Impact of Tether Cutting on Onboard Navigation During the Tethered Satellite Mission -1

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Abstract

The first Tethered Satellite System mission (TSS-1) is manifested for Shuttle Flight STS-44 in January of 1991. The TSS mission presents a new challenge to engineers, requiring advanced guidance, navigation and control concepts. As an example, current navigational systems track the Orbiter exclusively and do not model the accelerations induced by the tether on the Shuttle. Due to the offset of the center of mass of the system from the that of the Shuttle, the navigational system assumes the tracking data are biased, and tracks the center of mass of the system. This offset can be quite large, to several hundreds of feet. As a result, determination of the navigational state of the Shuttle becomes more difficult and less certain.

Current NASA flight rules require that the navigational state of the Orbiter at deorbit burn be known to an accuracy of 20 nautical miles. Response of the Shuttle crew to this contingency may involve cutting the tether prior to a complete retrieval. This paper examines the degradation of the navigational state accuracy as modelled by Shuttle navigation systems.

Responses to the loss of communication scenario are proposed for two cases. The first case examines navigational performance during a "nominal" attitude profile. The second case is identical to the first, with the inclusion of modelled tether electrodynamical forces.

Comparisons of trajectories propagated from the onboard navigational state-vector and a reference ephemeris state-vector were performed, with the tether cut simulated at various points during the mission. Additionally, updates to the onboard navigational state via ground uplinks were provided prior to the assumed loss of communication. Through these comparisons, the onboard navigation state error was determined. Alternative responses result from efforts to minimize this error during the various phases of TSS-1 deployment. These results demonstrated existing NASA flight rules could be violated by cutting the tether, and suggests responses to a loss of communications contingency to maintain a more accurate navigational state.

Introduction

Perhaps the most exciting and challenging Shuttle mission ever flown is scheduled for STS 44, in late January, 1991. A satellite will be deployed in an nominally outward radial direction on a conducting tether during the first Tethered Satellite System mission (TSS-1). The satellite is designed by an italian aerospace company, Aeritalia. Primary objectives for the mission are to demonstrate closed loop control of a tethered object, and to examine the behavior of a current carrying tether passing through the Earth's magnetic field.

The deployment of the satellite moves the center of mass of the system away from that of the Orbiter. For a twenty kilometer long tether, this separation can be as great as 100 meters. Additionally, the presence of the tether results in a tension force continually experienced by the Shuttle, a force unmodelled by current Shuttle ground-based navigational systems onboard Shuttle. Although the Inertial Measurement Units (IMUs) detect tether accelerations, these accelerations are within the noise thresholds. Therefore this data is not passed on to the navigational systems. These two facts make navigation difficult. When this force is suddenly removed, as in a cut or break of the tether, the Shuttle's orbit changes, and the system center of mass returns instantly to the Shuttle. The onboard navigation system is unaware of the removal of the tether, resulting in rapid navigational state degradation.

An accurate Shuttle state can be determined following a tether cut, given communications with ground based systems. The ground navigation systems are able to determine the new orbit of the Shuttle, then uplink an accurate state, resetting the onboard systems. Shuttle navigation proceeds as if the tether was never present. In a loss of communications contingency, however, an accurate updated state is unavailable to onboard systems.

This paper examines Shuttle navigational response to the removal of the tether. Additionally, responses are suggested to a loss of communications in an effort to minimize navigational error.

During a loss of communications, the onboard navigation systems perform unsatisfactorily, as no uplink can be provided. Efforts to minimize onboard navigational error growth result in responses to a loss of communications contingency. Navigation performance is improved to acceptable standards by reeling in the tether as much as possible prior to cutting.

Analysis tools used for the research of this paper include 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), an onboard navigation simulation (Reference 2); and the Standalone Orbital Navigation (SONAV) program, a ground system emulator (Reference 3). An additional tool is the Houston Operations Predictor/Estimator (HOPE). HOPE was used primarily as a propagator of Shuttle state in the absence of tether accelerations (Reference 4).

Effect of Tether on Shuttle Navigation Systems and State

Current navigational systems track the Orbiter exclusively and do not model the accelerations imparted to the Shuttle by the tether. These accelerations include gravity gradients, and the aerodynamic and electrodynamic drag of the tether. The gravity gradient accelerations are dominant of these three. Because the existing ground navigation systems do not incorporate these accelerations in their propagations, the combination of a propagation of the previous state and a weighted least-squares reduction of the observation data results in a state vector for that point in the TSS where the gravity gradient accelerations are zero. This point is approximately the center of mass of the system. Effectively, the ground navigation systems assume the observations are biased by the difference in position between the system center of mass and that of the Shuttle. As a result, the navigational accuracy of the shuttle deteriorates rapidly, particularly during reel-out, when these two points are moving apart. Reference 5 presents a further discussion of tether effects on inertial navigation.

To the onboard navigational systems, the presence of the tether goes completely unnoticed. Accelerations of the same magnitude as the tether tension appear as noise to the navigational systems. These forces are therefore not considered in the onboard state propagation.

The comparison of the ground ephemeris for the Shuttle and the simulated tethered trajectory in Figure 1 illustrates the effect of tethered operations on Shuttle navigation. During the initial phases of the mission (i.e. reel-out, see Figure 2 for a tether length profile), the navigational state error grows rapidly. Following the first uplink during the onstation portion of the mission, the ground system ephemeris matches the simulation quite closely. Navigation performance improves when the difference in the position vectors of the system center of mass and the Shuttle center of mass remains relatively constant, as it does during the onstation portion of the mission. The ground navigation systems predict the state of the Orbiter with greater accuracy, much more so then when the observation data biases are constantly changing.

