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GOES-I/M ASCENT MANEUVERS FROM TRANSFER ORBIT TO STATION*

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ABSTRACT

The Geostationary Operational Environmental Satellite (GOES)-I/M station acquisition sequence consists nominally of three in-plane/out-of-plane maneuvers at apogee on the line of relative nodes and a small in-plane maneuver at perigee. Existing software to determine maneuver attitude, ignition time, and burn duration required modification to optimize the out-of-plane parts and admit the noninertial, three-axis stabilized attitude.

The Modified Multiple Impulse Station Acquisition Maneuver Planning Program (SENARIO2) was developed from its predecessor, SCENARIO, to optimize the out-of-plane components of the impulsive delta-V vectors. Additional new features include computation of short-term J_2 perturbations and output of all premaneuver and postmaneuver orbit elements, coarse maneuver attitudes, propellant usage, spacecraft antenna aspect angles, and ground station coverage. The output data are intended to be used in the launch window computation and by the maneuver targeting computation (General Maneuver (GMAN) Program) software.

The maneuver targeting computation in GMAN was modified to admit the GOES-I/M maneuver attitude. Appropriate combinations of ignition time, burn duration, and attitude enable any reasonable target orbit to be achieved.

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1. INTRODUCTION

Salient features of the optimization software and targeting algorithms for the Geostationary Operational Environmental Satellite (GOES)-I/M station acquisition maneuvers are presented in this paper. Selected numerical results will be shown for maneuvers at apogee.

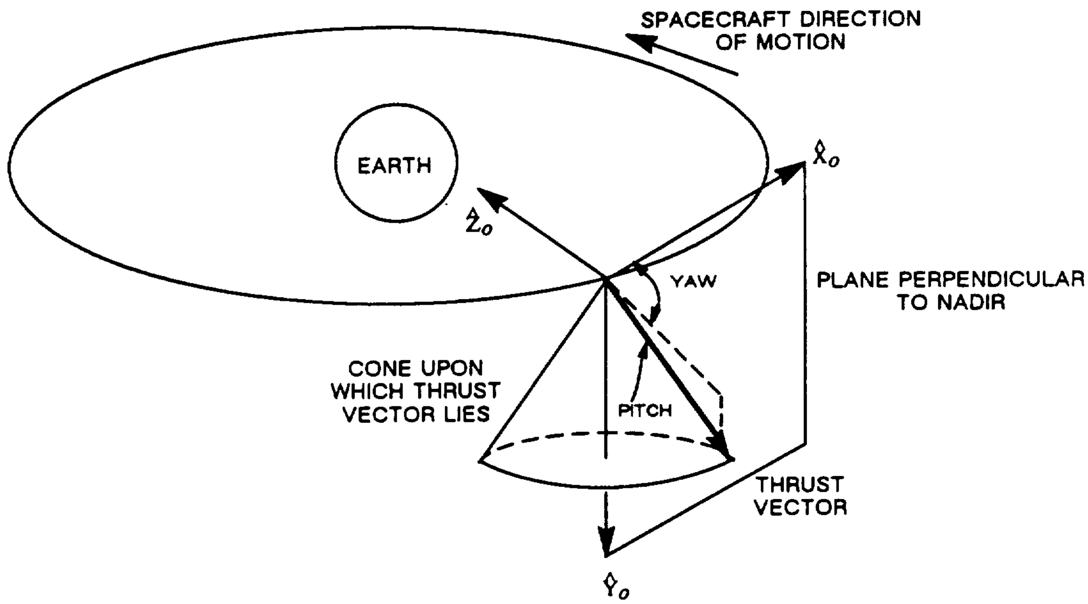
The nominal mission consists of three apogee maneuvers and one perigee maneuver. The initial orbit is an elliptic transfer orbit inclined at about 27.5 degrees. The desired orbit is geosynchronous at near-zero inclination at a desired right ascension of the ascending node (see Figure 1). The line of apsides and line of relative nodes are nearly coincident for each of the maneuvers so that in-plane and out-of-plane changes can take place simultaneously. The spacecraft is said to have acquired station when the final synchronous orbit has been achieved with the spacecraft at the desired longitude.

