 60 days In the 18th century, travelers had settled in to expect nearly two months of travel time to cross the Atlantic. Commercial ships would wait in port until their cabins and holds were filled. This could effectively double the time required for the traveler or the cargo to reach its destination.

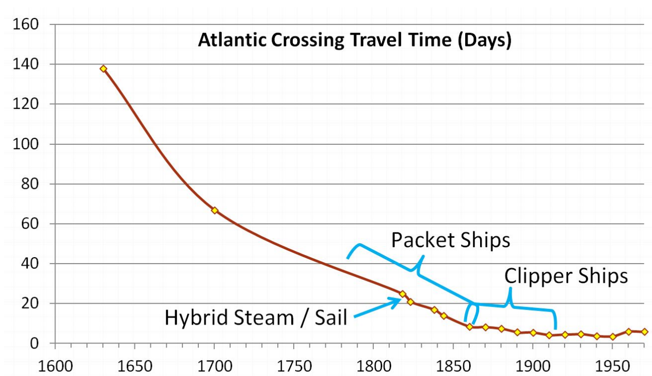

Figure 1. Atlantic Crossing: Days vs. Century

1800's: 20-30 days (21 day nominal) Commercial transatlantic transport became a commercial reality with the establishment of the Packet Ship in the late 1700's and early 1800's.[6] This regular transatlantic mail service is attributed to Postmaster General Benjamin Franklin. These Packet Ships, named for the mail packets that they carried, crossed the Atlantic in about two months, on average. Franklin documented the Gulf Stream current, which allowed the Packet Ship captains to cross the Atlantic Ocean in a mere 20 to 30 days.[7] A 14-day crossing has been documented as the record. Rain or shine, blow high, blow low, one of the *Black Ball* packets sailed from New York for Liverpool on the first and sixteenth of every month."[8]

MID 1800'S: 12-90 DAYS (43 DAYS NOMINAL) In the Mid 1800's, a 43-day transatlantic passage to the States was possible by sailing ship, plus a day of quarantine. However passage was 12 to 90 days depending on the season and the ship.

1840: 10-17 DAYS BY STEAM The steam powered transatlantic side-wheeler completed the transatlantic crossings in 14 to 17 days. Although, about 1840, Samuel Cunard & associates established a steam liner service that crossed the Atlantic in 10-12 days.

1849: CALIFORNIA GOLD RUSH When steamship owners were getting $14 a ton for freight from NY to San Francisco, clipper ships collected up to $60/ton carrying freight to the gold fields. In at least one case, the freight income from one trip was more than the cost to build & outfit the ship.

1850: 6.25 DAYS BY STEAM Steamers built in the late 1800's (e.g. - 1868) are still in use today.[9] The Collins Line, established in 1850, carried freight for $30 to $40/ton.

By the 1870's the side-wheeler and clipper ships had disappeared as transatlantic immigrant transport being replaced by the White Star Line class screw-steamship. In the 1890's the passenger steamers were crossing regularly in approximately 150 hours, less than a week. In summary, steamships brought travel time down from weeks to days for the fastest ships. What took 1-3 months prior to 1880, took 8-14 days via steam ship after 1880.

Today, the Queen Mary II (QM-2) displacing 150,000 tons, crosses the Atlantic in 6 days. For comparison, the Apollo weighed in at 3,100 tons with a 130 ton payload, and the Space Shuttle weighed in at 2,030 tons and carried a 12.2 ton LEO payload or 4.2 ton GTO payload.

4. Extrapolations

American immigrants endured shipboard travel times of 40 - 60 days in the 1700's, 20-30 days in the early 1800's, and 12-90 days in the mid-1800's. Travel time decreased with the ubiquity of the steamer to less than a week. At that point the number of American cabin passengers per year through only one port (New York) increased to six figures by 1890.[10]

Intercontinental passengers demonstrated that they would endure sea voyages of on the order of two months to reach their destinations. It is demonstrated in the following section of this paper that comparable interplanetary voyage durations are physically possible.

II. A Solution - High Energy Continuous Thrust Transfer Orbits

We are repeating the domain of travel two to three centuries ago, but rather than continent to continent across an ocean, we are considering planet to planet across interplanetary space. In this section we will explore travel times, accelerations, and potential interplanetary transfer orbits. Engine requirements will be discussed in a future paper.

Here will be examined the orbital parameters necessary to reach Mars in the times similar to those experienced by transatlantic travelers in the 1700's and 1800's. To address this question, a simplistic post-Keplerian simulation of a toy solar system and interplanetary flight was developed. It is clear that an impulse thrust solution, such as that for the common eight-to-nine month Hohmann Transfer Orbit,[11] does not meet this travel time criteria. The continuous acceleration model demonstrated here simulates flight times from Earth to Mars on the order of 10^{-2} to 10^{2} Earth gravities at various Earth-Mars synodic phase angles between $0°$ and $360°$. The results are shown in the table in Figure 3.

