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SHUTTLE TETHERED OPERATIONS: THE EFFECT ON ORBITAL TRAJECTORY AND INERTIAL NAVIGATION

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1991 will see one of the most ambitious Shuttle missions ever planned -- the first full-scale test of a large tethered satellite system. The Orbiter will be linked to a 500 kg payload by a 20 km tether, an action with a profound effect on the trajectory of the Orbiter. For the first time in the history of the Shuttle program, the vehicle will conduct prolonged operations with the center of mass of the orbiting system a significant distance from the center of mass of the Space Shuttle Orbiter, a violation of a fundamental assumption made in both the Orbiter ground-based and onboard navigation software.

Inertial navigation of tethered operations with the Shuttle is further complicated by the presence of non-conservative forces in the system: RCS translational effects, atmospheric drag, and electro-magnetic dynamics. These can couple with the conservative tether dynamics effects, and degrade the navigation software performance.

This paper examines the primary effects of tether dynamics on the Orbiter's trajectory, coupling by conservative forces during tethered operations, and the impact of both on the ability to meet inertial navigation constraints. The impact of electrodynamics, different RCS control modes, commanded attitudes, and attitude deadbands are presented. Operational guidelines which optimize successful mission navigation, and necessary navigation constraints are discussed.

INTRODUCTION:

In January, 1991, the Shuttle program will attempt one of its most ambitious missions to date -- the first full scale test of a large tethered satellite system. The Orbiter will be linked to a 500 kg payload by a 20 km tether, and tethered operations will occur over a 32-hour period. The Tethered Satellite System Mission 1 (TSS-1) has two major objectives: to attain a better understanding of the mechanics of tethered systems, and to investigate the feasibility of using conductive tethers to generate electricity. This mission will have the Shuttle Orbiter deploy the tethered satellite in an upward direction, with the Orbiter initially in a 28.5-degree inclination, 296 km (160 NMi), orbit.

TSS-1 poses unique challenges for Space Shuttle navigation. For the first time in the history of the Shuttle program, the vehicle will conduct prolonged operations with the center of mass of the orbiting system a significant distance from the center of mass of the Space Shuttle Orbiter, a violation of a fundamental assumption made in both the Orbiter ground-based and onboard navigation software. Inertial navigation of tethered operations with the Shuttle is further complicated by the presence of non-conservative forces in the system: Reaction Control System (RCS) translational effects, atmospheric drag, and electromagnetic dynamics. These couple with the conservative tether dynamics effects, degrading the navigation software performance.

The most significant sources of trajectory perturbations during TSS-1 tethered operations are due to tether-induced RCS attitude-control thruster firing. Direct tether effects, atmospheric drag on the tether and electrodynamic drag during periods when current is flowing through the tether, have effects an order of magnitude smaller than these tether-induced thruster firings.

The results presented in this paper were obtained through analysis conducted on and with three simulations: The Shuttle Tethered Object Control Simulation (STOCS) -- a high fidelity engineering simulation of the TSS-1 mission (Reference 1); the Shuttle Environment Navigation Simulation for Orbit and Rendezvous (SENSOR) program, an onboard navigation system simulation (Reference 2); and the Standalone Orbital Navigation (SONAV) program, a Space Shuttle ground navigation system emulator (Reference 3).

SHUTTLE ONORBIT INERTIAL NAVIGATION:

The Space Shuttle uses two navigation systems: the onboard navigation system which provides the navigation state used by the Shuttle flight system and the Ground (more accurately Ground-based) navigation system which provides independent validation of the onboard navigation. The onboard navigation incorporates sensed and modelled accelerations to propagate an Orbiter state vector. The Ground navigation system uses radar observations of the Orbiter to generate a new estimate of the state vector. When the onboard navigation state vector differs from the Ground-generated Orbiter ephemeris, the current ground ephemeris state vector is uplinked to onboard navigation system and replaces the onboard vector.

The onboard navigation propagates an initial state vector incorporating sensed accelerations and acceleration models into the equations of motion. The Orbiter's Inertial Measurement Units (IMUs) sense accelerations. When the acceleration are above a threshhold (the standard onorbit acceleration threshold during non-powered flight is 1000 micro-gravities), then these accelerations are directly incorporated into the propagation. If the sensed acceleration is below the threshhold, the sensed accelerations are replaced by an average model for RCS accelerations. The onboard navigation system also models geopotential effects and the effects of atmospheric drag on the Orbiter. A full description of the onboard navigation system can be found in Reference 4.

The onboard navigation accuracy degrades due to three reasons: initial state vector uncertainty, mismodelled or unsensed accelerations, and limitations of the environmental models. Any difference between the estimated state and the true state of the Orbiter increases linearly as it is propagated over time. The initial state vector is the best estimate of the Orbiter's position at that time. Even given optimal conditions, at least 50 meters of position uncertainty will exist in this estimate. Unsensed acceleration changes the true position of the Orbiter without being incorporated into the navigated state. A low-level acceleration present continuously over a period will produce a quadratic growth in in the navigation uncertainty. Finally, the environmental models used in the onboard navigation software are simplified models to save computation time and ease storage requirements. The onboard navigation uses a GEM10 4x4 geopotential model and a Babb-Muller drag model. These introduce an an error growth of 360 meters/rev into the navigation state.

These factors require the onboard navigation system to be periodically updated. Navigation solutions obtained by the Ground navigation system are used for this. The Ground navigation system takes an initial estimate of the Orbiter's state vector, propagate it using a more sophisticated set of environment models (GEM10 7x7 geopotential model and Jacchia-Lineberry atmosphere model). It performs a differential correction of the propagated trajectory through a weighted least-squares fit of tracking observations. Observation are taken from ground-based S-band and C-band tracking stations, and through Tracking and Data Relay System (TDRS) system S-band relay tracking. A new state vector is generated, until a convergent solution that minimizes tracking residuals -- the difference between the propagated state and the observed position at that time -- over the differential correction arc. Ground navigation can also model constant, Orbiter body-axis centered accelerations. A description of the Ground-based navigation systems can be found in Reference 5.

MECHANICS OF TETHERS:

Tethered operations are possible due to gradient effects of gravitional acceleration. The force of gravity attraction is proportional to the inverse of the distance between two bodies. Thus two bodies orbiting the Earth at different orbital radii have different gravitational acceleration -- the lower body has a greater acceleration acting on it than the higher body. If the difference in radius is small, then the difference is acceleration is also small. Two vehicles in low Earth orbit separated by 20 km difference in orbital radius experience a gravitational acceleration difference of approximately 0.05 m/sec2.

Under normal circumstances the greater orbital velocity of the lower object would cause it to separate from the upper object. If the two objects are connected they cannot separate. Instead the connection, whether a rigid truss or a flexible tether, exerts a tension force on the endpoints, equal and opposite to the difference in gravitational acceleration vectors. If the tethered endpoints are aligned radially to the Earth's center of mass, the tether tension acceleration acts purely radially. Whenever the tether is not aligned radially, the tension has a downtrack component, reducing the velocity of the leading object, and increasing the velocity of the lagging object. If the tether length is constant, equilibrium is achieved when the two objects are aligned radially with the Earth's center of mass. (See Figure 1.) A full derivation of tethered equations of motion can be found in Reference 6.