Using the two–body approximation, a set of impulsive delta-V vectors is first determined that enables the spacecraft to acquire station with satisfactory ground station coverage for the lowest fuel expenditure (minimum total delta-V). Elements for each of the post-maneuver orbits are then determined from the delta-V vectors. Next, ignition time, attitude, and burn duration are determined for the three-axis stabilized, noninertial maneuver attitude. The software is designed to permit quick replanning in case of contingency.

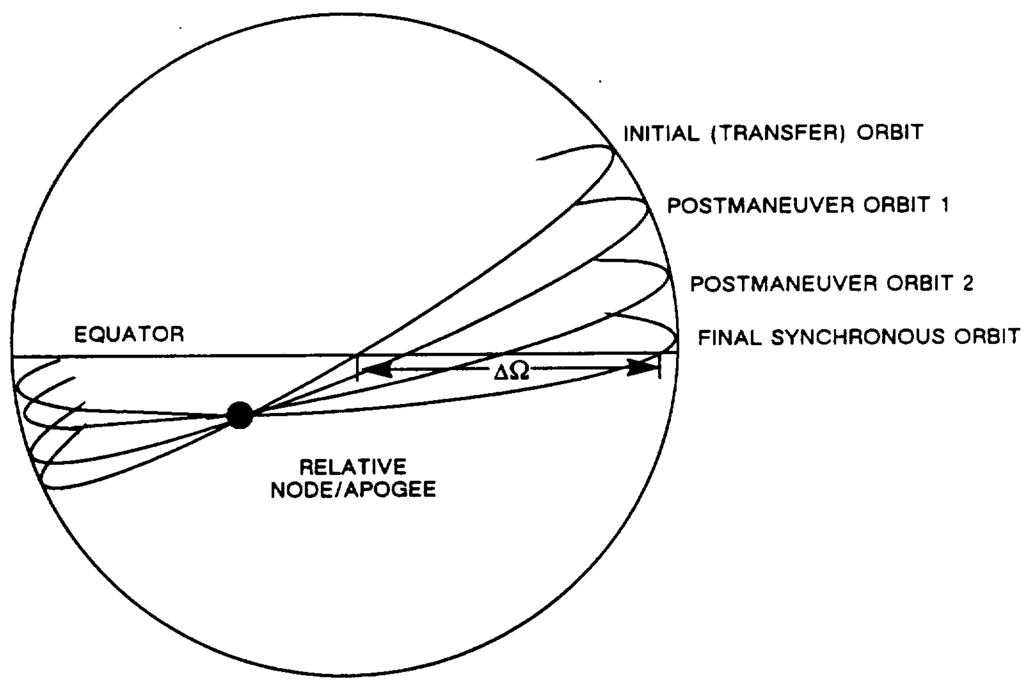
2. DESCRIPTION OF THE MANEUVER ATTITUDE AND THE STATION ACQUISITION SEQUENCE

The maneuver attitude is controlled as follows: Spacecraft pitch is held constant in the local orbital coordinate system with the Earth sensors and the thrust vector is held with the gyroscope at a fixed angle to the negative orbit normal of the initial orbit (determined by the initial yaw). The Earth sensors also maintain zero roll. The thrust vector is not inertially fixed, but sweeps out a cone about the negative orbit normal of the initial orbit. A diagram of the attitude appears in Figure 1.