Removal of the Tether

When a tether cut removes the TSS gravity gradient accelerations from the Shuttle, the ground navigation systems detect a displacement of the target's center of mass. Because the forces not modelled in the the ground system propagation are no longer present, the ground system no longer treats the observational data as biased, and once again generates state vectors for the center of mass of the Orbiter.

Just as the tether force went undetected while the tether was attached, the absence of the tether force also goes unnoticed. The onboard systems continue to propagate a state of the Shuttle determined with the tether attached, resulting in rapid navigational error growth. An uplink of a state-vector from the ground ephemeris resets the onboard state, however, and the onboard systems perform correctly.

At this point it is important to point out a limitation of the Shuttle navigational systems. The displacement of the center of mass following a tether cut can be thought of as an an acceleration being applied to the Shuttle. If the Shuttle experiences a large unmodelled force, ground navigation requires one full revolution of observation data to redefine the Orbiter's orbital energy. During this time, no uplink is provided to onboard systems. Consequently, the onboard navigation error becomes excessive (Figure 3).

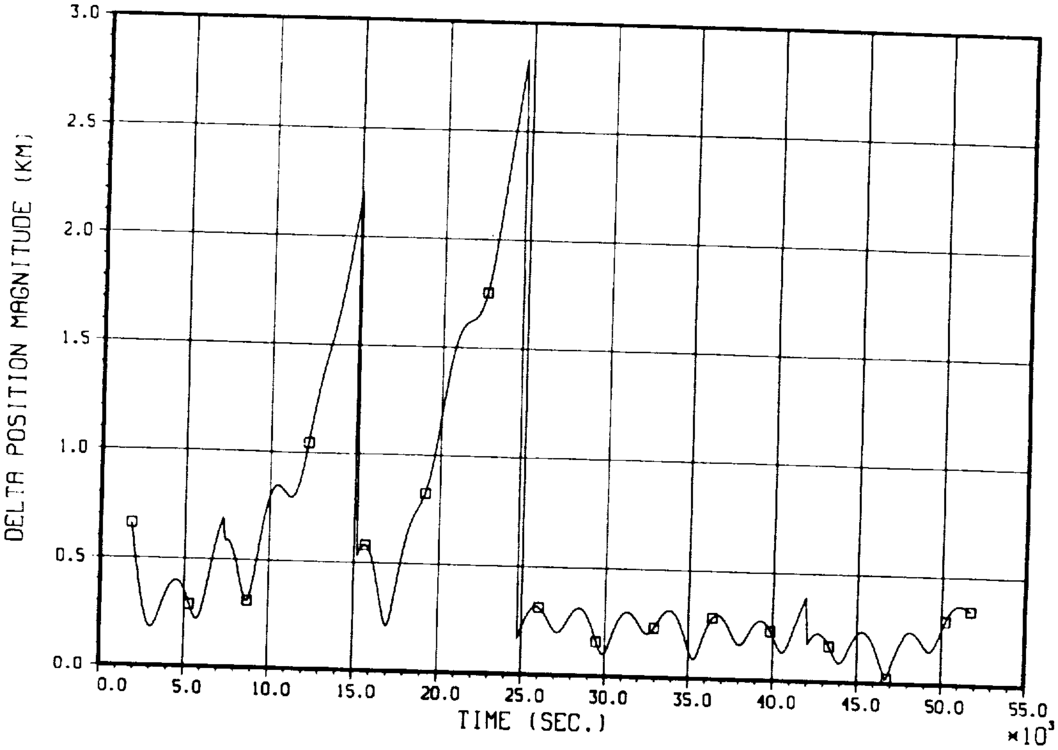

Figure 1: Comparison of Ground System vs. Simulated Trajectories

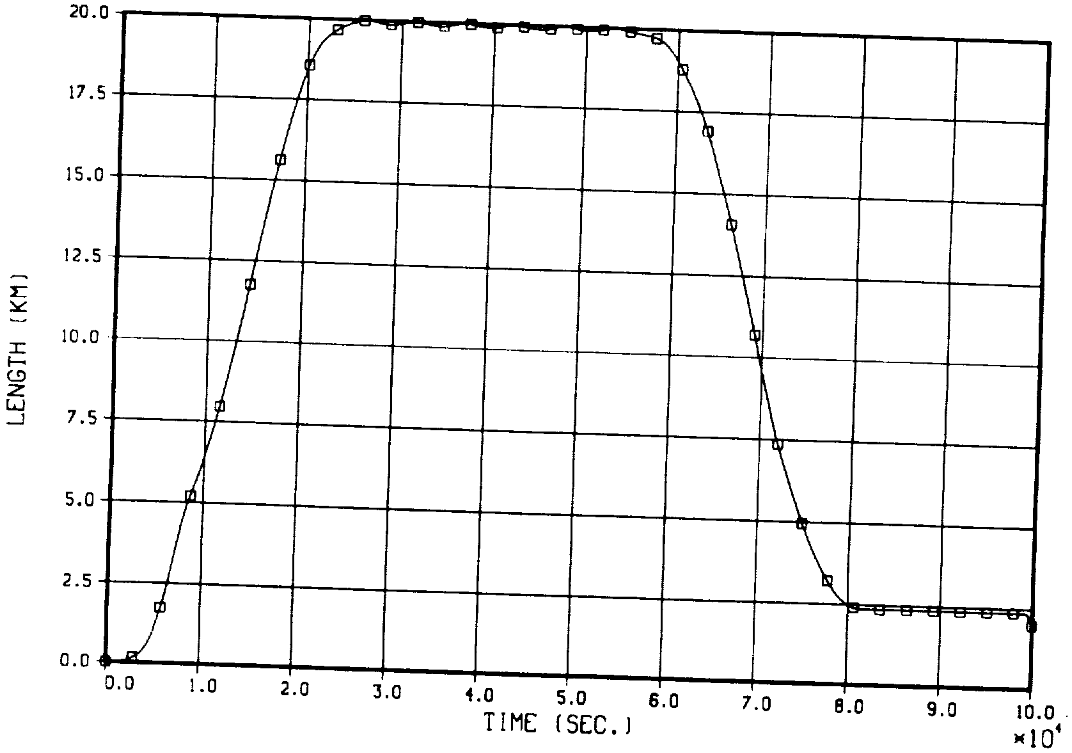

Figure 2: Tether Length Profile for Nominal and Electrodynamic Missions

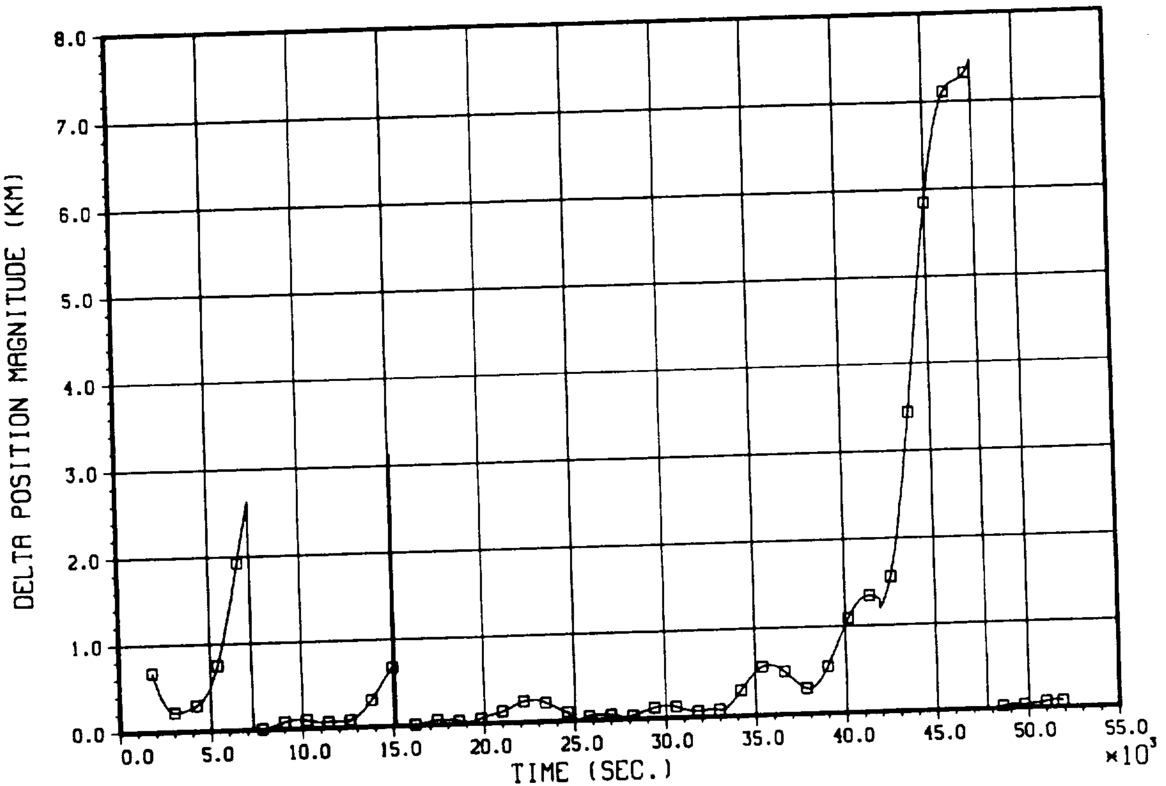

Figure 3: Comparison of Onboard vs. Simulated Trajectory

Simulation of a Cut Tether