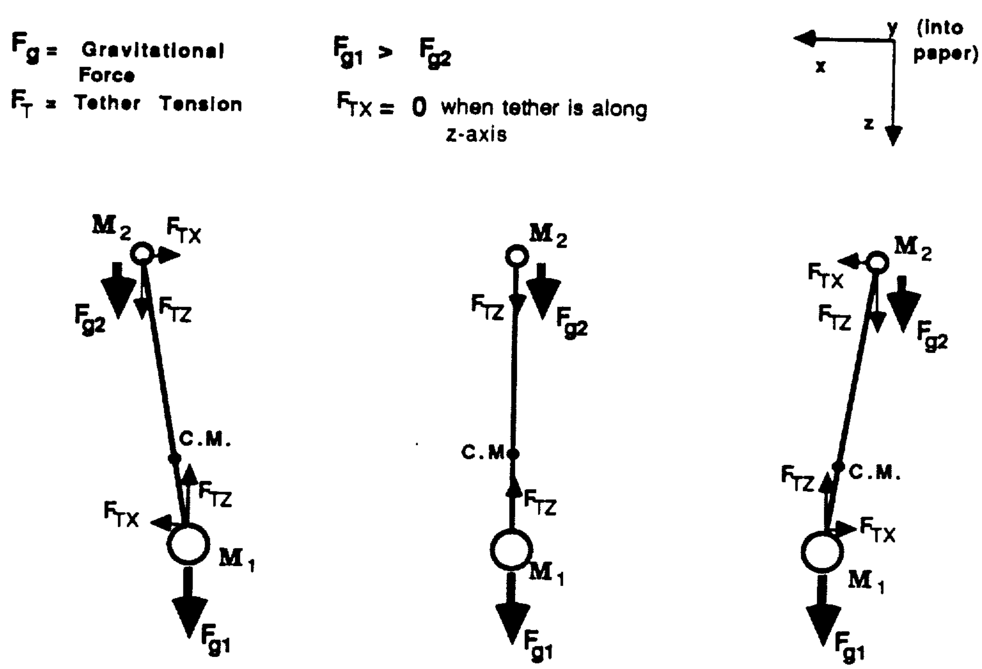


FIGURE 1: TETHER GRAVITY-GRADIANT STABLIZATION

Some interesting consequences result from this behavior. For tethers lengths of the order of interest of the TSS-1 mission (tether length is less than 1% of the orbital radius) the tethered system effectively orbits as if it were a point mass at the center of mass of the system. Changing the length of the tether changes the distance of the endpoints of the system from the system center of mass, without changing the orbital radius of the system C.M.

Tethers redistribute angular momentum, but do not create it. Changing the length of the tether, tether libration (rigid pendulous motion of the system), or spinning the endpoints are all means of redistributing angular momentum. Unless the tether is cut or broken, the energy transfer between endpoints of a tethered system is conservative.

Changing the length of the tether does change the orientation of the endpoints to each other. As the tether increases in length, the tension is reduced below the difference in gravitational force, and the lower endpoint begins to lead the upper endpoint. As the tether decreases in length, tether tension increase, and the upper endpoint begins to lead the lower endpoint. This behavior is illustrated in Figure 2, which shows relative motion between the Orbiter and the TSS-1 Object during tethered operations.

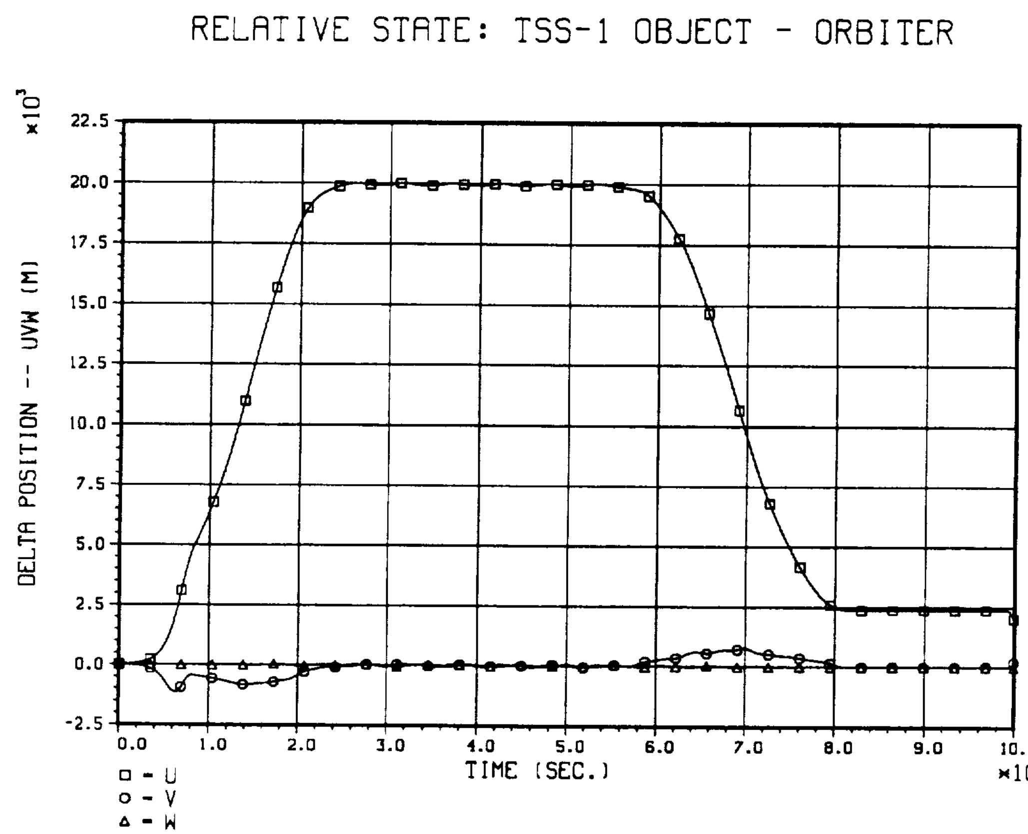


FIGURE 2: RELATIVE MOTION OF TETHERED ENDPOINTS (UVW FRAME)

TETHER LENGTH VS. TIME

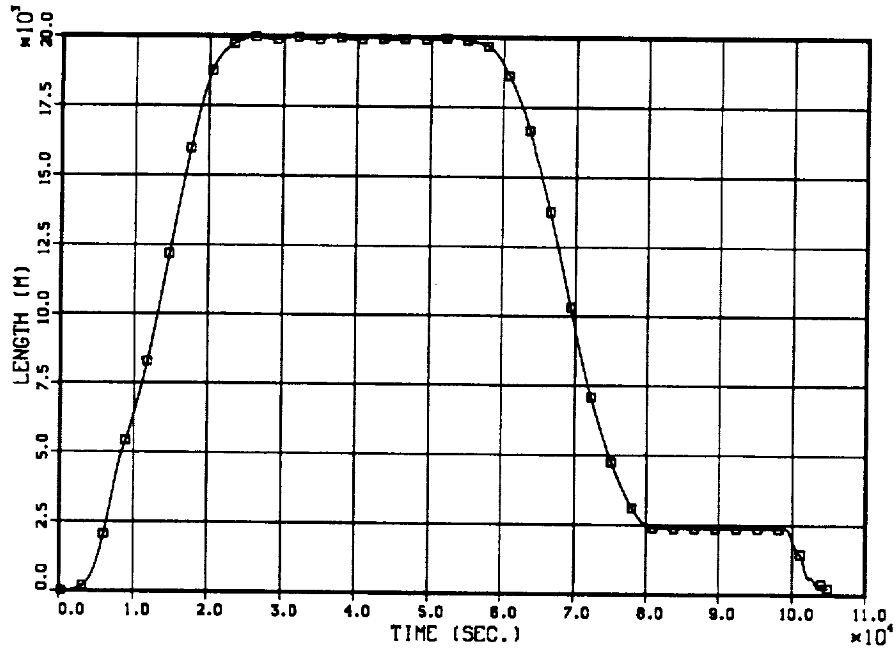


FIGURE 3: TSS-1 TETHER LENGTH PROFILE

Figure 3 illustrates the tether profile baselined for the TSS-1 mission. There are five phases in this profile. The tether deploy phase occurs over the first 24 000 seconds of tethered operations. The 20-km on-station phase runs from 24 000 seconds to 56 000 seconds. Retrieval to 2.4-km then begins and continues until 80 000 seconds. The 2.4 km on-station phase comprises the next 20 000 seconds, followed by retrieval to boom tip.