The nominal transfer orbit provided by the launch vehicle is elliptic (eccentricity approximately 0.73) with apogee near geosynchronous radius (maximum dispersion about ±100 km) at an inclination of approximately 27.5 degrees. The required final geosynchronous orbit has a near-zero inclination and a right ascension of the ascending node (Ω) near 270 degrees, which provides maximum stability to solar and lunar perturbations. Apogee will be placed on or near the line of relative nodes so that a simultaneous raising of perigee and reduction of inclination (coupled with the required change in Ω) can be accomplished optimally at each apogee motor firing. Perigee motor firings for fine adjustment of the apogee radius are small and purely in-plane. (An enhancement to include plane changes for the perigee maneuvers is under consideration for contingency planning.) Additional small maneuvers at either apsis are planned to achieve precise station acquisition. All maneuvers take place at designated apogees or perigees. Apogee maneuvers have either combined in-plane and out-of-plane parts or are purely in-plane.



(a) Yaw and pitch with respect to initial orbital coordinate system $(\hat{X}_o, \hat{Y}_0, \hat{Z}_0)$. $\hat{Y}_o$ is parallel to the initial negative orbit normal. $\hat{Z}_o$ is parallel to the nadir.



(b) Cross-sections of initial, postmaneuver, and final orbits for three apogee maneuvers. $\Delta\Omega$ is the desired nodal rotation

Figure 1. Maneuver Attitude (a) and Orbits (b) for the Station Acquisition Sequence

Maneuver durations of 45 to 60 minutes are anticipated for the first apogee motor firing, with shorter durations for the subsequent apogee motor firings. Apogee maneuvers with out-of-plane parts will be approximately centered about the line of relative nodes. In-plane maneuvers will be centered on an apsis.

3. SOFTWARE FOR DETERMINING IMPULSIVE DELTA-V VECTORS

Optimum, impulsive delta-V vectors are determined by the Modified Multiple Impulse Station Acquisition Maneuver Planning Program (SENARIO2). Postmaneuver orbital elements are computed for use in the maneuver targeting computation.

SENARIO2 was developed from SCENARIO (Reference 1) to compute impulsive delta-V vectors when maneuvers have an out-of-plane part. The solution is found in two stages. First, an optimum set of in-plane, impulsive delta-V vectors is determined in a two-body calculation to acquire station without regard to inclination or Ω (this is the original SCENARIO code). The user designates apogees and perigees for 3 to 10 maneuvers. Three maneuvers are solved for, placing the final apogee and perigee at geosynchronous radius with the last maneuver occurring at the desired longitude. For a two-maneuver sequence, the third maneuver is made negligibly small. To improve ground station coverage or in case of contingency, a nonoptimal set of in-plane delta-V vectors can be determined. Second, an optimum set of out-of-plane components to attach to the in-plane delta-V vectors of selected maneuvers is then determined using a standard minimization routine (a quasi-Newton algorithm available from the International Mathematics and Statistics Library (IMSL)). The optimization is described in detail in Reference 2. The result is achievement of the desired final inclination, ascending node, and in-plane goals. This simple procedure yields a rigorous optimization because apogee is very near geosynchronous radius and each perigee maneuver is purely in-plane. A more sophisticated optimization procedure might have been necessary otherwise.

Additional features of SENARIO2 include the following approximate calculations: short-term oblateness perturbations on semimajor axis and eccentricity up to the first apogee motor firing; maneuver attitude; azimuth, elevation, and range for up to 10 specified ground stations for a user-specified time interval surrounding each maneuver; spacecraft antenna aspect angle at each maneuver; and propellant usage according to the rocket equation. Premaneuver and postmaneuver orbital elements for use in the maneuver targeting and launch window computations are displayed.

4. SOFTWARE FOR MANEUVER TARGETING

The maneuver targeting computation in the General Maneuver (GMAN) Program determines the maneuver attitude, ignition time, and burn duration to achieve the postmaneuver orbits supplied by SENARIO2. GMAN uses these postmaneuver orbital elements to compute a coarse delta-V vector that sets an initial guess for the thrust direction and duration. An ignition time is either supplied by the user or calculated to result in a condition such as "maneuver center lies on the line of relative nodes." A thrust simulation is then performed. The achieved orbit parameters are compared against the desired ones. A modified coarse delta-V vector is then computed, which attempts to compensate for the differences between the achieved and desired orbits. This process is iterated. Further details can be found in Reference 3.

