ANALYSIS OF A SIMPLE TECHNIQUE FOR ESTABLISHING LUNAR ORBITS

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SUMMARY

An analytical study has been made of a simplified guidance technique designed to place the spacecraft that departs from earth in a close orbit around the moon. The technique consists of maintaining a constant angle between the thrust axis of the spacecraft and the line of sight to the lunar horizon while the orbit is being established. The nominal approach trajectory which was used had a transit time of 70.5 hours, a minimum altitude of 80 nautical miles, and a velocity at this point of 8308 feet per second. It was found that parking orbits which are closely confined to the pericynthion altitude of the approach trajectory (80 n. mi.) can be established very efficiently by use of the simplified guidance technique.

Author

INTRODUCTION

The lunar orbit rendezvous mode is to be used by this country initially to land man on the surface of the moon. In this concept, the spacecraft that departs from earth first establishes a close orbit around the moon. The primary guidance and control system for establishing this lunar parking orbit is presently scheduled to be automatic; however, manual control techniques which require a minimum of instrumentation would be useful for monitoring spacecraft progress or as possible backup modes of operation to increase the probability of mission success.

The study to be discussed in this paper is concerned with the establishment of a lunar parking orbit. The primary control function in orbit establishment is proper orientation of the vehicle thrust vector. The problem to be examined is to determine if the lunar horizon would be a convenient visual reference to aid the pilot in thrust vector orientation, and to determine the sensitivity of the parking orbit to errors in use of the reference or in vehicle initial conditions (start of braking maneuver).

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SYMBOLS

K	angle between the thrust vector and the line of sight to the lunar horizon, deg
r	radial distance from center of moon, ft
h	altitude above the lunar surface, ft or n. mi.
θ	angular travel over the lunar surface, deg
t	time, sec
W	earth weight of spacecraft, lb
ΔV	characteristic velocity, fps
F	thrust, lb

Subscripts:

O	initial conditions (at thrust initiation)
P	pericynthion conditions
A	apocynthion conditions

ANALYSIS

The phase of the lunar mission considered in this study is shown in figure 1. The spacecraft has departed from earth and is approaching the vicinity of the moon on a nominal approach trajectory. Relative to the moon, the vehicle has hyperbolic velocity and thus will not be captured by the lunar gravitational field. The pilot's task, therefore, is to apply retrothrust (braking maneuver) in such a manner as to adjust the velocity and altitude to the desired orbital values.

The nominal approach trajectory used in this study has a transit time of 70.5 hours. The point of closest approach to the lunar surface is 80 nautical miles, and the velocity at this point is 8308 feet per second.

The equations of motion used were for a point mass moving in a central force field and subject to a thrust force in the plane of motion. A constant-thrust engine producing an initial thrust-to-weight ratio of 0.262 and having a specific impulse of 313 seconds was assumed for the braking trajectories.

The procedure used was to compute efficient braking maneuvers and then to determine the orientation of the thrust vector relative to the lunar horizon. The efficient braking maneuvers were fuel-optimum trajectories computed by a steepest descent optimization procedure. The purpose was to determine whether any convenient geometric relationships existed between the thrust vector and the line of sight to the lunar horizon.

RESULTS AND DISCUSSION

As stated in the Analysis section, efficient braking maneuvers were computed from the nominal approach trajectory and then the orientation of the thrust vector was examined relative to the lunar horizon. Figure 2 shows the variation, during the braking maneuver, of the angle between the thrust vector and the line of sight to the lunar horizon for a fuel-optimum braking trajectory initiated at an altitude of 720,720 feet on the nominal approach trajectory. The parking orbit established by this braking trajectory was a circular parking orbit at an altitude of 80 nautical miles. As can be seen, the angle between the thrust vector and the line of sight to the lunar horizon remains nearly constant throughout the braking maneuver. Based upon this result, new braking trajectories were computed where the angle between the thrust vector and the line of sight to the lunar horizon was maintained constant. By an iteration process, it was found that if an angle of $K = 38.6^{\circ}$ were maintained throughout the braking maneuver, the constant-angle trajectory very closely approximated the fuel-optimum trajectory. A comparison of terminal conditions for both maneuvers is shown in figure 3, and the agreement is very good. This constant angle trajectory and its corresponding parking orbit will be used in an error analysis in a following section.

