Tethered Satellite System Dynamics and Control Review Panel and Related Activities Final Report for Phase 3

August 1991

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1.0 INTRODUCTION

This report documents the activities of Logicon Control Dynamics (CDy) under contract NAS8-35835, task b.5.5, during the period from December 1989 through November 1990. These activities include: 1. Serving as an observer and evaluator at selected tests of the Tethered Satellite System (TSS) hardware and software; 2. Organizing, Convening and chairing on behalf of NASA, the third meeting of the Dynamics and Control Review (DACR) Panel; 3. Serving as a member of the TSS Dynamics Working Group (DWG); and 4. Analyzing and confirming the potential severity of the skip rope dynamics phenomenon. These activities are described in detail in the following sections.

2.0 TSS TEST ACTIVITIES

CDy participated in selected phases of two major tests of the TSS hardware and software. The first test activity was the Formal Qualification Test (FQT) which occurred in November of 1989. This test served primarily to qualify the software and demonstrate that representative TSS hardware (engineering models of the major components with exceptions as noted) could be controlled through a complete mission by simulated uplink commands. The second test activity was the Hardware/Software Integration Test (HSIT) design reference mission (DRM) portion which occurred during March of 1990. This test setup included several components of actual flight hardware and demonstrated the ability to perform all phases of a TSS mission with nominal and contingency components. It also served to calibrate various encoders.

2.1 FORMAL QUALIFICATION TESTS (FQT)

2.1.1 OBSERVATIONS

The TSS formal qualification tests were conducted by Martin Marietta Aerospace Group (MMAG) at the Martin Marietta plant in Denver, Co. Room 102 of the SSB building was the site of the tests. The purpose of this series of tests was to verify the TSS flight software and demonstrate the engineering hardware. Access to the test area and the test conditions was under the supervision and control of quality specialists from MMAG. In addition to the test conductors and supervisors, observers were present from the Marshall Space Flight Center (MSFC), CDy and AFPRO.

The test setup consisted of the following items: 1. An engineering model of the deployer reel including the motor and levelwind mechanism; 2. The lower tether control mechanism (LTCM); 3. The upper tether control mechanism (UTCM) with a vernier motor; 4. A compliance tower; and 5. A takeup reel (TUR). A sketch of this setup is shown in figure 1.

No deployment boom or buglehorn (the small, cone shaped ceramic guide for the tether at the tip of the boom) was included in the test setup. Power supplies and drivers for the reel motor and vernier motor were included, though they were not flight equipment. The outboard tether was threaded through a compliance tower. The compliance tower consisted of three additional pulleys and three springs to simulate boom compliances and tether elasticity. After passage through the compliance tower, a second length encoder and a second tensiometer, the tether was collected by the takeup reel with its own levelwind mechanism, drive motor and power supply.

Commands to the takeup reel motor were generated by a computer model of tethered

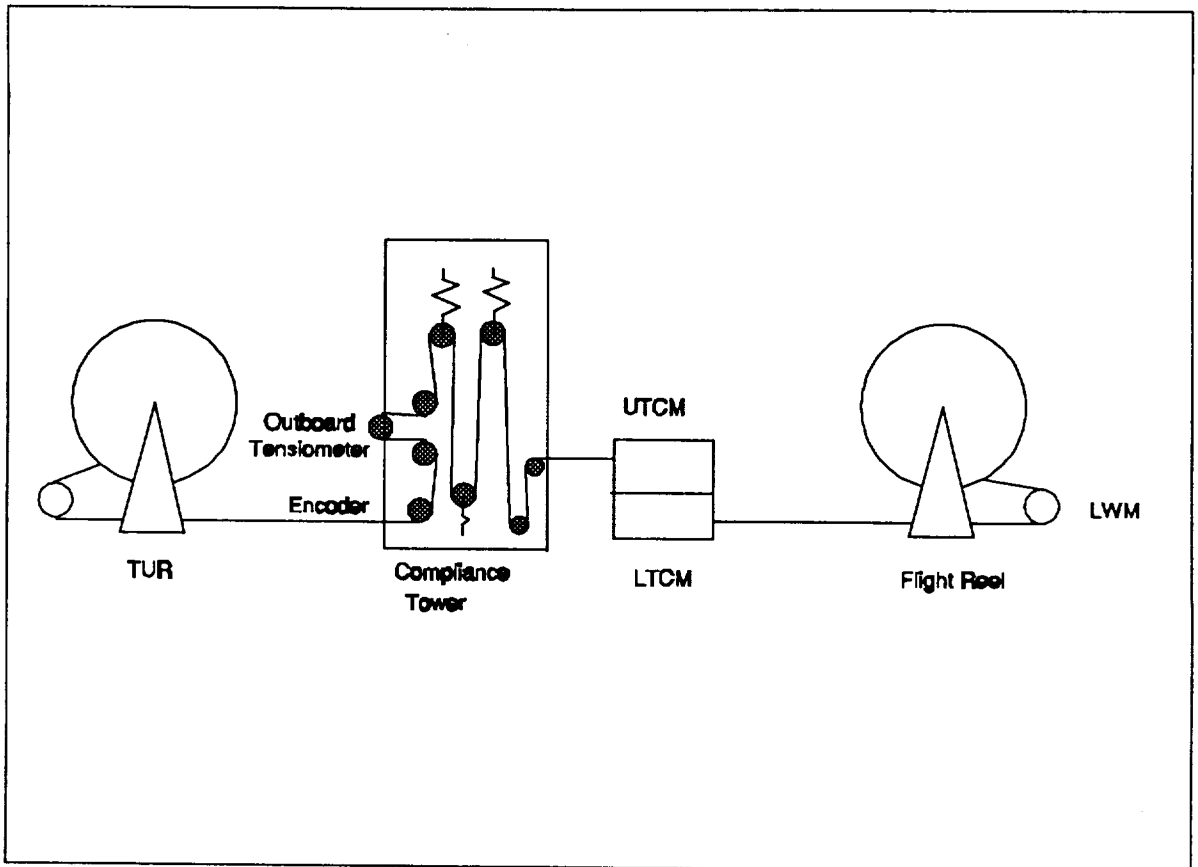

Figure 1. FQT hardware setup.

satellite system dynamics. This dynamic model was stimulated by the measured tension from the second tensiometer which was compared with the tension from the computer model. Commands to the takeup reel motor were controlled to make the measured outboard tension match the model value.

