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SPACE TUG GEOSYNCHRONOUS MISSION SIMULATION

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Systems Engineering Operations

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ABSTRACT

Near-optimal three dimensional trajectories from a low earth park orbit inclined at 28.5 deg to a synchronous-equatorial mission orbit have been developed for both the storable (thrust = 28,912 N (6,500 lbs), I_{sp} = 339 sec) and cryogenic (thrust = 44,480 N (10,000 lbs), I_{sp} = 470 sec) Space Tug using the iterative cost function minimization technique contained within the Modularized Vehicle Simulation (MVS) Program. The finite burn times, due to low thrust-to-weight ratios, and the associated gravity losses are accounted for in the trajectory simulation and optimization. The use of an ascent phasing orbit to achieve burnout in synchronous orbit at any longitude is investigated. The ascent phasing orbit is found to offer the additional advantage of significantly reducing the overall delta velocity by splitting the low altitude burn into two parts and thereby reducing gravity losses.

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INTRODUCTION

One intended Space Tug mission which receives much attention due to the expected frequency of use is the geosynchronous mission orbit. For this mission the Space Tug and attached payload are injected into a 28.5 deg inclined, low earth orbit by the Space Shuttle. The Space Tug then performs a maneuver* to enter a transfer orbit with apogee at synchronous altitude. Upon reaching apogee, the Tug's engine fires* again to circularize the orbit and the payload is subsequently deployed. After a series of phasing maneuvers the Tug retrieves a second payload from synchronous orbit and performs a retrothrust deorbit burn to enter a transfer orbit with a low altitude perigee. At perigee the Tug burns to enter a phasing orbit which will produce the correct phasing relationship between the Tug and the waiting Shuttle for rendezvous purposes. Having completed a revolution in the phasing orbit, the Tug enters an orbit coelliptic with, and about 18.5 km (10 n mi) above that of the Shuttle, and acts as the passive vehicle in the ensuing coelliptic rendezvous. The geosynchronous mission profile for the cryogenic Space Tug is shown in Fig. 1.

The purpose of the present study is to determine the ΔV required by the Space Tug to perform the ascent portion of the geosynchronous mission using the minimum fuel trajectory. Trajectories are developed for both the cryogenic Space Tug and the storable Space Tug. Baselines for both these vehicles are contained in Refs. 1 and 2, respectively, and baseline data pertinent to this study is shown in Table 1. In both cases a shuttle weight constraint of 29,484 kg (65,000 lbs) was assumed. This was also assumed to be the initial ignition weight for the Tug resulting in conservative losses.

From Table 1 we can see that for both Space Tug configurations the thrust-to-weight ratios are in the range where gravity losses due to finite burning times will be significant. For this reason the Modularized Vehicle Simulation (MVS) Program (Ref. 3) was used to accurately integrate the trajectories through

*This maneuver includes plane changes to achieve the geosynchronous-equatorial mission orbit.