The thrust direction for the GOES-I/M spacecraft is not inertially fixed. It changes about 5 degrees during the first apogee maneuver. The orbit maneuver attitude control model was implemented in GMAN using an instantaneous orbital coordinate system. Because the orbit plane changes during an apogee maneuver, the attitude (defined in Section 2) is maintained by a recalculation of the spacecraft yaw in every time step. See Reference 4 for details of the calculation. In many cases convergence occurs despite the poor initial guess for thrust direction. In some cases convergence does not occur. References 5 and 6 supplement the discussion of convergence that follows.

Convergence can be physically impossible. Apogee maneuvers with little or no change in apogee radius are desired. If a maneuver is centered on apogee, it is physically impossible to prevent the apogee radius from increasing slightly (about 30 km on the first apogee maneuver). Figures 2 and 3 illustrate the apogee raising. This may be explained by comparison with the spin–stabilized attitude that keeps the thrust direction fixed while achieving a similar target orbit. The three-axis stabilized thrust vector follows the velocity vector more closely than the spin-stabilized one (i.e., the angle between the thrust vector and the spacecraft velocity vector is smaller for the three-axis stabilized attitude than for the spin-stabilized attitude). Apogee radius therefore increases more rapidly during the first half of a maneuver. Apogee radius decreases during the last half of a maneuver at about the same rate for both attitudes and the amount of the decrease is small because the spacecraft is near apogee. There is no net change in apogee radius for the spin–stabilized attitude, but a net increase in apogee radius does occur for the three-axis stabilized attitude.

To obtain an attitude that does not change apogee radius, it is necessary to off-center a maneuver about apogee. A tradeoff exists between convergence of the in-plane and out-of-plane parts for any amount of offcentering. A discrepancy between the desired and achieved ascending node of a few degrees can usually be tolerated on an early maneuver to permit in-plane convergence because the excess nodal rotation can be compensated for in a later maneuver with a minimal delta-V penalty.

A scan of initial yaw and pitch angles was made to find the minimum apogee rise for an apogee maneuver centered on the relative node at apogee. Pitch was varied arbitrarily, but yaw was determined to maintain an angle of 39.42 degrees between the thrust vector and the negative orbit normal of the initial orbit for the sake of out-of-plane convergence. The apogee radius increase could not be reduced below 25.2 km, and this occurred when the pitch was approximately 2.4 degrees. See Table 1 and Figure 2. The time dependence of the apogee radius is shown in Figure 3 for three of the cases in Table 1. Notice that the initial rise in apogee radius is large and it is followed by either a continued rise or a gentle lowering.

Failure to converge may also occur because the thrust direction changes. The GMAN fine targeting algorithm assumes that if the thrust vector initially points in the direction of the

Table 1. Change in Apogee Radius Versus Attitude

YAW (deg)	PITCH (deg)	APOGEE RADIUS CHANGE (km)
50.966135	6.0	40.5
50.796640	4.5	30.4
50.767960	4.2	28.9
50.734438	3.8	27.5
50.696518	3.3	26.1
50.652485	2.6	25.2
50.647054	2.5	25.2
50.641837	2.4	25.2
50.623107	2.0	25.4
50.591219	1.0	27.6
50.591219	-1.0	39.2
50.623107	-2.0	48.6
50.676357	-3.0	60.4
50.696518	-3.3	64.0
50.751121	-4.0	74.5
50.847619	-5.0	90.8
50.966135	-6.0	109.4