The mathematical model of the TSS dynamics used to drive the simulation was based on some simplifying assumptions. It was assumed that the tether is straight and that the rotational motion of the end bodies is negligible. This model was judged to be sufficient to exercise the TSS software and could be run in real time. The test setup was not sufficient, however, to test tether dynamics over the full range of expected phenomena. In particular, low tension tether dynamics could not be simulated because of friction characteristics in the takeup system and the resulting limitations of the takeup reel motor controller. Also, string mode dynamics including the skip rope motion could not be modeled because of the assumption of a straight tether.

Low tension dynamic characteristics of the tether were studied during the hardware/software integration tests (HSIT). These results are discussed in section 2.2.1. Investigation of skip rope dynamics and other effects will have to be done analytically with verification on orbit.

2.1.2 FQT ANOMALIES

Few anomalies were observed during the FQT. An optical disk drive being used to save test telemetry data failed on the first day of the test when tether was to be moved. This failure delayed startup of the deployment sequence about two hours. A waiver was necessary to continue testing without saving the telemetry. It was decided that screen hard copies dumped every 15 minutes would be an acceptable substitute until the drive could be replaced. A replacement drive arrived in the late afternoon and was installed overnight. This seemed to be of no consequence to the overall goals of the test.

The current flowing to the takeup reel motor was observed to vary erratically. This was described by Carl Bodley of MMAG as normal behavior. The current driving the takeup reel motor varied by +/- one to three amperes. This occurred over periods of the order of a few seconds during certain phases of deployment as the takeup system tried to maintain outboard tension to the commanded values. This was apparently due to several characteristics of the takeup system and compliance tower hardware. In particular, such characteristics as friction, variations in tether pack thickness and wrap density on the takeup reel were contributors to this behavior. Carl Bodley's simulation of the FQT setup developed at MMAG showed similar variations.

It is probable that variations in tension as seen during FQT by the TSS deployer are greater than will be seen in flight. In proportional control mode (length feedback only) this variation would have no effect. In basic control mode (tension feedback) these tension variations are high enough in frequency that the filters in the control loop should effectively remove them. Based on these considerations, it was concluded that these variations were acceptable and did not compromise the tests.

Erratic operation of the reel at slow tether deployment or retrieval speeds was observed. The motor starts and stops and does not accelerate smoothly. This effect was said to be due to the control logic and the use of a digital speed sensor. The sensor determines rates by counting pulses per computer cycle. Thus, at low speeds, the output tends to be erratic. This is of some concern because of the apparent inability of the vernier motor to tolerate a stalled condition for more than thirty seconds. Fortunately, the reel was never observed to be stopped for more than one to two seconds during the FQT because of this effect. Based on this observation, we didn't consider this a significant problem. It is noted, however, in case other changes in the system hardware or software that may be made in the future modify this behavior adversely. Another mitigating feature is that this behavior was only exhibited at low speeds such as at the beginning of deployment. Subsequent testing and analysis have also lessened the concern because the vernier motor appears more rugged than first thought.

Length variations of several hundred meters during on-station, tension feedback control were observed. This was due at least in part to the poor initialization for tension control which resulted from the repeated switching between basic control and proportional control modes. This switching was done primarily to demonstrate the ability in the DACA software to switch between modes at ground command using either an abrupt or blended switchover. First, a blended switchover was made from basic (tension feedback) to proportional (length feedback) and back. This was followed by instantaneous switching between modes. Such large variations observed during FQT and also during other simulations has reduced confidence in the basic mode to the point that its use has been dropped from the nominal plan and remains only as a contingency.

The softstop and resume tests worked as expected. On-station softstop (also called Tomlin Maneuver) also worked as expected. This is a way of removing in-plane libration through use of the satellite softstop logic. The softstop maneuver is designed to bring deployment or retrieval to a stop with minimal residual satellite/tether libration angle. The Tomlin Maneuver is initiated with the satellite already on-station in a known libration state determined by orbiter radar or other means. In-plane librations can be reduced by initiating the maneuver with the proper conditions and timing.

2.1.3 CONCLUSIONS ON FQT

The formal qualification tests demonstrated that the flight software could be commanded with simulated ground commands and would generate the proper responses in the hardware. Certain anomalies were observed but these were not judged to be significant to the performance of the flight software. At the time of the FQT, there was an expressed desire to add vernier motor cutoff logic to the DACA software to cut power to the vernier motor if it is stalled for more than 30 seconds. This was felt to be the maximum acceptable period of motor stall which would not damage the motor. MMAG was reluctant to do this because they felt it was unnecessary. According to their logic, such a condition is highly unlikely and it is sufficient to have the crew be watchful of the vernier motor, cutting power if a persistent stall occurs. Such a stall is most likely to occur in a low speed condition of the deployer such as occurs at flyaway or at a softstop.

Reliance on the crew to prevent vernier stall is undesirable since the reasons which prompted the softstop may distract attention long enough for damage to the vernier to occur. A study of what action is proper to take after a vernier stall needs to be made. Also, a trade study should be made to consider the effects of an undetected vernier stall vs an inappropriate vernier shutdown. More recent information indicating greater vernier motor stall tolerance has lessened the concern regarding vernier stall.

As mentioned previously, the FQT sequence of tests was run without a real or even simulated buglehorn. The buglehorn will add friction to the deployer system and may significantly affect the results. The lack of a buglehorn in the FQT test series was not judged to be critical since a more complete deployer system including a buglehorn was to be tested in HSIT. The HSIT results are described in section 2.2.

2.2 HARDWARE/SOFTWARE INTEGRATION TESTS(HSIT)

2.2.1 OBSERVATIONS

The hardware/software integration test series was carried out during the period January - March 1990. The tests were conducted at the SSB building in the Near Field Test chamber. Access was controlled through a door with a combination lock. The flight hardware was inside a roped off area. Access to the hardware required static electricity control procedures and special grounding to prevent damage to the electronics. Test observers typically were not required to access the static protected area.

Control Dynamics supported the Design Reference Mission (DRM) portions of the HSIT in which tether was actually moved between the flight reel and the takeup reel. The activities of this phase of the HSIT were many and varied. To describe the activities and the involvement of CDy, a day-by-day summary is presented.