A. A Toy Model Simulation

To minimize development time, this simulation was written in Visual Python.[c] The software ran on a home-brew PC server farm. Each column in the table of Figure 3 was generated by one dedicated server. Each row of each column is one voyage. The simulation step size was between one minute and one hour, as selected by the operator. A one-day step size was used to test the math.

To simplify the model, certain assumptions were made regarding the toy Solar System.

[c] Information on Visual Python may be found online: http://vpython.org/

1. *Simplifications*

It was assumed that: both Earth and Mars are in circular co-planar orbits; the spacecraft is expected to travel from Earth orbit to within Mars' Hill sphere[d] where it will arrive at less than Mars' escape velocity; the spacecraft is equipped with a continuous variable[e] thrust engine, and can sustain subgravity acceleration for the duration of the voyage. Thus the only forces acting on the spacecraft are its own acceleration and the gravitational forces of the Sun, Mercury, Venus, Earth, Mars, and Jupiter. By assuming a specific acceleration, the effects of interplanetary gas, e.g. the Solar Wind, and changes in spacecraft mass can be ignored. The spacecraft's engine automatically performs whatever thrust modification is necessary to maintain the constant acceleration through the spacecraft's axis within some epsilon.

The travel times are based on the assumption that the ship accelerates at the specified thrust for approximately the first half of the voyage (see Figure 2) and then performs a *Turnover* (inverts its attitude) to decelerates at the same thrust for the remainder of the voyage. The duration is orbit to orbit, docking and/or landing times are excluded.

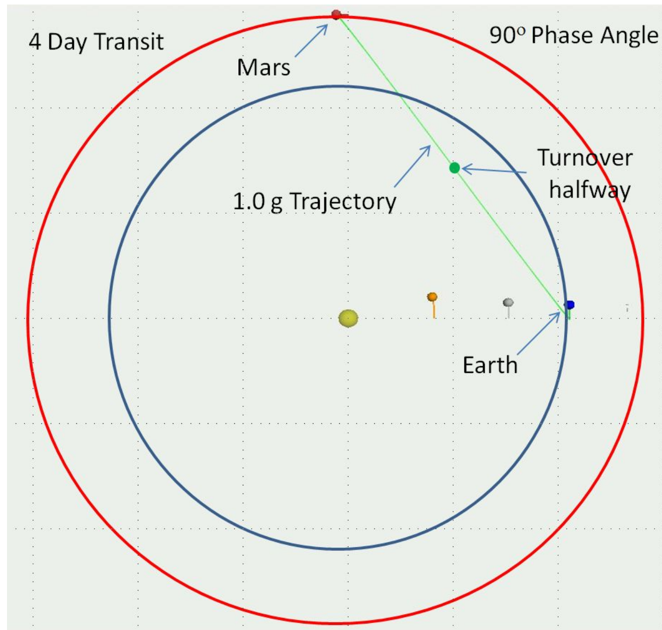

Figure 2. 90° Phase Angle Transfer Orbit at 1.0g

2. *The Midcourse Skew Flip Turnover*

Turnover, is a maneuver that rotates the ship through 180° so that the bow points aft, and the engines can thrust forward along the velocity vector to slow the ship. The maneuver is designed so the power plant can continue to thrust through the ships central axis and can maintain the artificial gravity for the passengers' comfort. Alternatively, *Turnover* may be a micrgravity maneuver if maintaining artificial gravity is not a priority.

B. Travel Time

Figure 3 shows the duration in days and hours required for synodic orbital phase angle versus spacecraft acceleration in Earth gravities g. A suitable increase in acceleration yields a reduction in travel time . At one gravity acceleration Mars is as close as sailing to Europe today.

As can be seen in the figure's table, the transfer orbits selected depend on the time of year, or more precisely on the relative positions of the planets in their respective orbits, i.e. the synodic phase angle. Martian travel arrangements will be synchronous with Mars' synodic cycle of about 780 Earth days. Optimal departure times will be closest to Mars opposition, with less desirable voyages occurring near Martian conjunction. Note that the synodic period is not in phase with Martian 'seasons', which have their own Martian annual cycle.

1. *0.01g - Pre-1800's Travel Times*

Earth-Mars orbital transfers at one-hundredth of an Earth gravity provides a travel time of one to two months when launched within ±90° of opposition. Historically, this would be a reasonable travel time for potential colonists while minimizing exposure to the harsh environment of interplanetary space. Even at subgravities such as one-hundredth of a g the results are encouraging, as shown. At 0.01g the entire Mars synodic cycle is accessible from Earth orbit in from one to four months.