NOTE: Apogee on relative node, burn centered on apogee

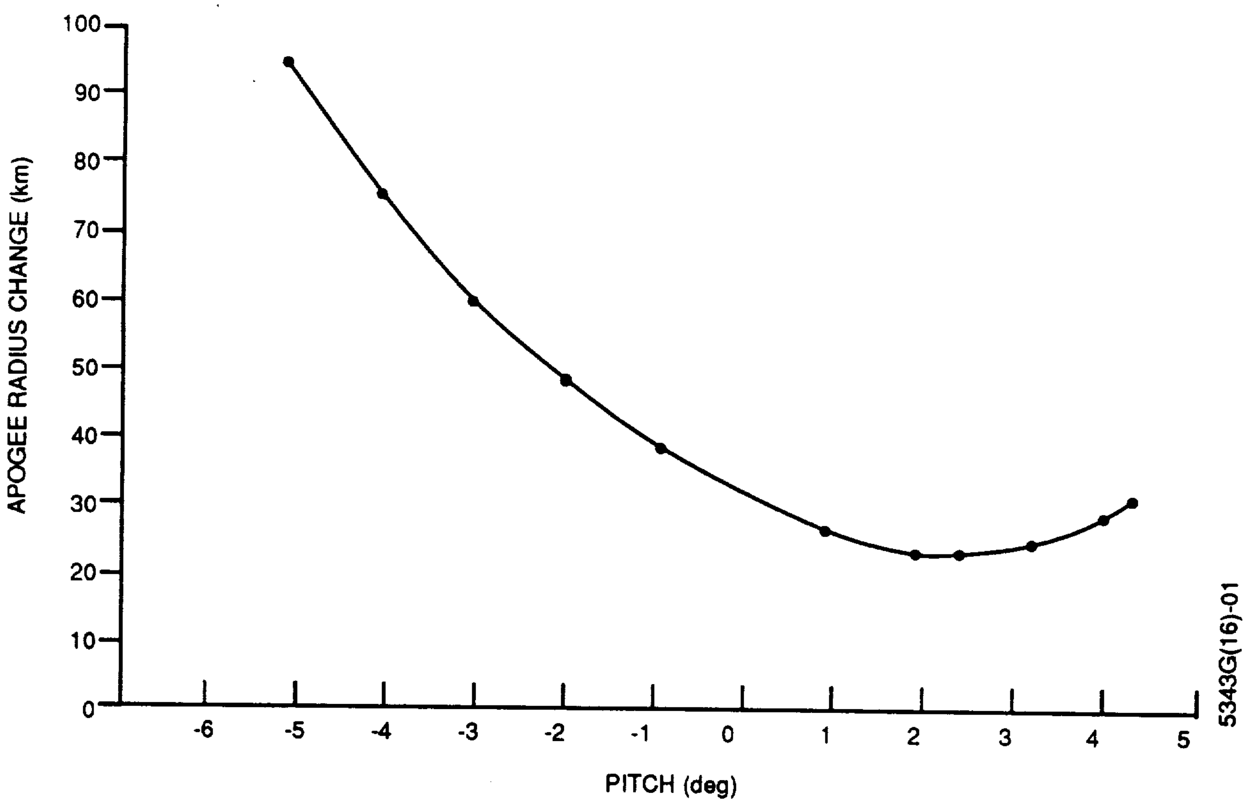


Figure 2. Apogee Radius Change Versus Pitch

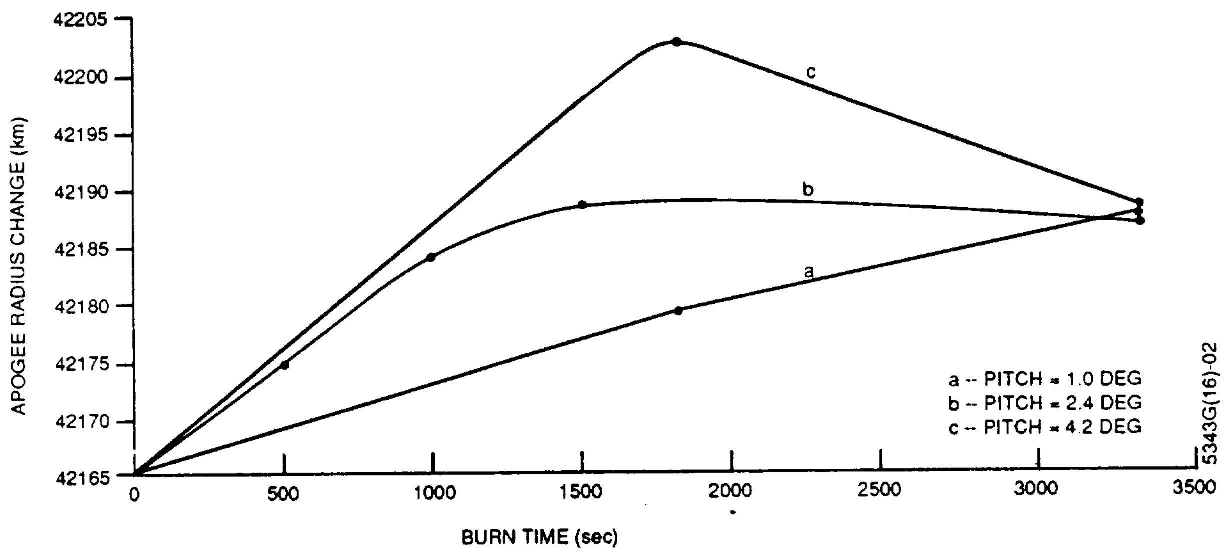


Figure 3. Apogee Radius Versus Burn Time

coarse delta-V vector, the resultant delta-V vector will be close to the coarse delta-V vector. The change in thrust direction obviates this assumption. To correct GMAN, a bias is applied to the initial Euler angles so that the resultant delta-V vector produced by the fine targeting module is close to the coarse delta-V vector (see Reference 4). This correction results in the attainment of convergence when an increase in apogee radius is desired, and produces a minimum apogee rise when no change in apogee radius is desired.

For a given set of initial and end trust conditions, Table 2 shows the uncorrected yaw and pitch and associated in-plane errors (difference between achieved and desired values) on the third and subsequent iterations of GMAN targeting for the first apogee maneuver, and corrected yaw and pitch and associated in-plane errors on the fourth and subsequent iterations. Errors in the out-of-plane part are small and not shown.

The difference in direction between the uncorrected delta-V vector produced by fine targeting and the corrected delta-V vector is 0.78 degree.