DRM DAY ONE

The low tension flyaway test started on March 21, 1990. It was delayed from morning until afternoon to allow the procedures to be reworked. Figure 2 shows a schematic of the test setup. A free weight was used to assure that the outboard tension in the tether was less than two Newtons. For the first test, the amount of free weight was adjusted to bring the UTCM fine tensiometer reading to 1.73 N. Deployment started smoothly with the weight moving down freely. As the tether began to move, the tension dropped to 0.9 N. The takeup reel was manually driven to keep the free weight at a constant length. The measured tension was steady at approximately 0.9 N. When the deployment rate exceeded 0.1 m/s near 100 m deployed length, a software limit was exceeded, tripping the brake on the reel. This limit should already have been reset but

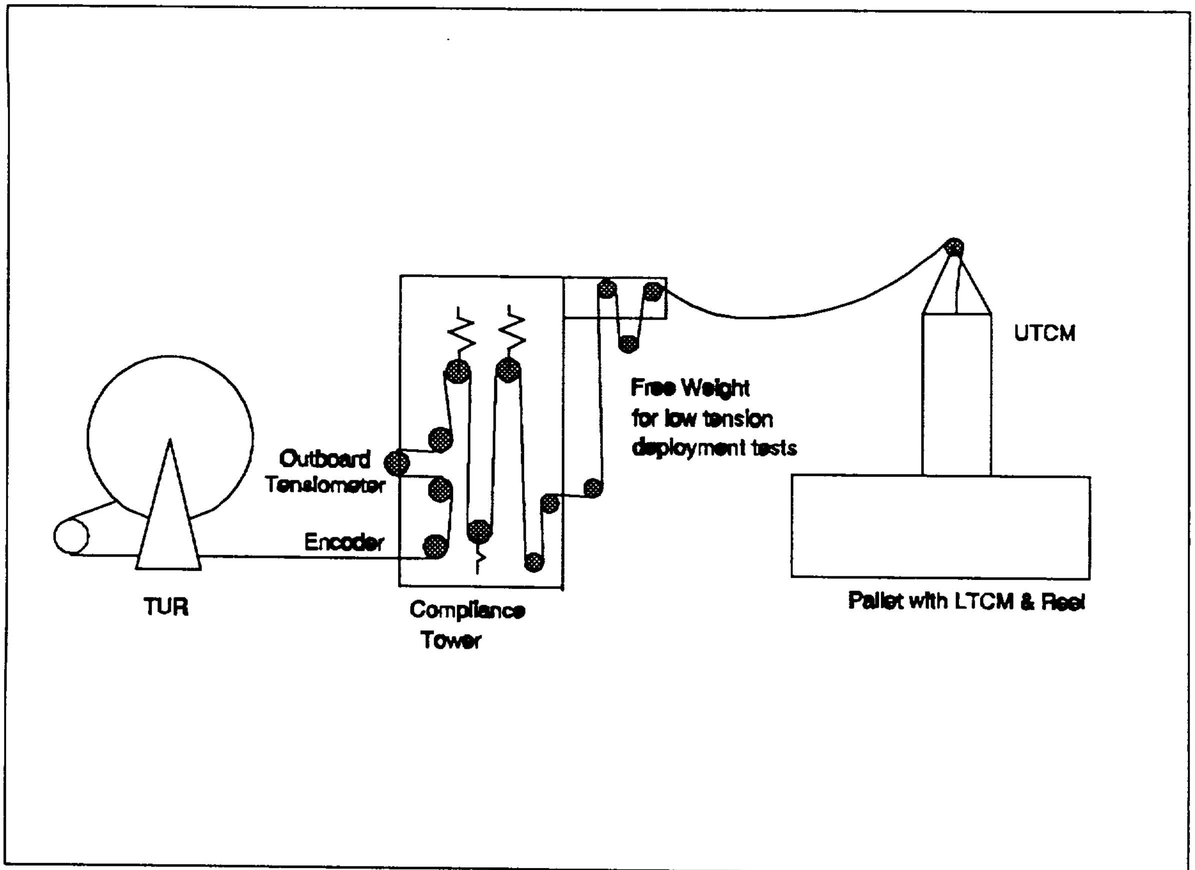

Figure 2. HSIT hardware setup.

this detail was left out of the test procedure. It was concluded that sufficient data had been obtained so that a retest was not necessary. The next test was a low tension retrieve to dock. This was performed smoothly.

The low tension deployment test was performed with FQT nominal gains (rate gain 100 Vs/m, length gain .5 V/m). System performance was less than satisfactory. The reel motor control assembly alternated between motor and generator modes at approximately one second intervals. This went on for the first ten minutes of deployment. Momentary negative deployment rates were observed intermittently on the video displays. As a consequence of these observations, it was decided to move up a planned engineering test order (ETO) test from day five to day two of the design reference mission (DRM) test series. This ETO was to test modified control gains (rate gain 40 Vs/m, length gain 5 V/m).

DAY TWO

Procedural details for the control gain ETO were worked out early on day two. Added to the test procedure was a slack tether test and a slack-taut test. At the planning discussions on day two, the designers of the UTCM expressed confidence that it could easily accommodate a slack tether and concluded that no harm to the system could result from the test. Delays in getting all the authorizing signatures on the procedures and a photographer who showed up unexpectedly to take pictures delayed start of the test until mid afternoon.

The control gain ETO with the modified gains was conducted first. As hoped, the performance was significantly smoother. The motor mode/generator mode chatter observed on day one was absent. The test was declared successful and terminated with 60 m of tether deployed.

The slack and slack-taut tests were performed next. The test procedure required a technician to work from a platform which was positioned so he could reach the tether and pull or hold to make the outboard tension increase or go to zero. This test was done successfully. No adverse effects on the system were observed. Slack periods of up to 30 seconds were created along with slack-taut cycles. At one point, the reel was stopped by a steady pull on the tether. This was done during the open-loop, constant pulse width phase of retrieval. Test observers were caught a bit by surprise by this but soon realized the situation. The reel started moving again in a few seconds.

The retrieval test was declared successful. A similar procedure was followed for deployment. Slack in the tether was maintained for periods up to 30 seconds. The slack tether was observed to coil in the docking cone just above the buglehorn. Tether continued to feed through the deployer mechanism as expected with no tangling. Apparently, the conducting tether is sufficiently stiff to thread itself through the system. Slack-taut cycles were simulated with no apparent ill effects. All in all, these were most impressive demonstrations of the hardware and its tolerance to slack conditions.