A similar analysis, as just described, was made for braking trajectories initiated at other altitudes along the nominal approach trajectory. In some cases the variation of the angle between the thrust vector and the line of sight to the lunar horizon varied somewhat for the optimum braking maneuvers. However, it was found that a constant angle near the average variation could still be used to establish the parking orbit for an altitude range of 500,000 feet to 720,720 feet on the nominal approach trajectory. Figure 4(a) shows the constant thrust angle K and the thrusting time to use in generating the constant angle trajectories, and figure 4(b) gives the minimum and maximum altitudes of the resulting parking orbits. Notice in figure 4(b) that the use of constant angle trajectories results in parking orbit altitudes which vary from approximately 75 nautical miles to 80 nautical miles. It appears, therefore, that the lunar horizon would be a convenient visual reference for manual control in lunar orbit establishment. The fuel consumption in terms of thrusting time and characteristic velocity is shown in figure 5 for both the constant angle trajectories and fuel-optimum trajectories. As indicated by the figure, the constant angle trajectories are efficient braking maneuvers.

Error study.- Since a completely visual braking maneuver is open loop, it was of interest to examine the effects of various possible operational errors on the parking orbit. The next step, therefore, was to determine the effects of errors in thrust vector orientation, thrust level, thrusting time, lunar surface irregularities, and various initial conditions of a nominal braking maneuver on the parking orbit. The braking maneuver previously discussed, which was initiated at an altitude of 720,720 feet (fig. 3), was arbitrarily chosen as the nominal braking maneuver. The associated nominal parking orbit is approximately circular at an altitude of 80 nautical miles. The variation of the apocynthion and pericynthion altitudes of the nominal parking orbit with various individual errors is shown in figure 6. Lunar surface irregularities would result in errors in thrust vector orientation. For example, a 5000-foot-peak mountain results in an error in K of about 0.1 degree. If the errors shown in figure 6 are assumed to be representative of those that might occur in actual practice, then it appears that safe parking orbits can be obtained under a wide range of errors. In general, the effects of combinations of errors cannot be obtained by summing the effects of individual errors. This is because of the coupling of orbit parameters in the trajectory equations.

The next phase of the study deals with the correction of off-nominal conditions.

Correction of errors.- If the spacecraft is on an approach trajectory which varies slightly from the nominal, it will have different velocity components when it reaches the nominal altitude, or time, at which the braking maneuver is to be initiated. If it is assumed that these off-nominal values in velocity can be determined accurately, then appropriate corrections can be made in the nominal thrust angle and thrusting time to compensate for these off-nominal conditions. Figure 7 shows the proper change in thrust angle and thrust time for various combinations of errors in velocity components, $\dot{r}_0$ and $(r\dot{\theta})_0$, at the nominal altitude ($\Delta h_0 = 0$). Combination errors are considered over a range of ±100 feet per second in each velocity component. The parking orbits resulting from the use of figure 7 are confined to an altitude of approximately 80 ± 5 nautical miles. Thus, corrections can be made for small variations in the nominal approach trajectory. The off-nominal approach trajectories being considered in figure 7 have pericynthion altitudes which vary about ±5 nautical miles from the nominal 80-nautical-mile altitude.

The use of the lunar horizon for thrust vector orientation appears to allow the pilot to perform an efficient braking maneuver while reducing the velocity and altitude to values consistent with an approximate 80-nautical-mile circular orbit. In reference to the Apollo mission, the lunar horizon is visible through the onboard telescope during the braking maneuver; and hence the technique that has been presented appears attractive for monitoring an automatic system or for manual control in the establishment of a parking orbit. Flight simulations will determine how well the technique can be executed.