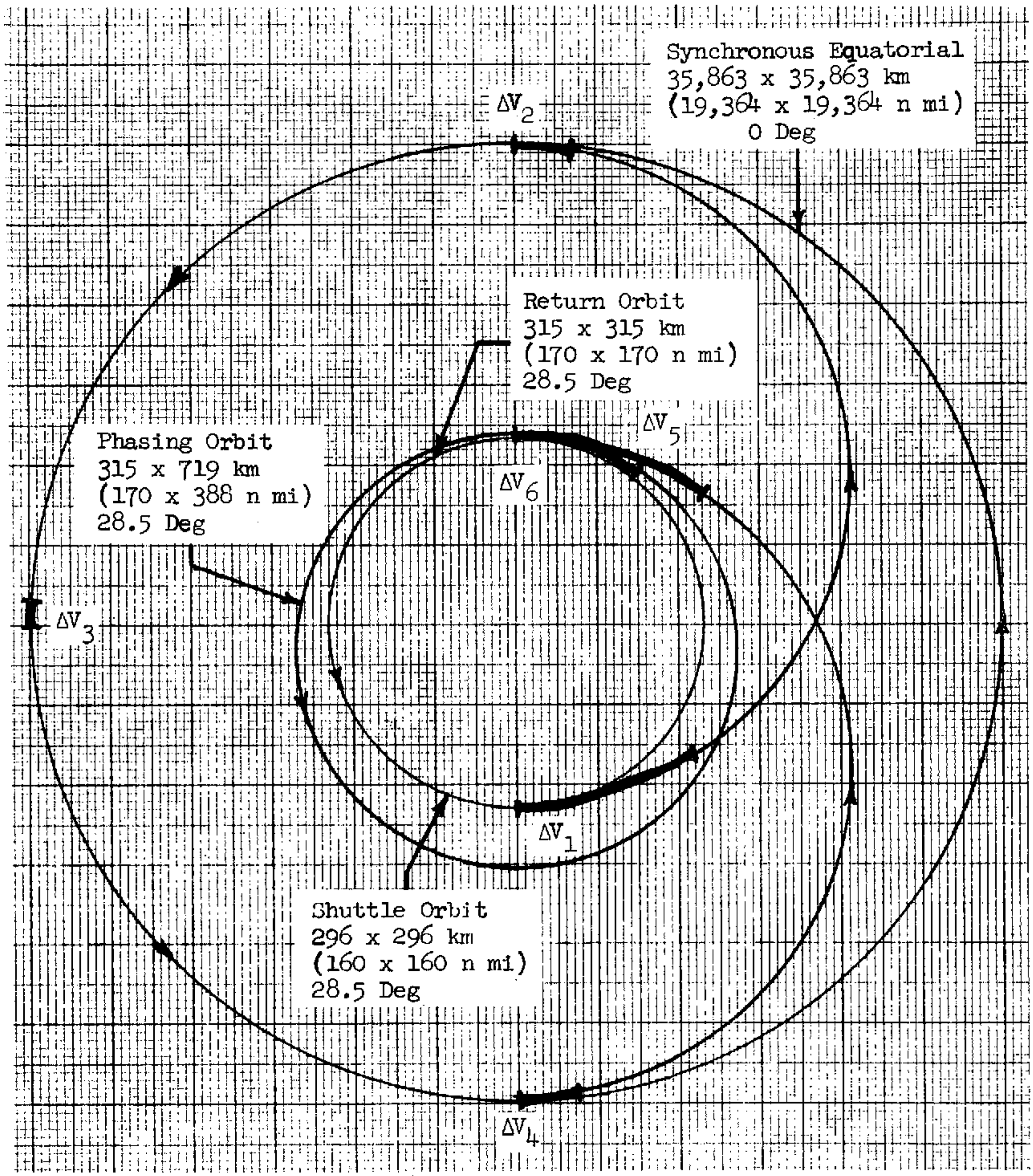


Figure 1. Nominal Space Tug Geosynchronous Mission

powered and coasting flight, thus including these gravity losses in computing the required ΔV.

Table 1. Tug Baselines

Storable Tug Baseline*

Thrust	-	28,912 N (6,500 lbs)
Specific Impulse	-	338 sec
Shuttle Park Orbit	-	278 x 278 km (150 x 150 n mi) i = 28.5 deg
Mission Orbit	-	35,787 x 35,787 km (19,323 x 19,323 n mi) i = 0 deg