DAY THREE

A series of deployments and retrievals of a marked, 150 m length of tether was run next in order to calibrate the encoder and the length measurement wheel. After an hour of these, an event occurred which caused a brake to set and the tension reading to jump to unreasonable values. While the system was being fixed, a meeting was held to decide whether to incorporate the new control gains tested in the ETO test. The decision was made to incorporate the new gains into the software baseline if they successfully passed additional testing in the other flight regimes where they would be significant. Figure 3 shows how these gains are used in the length control mode. The control is smoothly blended over to a lower set of gains when the deployment or retrieval rate exceeds 0.1 m/s.

DAY FOUR

The motor power conditioner (MPC) simulator malfunctioned and had to be removed from the system for troubleshooting. A temporary substitute power supply was installed to power the DACA and got the system running again. Several more of the so-called 150's (150 m spool-outs and spool-ins) were run to provide more statistical data

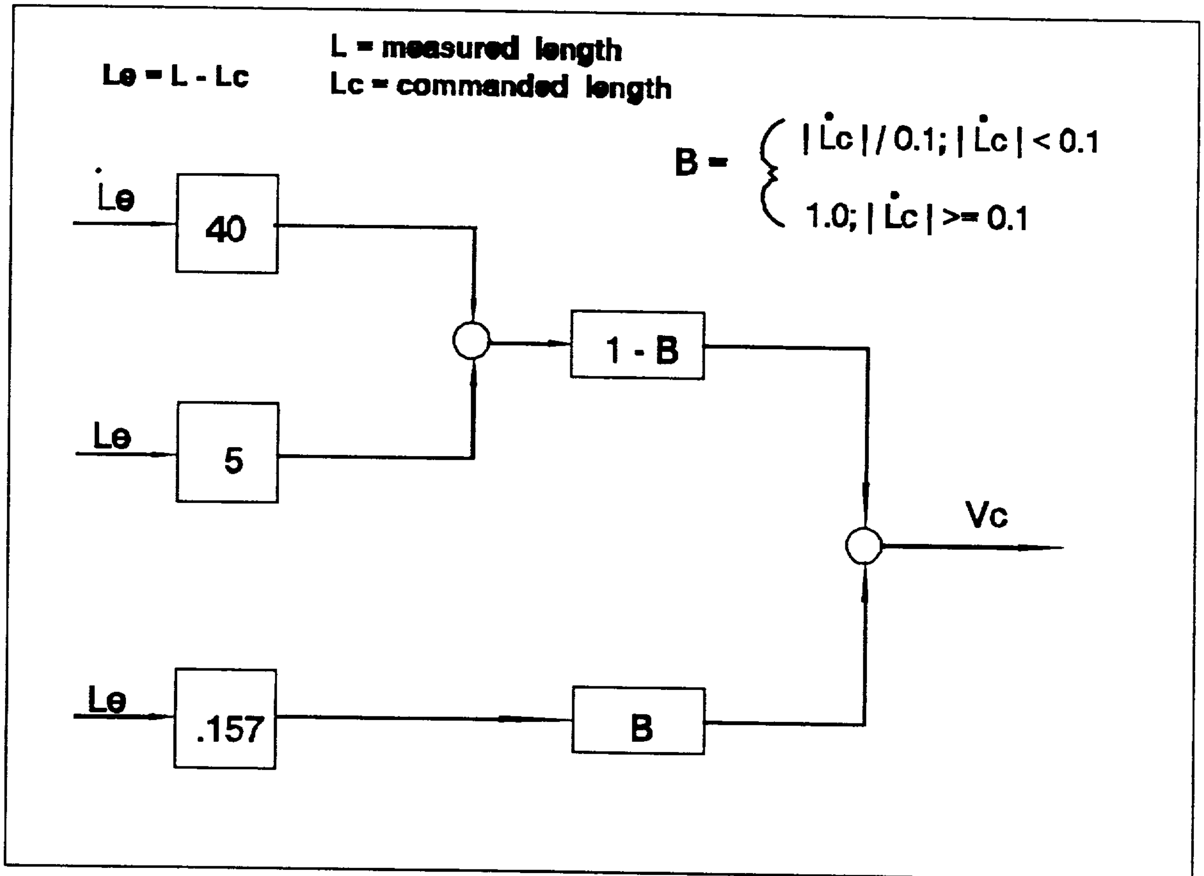

Figure 3. Proportional control.

to calibrate the scale factor for the length encoder wheel. This was all that was done on day four.

DAY FIVE

The test was begun with the old gains in the software and again the chattering behavior occurred. The deployer reel was observed to rotate backwards by 1-2 inches at the circumference. This is likely to back drive the vernier motor if only slightly. Given the vernier motor's expected sensitivity to stalls, this is clearly an undesirable situation. These observations reinforced the motivation to change control gains.

As deployment was nearing completion at 20 km and the deployment rate dropped below 0.1 m/s, chattering as described previously began again. An interesting and puzzling effect was noted here. As the tether reeled out, tension at the takeup reel differed by as much as 20 N from the tension measured at the UTCM coarse tensiometer, but as tether reeled in, the difference became less than 1 N. It was not clear why this happened. It was speculated that some pulley had different friction values in the + and - directions. This effect was not satisfactorily explained during the test series.

DAY SIX

While more 150's were being run at 20 km deployed length, a meeting was held to discuss a proposal to make the softstop/resume test into an ETO to test the new gains and eliminate the extra day ETO. This proposal was approved.

The retrieval phase was started with the FQT length and rate gains. As occurred for the test on day one, the startup was rough with frequent switching between motor and generator mode of the MCA. Other than this, the test was uneventful for the next ten hours. Near the end of the test someone evidently read the wrong procedure. The switch for the brake application rate limit was set for low rather than high rates. At 400 m to dock, the deployer brake tripped and the TUR immediately began to roll tether out onto the floor. This caught everyone including the test conductor by surprise. The loose tether was rolled back onto the TUR. A restart was attempted after the brake application switch was moved to high. Since the DACA had continued to run during this period, a large length error had developed. The reel went to large rates and tripped the brake anyway. The brake was again reset and temporarily inhibited. The next restart induced some high tensions and rates (~120 N at the LTCM and ~1 m/s). Then just as the last meter of deployed tether was being taken out, the TUR attempted to reel in some tether for reasons that were unclear. Speculation was that the procedural glitch compromised fidelity of the simulation. Events subsequent to that were questionable. Since the time was 1:10 am by this time, it was decided to call it a day.

DAY SEVEN

The running of a contingency mission profile was the test plan for this day. This included a softstop and resume at maximum rate during deployment and retrieval. The new gains were being used in the deployer. The system behaved smoothly as before with these gains. The previously observed limit cycle was nearly eliminated. Some oscillation was noted at station one but the amplitude and frequency was much smaller than before. Control performance was quite good over all. There was no repeat of the faux pas of day six. All events were nominal in the resume to dock.