TETHER INTERACTION WITH THE ORBITER:

While tethered mechanics are conservative, the effect that they will have on the Orbiter's trajectory during the TSS-1 mission will not be. Two environmental sources -- atmospheric drag and electrodynamic drag introduce non-conservative energy perturbations to the system. Both these enviromental perturbations and tethered mechanics, induce firing by the Orbiter's Reaction Control System (RCS) to maintain the Orbiter's commanded attitude. This thrusting adds or subtracts energy from the system as a function of the Orbiter's orientation. The attitudes and attitude control modes baselined for the TSS-1 mission will result in a net loss of energy.

Atmospsheric drag on the tether and TSS-1 Object are minor, though constant perturbations. Drag is primarily a downtrack acceleration reducing net orbital energy. Less than 1% of the drag acceleration acts perpendicular to the orbital plane.

Electrodynamic drag results from using the tether to generate electricity. Electricity is generated by using the tether as a portion of a current loop, which is passing through the Earth's magnetic field. This generates a force normal to the Earth's magnetic field lines, proportional to the electrical power generated by the tether. (Note that "negative" electrical power -- pumping energy into the tether -- give a net gain in orbital energy.) Since the Earth's magnetic field is a tilted dipole, the magnetic field lines are rarely perpendicular to the Orbiter's velocity vector. A significant percentage of the electrodynamic perturbation will act out-of-plane. Electrodynamic force is functionally identical to atmospheric drag -- the in-plane component of force reduces the net orbital energy.

Tether tension does not directly affect the inertial trajectory of the system, but does have a significant induced effect. The tether applies a tension force on the endpoints. Unless the Orbiter's center of mass and the tether attach point are aligned with the tension vector, the tension will apply a torque, rotating the Orbiter until the attach point, Orbiter C.M. and tension vector are aligned. The planned attach point for the tether boom is ahead of the Orbiter C.M. The Orbiter will stabilize into a nose-forward, positive-pitch attitude (see Figure 4). The angle between the local vertical axis and Orbiter X-body axis that results is called the hang angle. Given the currently manifested tether attach point, and a stable tether of 20 km length, the Orbiter will settle into a +25 degree pitch attitude. Different attach points and tether lengths change this angle.