Shift in Ignition Time To Improve In-Plane Convergence

When an unwanted apogee rise cannot be avoided because apogee lies near burn center, a shift of ignition time can enable apogee radius to remain unchanged. The amount of the shift is calculated by determining the location on the initial orbit where the position vector is lower than the original radius at burn center by an amount equal to the apogee radius rise. The difference in time corresponding to the difference in position is the amount of the shift. See Reference 4 for further details.

In Table 3, convergence for the first apogee maneuver is achieved for an ignition delay of 8 to 26 minutes or advancement by 11 to 28 minutes. The out-of-plane part fails to converge for larger shifts in ignition time. Notice that pitch exceeds 5 degrees in the cases

Table 2. In-Plane Errors for a GMAN Run

$\Delta apogee_{DESIRED}$ = 40.0 km	$apogee_{INITIAL}$ = 42165.0 km
$\Delta perigee_{DESIRED}$ = 9304.0 km	$perigee_{INITIAL}$ = 6548.0 km
$i_{DESIRED}$ = 9.2104 deg	$i_{INITIAL}$ = 27.0035 deg
$\Delta\Omega_{DESIRED}$ = −0.4206 deg	$\Omega_{INITIAL}$ = 353.77 deg

uncorrected yaw (deg)	uncorrected pitch (deg)	error in apo (km)	error in per (km)	corrected yaw (deg)	corrected pitch (deg)	error in apo (km)	error in per (km)
50.648	0.046	-10	9	50.601	-1.654	-0.7	0.7