2.2.2 CONCLUSIONS ON HSIT

There were many procedural rough spots during the HSIT in contrast to FQT where things went more smoothly. Wiring errors in the hardware test setup caused over voltage conditions to be placed on flight hardware. These events delayed the start of the DRM from the December-January time frame to March. Apparently the tightness of the schedule was the main culprit for this. Maturity of the system was clearly lacking. Some of the flight hardware was not available for use in the DRM. This made it necessary to implement many work-arounds to complete the test activities. Thus, it was not a full up system test as would have been desirable. There were anomalies in the qualitative nature of the test data. The puzzling nature of the tension data suggests that the system friction characteristics were not consistent and required more analysis and evaluation of the hardware. Friction characteristics must be well understood and within spec values to assure success of the deployment and retrieval. The discrepancies in friction data is considered a major shortcoming of the test program and needs to be eliminated and the data understood before the hardware is committed to flight.

3.0 THIRD DACR PANEL MEETING (APRIL 1990)

3.1 HISTORY OF PANEL ACTIVITIES

The Dynamics and Control Review Panel first met in March of 1987 at the Control Dynamics Company Offices in Huntsville, AL. The purpose of the meeting was to review the TSS program and comment on readiness for flight. A second meeting was held at the same location in June of 1987. Several significant recommendations were made by the panel. These recommendations and details of the panel activities for these early meetings are described in "Tethered Satellite System Dynamics and Control Review Panel Final Report for Phases 1 & 2", prepared by Logicon Control Dynamics.

3.2 BACKGROUND FOR THE THIRD PANEL MEETING

Significant changes to the TSS Program have occurred since the first two meetings of the DACR Panel. Many of these changes came about because of the recommendations from the Panel. In the light of these changes and with the approach of the hardware delivery date, NASA decided that a third meeting of the Panel would be desirable. Planning activities were initiated for a third Panel meeting to occur in the April - May 1990 time frame. Some changes in panel personnel and organization were required. Because of schedule conflicts Dr. Owen Garriott was unable to continue as a panel member. He was Replaced by Dr. Roger Carr, also a former astronaut. In addition, Dr. Eugene Worley was unable to serve as panel chairman but continued as a member. Dr. John Glaese of CDy served as panel chairman. The panel members for the third DACR panel are listed below:

Dr. Gerald Carr, Camus, Inc.;

Dr. Daniel DeBra, Stanford University;

Dr. Leonard Meirovitch, Virginia Polytechnic Institute and State University;

Dr. Jerrel Mitchell, Ohio University;

Dr. Eugene Worley, USBI;

Dr. J. Norris Krone, ASAP;

Dr. John Glaese, CDy - Chairman.

The DACR panel meeting was scheduled for April 26 and 27 at the Radisson Suite Hotel in Huntsville, AL. The goal of the meeting was to assess compliance with the previous panel recommendations and to evaluate the current state of the program.

3.3 AGENDA FOR THIRD MEETING

The meeting agenda consisted of descriptive presentations of TSS hardware and problems by MSFC, MMAG and Aeritalia/Italian Space Agency (AIT/ASI) personnel. The agenda of the meeting is listed below:

APRIL 26, 1990

1. Introduction	John Glaese/CDy	8:00 - 8:05
2. Mission Objectives	John Price/MSFC	8:05 - 8:15
3. 1987 Panel Comments and Project Response	Keith Mowery/MSFC	8:15 - 8:30
4. Control Requirements	Keith Mowery/MSFC	8:30 - 8:50
5. Deployer/Orbiter Profile/Soft Stop/Resume	Carl Bodley/MMAG	8:50 - 10:10

Control System Design		
- Control Laws	John Tietz/MMAG	
- Friction	Carl Bodley/MMAG	
- "Tomlin" maneuver	Carl Bodley/MMAG	
Break		10:10 - 10:20
Tool Validation	Zachery Galaboff/MSFC	10:20 - 10:50
Control System Analyses		10:50 - 12:00
- Nominal	John Tietz/MMAG	
- Off Nominal	Carl Bodley/MMAG	
Lunch		
Tests		1:00 - 2:50
- Tether	Carl Bodley/MMAG	
- Software	"	
- Component	"	
- Integrated Hardware	"	
Break		
6. Satellite		3:00 - 5:00
Control System Design	Bruno Musetti/ASI/AIT	
Control System Analysis	Bruna Cibrario/ASI/AIT	
Tests	ASI/AIT	

April 27, 1990

1. Safety/OHSP	Ernie Ress/MMAG	8:00 - 9:30
2. Problems and Solutions	H. Flanders/MMAG	9:30 - 10:00
Break		10:00 - 10:15
3. Operational Plans		10:15 - 11:30
4. Adjournment		
5. Panel working lunch		
6. Panel Deliberations		

3.4 PANEL COMMENTS:

The DACR Panel met in closed session in the afternoon of April 27th. The discussions focused on several concerns. Six items of concern were identified and recommendations were formulated for each. These items and the Panel recommendations are presented in the following:

1. Insufficient resources are being put into solving the skip rope dynamics problem. Analysis indicates there is a significant risk of skip rope developing. The major driver of skip rope oscillations is the interaction of current flowing through the tether with the earth's magnetic field. Skip rope dynamics has the potential to interfere with retrieval of the satellite due to loss of satellite attitude control. Loss of the satellite would be a serious embarrassment to the U. S. space program. The panel members feel it is imprudent to fly the TSS without taking steps to minimize mission sensitivity to skip rope. Finding solutions to the skip rope problems was considered by the panel to be the number 1 priority of the TSS dynamics community.

   Several suggestions were made by the panel members to eliminate the skip rope dynamics problem: 1. Tether current flow control (active control or magnitude limiting) to damp skip rope or reduce its excitation; 2. Orbiter maneuvers such as yaw maneuvers, orbiter translations or rotations; 3. Lateral damping of tether attach point to satellite or boom ("Bungee cord" solution); 4. Anisolastic attach point connection to satellite; 5. Passive angular rate dampers in satellite; and 6. Three axis attitude control of satellite.