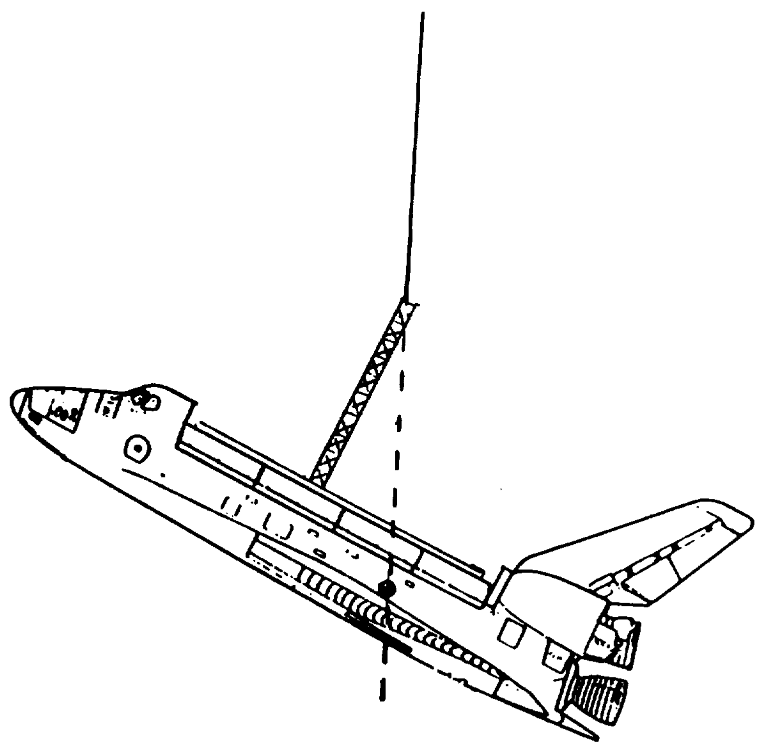


FIGURE 4: HANG-ANGLE INDUCED ORBITER ATTITUDE STABILIZATION

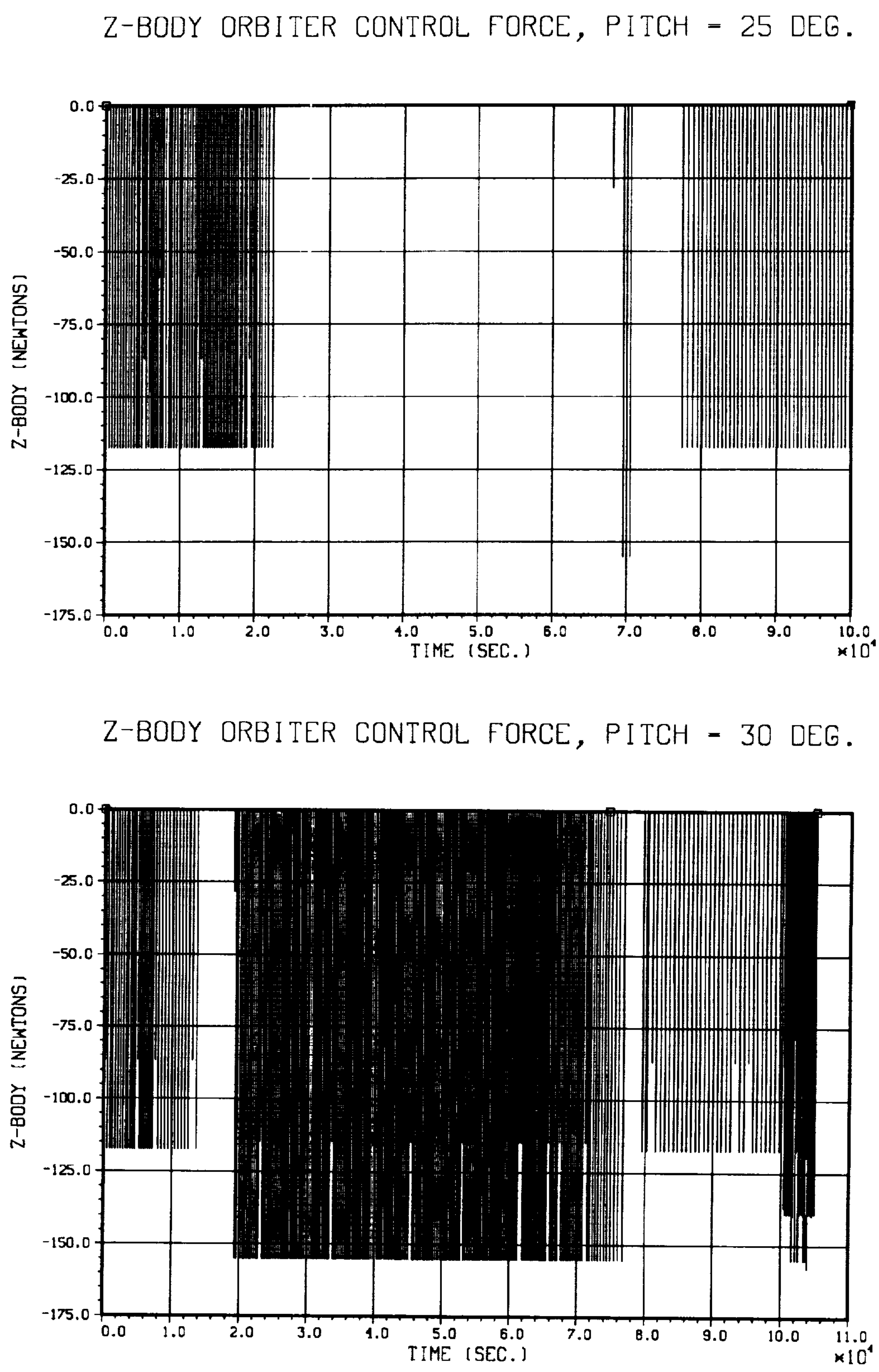


FIGURE 5: HANG-ANGLE INDUCED Z-BODY THRUSTER FIRING

Tether-induced hang-angle perturbations interacts with the Orbiter's RCS two ways. If the commanded pitch differs from the hang angle by less than the attitude angle deadband, then the tether will act to stablize the Orbiter into its commanded attitude, much as a tail stabilizes a kite. If the difference between the commanded attitude and the hang angle exceeds the attitude deadband, high RCS thrusting results. The tether pulls the Orbiter towards the hang angle until the attitude deadband is reached. Then the RCS jets fire to restore the Orbiter to its commanded attitude.

Figure 5 illustrates these different behaviors. The upper graph presents the Z-body axis thruster firings in a simulation in which the Orbiter was commanded to a hold a pitch of 25 degrees. The bottom graph presents Z-body axis firings in a simulation where the Orbiter had a commanded pitch of 30 degrees. In both cases, vernier control with a 2 degree attitude deadband was used, allowing the Orbiter to drift up to two degrees from the commanded attitude. During the period that the tether was in the 20 km on-station phase of the mission, the hang angle was 25-degrees. No RCS thrusting occurred over that time in the 25 degree commanded pitch case. The 30 degree pitch case exhibited high RCS activity over the same period.

Tether libration also induces attitude deadband firing. In-plane libration causes pitch deadbanding. Out-of-plane libration induces yaw and roll deadbanding. Figures 6 and 7 illustrate RCS thrusting present in a in-plane and out-of-plane libration simulation respectively. Both cases used a 5 degree tether libration. Libration-induced deadbanding can be caused by other tether perturbations. Electrodynamic drag produces both out-of-plane and in-plane force on the tether. The out-of-plane force induces out-of-plane libration, in turn, inducing yaw and roll deadbanding.

TETHER EFFECTS ON THE TRAJECTORY:

Tether interactions with the Orbiter perturbs the orbital trajectory of the system, directly or indirectly. Downtrack effects of continuous drag forces behave in a straightforward manner -- a continuous retrograde acceleration (shown in Table 1).

Tether-induced RCS firings produce more subtle effects. They could cause the dramatic effects shown in Table 1, if fired continuously while aligned in the downtrack axis. In reality, RCS jets are impulsive rather than continuous, and rarely aligned with the downtrack axis. Combinations of thrusters can either cancel or amplify translational effects. Despite the larger magnitude of the individual PRCS jets, these have a smaller translation effect when used for attitude control than the Vernier jets. The combinations of PRCS jets used for attitude control have much higher rotational coupling, and lower net translation.