[d] *Hill sphere* - the region surrounding a celestial body (e.g. - a planet) where its gravity dominates other bodies (e.g. - Sun, moons, and other planets). The L1 and L2 points lie on the surface of the Hill sphere.

[e] *Variable* in the sense that both force and direction can be dynamically modified.

Angle	0.01g		0.1g		1.0g		10.0g		100.0g	
	Days	Hours	Days	Hours	Days	Hours	Days	Hours	Days	Hours
0	20	02	6	11	2	01	0	15	0	01
30	24	07	8	03	2	14	0	19	0	01
60	30	04	10	05	3	07	1	00	0	02
90	35	20	11	23	3	20	1	05	0	02
120	39	02	13	03	4	05	1	07	0	03
150	36	19	13	08	4	09	1	09	0	03
180	35	02	12	20	4	07	1	09	0	03
210	38	19	13	10	4	09	1	09	0	03
240	39	05	12	23	4	04	1	07	0	02
270	37	07	11	22	3	19	1	04	0	02
300	33	01	10	07	3	06	1	00	0	02
330	26	05	8	02	2	13	0	19	0	01

Figure 3. Approximate Mission Duration: Synodic Phase Angle vs. Acceleration in Earth Gravities

2. 0.1g - Mid-1800's Travel Times

The one-tenth g transfer orbit provides travel times similar to those of the era when nearly 100,000 European immigrants per year passed through the Port of New York on steamships.

3. 1.0g - Post-1900's Cruise Times

As can be seen in the 1.0 g column, at opposition (0°) travel time is less than 3 days. A worse case scenario at 1.0 g, when Mars is in conjunction (180°) with the Earth, that is, behind the Sun, travel time is on the order of a week or longer as the spacecraft must divert from a straight line to avoid the Sun's radiation.

Indeed, with the proper technology, a two week Martian sojourn during the opposition season has time enough to include spending a week on Mars.

4. 10g to 100g - Emergency Deliveries

Note that 10g and 100g transfer orbits are displayed for the sake of symmetry and completeness. As is shown, it is possible to deliver robust goods to Mars in a few hours if required, in a medical emergency for example. Hence a Martian outpost is not completely cutoff from Terrestrial resources when the high-energy thrust technology becomes available.

5. 0.376g - One Mars Gravity

As shown in Figure 4, a voyage at Mars surface gravity takes less than a week. Such an acceleration would provide the passenger the opportunity to acclimate to Martian surface gravity. In fact, while not shown here, it should be possible to gradually vary the acceleration from 1g to 0.376g during the voyage to transition the passengers from Earth's gravity to Mars' gravity.

Angle	0.376g	
	Days	Hrs
0	3	08
30	4	05
60	5	08
90	6	05
120	6	20
150	7	02
180	6	21
210	7	01
240	6	18
270	6	04
300	5	07
330	4	03

Figure 4. Transit Times using Mars' Gravity for Voyage Acceleration

III. Conclusion

In this paper we have studied interplanetary orbital transfers assuming a theoretical vehicle whose acceleration characteristics approach one Earth gravity (1g). It has been assumed here, in absence of other data[f], that humans would be more

[f]The International Space Station (ISS) has provided the opportunity to perform research in the domain of microgravity. But this author is unfamiliar with examples of research that has been performed to determine human physiological or psycho-

comfortable traveling in a subgravity environment than in a microgravity environment.

Trajectories have been chosen whose accelerations would allow the passengers to travel in this subgravity comfort range. We have shown, via spaceflight simulation software, that interplanetary journeys at these accelerations have more reasonable durations than those journeys at microgravity accelerations.

Drawing parallels with historical American colonization data, it has been shown that travelers might endure voyage durations comparable to that required to reach Mars at a minimum of 0.01 G acceleration. It is common knowledge that tourists today endure and even enjoy voyage durations comparable to that required of a 0.5g to 1.0 g acceleration near opposition, that is two days to a week each way.

It is known that long duration microgravity voyages cause physiological changes in the human body that can lead to infirmities and a shorter lifespan. It is not yet known what are the physiological effects of long duration subgravity voyages. Hence, such subgravity travel times should be kept to a minimum until we have the results of suitable research demonstrating optimal accelerations. There may be similar constraints for non-human cargo, e.g. sensitive medical, scientific, or other equipment.

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logical response to a subgravity environment, or research in the determination of the optimal gravitational environment, i.e. acceleration, for human travelers.