CONCLUDING REMARKS

An analytical study has been made of a simplified guidance technique designed to place the spacecraft that departs from earth in a close orbit around the moon. The technique consists of maintaining a constant angle between the thrust axis of the spacecraft and the line of sight to the lunar horizon while the orbit is being established. The nominal approach trajectory which was used had a transit time of 70.5 hours, a minimum altitude of 80 nautical miles, and a velocity at this point of 8308 feet per second. It was found that parking orbits which are closely confined to the pericynthion altitude of the approach trajectory (80 n. mi.) can be established very efficiently by the use of the simplified guidance technique.

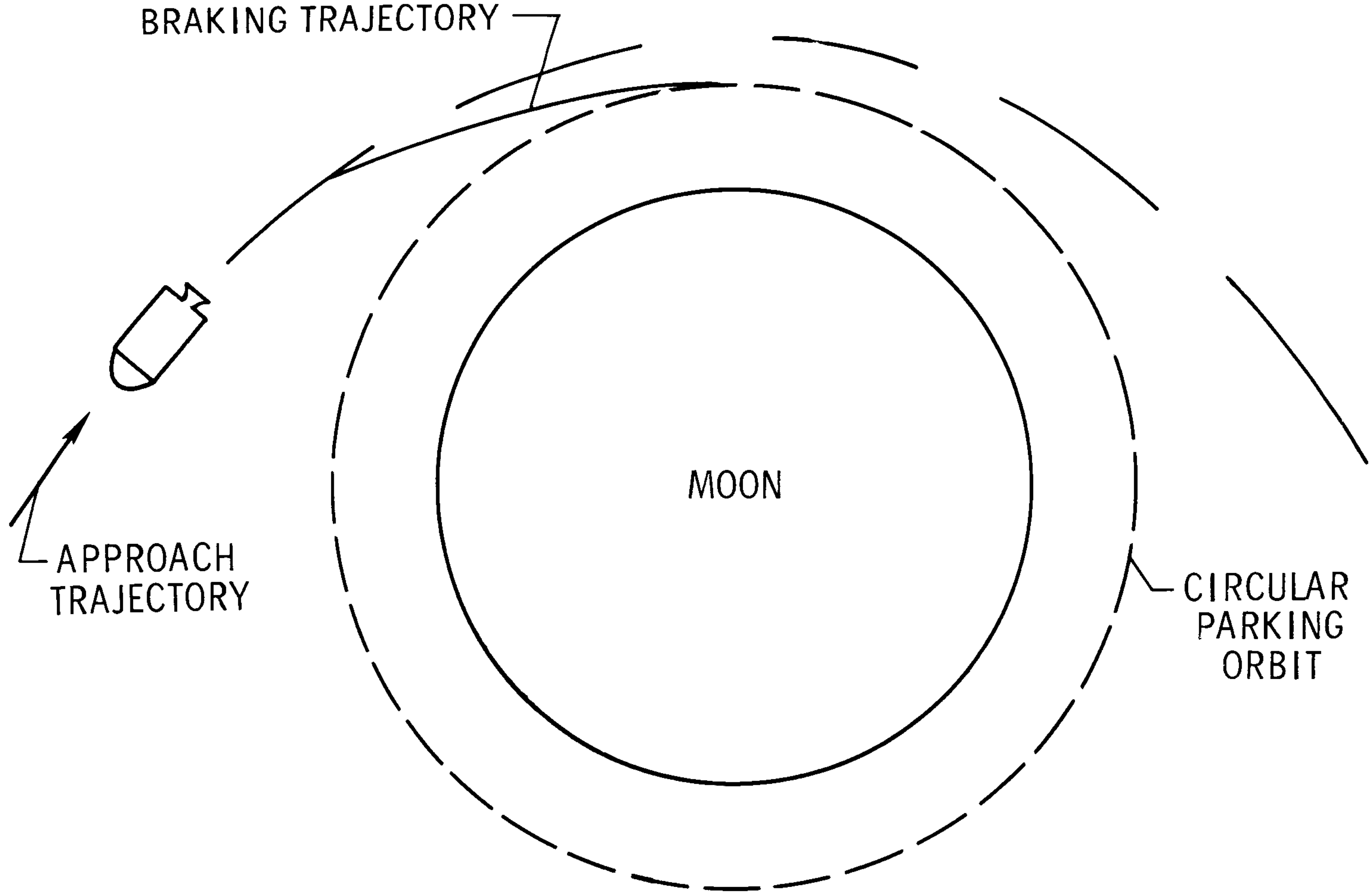

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Figure 1.- Illustration of lunar orbit establishment.