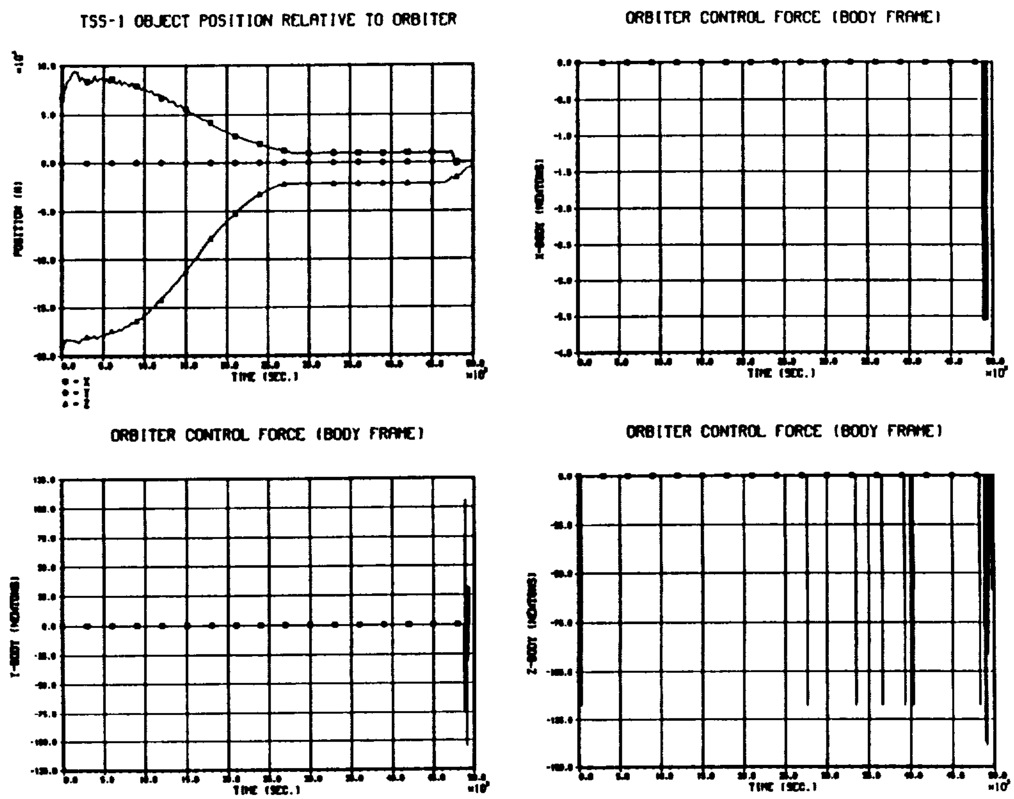


FIGURE 6: ORBITER THRUSTER FIRING -- IN-PLANE LIBRATION CASE

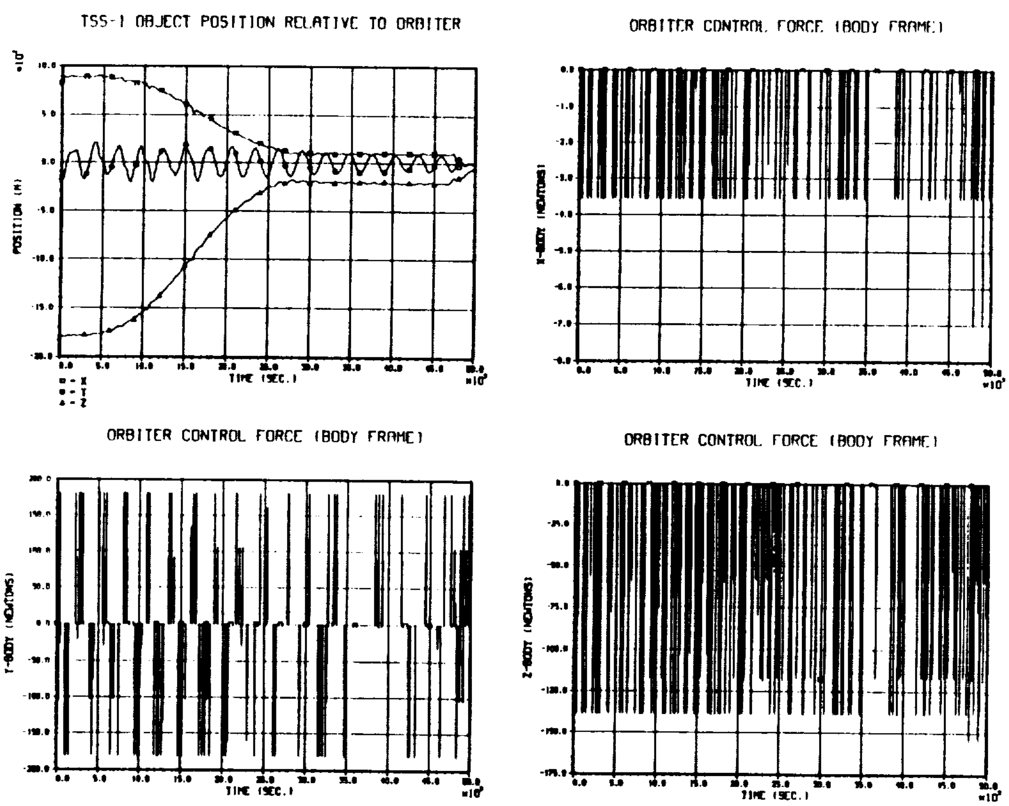


FIGURE 7: ORBITER THRUSTER FIRING -- OUT-OF-PLANE LIBRATION CASE

TABLE 1: PERTURBATION SOURCES AND TRAJECTORY EFFECT

PERTURBATION SOURCE	ACCELERATION (micro-Gravities)	NET CHANGE IN TRAJECTORY AFTER 5 REVS * (meters)
CONTINUOUS EFFECTS		
Atmospheric Drag on Tether (296 KM)	0.04	320
Electrodynamic Drag (1-Amp Current)	0.63	4 300
IMPULSIVE EFFECTS		
Vernier Attitude-Hold Thrusting (per Jet)	3.5	24 000
Primary RCS Attitude-Hold Thrusting (per Jet)	120	820 000

* Assumes perturbation is active over entire 5 revs -- for RCS jets this implies a thruster failed on. Shuttle fuel limitations would prevent this from occurring. This table is intended to show relative effects of these sources

The Orbiter normally uses Vernier attitude control during on-orbit mission phases. This is baselined as the nominal control mode for the TSS-1 mission. The Orbiter has six Vernier thrusters. The vernier attitude-control firing patterns are shown in Figure 8. All six verniers are aligned in the Orbiter body frame Y-Z plane. Four of the jets thrust in the +Z-body direction, translating the Orbiter in the -Z direction. Any pitch or roll rotation yields a net -Z-axis translation of the Orbiter. When the Orbiter is in a +25 to +30 degree pitch relative to to local horizon, significant downtrack perturbations occur. Table 2 gives the net downtrack acceleration that results from deadbanding when the Orbiter is in the nose-forward +25 degree pitch baselined for the 20-km on-station phase of the TSS-1 mission.

The total trajectory displacement induced by RCS attitude control thrusting is the product of the downtrack acceleration and the number of thruster firings. The best illustration of this behavior can be shown by comparing simulated trajectories of nominal deploy and the 5-degree high-pitch deploy (the cases which generated the

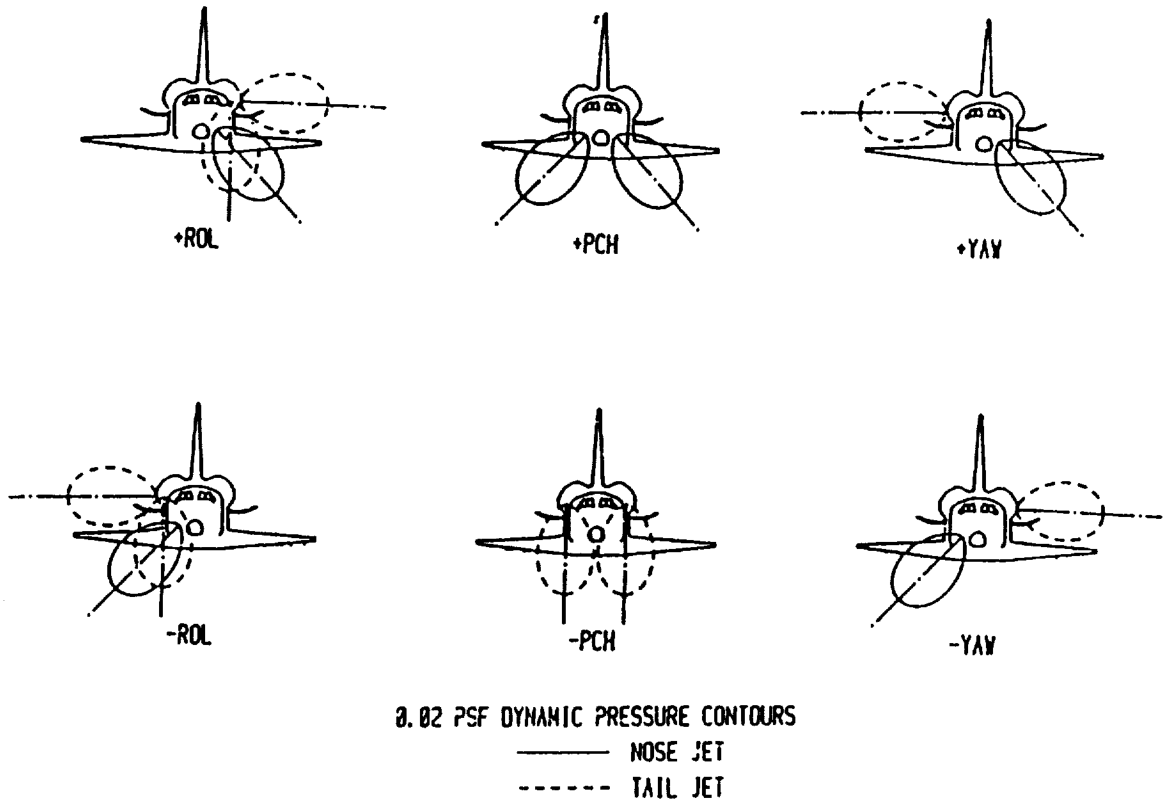
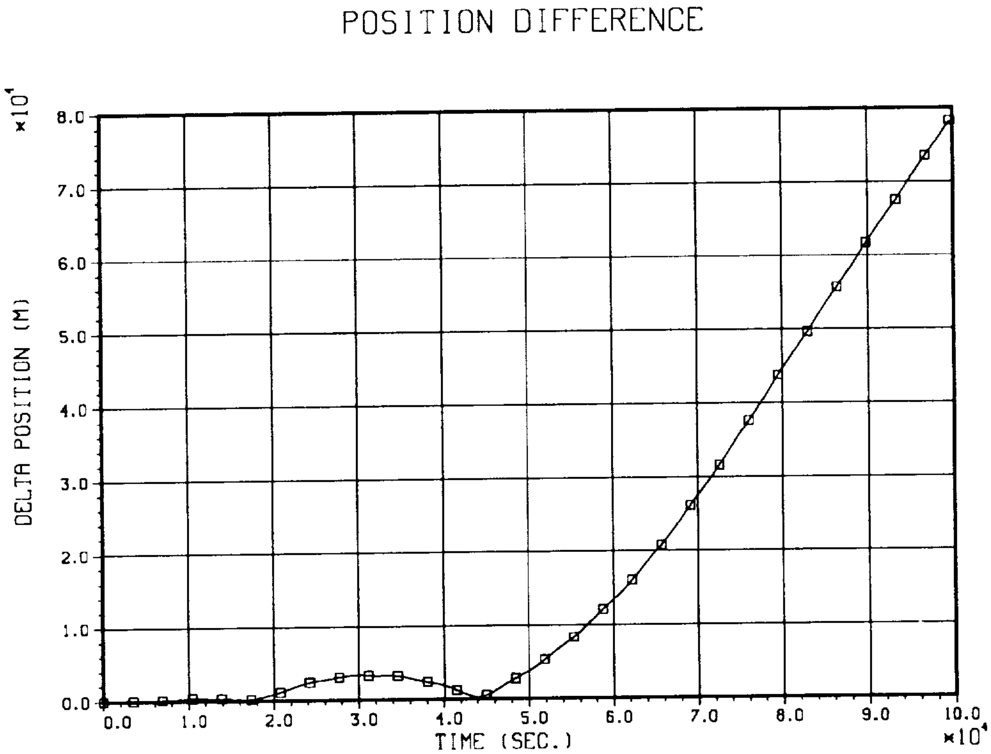