Two mission profiles were considered in the study of an immediate cut and return response. The Shuttle was in an local vertical, local horizontal (LVLH[1]) attitude hold for both profiles, with a constant pitch angle of 25 degrees, zero roll and yaw.

The first profile, considered a nominal case, assumes no current flows through the tether during any portion of the mission. The second is identical to the first, with the current turned on during the onstation portions of the mission.

A propagation of a Shuttle state-vector served as a simulation of Shuttle trajectory following a cut tether. The vector was propagated with gravitational and environmental accelerations, but without tether tension force. Assumptions validating this method of simulation begin with the assumption the cut is placed at the boom tip. By putting the cut at the boom tip, the dynamic behavior of recoiling tether need not be considered.

An additional assumption pertains to the change in energy of the Orbiter. If it is assumed a negligible amount of tether energy is imparted to the Orbiter as a result of cutting the tether, a propagation excluding tether related forces of the Shuttle state-vector is a valid simulation of a cut. Furthermore, in the STOCS generated trajectories

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[1] The LVLH coordinate system is a right-handed cartesian coordinate system with its Z axis pointed toward the center of mass of the Earth, and in the instantaneous orbital plane. The Y axis is formed by taking the cross product of the position and velocity vectors, in that order. The X axis is mutually orthogonal to the Y and Z axes.

presented here, a massless tether was used. This assumption neglects transmitted tether energy from sources such wave transmission.