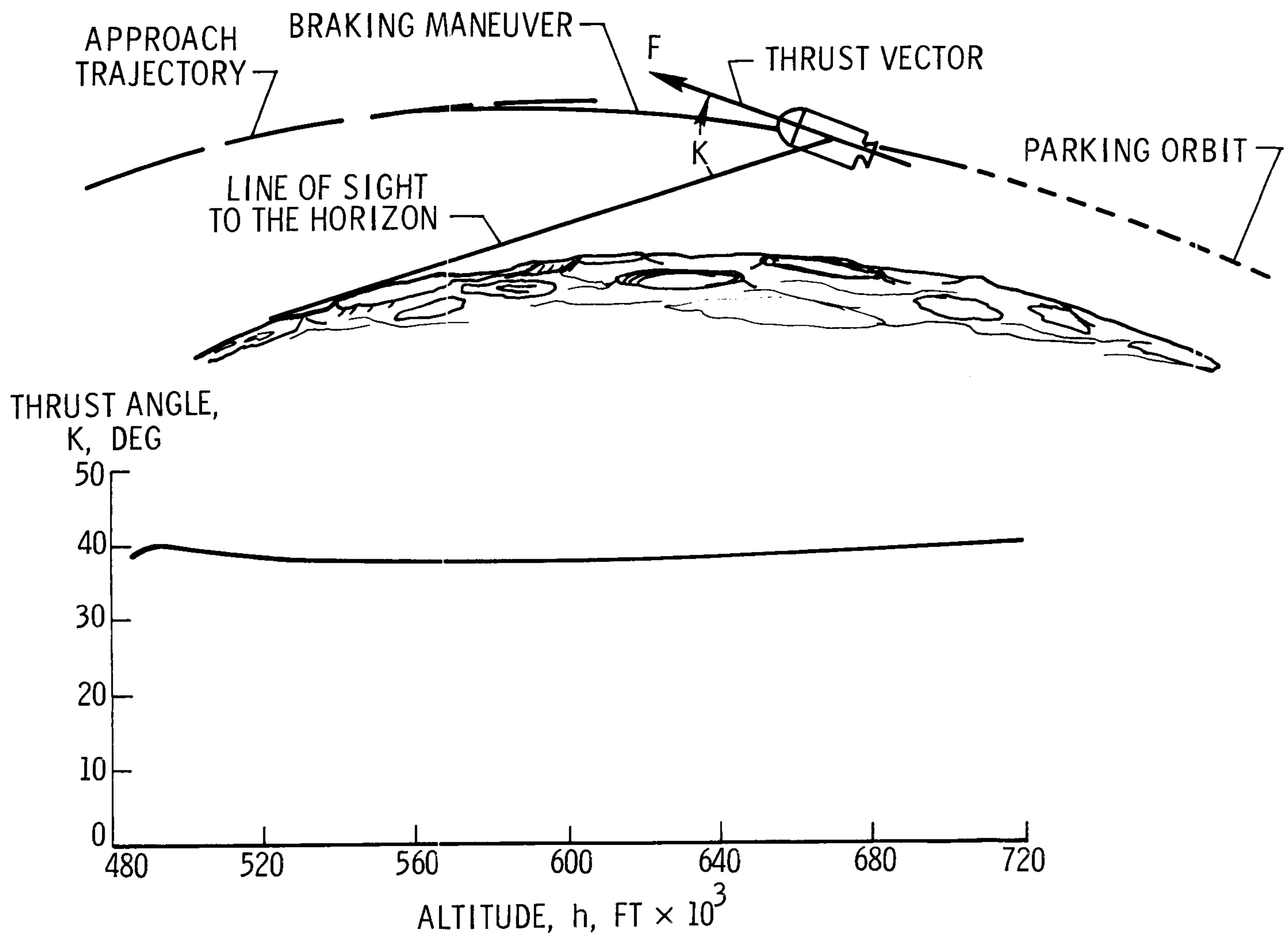

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Figure 2.- Variation of the angle between the thrust vector and line of sight to lunar horizon for optimum braking trajectory.

<u>INITIAL CONDITIONS</u> -	OPTIMUM TRAJECTORY	CONSTANT ANGLE TRAJECTORY K = 38.6^{0}
ALTITUDE, h, FT	720,720	720,720
RADIAL VELOCITY, $\dot{r}$, FPS	-1709.29	-1709.29
TRANSVERSE VELOCITY, $r\dot{\theta}$, FPS	8003.36	8003.36
<u>TERMINAL CONDITIONS</u> -		
ALTITUDE, h, FT	486,142	487,751
RADIAL VELOCITY, $\dot{r}$, FPS	0	-1.43
TRANSVERSE VELOCITY, $r\dot{\theta}$, FPS	5286.9	5284.4
ANGULAR TRAVEL, θ, DEG	19.5	19.5
THRUSTING TIME, t, SEC	315	315
<u>PARKING ORBITS</u> -		
MINIMUM ALTITUDE, h_p, N. M.	80	78.8
MAXIMUM ALTITUDE, h_A, N. M.	80	80.3