Table 3. In-Plane Convergence Improvement Via Offcentering on the First Apogee Maneuver (Coincident Apogee and Relative Node)

INITIAL ORBITAL PARAMETERS AND GOALS

	INITIAL VALUES	DESIRED VALUES	TOLERANCES	UNITS
INCLINATION	27.0035	9.21035	0.05	deg
Ω	353.8	353.4	7.0	deg
APOGEE	42165.0	42165.0	5.0	km
PERIGEE	6548.0	15852.0	30.0	km

IGNITION DATE: 900401 RESULTS

IGNITION TIME (HHMMSS)	INITIAL ATTITUDE		MANEUVER DURATION (sec)	ΔV (M/S)	ERRORS (ACHIEVED-DESIRED VALUES)			
	YAW (deg)	PITCH (deg)			INCLINATION (deg)	Δ RAAN (deg)	Δ APOGEE (km)	Δ PERIGEE (km)
142857	50.567	-3.770	3302	2977	0.088	6.53	0.29	-1.14
144557	50.644	-3.971	3293	2967	-0.018	2.37	3.23	-4.20
*145657	50.586	0.046	3285	2959	-0.0007	-0.34	29.8	26.70
150457	50.759	5.071	3293	2967	-0.012	-2.34	3.94	3.46
152257	50.999	5.195	3314	2989	-0.022	-6.96	0.88	-1.26

*MANEUVER CENTERED ON RELATIVE NODE.

of ignition delay. The maximum pitch available from the onboard control system is near this value.

Shift in Ignition Time To Improve Out-of-Plane Convergence

Errors affecting the out-of-plane convergence can similarly be compensated for by a shift in ignition time. Determine the achieved relative node and its distance from the desired relative node. The difference in time corresponding to the difference in position of the relative nodes is the amount of the shift. See Reference 4 for further details.

The following example for the second apogee maneuver demonstrates improved convergence with a burn center offset of 1 minute. The difference between achieved and desired inclination and Ω are shown as errors on the fourth iteration.

Table 4. Improved Out-of-Plane Convergence With a Time Shift

INITIAL ORBITAL ELEMENTS			GOALS
a = 29037.7 km	Ω = 352.3 deg		Δapogee = 0.0 km
e = 0.4531738	ω = 181.5 deg		Δperigee = 24556.7 km
i = 9.2 deg	M = 169.3 deg		i = 0.1 deg
	$t_{ignition}$	i_{ERROR} (deg)	Ω_{ERROR} (deg)
Centered	900403.214057	0.0300	-3.60
Offcentered	900403.213955	0.0002	-0.01

In addition to improving convergence, an a priori shift in ignition time may be a desirable, conservative measure to safeguard against hardware system problems or to balance the amount of apsidal motion between the prime and backup choices of apogee number for a maneuver.

Displacement of Apogee From the Relative Node

A slight shift in the argument of perigee displaces apogee from the relative node. A burn centered on the relative node could then be expected to have smaller in-plane errors. Table 5 compares an example of the second apogee maneuver with coincident apogee and relative node (item 1) against an identical one except for a displacement of 2 degrees between apogee and relative node (item 2). The change in apogee radius is 34.8 km when the burn is centered on the relative node with coincident apogee. When the apogee is 2 degrees from the relative node, the apogee radius change is –5.0 km. This result is within the convergence tolerance for the run.