2. Deployer friction is not currently well understood. Anomalous friction during the

hardware/software integration tests raised doubts about adequacy of the analysis upon which the mission planning is based. Excessive friction in the deployer has the potential to cause loss of satellite and mission. The panel members believe that existing test data relating to friction should be thoroughly analyzed and understood. A special test program should be conducted to quantify existing friction and expected variations due to environment and other factors. Test data should be correlated with analytical models and differences should be resolved.

3. The simulation validation process should be completed as soon as possible. Simulation tools are currently being used without complete verification to address problems such as those mentioned above. The panel recommends that a target date be set for completion. At the same time adequate resources should be made available to assure that the target date is met and that no shortcuts or expedients are taken. Other simulation and analysis tools need to be considered in the verification/validation process. The software which was used to drive the takeup system for FQT and HSIT during the DRM test phases should be examined or, as a minimum, verification steps taken by the contractor should be reviewed as part of the verification process and adequacy assessed.

4. The test program being carried out by TSS seems to lack focus and direction. It does not seem to be aimed at providing answers to the most pressing questions. Nothing directly addresses skip rope dynamics and nothing directly addresses the adequacy of the system design for achieving docking at the end of the mission. Much is depending on the analytical models. Thus, it comes full circle back to the importance of the verification/validation process. The analysis of the HSIT

anomalies should be completed and all discrepancies should be resolved. The adequacy of the analytical models of the deployer should be assessed based on the test results. Friction or other tether motion anomalies observed during the tests should be reviewed and resolved.

5. Additional testing of TSS hardware should be performed at the John F. Kennedy Space Center (KSC). A full complement of the flight hardware will be assembled for the first time. HSIT activities raised questions about excessive friction in the deployer mechanism. Friction sufficient to stall the vernier motor was noted in some cases, although the duration of the stall was but a few seconds and deployment eventually resumed. This needs to be thoroughly understood and necessary steps undertaken to assure no repeat in flight. Also, HSIT contained sufficient procedural irregularities and glitches to warrant repeating all or selected portions of the DRM test series. A full demonstration of a complete, nominal deployment and retrieval mission along with a soft stop and resume should be performed at KSC with the system assembled for flight and mounted to the flight pallet.

6. The success of the first flight of the TSS depends strongly on the performance of the crew for proper implementation of procedures to control skip rope, manage libration, monitor and evaluate progress of the mission. Because of this extensive crew involvement with the TSS mission it is prudent to begin crew training as early as possible to maximize their familiarity and understanding of the mission.

Additional comments were submitted in writing by Professor Leonard Meirovitch of VPI&SU and Professor Jerrel Mitchell of Ohio University to be included with the report of

DACR Panel activities. These are included as Appendix A.

3.5 IMPACT OF THIRD PANEL MEETING

The findings of the DACR Panel were presented to NASA/MSFC Science and Engineering (S&E) and TSS Project personnel in April and May of 1990. A copy of the presentation is included in this report as appendix B. An accompanying presentation was made by MSFC's Don Tomlin. A copy of this presentation is included as appendix C. A study made by Carl Bodley/MMAG of the anomalous friction behavior observed during HSIT has been documented. This documentation is included in appendix D of this report.

The concerns of the Panel members and their recommendations were seriously considered and acted upon by the TSS Project. The following is a summary of TSS Project actions:

1. Approved additional manpower at MSFC, JSC and MMAG to study skip rope dynamics problems and to develop solutions. The additional manpower has aided in simulation studies of skip rope phenomena allowed design and analysis of the passive skip rope damper. It has also aided in the completion of the verification/validation of the simulation tools used in TSS dynamics analysis.

2. Funded MMAG Design and implementation of a passive skip rope damper to be mounted in the plane of the docking ring. The damper uses low tension negator motors with their inherent hysteresis to provide damping forces on lateral tether oscillations. Simulations show that the damper is effective for tether lengths within 150 - 200 meters and less.

3. Approved implementation of skip rope observer algorithms into ground software at the payload operations control center (POCC). Two observer algorithms have been

developed and tested through engineering codes. The primary observer is a time domain algorithm using Kalman Filtering techniques. The observer filter uses satellite data from the gyros, the horizon sensor and the magnetometers. The secondary observer uses a frequency domain process based on gyro data. The observer outputs are to be used to monitor skip rope amplitude growth and to provide the data to the crew. Procedures are being developed including performance of orbiter maneuvers at the 2.4 km stop position to reduce skip rope amplitude below 20 m. Simulations have shown that amplitudes greater than 20 m result in loss of satellite pitch and roll attitude during passage through the frequency coalescence which occurs at approximately 430 m deployed length.

4. Implemented plans to perform additional TSS hardware tests at KSC including a repeat of the DRM tests.

5. Requested and received approval from the Italian Space Agency and Aeritalia for canting of satellite lateral thrusters in order to provide pitch and roll torques. This gives the crew the capability to damp satellite angular rates, but precludes use of satellite thrusters for libration control (their original purpose) but sufficient capability exists elsewhere to control libration.

4.0 DYNAMICS WORKING GROUP PARTICIPATION

CDy support to the DWG has consisted of participation in the weekly DWG telecons, technical interchange meetings, hardware reviews, performance of selected analyses and simulations and advice to S&E and TSS Project personnel in areas of expertise.

Typical of this kind of activity is our support to the project in analysis of methods for eliminating skip rope oscillations. For example, we demonstrated by simulation that three axis satellite attitude control has the potential to remove most or all skip rope oscillation amplitude by slow retrieval through frequency coalescence. This is the length where skip rope and pendulous frequencies become equal (approximately 430 meters). Transfer of energy and angular momentum from skip rope to satellite is most efficient at this length. It is also the area of most disturbance to the satellite when it is uncontrolled in pitch and roll. As a result of these considerations, an Engineering Change Request (ECR) was written requesting a change to the lateral control thrusters on the satellite. The ECR requested that the side thrusters be canted as much as practical so that they produce pitch and roll control torques for satellite control instead of their original function of libration control. Libration is to be controlled through careful length rate management and orbiter thrusters.