HOPE was used as the propagator for generation of post-cut trajectories. HOPE is a generic spacecraft trajectory navigation analysis tool, utilized to measure performance of new trajectory generation or navigation software. The HOPE propagator does not model tether-induced accelerations, but does have geopotential, atmospheric, and solar radiation models. Additionally, mass, attitude, and payload door timelines characteristic of TSS-1 mission can be included.

A complete TSS trajectory during which the tether has been cut can be formed by splicing the STOCS simulated trajectory and the propagation. These spliced trajectories were used for this study.

Responses to a Loss of Communication Contingency

With some insight into the systems navigating the Shuttle, examining a loss of communications scenario becomes possible. NASA flight rule 4-50 (Reference 6) sets a limit on the navigation uncertainty for a deorbit burn. It states the navigational state error at deorbit must not exceed 20 nautical miles (approximately 37.039 kilometers). Additionally, it states for the case of emergency deorbit with loss of communications, designers are to assume it will take four revolutions to find an appropriate landing site.

There are basically four responses to a loss of communications: immediate cut and return, a partial retrieval and return, a complete retrieval. or a tether length hold prior to cut and return.

At the time of writing this paper, simulation data for a complete retrieval from maximum tether length to the boom tip is not available, as the baseline tether retrieval includes a hold phase at a tether length of 2.4 kilometers (the reader is again referred to Figure 2). Therefore this option is not considered here.

Immediate Cut Response

Navigational error envelopes were generated for the four revolutions following the loss of communications. A cut was simulated by propagating the Shuttle state in the absence of tether accelerations, using a STOCS state-vector as the initial state of the Shuttle. The identical process was then performed using a state-vector determined by the onboard systems simulator, SENSOR. After the four revolution propagation, the resulting trajectories were compared. Any differences were recorded as the navigational state error of the onboard systems. The time of the tether cut was incremented in fifteen minute steps.

The navigational error of the onboard system during the nominal mission appears in Figure 4. The data shown represents the navigational error after the four orbital periods. The navigational error never exceeds 30 kilometers, and Flight Rule 4-50 is not violated. The maximum error occurs at the onset of the onstation portion, reflecting the effect of the system center of mass moving away from the Shuttle center of mass on Shuttle navigation. After the first uplink during the onstation portion, the navigation systems begin to maintain an accurate state when compared to the simulation. Navigational accuracy improves with constant measurement biases and small perturbative forces. Furthermore, note the decrease in error during the first reel in of the retrieval phase of the mission (approximately 53,000 seconds to 80,000 seconds). Because the two centers of mass are approaching each other, navigational performance improves in the absence of perturbing accelerations.

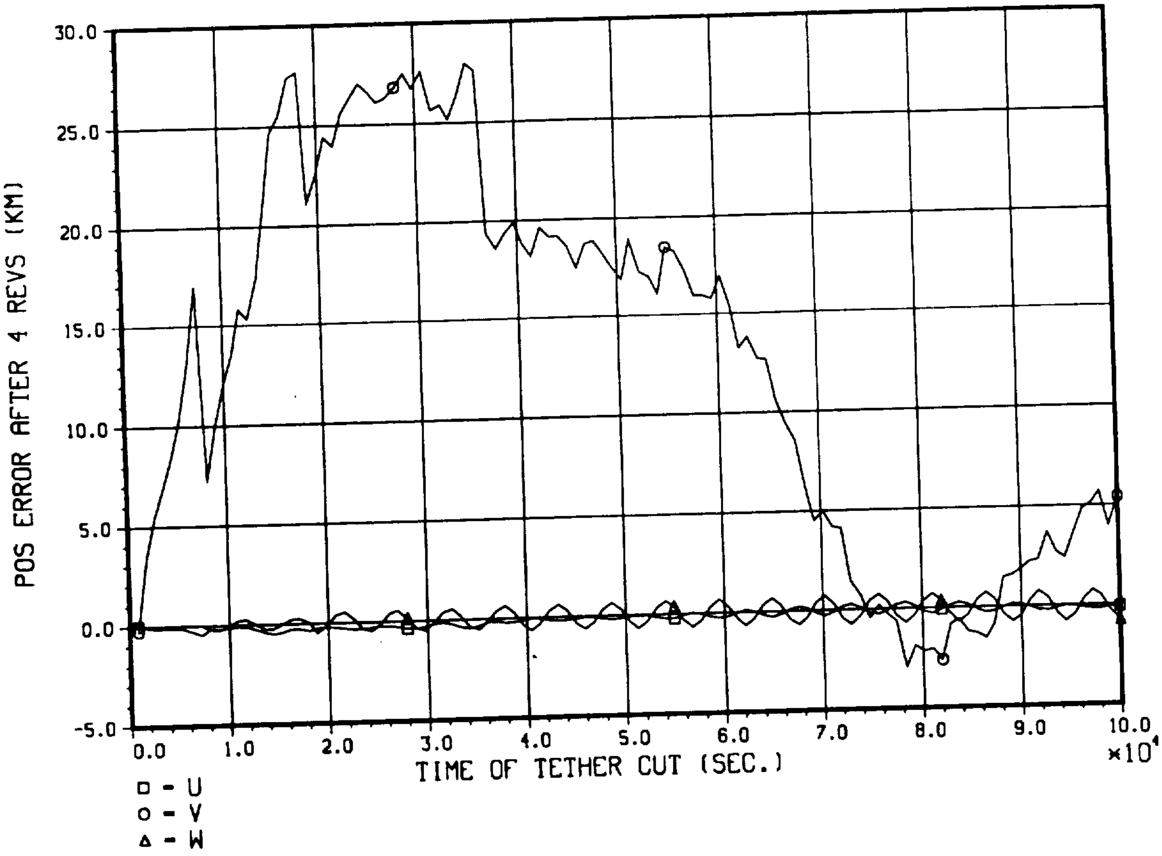

Figure 4: Nominal Mission Navigational Error After 4 Revolutions

Figure 5 shows the onboard navigational performance during a TSS mission with current flowing through the tether. The current is first turned on when the tether is fully deployed to a final length of 20 kilometers (at an approximate mission elasped time of 20,000 seconds). The onboard state error approaches 37 kilometers at this time. After an uplink, providing the onboard systems with an accurate state and constant observational biases, the navigational state error four revolutions after the tether cut increases to within 160 meters of violating NASA flight rule 4-50. Because these data were generated following current navigational procedures, it is very likely this situation could occur during the course of the actual mission. An immediate cut and deorbit response is inappropriate for TSS-1.