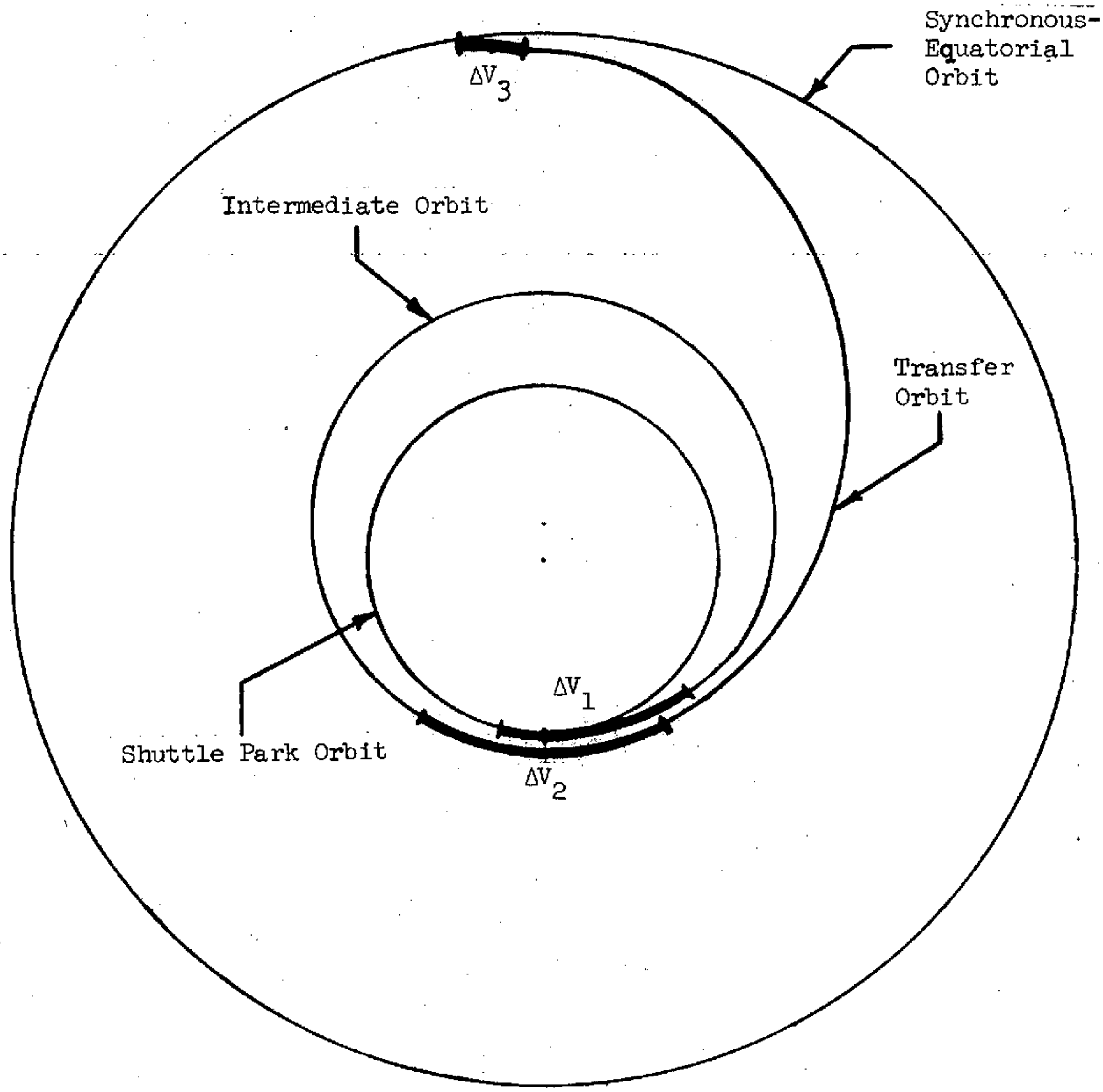
Cryogenic Tug Baseline**

Thrust	-	44,480 N (10,000 lbs)
Specific Impulse	-	470 sec
Shuttle Park Orbit	-	296 x 296 km (160 x 160 n mi) i = 28.5 deg
Mission Orbit	-	35,863 x 35,863 km (19,364 x 19,364 n mi) i = 0 deg

* Taken from Ref. 2

** Taken from Ref. 1

In order to reduce these gravity losses, a three burn ascent, in addition to the nominal two burn ascent shown in Fig. 1, is analyzed. The three burn ascent which reduces gravity losses by splitting the large low altitude burn into two smaller burns which are performed closer to perigee, is shown schematically in Fig. 2. The first burn produces an intermediate orbit with a specified apogee altitude and accomplishes a small amount of plane change (generally of the order of one degree). Due to the finite burn time perigee altitude is also



ΔV_1 Produces intermediate orbit with specified apogee altitude, incidentally increasing the perigee altitude. A small portion of the total plane change is accomplished.

ΔV_2 A burn straddling perigee produces a transfer orbit with apogee at synchronous altitude. Total plane change is increased to 2 deg.

ΔV_3 A burn initiated near apogee circularizes the orbit and accomplishes the remaining 26.5 deg of plane change.

Figure 2. Three Burn Ascent to Synchronous-Equatorial Orbit

raised. The second burn straddles perigee and raises apogee to synchronous altitude. The total plane change is increased to 2 deg. Slightly before reaching apogee, the circularization burn is performed and the remaining 26.5 deg of plane change is accomplished. In addition to providing a lower total ΔV, the three burn mission has the additional advantage of offering an ascent phasing orbit which can be selected to achieve longitude phasing in synchronous orbit. Thus, optimal low thrust two and three burn ascent trajectories will be developed for both cryogenic and storable Space Tugs using the Modularized Vehicle Simulation Program. For the three burn ascent missions, the optimal intermediate orbit apogee altitude will be sought as part of this study.

2. METHOD OF ANALYSIS

The Modularized Vehicle Simulation Program has available an option to minimize a cost function specified by the user by means of an iterative convergence subroutine. For the purpose of this study the following cost function was specified for minimization:

$$J = \omega_1 \ (\Delta V) + \omega_2 \ (h_a - h_s) + \omega_3 \ (e) + \omega_4 \ (i)$$

where ΔV^* = delta velocity expended in reaching final orbit

h_a = apogee altitude of final orbit

h_s = synchronous altitude

e = eccentricity of final orbit

i = inclination of final orbit

ω_j = numerical weighting factors, determined by preliminary MVS runs

Minimization of the above cost function provides a fuel optimal trajectory to a final orbit which is very nearly synchronous and equatorial. The parameters which are allowed to be varied in achieving the above minimization are the thrust vector angles α and β (defined in Fig. 3) during the burns and the start times of each burn.