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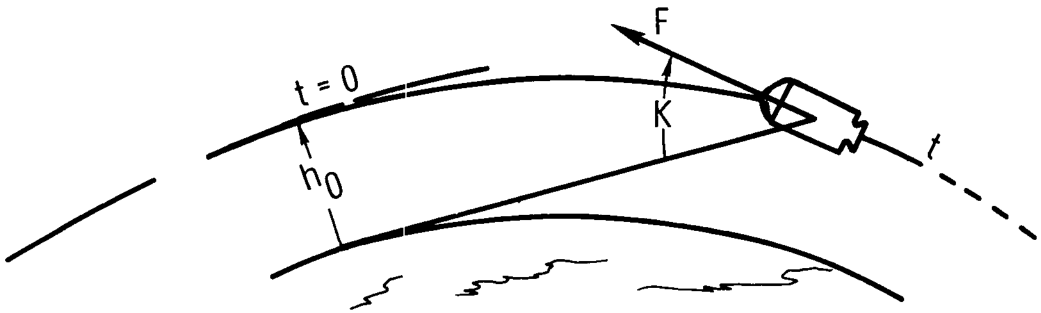
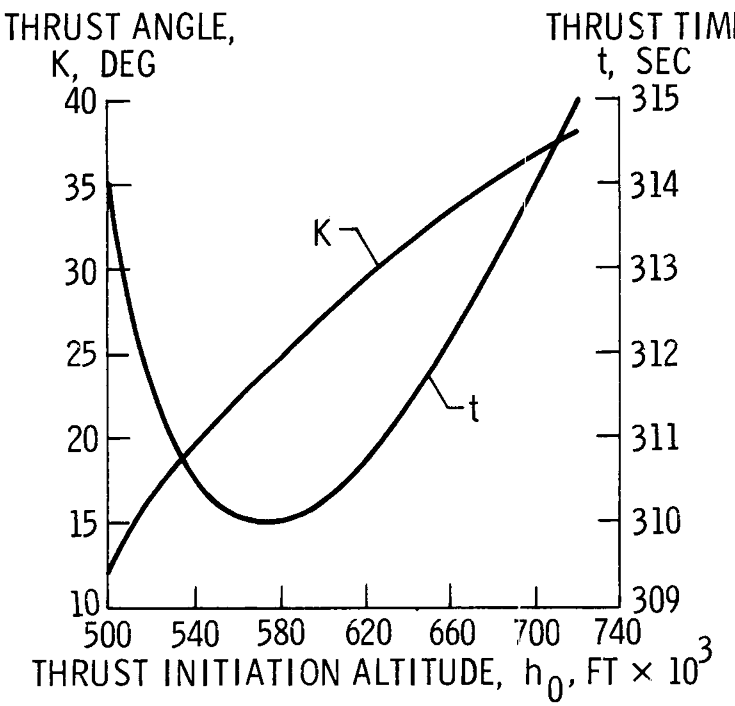
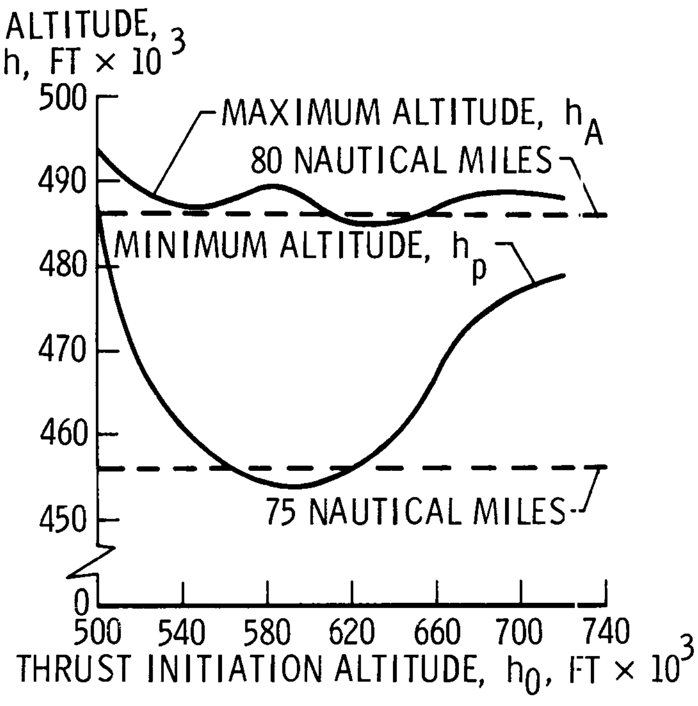
Figure 3.- Comparison of initial conditions, terminal conditions, and parking orbits of optimum braking trajectory with those of a constant angle trajectory.





(a) Constant angle trajectories.



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(b) Parking orbits.

Figure 4.- Constant angle trajectories and subsequent parking orbits for various thrust initiation altitudes along the approach trajectory.