The presence of perturbing accelerations induced by the tether cause the onboard state to quickly degrade. Similar to the nominal profile, note the initial improvement in onboard navigational performance during retrieval. Following an uplink in the middle of the onstation phase, however, the navigational error begins to grow, unlike the nominal case. Out-of-plane tether librations (see Figure 6) cause the Vernier Reaction Control System (VRCS) to hit roll and yaw deadbands, increasing the number of VRCS jet firings. These jet firings increase navigational degradation. Out-of-plane librations are the result of electrodynamical interactions of the tether and the Earth's magnetic field, begun during the onstation period. Because the

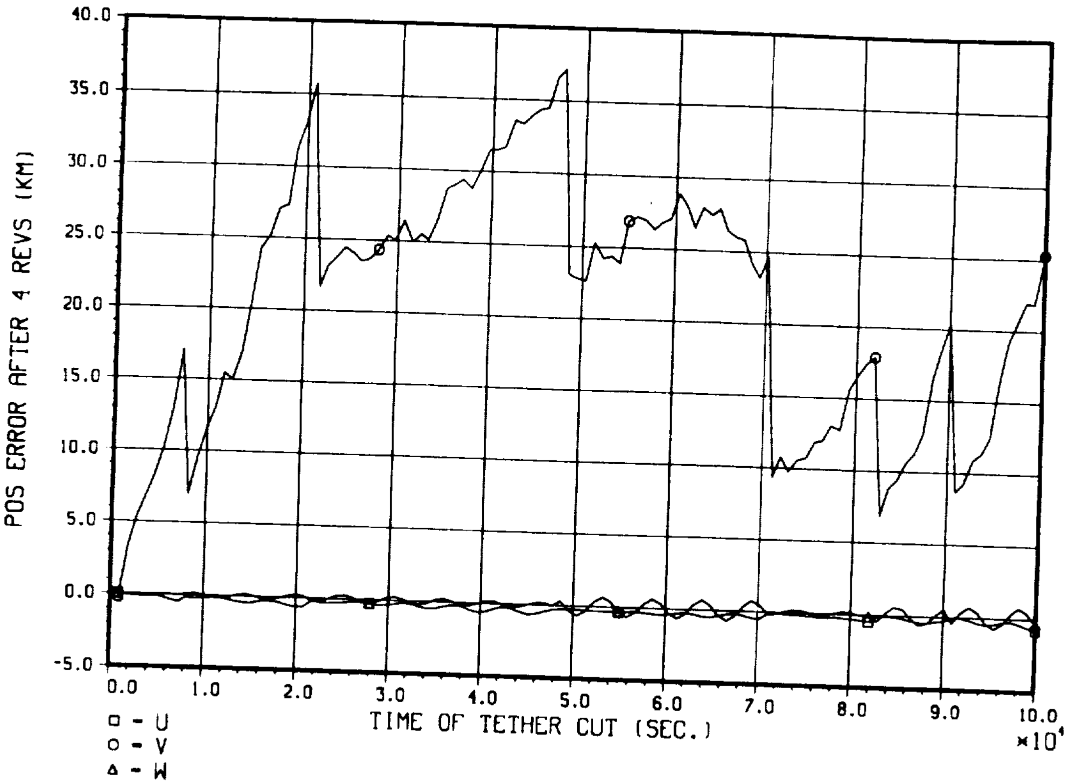

Figure 5: Electrodynamic Mission Navigational Error After 4 Revolutions

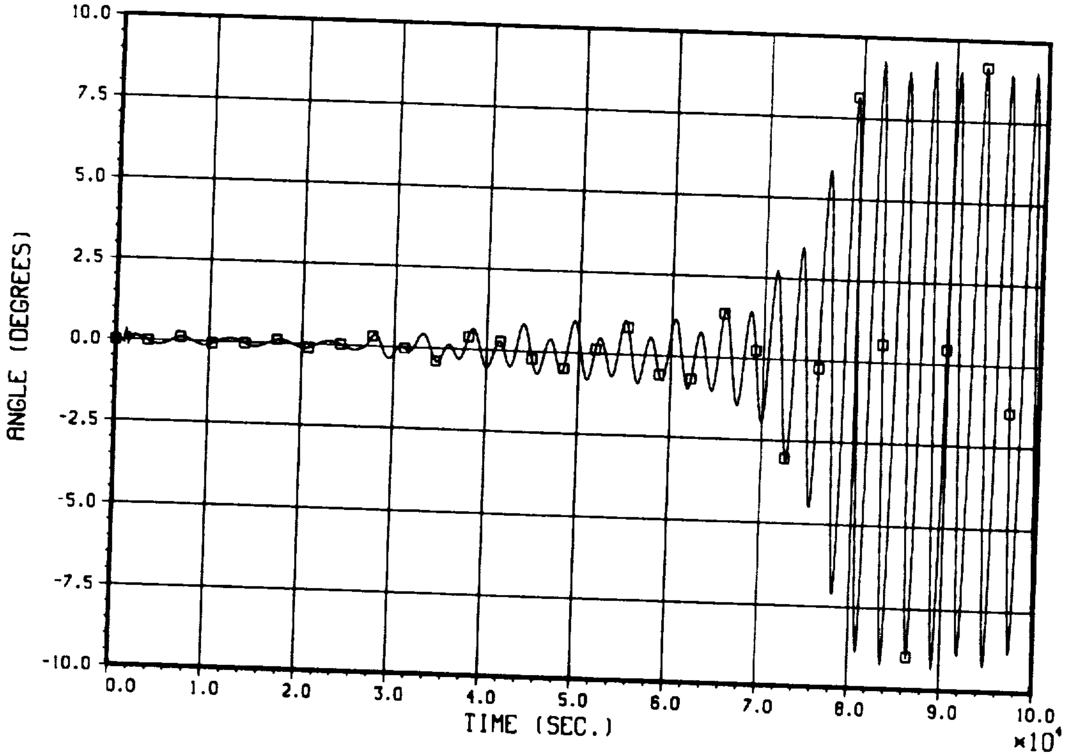

Figure 6: Electrodynamic Mission Out of Plane Librations (angle wrt local vertical)

Shuttle's trajectory is inclined with respect to the magnetic field lines, the tether electrodynamic force contains a component perpendicular to the Shuttle's orbital plane. At full deployment, the librations are relatively small and benign. As the tether length decreases, however, these librations increase in amplitude, resulting in more frequent RCS deadbanding.

Partial Retrieval and Cut

In a partial retrieval, followed by a tether cut, the tether is assumed to be reeled in following a nominal tether length profile to a given tether length and then cut. The loss of communications was assumed to occur just prior to an uplink, representing a worst case scenario. A electrodynamic mission profile was used, with the uplinks modified to place the missed uplink at the onset of retrieval. Onboard navigational errors were determined for a period of four revolutions after the beginning of retrieval.

In Figure 7, navigational error data show navigational performance improves in a loss of communications contingency if the tether is partially reeled in prior to cutting. A cut at 20 kilometers represents an immediate cut (in which the onboard navigational system performed unacceptably), demonstrating an error of 41 kilometers at the end of the four revolution period. Figure 8 compares the onboard navigational state to a simulated cut tether trajectory. The navigational state error grows linearly approximately 35 kilometers in four revolutions, or 8.75 kilometers per revolution.