5.0 SKIP ROPE DYNAMICS

The potential severity of skip rope oscillations had been overlooked by NASA and the TSS contractor MMAG. Initially, David Arnold, SAO was alone in pointing out the potential dangers. His contentions based on theoretical arguments and results from SKYHOOK and other SAO simulation tools were contradicted by results produced by MMAG and JSC simulations. Since the MMAG and JSC results seemed to agree with each other and were the most detailed models of the phenomena, those results were assumed to be correct. Still, the theoretical arguments to the contrary were quite strong and convincing. We at CDy conducted an investigation of skip rope dynamics at the request of NASA/MSFC. This was done in collaboration with David Arnold at SAO. Our theoretical analyses and simulation results agreed fundamentally with the SAO observations. Results of this investigation were presented to NASA. A copy of this presentation is included in this report in Appendix E. We and SAO jointly undertook a review of the simulations used by JSC and MMAG to resolve the apparent discrepancy. Their results showed a significant damping of skip rope oscillations, our results showed no such effect. The review was performed with the interested cooperation of these organizations without whose help we could not have proceeded. We first concentrated on the JSC simulation. The tether dynamics models were based on the programs TOSS and GTOSS developed by Dave Lang Associates. Simple run cases were defined to investigate the fundamental property, conservation of angular momentum during tether deployment or retrieval in deep space situations isolated from orbital effects and with such symmetry that the results could be determined entirely from first principles. These results indicated a discrepancy in the TOSS results and pointed to a potential deficiency in the formulation. Arun Misra, working for the summer at SAO in support of David Arnold, was asked to review the formulation of the program and see if he could find a problem. He determined that some terms of the convective derivatives which are required to properly account for tether deployment and retrieval had been left out of the formulation. This seemed to explain the unnatural damping observed in the JSC results because when these terms were added the damping was no longer present. It remained, however, to determine why MMAG results seemed to show the same damping, even though their simulation was formulated independently. As a result of the CDy review of MMAG's Model 3 formulation, it was determined that they also had left out the same type from the convective derivatives from their formulation. Thus, their results were also optimistic with respect to damping of skip rope oscillations and when the correct terms were added the skip rope damping went away so that now all simulations agreed on the amplitude growth of the skip rope oscillation with retrieval.

This agreement and resolution of the model discrepancies was not good news for the project but provided warning and set the stage for subsequent activities to eliminate the skip rope oscillations. This activity is necessary if satellite recovery is to be realized at the end of the mission. It is the characteristic of the skip rope phenomenon that its major impact is on the ability to retrieve the satellite to the docked position. It can cause loss of satellite attitude stability and consequent inability to dock if uncontrolled.

6.0 OVERALL CONCLUSIONS

Three meetings of the DACR Panel have been conducted under the sponsorship of NASA and chaired by CDy since early 1987. These meetings reviewed the hardware and software designs of the major TSS components. Problem areas were identified recommended solutions were developed and provided to TSS Project Management. These recommendations have generally been accepted and acted upon.

In addition, two major tests of TSS engineering and flight units have been conducted to date to demonstrate functionality of the hardware and software. CDy participated in the evaluation of the results of these tests and provided comments to the TSS Project. Deficiencies in the HSIT led to a recommendation for more testing to be performed at KSC.

CDy analyzed selected problem areas of tether dynamics and provided other support to the TSS Dynamics Working Group. Areas of analysis included items such as verification of the severity of the skip rope oscillations, verification or comparison runs to explore dynamic phenomena observed in other simulations, data generation runs to explore performance of the time-domain and frequency-domain skip rope observers and provided other support to the TSS Dynamics Working Group. These efforts contributed to the verification of the primary simulation tools for studying TSS dynamics problems and provided supplemental data for observer verification. CDy also participated in various Technical Interchange Meetings to help define requirements for and test a Passive Damper Device for damping skip rope and participated in Review Meetings to assess damper test results and confirm adequacy of the design.

APPENDIX A

PANEL MEMBER COMMENTS SUBMITTED IN WRITING

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Tethered Satellite System (TSS) Dynamics and Control Review Panel

Some Comments Following the Meeting of April 26 and 27, 1990

Leonard Meirovitch, Member of the Review Panel

May 8, 1990

In addition to the comments made at the final meeting of the panel in the afternoon of April 27, 1990, I would like to submit the following personal opinions and impressions:

The mathematical model of the TSS should consist of the orbiter, the flexible boom, the tether and the satellite. The orbiter and the satellite can be modeled as rigid bodies possessing six degrees of freedom each, three translations and three rotations. The flexible boom can be modeled by two elastic degrees of freedom corresponding to bending about two orthogonal axes. The tether should be modeled as a one-dimensional distributed-parameter system described by an extensional displacement and a transverse displacement. Although in theory each tether displacement implies an infinite number of degrees of freedom, each can be represented by a finite number of degrees of freedom. Consistent with this, the equations of motion for the system constitute a simultaneous set of ordinary and partial differential equations, which can be transformed into a truncated set of ordinary differential equations. Because the system involves in general large rotational motions, the equations are nonlinear. Moreover, during deployment and retrieval they are time-varying due to the varying length of the tether.

During the various presentations, I could see no such complete set of simultaneous equations. Although the STOCS model is supposed to include all the above degrees of freedom, the equations of motion themselves were never presented.

The control design was essentially carried out in the frequency domain, which implies a linear system with constant coefficients. Of course, under certain circumstances, a nonlinear time-varying system can be linearized and regarded temporarily as time-invariant. However, I would have felt better if I saw how the process of approximation was carried out, with the assumptions clearly spelled out. Finally, because the system possess a relatively large number of degrees of freedom, I would have felt more comfortable with a time-domain control design and a corresponding time-domain simulation of the performance of the closed-loop system.

The above comments are not to be interpreted as implying that there are basic flaws in the dynamic analysis and control design. They merely express what I would have liked to see and how I would have approached the problem.

REPORT AND COMMENTS

on the

THIRD TETHER SATELLITE MEETING

held

April 26-27, 1990

at

Raddison Suite Hotel

Huntsville, AL

by

Jerrel R. Mitchell, Ph.D., P.E.
Russ Professor and Chairman
Department of Electrical and Computer Engineering
Ohio University

Athens, OH 45701

will have 90 degrees less phase lag per first order stage of conpensation. The right half w-plane zeros should be eliminated from the controllers. This introduces unnecessary phase lag and invites stability problems. These modifications in the compensation can significantly decrease the amplitude of the limit cycle and may allow the utilization of the measurement of tension in the basic control law. A describing function analysis can be used to predict the outcome. (I would be happy to help with the evaluation of this alternate compensation.)