In order to achieve convergence it was necessary to restrict somewhat the scope of these variables. The angle between the velocity vector and the component of the thrust vector in the orbital plane, α, was assumed to be a linear function of time during each burning period. In this way the time history of α during each burn could be represented in the optimization by two parameters, the value of α at the beginning of the burn and the value of α at the end of the burn. To determine α at any intermediate point the program used linear interpolation. The out of plane angle of the thrust vector, β, was assumed to be a constant for each burn. In fact, for low altitude burns the value of β was

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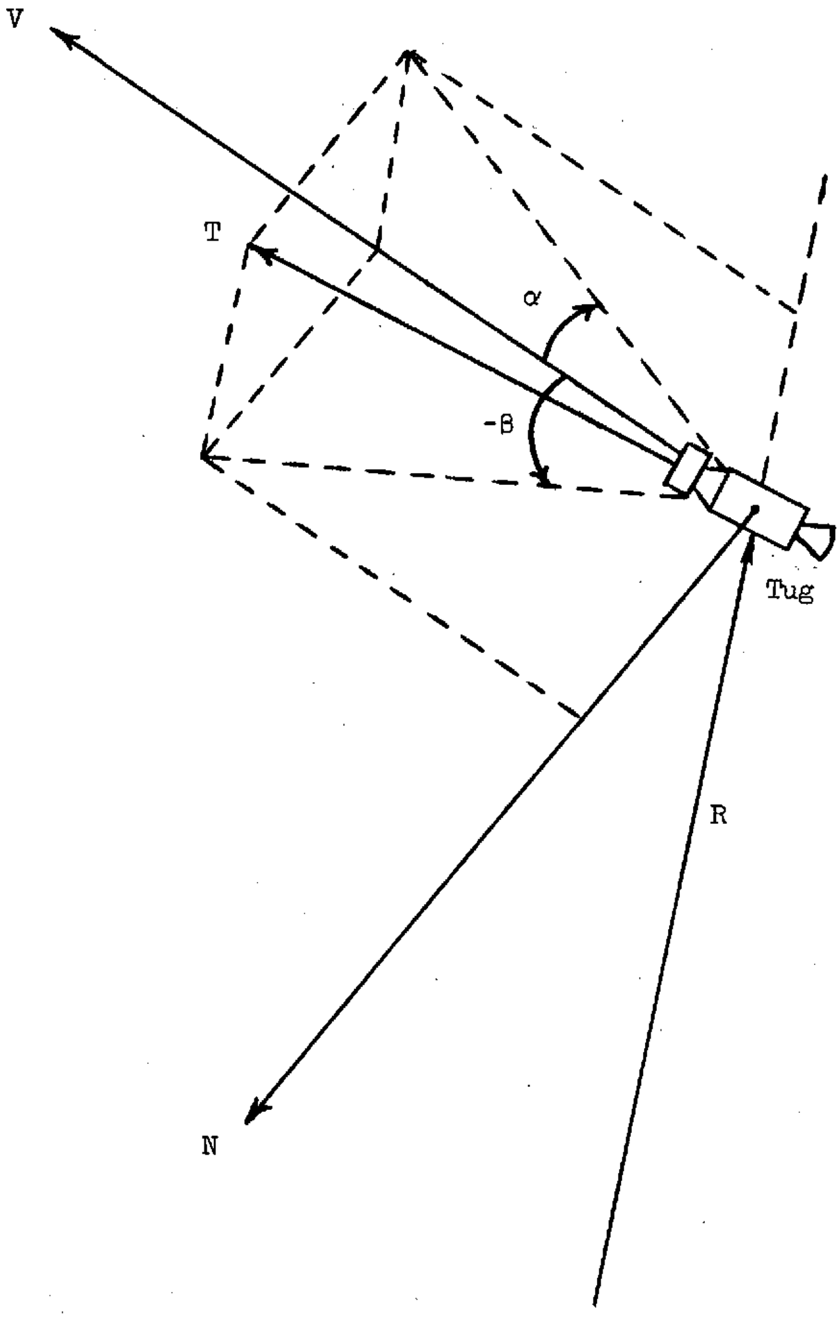
*where $\Delta V = \int (\text{thrust acceleration})\, dt$



V = Velocity Vector

R = Radius Vector

N = Out of Plane Vector

T = Thrust Vector

α = Angle Between Velocity Vector and Projection of Thrust Vector into Orbital Plane. Positive Outwards.

β = Out of Plane Angle of Thrust Vector. Negative in the Direction of N.

Figure 3. Definition of Thrust Angles

specified as 7.8 deg, since this value was found to produce the desired 2 deg and 26.5 deg plane changes during low altitude and high altitude burns respectively. This plane change split is the optimal way to perform the required total 28.5 deg plane change with impulsive burns and was found to be optimal as well for these low acceleration trajectories by simulating other plane splits about this value. The value of β during the final circularization burn was iterated upon by the MVS Program, as were the start times of the burns. The above restrictions on the variables allowed quick convergence of the iterative scheme without significantly compromising the solution.