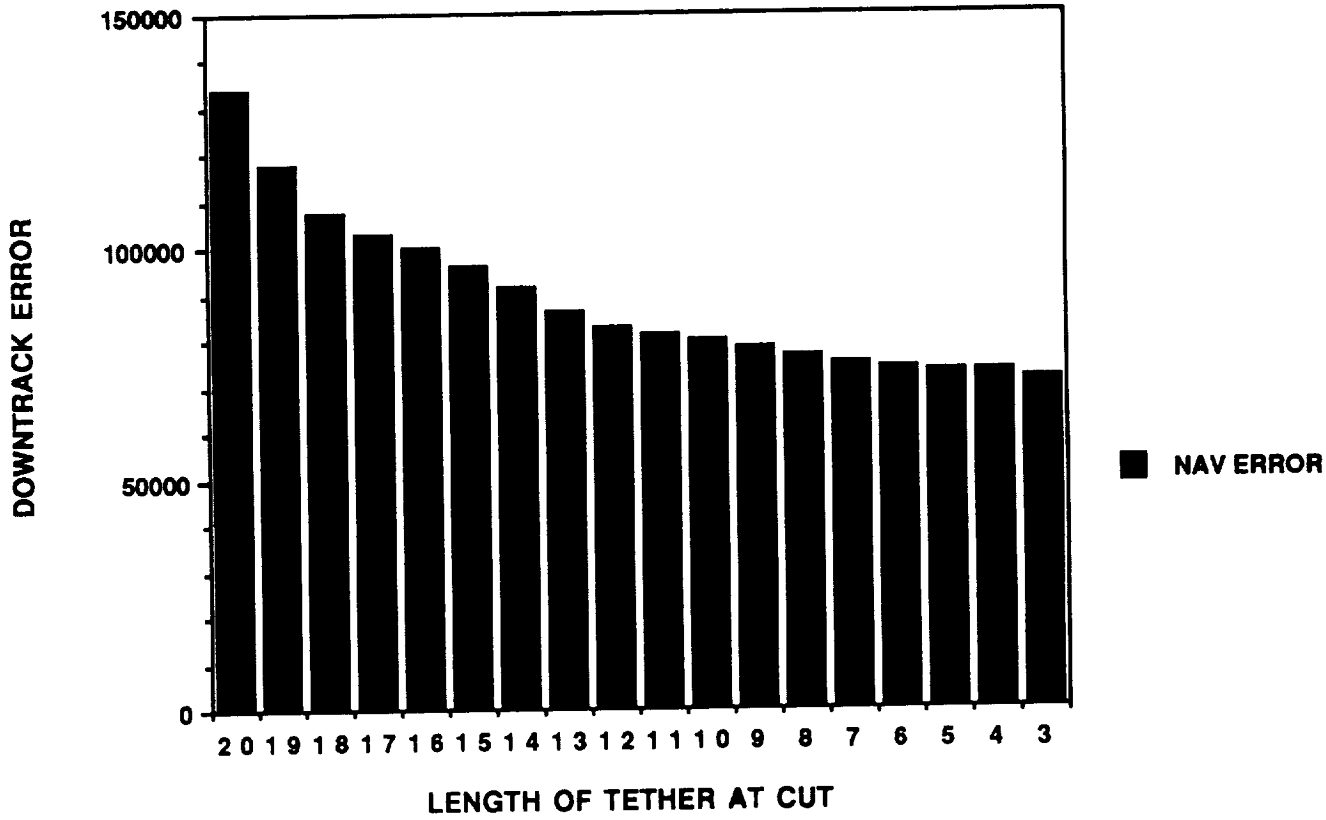

Figure 7: Accumulated Navigational Error After Partial Retrieval

As the tether is further shortened, navigational accuracy improves. The closer the satellite is reeled in, the better the navigational performance. At a tether length of 3 kilometers, the final navigation error is approximately 22 kilometers, well within the limits set by the NASA flight rule. A comparison similar to Figure 8 appears in Figure 9 for a partial retrieve to a final tether length of 3 kilometers. Note the navigational error growth rate after the tether cut is close to that of an immediate cut, approximately 8.75 kilometers per revolution. The increase in performance occurs during the retrieval portion of the response, due to the relatively slower navigational error growth rate.

Tether Length Hold Prior to Cut

The simplest operational response to a loss of communications contingency is to do nothing. In the TSS-1 mission, doing nothing means holding the tether length constant, and cutting the tether at the last possible moment before deorbit preparation must begin.

This response has a number of advantages. Because the Orbiter does not alter its orbit significantly until just prior to the deorbit burn, the onboard navigational systems propagate Shuttle state more accurately. Due to the operational simplicity of this response, a double failure is much less likely. The systems supporting the tether are used minimally, and it is less likely something else would go wrong.

The navigational error just prior to the deorbit burn for a 3 revolution hold followed by a tether cut appears in Figure 10. The loss of communications was assumed to occur just prior to an uplink in the middle of the onstation phase. The final error during this response is 23.5 kilometers, well within the limit set by the NASA flight rule.