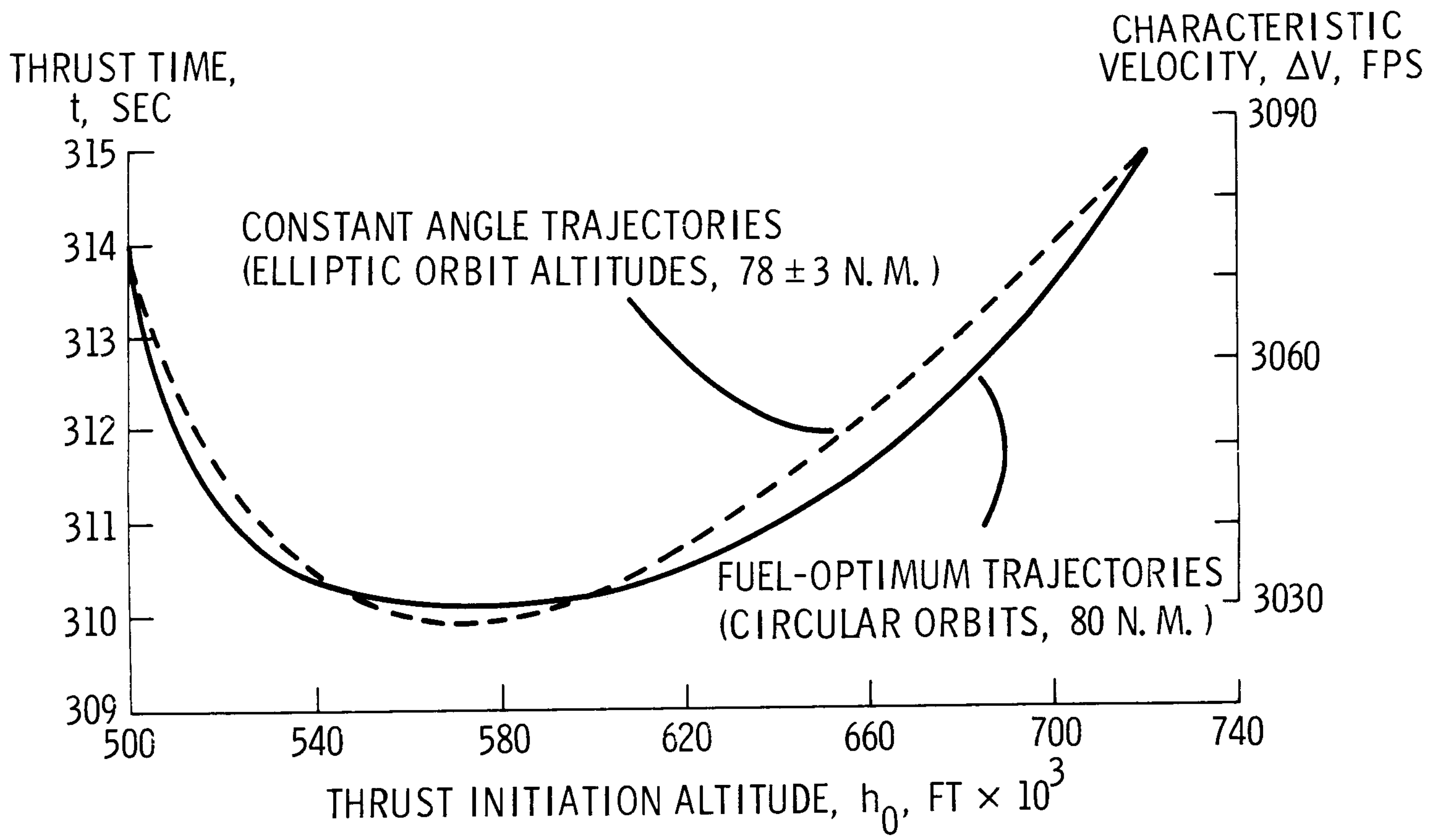

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Figure 5.- Thrusting time and characteristic velocity requirements for fuel-optimum and constant-angle braking trajectories for various thrust initiation altitudes.

PARAMETER	ERROR	Δh_p, N. M.	Δh_A, N. M.
ΔK, DEG	1 -1	-5 -13.3	13.3 6.7
$\Delta F/W_0$, PERCENT	1 -1	-26.7 —	— 26.7
Δt, SEC	1 -1	-8.3 —	— 8.3
Δh_0, N. M.	2 -2	.4 -5	5.3 —
$\Delta \dot{r}_0$, FPS	10 -10	-2 1.1	1.2 2.1
$\Delta (r\dot{\theta})_0$, FPS	10 -10	— -7.7	7.7 —