3. RESULTS OF THE STUDY

3.1 Two Burn Ascent Mission

For the two burn ascent to synchronous-equatorial orbit the simulation was developed so that cutoff of the first burn was achieved when apogee reached synchronous altitude and cutoff of the second burn when the Tug's velocity reached synchronous velocity. Start times of the burns and thrust angles were iteratively determined as explained earlier. The resulting trajectories for both the storable and cryogenic Tugs are shown in Tables 2 and 3, respectively. The first trajectory shown in each Table is the pseudo* optimized trajectory obtained when the in-plane thrust during the first burn is assumed to lie along the velocity vector (tangential in-plane thrust, $\alpha_1 = 0$ deg). The second trajectory is the optimized trajectory obtained when α_1 is not constrained to be zero. It is clear from comparing total ΔV figures that the tangential in-plane thrusting during the first burn is an excellent approximation to optimal thrusting as far as overall ΔV is concerned.

The higher gravity losses associated with lower thrust-to-weight ratios is evidenced by the fact that the 44,480 N (10,000 lbs) thrust cryogenic Tug required about 69 mps (225 fps) less to complete the ascent than does the 28,912N (6,500 lbs) thrust storable Tug. Likewise, the burn times for the cryogenic Tug are considerably shorter as is the total elapsed ascent time. For comparison, the average impulsive thrusting solution is 4,235 mps (13,895 fps), so that overall gravity losses are 161 mps (527 fps) for the storable Tug and 91 mps (299 fps) for the cryogenic Tug.

It is interesting to note that, when the program is allowed to optimize α_1, the resulting increase in perigee altitude of the transfer orbit is

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*Complete optimization was limited by the assumptions on the form of the control.

less than when α_1 is constrained to be zero. In all cases the inclination of the transfer orbit is quite close to the desired 26.5 deg.

Table 2. Storable Tug

Two Burn Ascent to Synchronous-Equatorial Orbit

Thrust Level (lbs)	Initial Orbit	First Burn	Transfer Orbit	Second Burn	Final Orbit
6,500	278 x 278 km (150 x 150 n mi) i = 28.5 deg	α_1 = 0 deg β_1 = 7.8 deg ΔV = 2,636 mps (8,648.8 fps) Δt = 30m 56s	906 x 35,787 km (489 x 19,323 n mi) i = 26.47 deg	α_2 = -2.49 to -.72 deg β_2 = -37.1 deg ΔV = 1,763 mps (5,785.2 fps) Δt = 10m 31s	35,779 x 35,779 km (19,319 x 19,319 n mi) i = -.0001 deg elapsed time = 5h 38m 19s Total ΔV = 4,400 mps (14,434.0 fps)
6,500	278 x 278 km (150 x 150 n mi) i = 28.5 deg	α_1 = -9.21 to 4.02 deg β_1 = 7.8 deg ΔV = 2,627 mps (8,618.7 fps) Δt = 30m 51s	828 x 35,787 km (447 x 19,323 n mi) i = 26.5 deg	α_2 = -2.56 to -.73 deg β_2 = -36.9 deg ΔV = 1,769 mps (5,803.6 fps) Δt = 10m 35s	35,776 x 35,779 km (19,317 x 19,319 n mi) i = .003 deg elapsed time = 5h 37m 41s Total ΔV = 4,396 mps (14,422.3 fps)

Table 3. Cryogenic Tug

Two Burn Ascent to Synchronous-Equatorial Orbit

Thrust Level (lbs)	Initial Orbit	First Burn	Transfer Orbit	Second Burn	Final Orbit
10,000	296 x 296 km (160 x 160 n mi) i = 28.5 deg	α_1 = 0 deg β_1 = 7.8 deg ΔV = 2,548 mps (8,358.0 fps) Δt = 21m 37s	617 x 35,863 km (333 x 19,364 n mi) i = 26.42 deg	α_2 = -1.75 to -.53 deg β_2 = -36.2 deg ΔV = 1,779 mps (5,836.4 fps) Δt = 9m 23s	35,857 x 35,859 km (19,361 x 19,362 n mi) i = .003 deg elapsed time = 5h 31m 53s Total ΔV = 4,327 mps (14,194.4 fps)
10,000	296 x 296 km (160 x 160 n mi) i = 28.5 deg	α_1 = -10.0 to -1.78 deg β_1 = 7.8 deg ΔV = 2,545 mps (8,350.0 fps) Δt = 21m 36s	593 x 35,863 km (320 x 19,364 n mi) i = 26.45 deg	α_2 = -2.39 to -.82 deg β_2 = -36.2 deg ΔV = 1,782 mps (5,845.2 fps) Δt = 9m 24s	35,844 x 35,863 km (19,354 x 19,364 n mi) i = .003 deg elapsed time = 5h 30m 55s Total ΔV = 4,327 mps (14,195.2 fps)