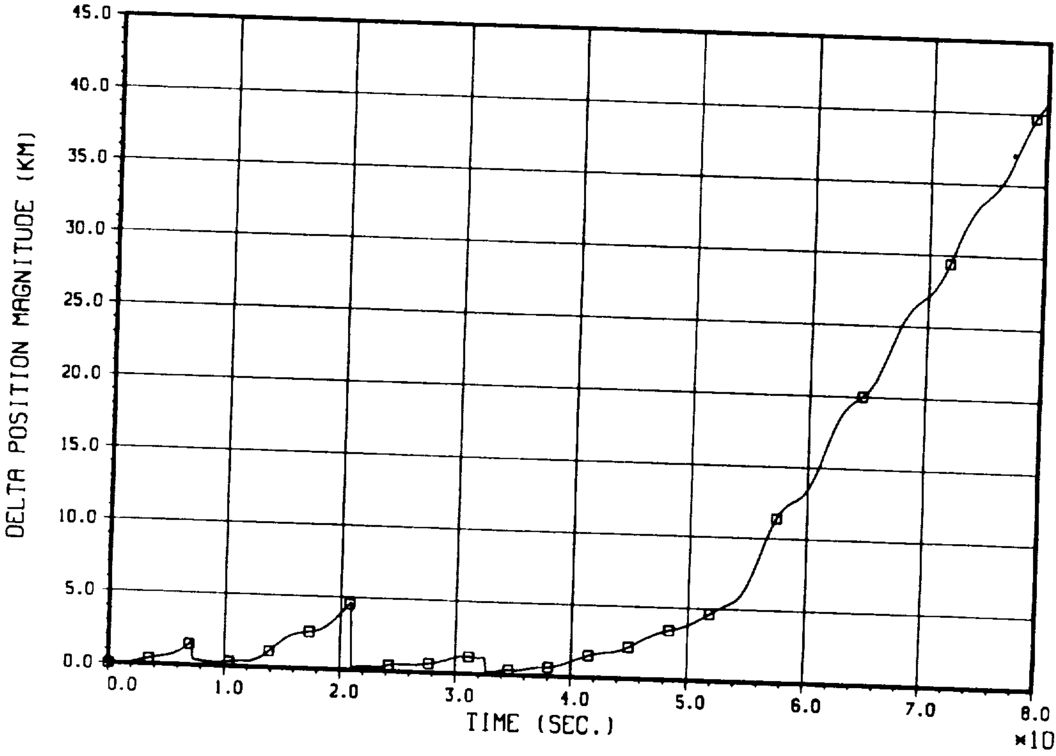

Figure 8: Electrodynamic Mission Navigational Error Growth - Cut at 20 km

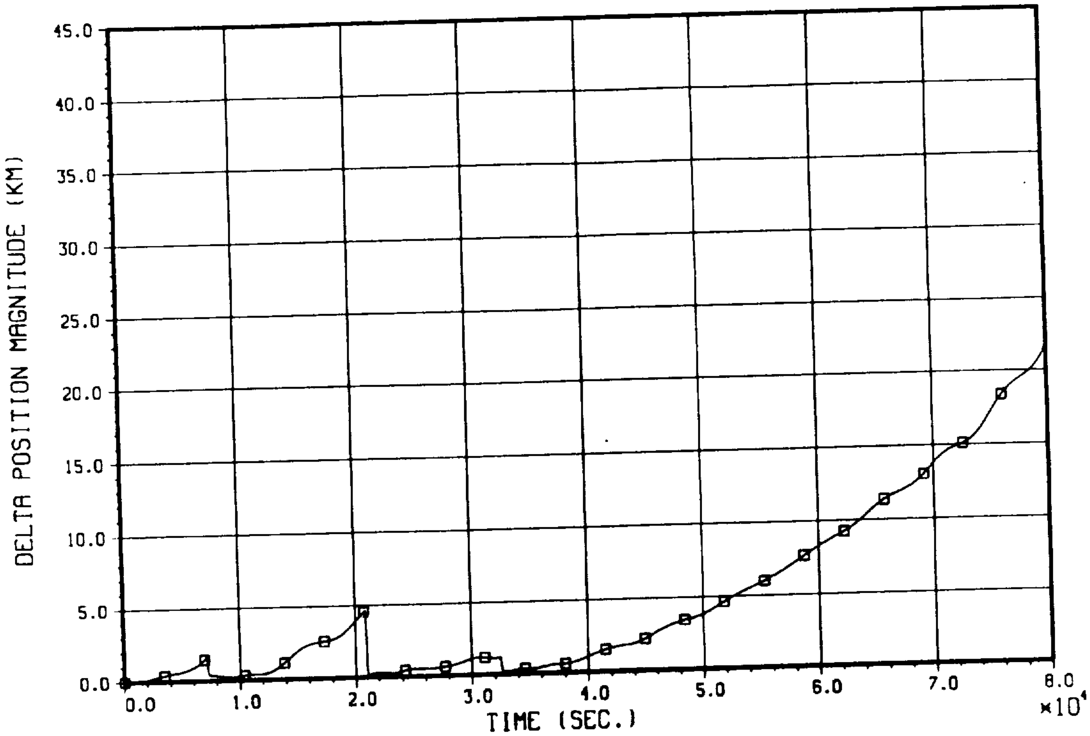

Figure 9: Electrodynamic Mission Navigational Error Growth - Cut at 3 km

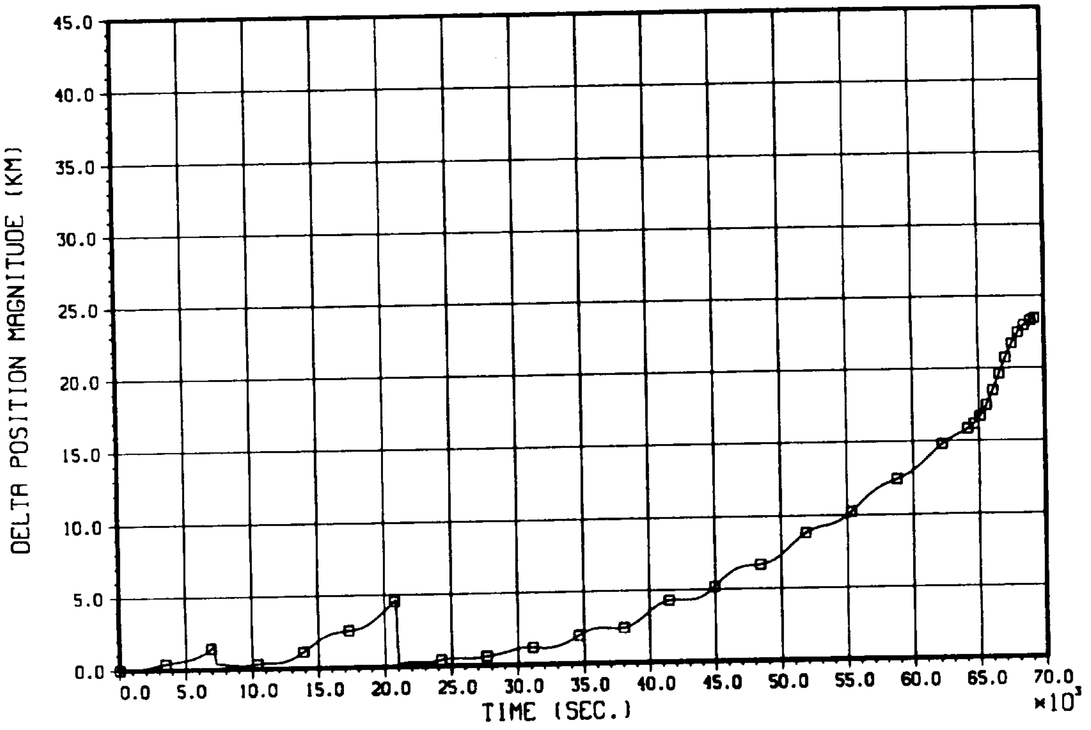

Figure 10: Comparison of Onboard vs. Simulated Trajectories - 3 Rev Hold and Cut

Conclusions

A cut tether contingency does not represent a threat to the a tethered system mission, provided the onboard navigation systems have contact with the ground. Although the onboard navigational error grows at an alarming rate immediately after a tether cut, the onboard systems can be reset with an uplink from the ground systems. Once reset, the onboard systems perform accurately.

During a loss of communications contingency, however, an incorrect action during the tether cut can threaten the mission, to the point of violation of NASA flight rules. Appropriate action requires not cutting the tether immediately after losing communications.

Tether retrieval, even partially, improves navigational performance. A tether hold offers an attractive alternative to retrieval, demonstrating comparable accuracy while remaining operationally simpler. The price for this simplicity, however, is loss of the satellite.

The benefits of retrieving the satellite outweigh reduced onboard navigational performance, provided existing flight rules are not violated. Therefore the best response to a loss of communications contingency would simply be to do nothing for as long as possible while attempting to reestablish contact with the ground systems. This response offers acceptable navigational accuracy, and is operationally simple. If contact can be reestablished, the satellite can be recovered.

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