FIGURE 8: VERNIER ATTITUDE CONTROL -- JET-FIRING PATTERNS

jet-firing histories of Figure 5). Figure 9 presents both the difference in position and in the semi-major-axis between these cases. (Delta-SMA indicates total energy changes between two orbits.) The High-Pitch case lost energy relative to the Standard Deploy. Pitch-axis deadbanding was the primary cause of a trajectory position delta of nearly 80 000 meters, and and an SMA change of -900 meters after 100 000 seconds of propagation.

TABLE 2: VERNIER-INDUCED DOWNTRACK ACCELERATION AT ORBITER ATTITUDE: PITCH = 25 deg; ROLL = 0 deg; YAW = 0 deg

Maneuver	Downtrack Accel (micro-G)
+PITCH	-0.38
-PITCH	-0.53
±ROLL	-0.45
±YAW	-0.19



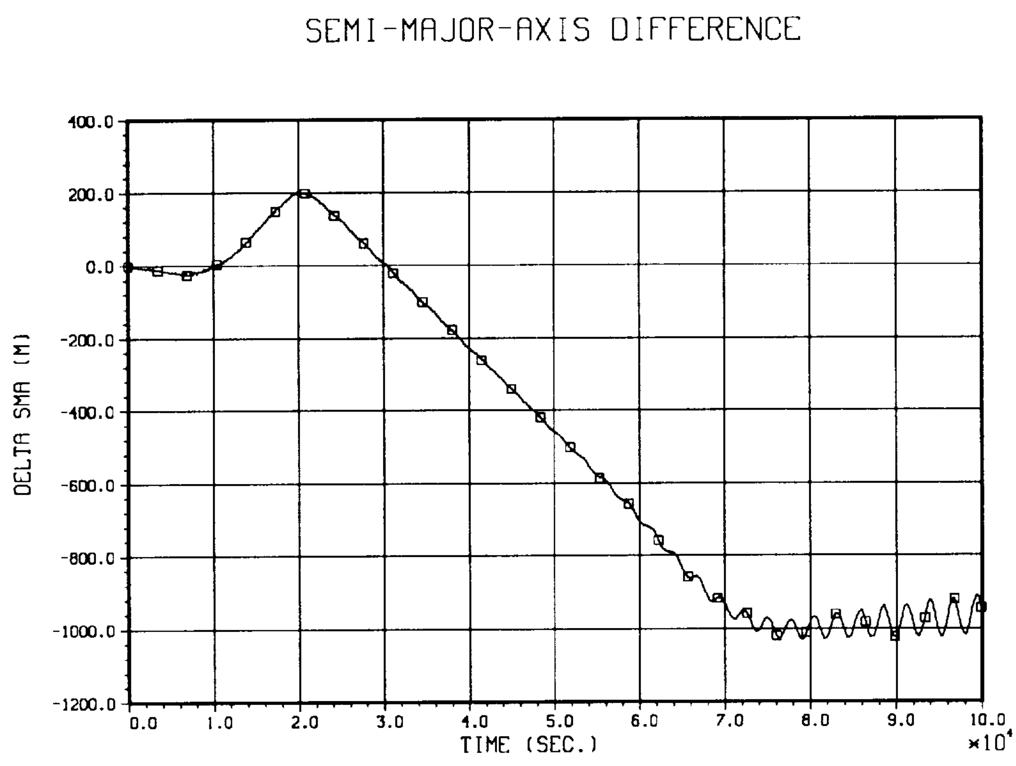


FIGURE 9: TRAJECTORY DELTAS -- STANDARD PROFILE VS. HIGH-PITCH CASE

One item of interest is the net gain in energy that the High-Pitch case demonstrates over the first 20 000 seconds of the profile. This is the period when the tether is being deployed, and the hang angle is +30 degrees pitch. Thus, the +30 degree commanded pitch of the High-Pitch case was closer to the tether-induced hang angle than the +25 commanded pitch of the Standard case over that phase of the mission. During the 20-km portion on-station of the mission through retrieval to the 2.4-km on-station period, the Standard case pitch was closer to the tether hang angle.

The net trajectory perturbation induced by tethered operations is a product of all tether-induced perturbation sources. Separating these effects is difficult due to coupling between them (e.g. electrodymanic drag exciting out-of-plane libration). Gross estimates of these effects can be developed by comparing trajectories with different perturbations present against a constant yardstick. Table 3 summarizes differences observed in six different simulated tether trajectories.

The Standard Profile used baselined TSS-1 mission tether profile with the following parameters: Commanded attitude: Nose-forward +25 degree pitch; Attitude deadbands of ± 2 degrees, Vernier attitude control, no tether electrodynamics, no tether libration. Each of the other five cases varied one of these parameters, but was otherwise identical.

TABLE 3: TRAJECTORY DIFFERENCES DUE TO TETHER-INDUCED PERTURBATIONS

COMPARED TRAJECTORIES	POSITION DELTA (Meters)	SMA DELTA (Meters)	SIM. TIME DELTA (Seconds)	PRIMARY PERTURB. SOURCES
Standard Profile vs. High-Pitch	79 200	-314	100 000	Pitch Deadbanding
Standard (Vernier) vs. PRCS Cntl	-106 700	1070	100 000	Vernier vs. PRCS Translation
Standard Profile vs. Science (Tether Electro-dynamics On)	56 400	-1280	100 000	Attitude Dead-banding, Out-of-Plane Libration, Electrodynamics
Standard Profile vs. 5 deg In-Plane Libration	42 700	-60	55 000	Pitch Deadbanding
Standard Profile vs. 5 deg Out-of-Plane Libration	219 400	-4110	55 000	Yaw and Roll Axis Deadbanding

The High-Pitch case used a commanded pitch attitude of +30 degrees. The PRCS case used the Orbiter PRCS jets for attitude control. The Science case modelled the effects of a 1-ampere current flowing through the tether during the 20-km and 2.4-km on-station phases. The In-Plane and Out-of-Plane Libration cases began with a 5-degree libration in each of the respective axes. The High-Pitch, PRCS, and Science cases were each run over the entire tethered operation phase. The two libration cases began during the 20-km on-station phase, using the current Standard case parameters as their initial conditions, with a displaced TSS Object (to induce the libration). Comparisons in Table 3 are made against the Standard case. Negative SMA indicates that the compared case has less orbital energy at time of comparison than the Standard case.