3.2 Three Burn Ascent Mission

The three burn ascent to synchronous orbit (shown in Fig. 2) offers the advantages of reduced ΔV, due to lower gravity losses, and the possibility of using the intermediate orbit as a phasing orbit to allow the Tug to inject into synchronous orbit at any longitude. For this analysis several intermediate orbit apogee altitudes were chosen for both the cryogenic and storable Space Tugs and optimal low thrust trajectories utilizing these intermediate orbits were developed. The results are shown in Table 4 for the storable Tug and Table 5 for the cryogenic Tug. For these three burn simulations, both α_1 and α_2 were constrained to be zero. This was necessary to keep computer time from becoming prohibitive due to the additional variables associated with the third burn. As was noted in the previous subsection, the ΔV penalty associated with tangential in-plane burning instead of true optimal burning is small for low altitude burns, so that the trajectories of Table 4 and 5 are very nearly optimal.

Plotting ΔV as a function of intermediate orbit apogee altitude for the storable and cryogenic Tugs yields the curves shown in Fig. 4.

For the storable Tug the optimal intermediate orbit apogee altitude is approximately 8,519 km (4600 n mi) and the associated minimum ΔV is 4,302 mps (14,115 fps). The optimal intermediate orbit apogee altitude for the cryogenic Tug is approximately 6,482 km (3,500 n mi) and the minimum ΔV is about 4,269 mps (14,005 fps). Use of an optimal three burn ascent has thus reduced gravity losses to 67 mps (220 fps) and 33.5 mps (110 fps) for the storable and cryogenic Tugs, respectively.

The dotted lines in Fig. 4 cover the range of intermediate orbits about the minimum ΔV point whose orbital periods differ by as much as 90 minutes, which is roughly the period of the Shuttle park orbit.

Table 4. Storable Tug

Three Burn Ascent to Synchronous-Equatorial Orbit

Thrust Level (lbs)	Initial Orbit	First Burn	Intermediate Orbit	Second Burn	Transfer Orbit	Third Burn	Final Orbit
6,500	278 x 278 km (150 x 150 n mi) i = 28.5 deg	α_1 = 0 deg β_1 = 7.8 deg ΔV = 166 mps (544 fps) Δt = 2m 45s	280 x 876 km (151 x 473 n mi) i = 28.36 deg	α_2 = 0 deg β_2 = 7.8 deg ΔV = 2,445 mps (8,022.7 fps) Δt = 27m 59s	811 x 35,787 km (438 x 19,323 n mi) i = 26.46 deg	α_3 = -2.30 to -.59 deg β_3 = -36.84 ΔV = 1,769 mps (5,803.9 fps) Δt = 10m 37s	35,779 x 35,729 km (19,319 x 19,319 n mi) i = .005 deg elapsed time = 7h 07 m 56s Total ΔV = 4,380 mps (14,370.6 fps)
6,500	278 x 278 km (150 x 150 n mi) i = 28.5 deg	α_1 = 0 deg β_1 = 7.8 deg ΔV = 1,417 mps (4,649.7 fps) Δt = 19m 37s	441 x 8,519 km (238 x 4,600 n mi) i = 27.27 deg	α_2 = 0 deg β_2 = 7.8 deg ΔV = 1,096 mps (3,595.6 fps) Δt = 10m 21s	472 x 35,787 km (255 x 19,323 n mi) i = 26.39 deg	α_3 = -2.31 to -.53 deg β_3 = -35.87 deg ΔV = 1,789 mps (5,869.3 fps) Δt = 11m 02s	35,766 x 35,792 km (19,312 x 19,326 n mi) i = .006 deg elapsed time = 8h 36m 23s Total ΔV = 4,302 mps (14,114.5 fps)
6,500	278 x 278 km (150 x 150 n mi) i = 28.5 deg	α_1 = 0 deg β_1 = 7.8 deg ΔV = 1,926 mps (6,319 fps) Δt = 24m 50s	609 x 14,990 km (329 x 8,094 n mi) i = 26.93 deg	α_2 = 0 deg β_2 = 7.8 deg ΔV = 630 mps (2,067.6 fps) Δt = 5m 28s	622 x 35,787 km (336 x 19,323 n mi) i = 26.42 deg	α_3 = -2.51 to -.66 deg β_3 = -36.3 deg ΔV = 1,780 mps (5,839.8 fps) Δt = 10m 51s	35,770 x 35,783 km (19,314 x 19,321 n mi) i = .0004 deg elapsed time = 10h 11m 45s Total ΔV = 4,336 mps (14,226.6 fps)