Table 5. Comparison of Maneuver Goals Against Achieved Changes

		GOALS				ACHIEVED			
ITEM	TIME HHMMSS	INCLINATION (deg)	NODE CHANGE (deg)	APOGEE CHANGE (km)	PERIGEE CHANGE (km)	INCLINATION (deg)	NODE CHANGE (deg)	APOGEE CHANGE (km)	PERIGEE CHANGE (km)
1	213832	0.10000	-15.0000	0.0	24556.7	0.100	-34.47	34.8	24647.7
2	212740	0.10000	-15.0000	0.0	24556.7	0.099	-34.26	-5.0	24562.1

ITEM 1 -- AMF2 CENTERED ABOUT RELATIVE WITH APOGEE ON RELATIVE NODE.
ITEM 2 -- AMF2 CENTERED ABOUT RELATIVE NODE WITH APOGEE 2 DEGREES OFF THE RELATIVE NODE.

Apogee and relative node can be arranged to be noncoincident on the second apogee maneuver by adjusting ignition time on the first apogee maneuver. The amount of adjustment needed can be interpolated from the data in Table 6, which shows the angular displacement between relative node and apogee at the beginning and end of a maneuver for various ignition times. In this table the burns are not centered on the relative node.

Table 6. Angular Displacement Between Relative Node and Apogee for the First Apogee Maneuver Versus Ignition Time

IGNITION DATE: 900401 IGNITION TIME (HHMMSS)	INITIAL I (deg)	FINAL I (deg)	INITIAL Ω (deg)	FINAL Ω (deg)	INITIAL ARGUMENT OF PERIGEE (deg)	FINAL ARGUMENT OF PERIGEE (deg)	DISPLACEMENT OF RELATIVE NODE FROM APOGEE		CHANGE IN DISPLACEMENT OF RELATIVE NODE FROM APOGEE (deg)
							INITIAL ORBIT (deg)	FINAL ORBIT (deg)	
142857	27.5036006	9.2980758	353.76648	359.87827	180.21130	176.68929	3.00	-12.60	-15.60
143057	27.0036029	9.2840926	353.76648	359.39610	180.21128	176.91120	2.74	-11.70	-14.44
143557	27.0036083	9.2533123	353.76648	358.18352	180.21124	177.44410	2.09	-9.28	-11.37
144557	27.0036161	9.1926351	353.76648	355.71996	180.21117	177.72551	0.80	-5.24	-6.04
*145657	27.0036204	9.2096651	353.76648	353.00797	180.21109	180.40966	0.18	0.74	0.56
150657	27.0036205	9.1986236	353.76648	350.51139	180.21102	183.24895	-1.47	1.69	3.16
151057	27.0036196	9.2014617	353.76648	349.50236	180.21099	183.36782	-1.99	3.10	5.09
151457	27.0036182	9.1967485	353.76648	348.47664	180.21096	183.80722	-2.52	4.21	6.73
152157	27.0036143	9.1892858	353.76648	346.65480	180.21091	184.65892	-3.46	6.12	9.58

TOLERANCE ON APOGEE CHANGE = 5 km
(EXCEPT FOR THE CENTERED MANEUVER – SEE TABLE 3)

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If desired, both a change in the argument of perigee for the sake of a later maneuver and offcentering for the sake of convergence can be performed together on a maneuver.

5. SUMMARY

The SENARIO2 algorithm for the determination of optimum delta-V vectors for station acquisition, including combined in-plane/out-of-plane apogee maneuvers, was described. Associated computations of ground station coverage, coarse maneuver attitude, postmaneuver orbit elements, and approximate propellant usage enable the user to obtain a satisfactory station acquisition sequence for subsequent refinement.

The GOES-I/M maneuver attitude was implemented in GMAN. Convergence was ensured by modifying the targeting algorithm to bias the initial attitude to compensate for the change in thrust direction during a maneuver. An unavoidable rise in apogee radius occurs for maneuvers with apogee near the burn center. The rise can be avoided by shifting the ignition time or by changing the argument of perigee of the initial orbit so that apogee is displaced from the burn center.

Data from the spacecraft manufacturer on the INSAT-1D station acquisition are being studied for use in verifying the new software.

ACKNOWLEDGMENTS

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