TETHER EFFECTS ON INERTIAL NAVIGATION:

A tether separates the system center of mass from the tracked radar target (the Shuttle Orbiter) and induces acceleration which is not modelled by either the onboard or ground navigation systems and which is below the onboard navigation sensed-acceleration thresholds. Both acceleration mismodelling and C.M.-Tracking Target offset affect Shuttle navigation.

As the tether length increases, the Orbiter moves away from the system center of mass. The Ground-based radar observations track the Orbiter rather than the system C.M. When the tether is deployed to its full length (20 km), the radar observations are offset from the true center of mass of the system by 100 meters. A navigation solution minimizing the radar observation residuals of a single tracking pass produces a state vector which places the Orbiter in an orbit 100 meters below the actual semi-major-axis of the system. Propagating this vector yields a position difference from the actual trajectory of the Orbiter that grows by 4500 meters per revolution.

If several sets of radar observations, taken from different tracking stations and distributed over at least one orbital period are used a different solution occurs. Minimizing all tracking residuals over the period in question yields a state vector near the system's true C.M. The tracking residuals behave as if they were all biased by the offset difference. Reducing the residuals below that threshold at one station produces much larger residuals at the other stations.

Similar behavior is observed when single-station solutions are weighted with a covarience matrix. The covarience constrains the amount that the orginal input state vector can alter by changing the weighting placed on the observations in the least-squares regression. The result moves the solution's new state vector to the system C.M. rather than at the Orbiter. The C.M.-Tracking Target offset does not degrade navigation performance unless unconstrained single-station solutions are attempted.

The center of mass offset does not affect the onboard navigation system because this system does not use external inertial predictions of the Orbiter's state. It propagates an initial state vector, assumed to be at the center of mass of the orbital system. This assumption is correct prior to the beginning of tethered operations. The Orbiter is at the system C.M. As tethered operations begin, and the Orbiter drops below the system C.M. the onboard navigation state vector remains at the system C.M. until it deviates due to environmental mismodelling and unsensed acceleration.

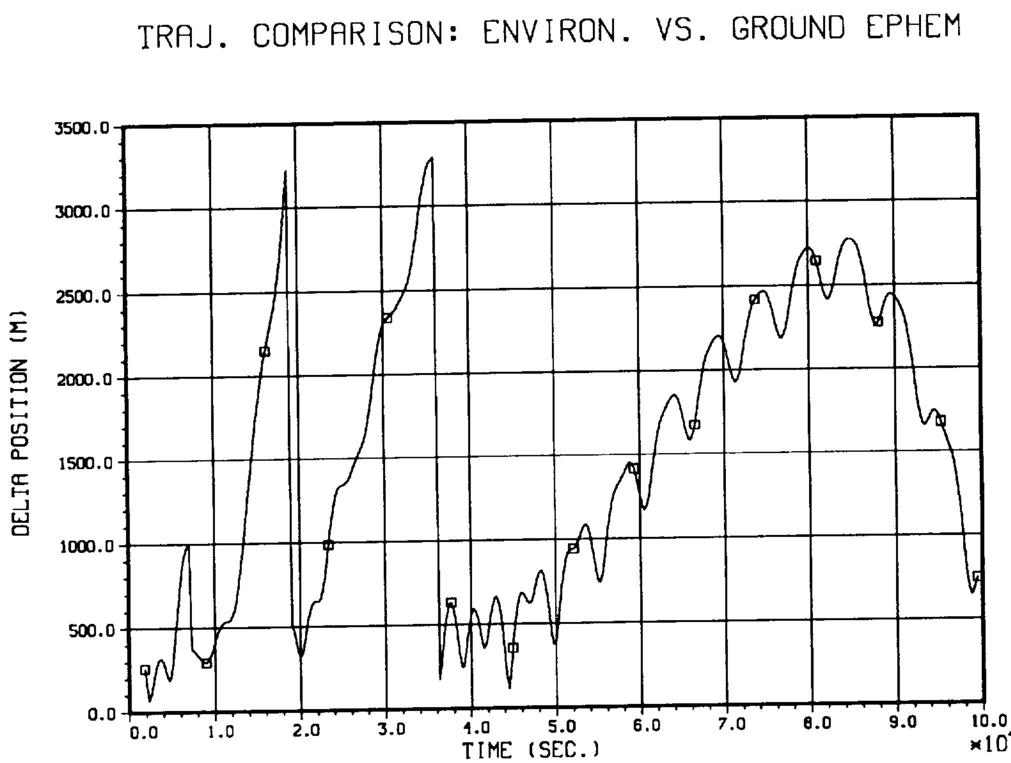
Tether-induced acceleration has more significant effects on Shuttle navigation. These accelerations are unmodelled by Ground Navigation and unsensed by the onboard navigation. With both systems, an accurate state vector propagates poorly over periods when the tether is inducing significant non-conservative acceleration. This has a greater impact on onboard navigation than on Ground navigation because the onboard navigation has no means of correcting for unincorporated accelerations, except by replacing the onboard navigation state with a new solution. The radar observations used in Ground navigation reset the Orbiter's state vector to the system C.M. with each set of radar data processed.

Figures 10 and 11 illustrate this behavior in the Standard and High-Pitch cases respectively. These illustrate navigation performance in quiet and active tether cases. The top graph shows the difference in position between the Ground ephemeris -- a propagation of a "best" constrained local solution -- with the STOCS-generated simulated trajectory. The lower graph displays the position difference between the Ground ephemeris and the onboard navigation state.

The Standard case had minimal tether-induced trajectory perturbation over the 20-km on-station portion of the mission. No RCS jet firings occurred, and the only mismodelled environmental perturbation present was atmospheric drag on the tether and TSS Object. The Ground ephemeris had to be updated three times, twice during the deploy phase and once during the on-station phase of the mission. Following the on-station update of the ground ephemeris, 36 000 seconds after the beginning of tethered operations, propagation of the ephemeris vector over the next 64 000 seconds yielded a maximum difference with the environment trajectory of less than 3700 meters.

The Onboard state deviated from the ground ephemeris by small amounts -- 900 meters maximum with differences smaller than 200 meters over the 20-km on-station phase. This is expected, as these differences represent the difference in propagation models in the two systems. Neither system propagates the unmodelled accelerations characteristic of tether-induced perturbations. The ground navigation system detects these as tracking passes subsequent to the pass from which the ground ephemeris was generated are processed, and correct the Orbiter's position. When these differences between the ground ephemeris and the local solutions exceed console guidelines (20 * delta-SMA + delta downtrack position $\geq$ 6100 meters), the ground ephemeris is replaced with a current good ground solution.