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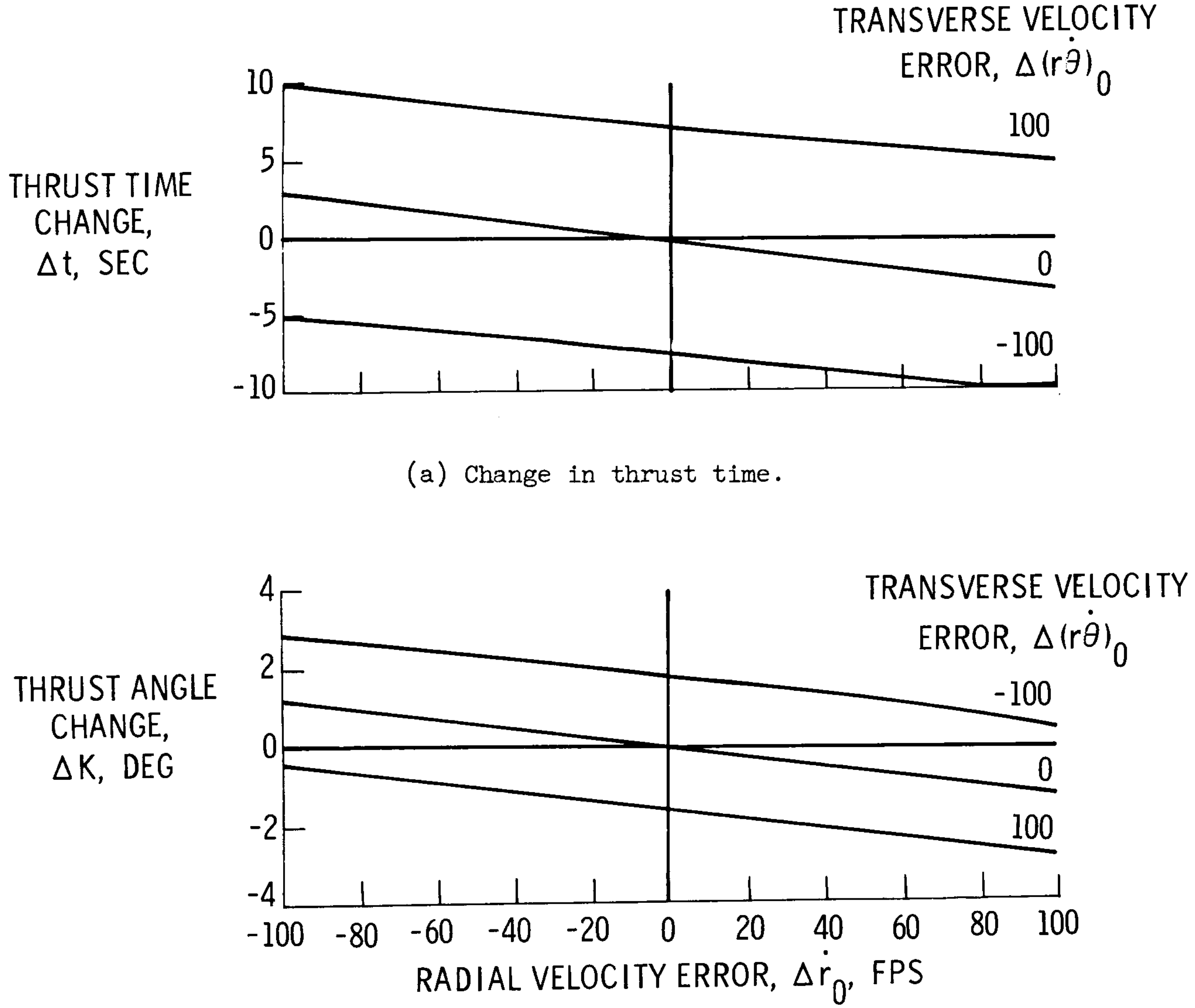
Figure 6.- Effect of various individual errors on the nominal parking orbit.



(a) Change in thrust time.

(b) Change in thrust angle.

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Figure 7.- Variation of nominal braking trajectory to compensate for initial velocity errors. (Resulting parking orbit altitudes - 80 ± 5 n.m.)

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