Table 5. Cryogenic Tug

Three Burn Ascent to Synchronous-Equatorial Orbit

Thrust Level (lbs)	Initial Orbit	First Burn	Intermediate Orbit	Second Burn	Transfer Orbit	Third Burn	Final Orbit
10,000	296 x 296 km (160 x 160 n mi) i = 28.5 deg	α_1 = 0 deg β_1 = 7.8 deg ΔV = 1,044 mps (3,423.7 fps) Δt = 10m 19s	332 x 5,556 km (179 x 3,000 n mi) i = 27.5 deg	α_2 = 0 deg β_2 = 7.8 deg ΔV = 1,432 mps (4,699.4 fps) Δt = 10m 50s	378 x 35,8[illegible]3 km (204 x 19,36[illegible] n mi) i = 26.4 deg	α_3 = -1.77 to -.50 deg β_3 = -35.5 deg ΔV = 1,793 mps (5,883.1 fps) Δt = 9m 36s	35,857 x 35,859 km (19,361 x 19,362 n mi) i = .017 deg elapsed time = 7h 53m 14s Total ΔV = 4,269 mps (14,006.2 fps)
10,000	296 x 296 km (160 x 160 n mi) i = 28.5 deg	α_1 = 0 deg β_1 = 7.8 deg ΔV = 1,388 mps (4,552.3 fps) Δt = 13m 14s	372 x 8,521 km (201 x 4,601 n mi) i = 27.3 deg	α_2 = 0 deg β_2 = 7.8 deg ΔV = 1,092 mps (3,583.3 fps) Δt = 7m 57s	393 x 35,86[illegible] km (212 x 19,36[illegible] n mi) i = 26.4 deg	α_3 = -1.78 to -.48 deg β_3 = -35.6 deg ΔV = 1,793 mps (5,881.2 fps) Δt = 9m 35s	35,857 x 35,859 km (19,361 x 19,362 n mi) i = .0016 deg elapsed time = 8h 31m 44s Total ΔV = 4,272 mps (14,016.8 fps)
10,000	296 x 296 km (160 x 160 n mi) i = 28.5 deg	α_1 = 0 deg β_1 = 7.8 deg ΔV = 1,727 mps (5,655.3 fps) Δt = 15m 54s	426 x 12,59[illegible] km (230 x 6,801 n mi) i = 27.0 deg	α_2 = 0 deg β_2 = 7.8 deg ΔV = 771 mps (2,529 fps) Δt = 5m 24s	443 x 35,8[illegible] km (239 x 19,36[illegible] n mi) i = 26.4 deg	α_3 = -1.77 to -.49 deg β_3 = -35.7 deg ΔV = 1,789 mps (5,870.8 fps) Δt = 9m 32s	35,857 x 35,859 km (19,361 x 19,362 n mi) i = .008 deg elapsed time = 9h 29m 12s Total ΔV = 4,284 mps (14,055.4 fps)