The High-Pitch case, with numerous RCS attitude firing throughout tethered operations, showed markedly different performance. The



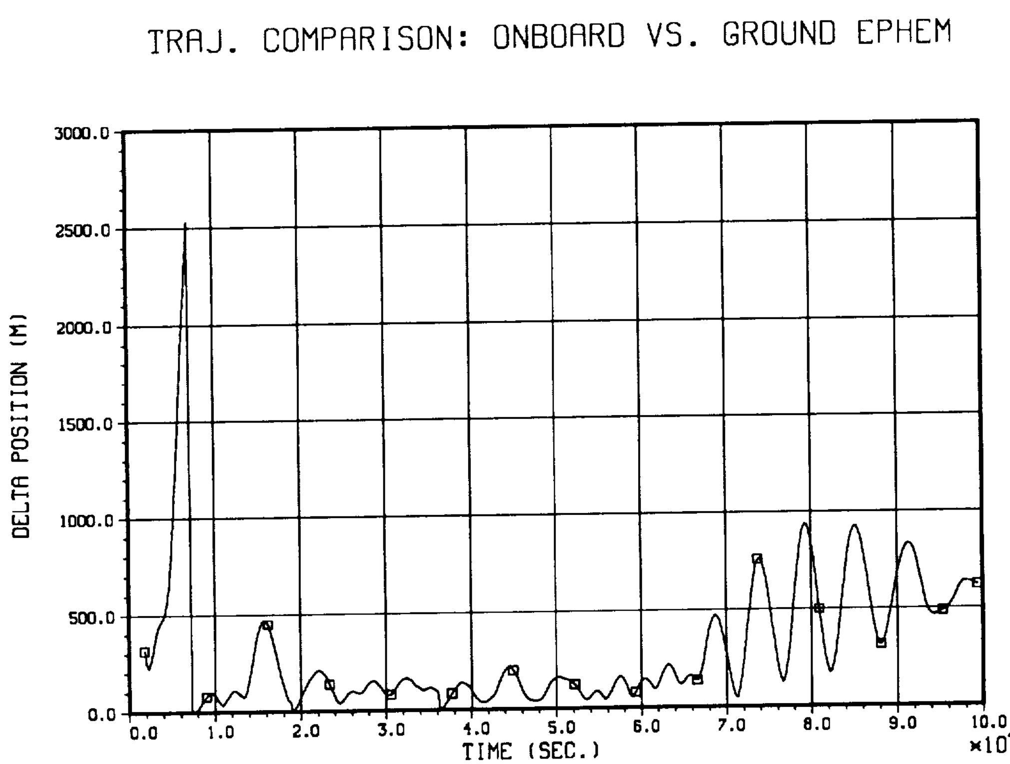


FIGURE 10: NAVIGATION PERFORMANCE -- STANDARD PROFILE

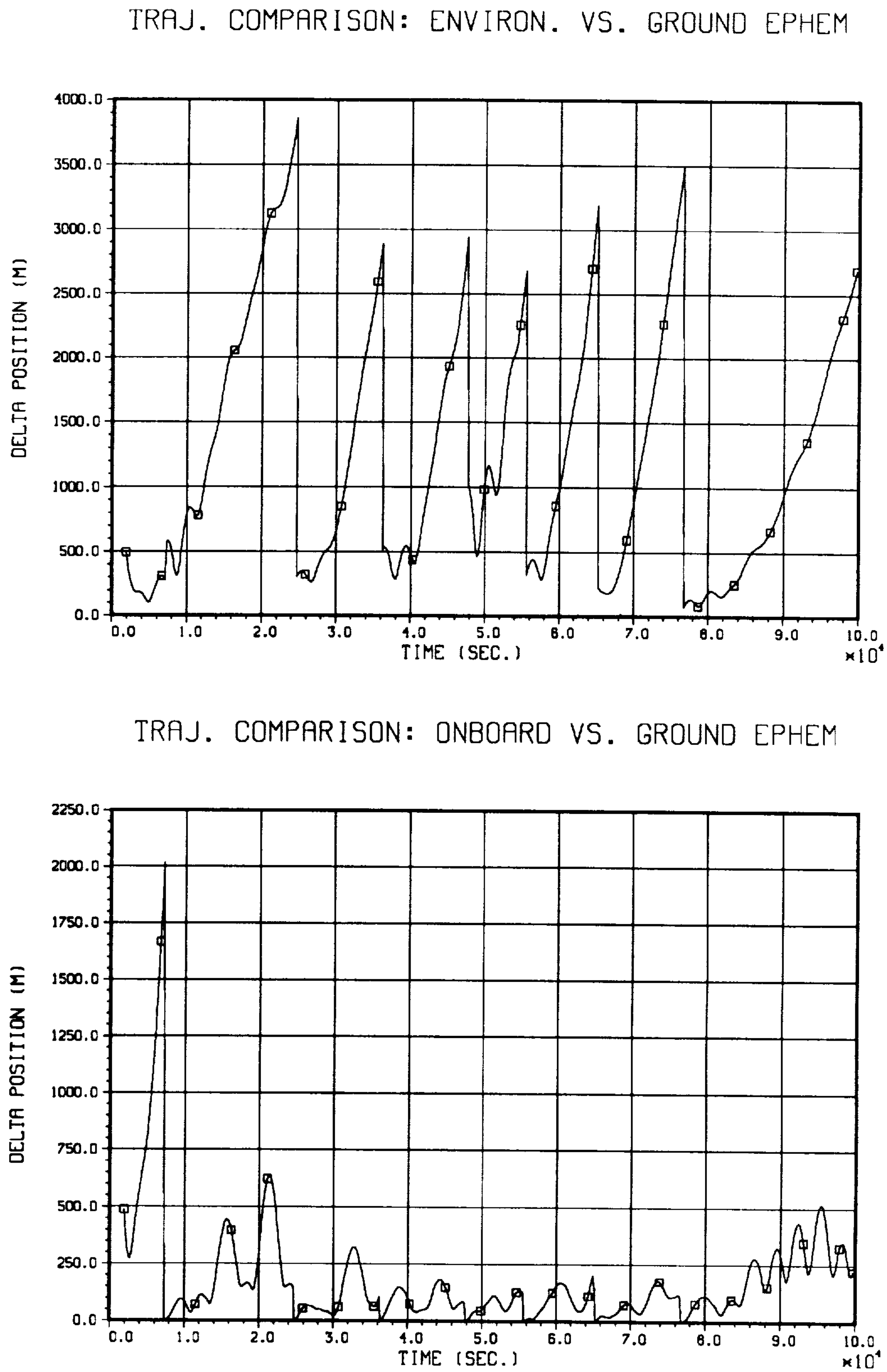


FIGURE 11: NAVIGATION PERFORMANCE -- HIGH-PITCH CASE

Ground ephemeris required frequent updating to correct the unmodelled acceleration introduced by the RCS system. Differences between Ground ephemeris and environment trajectory were much higher than those seen in the Standard case. Similarly degraded performance is demonstrated by the onboard navigation system.

CONCLUSION:

Tethered operations will have a significant effect on both the inertial trajectory of the TSS-1 mission and the navigation of that mission. Pure tether mechanics effects -- typified by the offset between the system center-of-mass and the Orbiter -- cause behavior that is interesting rather than damaging. Mission navigation is not adversely affected.

Tether-induced force does degrade navigation by causing low-level acceleration that are not directly incorporated into the propagation of the trajectory. These effect are cause major changes to the orbital trajectory over time. Even in this worse case, navigation performance using existing Mission Control Center software and processing guidelines did not degrade below acceptable limits. Tethered operations as exemplified by the TSS-1 mission will provide navigation challenges, but challenges that can be met.

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