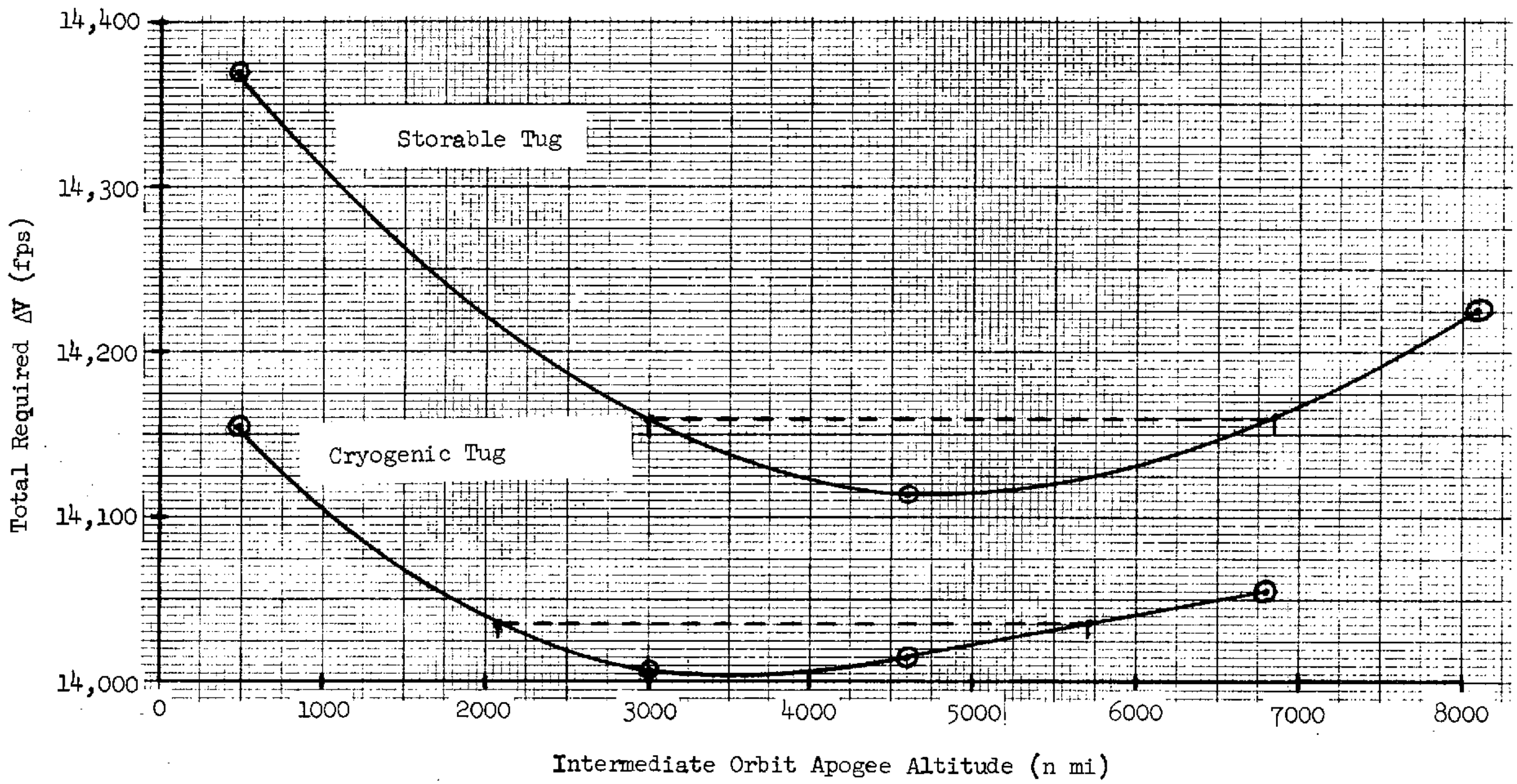

Figure 4. **Total ΔV Versus Intermediate Orbit Apogee**
for Three Burn Ascent Mission

Thus by choosing an intermediate orbit within the span of the dotted lines, the phasing of the Tug can be changed anywhere from 0 to 90 min or, equivalently, anywhere from 0 to 1 revolution in the park orbit.

Consequently, by waiting in the park orbit for an integral number of revolutions (eight revolutions, at most) and then injecting into the correct intermediate orbit within the span of the dotted lines in Fig. 4, the Space Tug can inject into synchronous-equatorial orbit at any longitude. From Fig. 4 it is then clear that to allow for worst case longitude phasing in a three burn ascent to geosynchronous orbit, a ΔV of 4,316 mps (14,160 fps) is required for the storable Tug and a ΔV of 4,278 mps (14,035 fps) is required for the cryogenic Tug.

Again the increased gravity loss for lower thrust-to-weight ratios is evident. The storable Tug requires roughly 38 mps (125 fps) more to accomplish the same mission as the cryogenic Tug.

The ΔV required to accomplish the three burn ascent, even allowing for longitude phasing, is considerably less than the two burn ascent. For the storable Tug a savings of 80 mps (262 fps) is realized and for the cryogenic Tug a savings of 49 mps (160 fps) is realized.

4. CONCLUSIONS

Near-optimal three dimensional trajectories from a low earth park orbit inclined at 28.5 deg to a synchronous-equatorial mission orbit have been developed using the Modularized Vehicle Simulation (MVS) Program for both the storable and cryogenic Tug baselines. The finite burn times, due to low thrust-to-weight ratios, and the associated gravity losses are accounted for in the trajectory simulation and optimization.

A two burn ascent, employing one burn to depart the park orbit and one burn to enter geosynchronous orbit was found to require 4,396 mps (14,422 fps) for the storable Tug and 4,327 mps (14,195 fps) for the cryogenic Tug.

A three burn ascent mission was also investigated. Here the first burn produces an intermediate orbit with a specified apogee altitude. The second burn, which occurs about perigee, injects the Tug on a transfer orbit to synchronous altitude. The final burn circularizes the Tug into geosynchronous orbit. For the storable Tug, the optimal intermediate orbit apogee was found to be about 8,519 km (4,600 n mi) and the associated minimum ΔV was 4,302 mps (14,115 fps). For the cryogenic Tug an intermediate orbit apogee altitude of 6,482 km (3,500 n mi) and ΔV of 4,269 mps (14,005 fps) was optimal. As a comparison, the ideal impulsive thrust solution, in which there are no gravity losses, is 4,235 mps (13,895 fps).

The Tug can inject into geosynchronous orbit at any longitude if the intermediate orbit is treated as an ascent phasing orbit. In this case a range of intermediate orbit apogees must be allowed and the ΔV is correspondingly higher. The storable Tug requires a range of intermediate orbit apogee altitudes from 5,556 to 12,686 km (3,000 to 6,850 n mi) and a worst case ΔV of 4,316 mps (14,160 fps). The cryogenic Tug requires a range of apogee altitudes from 3,889 to 10,556 km (2,100 to 5,700 n mi) and a worst case ΔV of 4,278 mps (14,035 fps). Even with these increases in ΔV to allow longitude phasing, the three burn ascent offers a significant ΔV savings over the two burn ascent mission.

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