At this time the full effects of the skip rope mode on the success of the mission are not known. While the effects of the skip rope are being assessed, it is recommended that parallel studies be conducted to determined ways of damping this mode. There are three ways to exert control over this mode: (1) control the current in the tether, (2) control the attitude of the orbiter, and (3) control the attitude of the satellite. The skip rope mode can be measured by measuring the attitude of the satellite or by measuring the attitude of the orbiter. NASA/MSFC has a contractor (at the University of New Orleans) who is presently investigating the measurement of the skip rope mode from rate gyro information on the satellite. It is recommended that a parallel study be conducted for the orbiter. If either of these can provide measurements with sufficient fidelity, it is recommended that feedback control control laws for adding damping to this mode be investigated and evaluated. Since, as mentioned above, there are three ways to control the skip rope mode, parallel studies could be conducted to evaluate the merit of closing loops through each. If it turns out that the skip rope mode is not a problem in regard to jeopardizing the mission, these studies can be aborted. (I would also be happy to get involved with these studies.)

Comments on Testing and Simulations

MMAG has developed the HSIT test facility for validating hardware and software. However, it does not appear that results from this facility have been used to fully validate the TSS system simulation. It is strongly recommended that the results from HSIT and the simulation be closely compared to solve hardware problems and to fine-tune the simulation. Every test run of the HSIT should be simulated prior to the test and discrepancies should be "ironed out". The result will be a hardware test facility and a simulation that can predict what will happen in space and can be of great utility if problems result when the Shuttle/TSS is placed in space and becomes operational.

APPENDIX B

PRESENTATION OF FINDINGS AND RECOMMENDATIONS

FROM THE THIRD DACR PANEL MEETING

APRIL 26 & 27, 1990

AGENDA

- BACKGROUND
- SUMMARY OF THIRD PANEL MEETING
- PANEL CONCERNS AND RECOMMENDATIONS
- CONCLUSIONS

BACKGROUND

- DR. SHERMAN M. SELTZER/CDy ASKED BY NASA TO FORM BLUE RIBBON TETHER PANEL IN LATE 1986
- 1ST AND 2ND PANEL MEETINGS HELD IN MARCH AND JUNE OF 1987
- PANEL MADE RECOMMENDATIONS TO TSS PROJECT
- FOLLOW-UP MEETING HELD 26-27 APRIL 1990 TO ASSESS COMPLIANCE AND TO EVALUATE CURRENT STATE
- EXCELLENT SUPPORT GIVEN BY NASA, MMAG AND AIT/ASI

BACKGROUND (CONTINUED)

- ALL PANEL MEMBERS IN ATTENDANCE
  - DR. GERALD CARR REPLACED DR. OWEN GARRIOTT
  - DR. H. EUGENE WORLEY, PREVIOUS CHAIRMAN, UNABLE TO SERVE AS CHAIRMAN THIS TIME, SERVED AS PANEL MEMBER
  - DR. JOHN R. GLAESE SERVED AS CHAIRMAN

- CURRENT PANEL MEMBERSHIP:
  - DR. GERALD CARR, CAMUS, INC.
  - DR. DANIEL DeBRA, STANFORD UNIVERSITY
  - DR. LEONARD MEIROVITCH, VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY
  - DR. JERREL MITCHELL, OHIO UNIVERSITY
  - DR. H. EUGENE WORLEY, USBI
  - DR. J. NORRIS KRONE, ASAP
  - DR. JOHN R. GLAESE, CONTROL DYNAMICS - CHAIRMAN

SUMMARY OF MEETING

- TOTAL OF 42 ATTENDEES
- 11 PRESENTERS FROM NASA, MMAG, AIT/ASI
- ONE AND ONE-HALF DAYS OF PRESENTATIONS
- ONE-HALF DAY WRAP-UP SESSION
- ONE TO TWO-WEEKS FOR COMPILATION OF PANEL RESPONSES

PANEL CONCERNS AND RECOMMENDATIONS -- 1

SKIPROPE

- INSUFFICIENT RESOURCES ARE BEING PUT INTO SOLVING SKIPROPE DYNAMICS PROBLEMS
  - SKIPROPE HAS POTENTIAL TO CAUSE LOSS OF SATELLITE
  - LOSS OF THE SATELLITE WOULD BE A SERIOUS EMBARRASSMENT TO THE U. S. SPACE PROGRAM
  - FAILURE OF RETRIEVAL WOULD PLACE IN SERIOUS JEOPARDY THE FUTURE USE OF TETHERS IN SPACE

- RECOMMENDATIONS:
  - MAKE FINDING SOLUTIONS TO SKIPROPE PROBLEM NUMBER 1 PRIORITY OF TSS DYNAMICS COMMUNITY
  - PROVIDE ADDITIONAL RESOURCES TO STUDY OF SKIPROPE DYNAMICS
  - IDENTIFY POTENTIAL SOLUTIONS TO SKIPROPE AND DEVELOP IN PARALLEL

CURRENTLY SUGGESTED SOLUTIONS TO SKIPROPE

- TETHER CURRENT FLOW CONTROL
  - ACTIVE CONTROL
  - MAGNITUDE LIMITING

- ORBITER MANEUVERS
  - TRANSLATION
  - YAW MANEUVERS

- LATERAL DAMPING OF TETHER ATTACH POINT - "BUNGEE CORD"

- ANISOLATIC ATTACH POINT

- PASSIVE ANGULAR RATE DAMPERS IN SATELLITE

- THREE AXIS ATTITUDE CONTROL OF SATELLITE

PANEL CONCERNS AND RECOMMENDATIONS -- 2

FRICTION

- FRICTION IN THE TSS DEPLOYER IS INADEQUATELY UNDERSTOOD AND IS A POTENTIAL CAUSE OF MISSION FAILURE
  - EXCESSIVE FRICTION HAS POTENTIAL TO CAUSE LOSS OF MISSION
  - CURRENT TEST RESULTS SHOW ANOMALOUS BEHAVIOR - GREATER THAN EXPECTED FRICTION IN HSIT VS. FQT
- RECOMMENDATIONS:
  - STUDY CURRENT TEST RESULTS, UNDERSTAND NATURE OF OBSERVED FRICTION
  - DEVELOP TEST PROGRAM TO QUANTIFY EXISTING FRICTION AND EXPECTED VARIATIONS DUE TO ENVIRONMENT AND OTHER FACTORS
  - CORRELATE TEST DATA WITH ANALYTICAL MODELS AND RESOLVE DIFFERENCES

PANEL CONCERNS AND RECOMMENDATIONS -- 3

VALIDATION

- DYNAMICS STUDIES ARE BEING PERFORMED AND FLIGHT PROCEDURES DEVELOPED EVEN THOUGH THE VALIDATION PROCESS ON THE PRIMARY ANALYSIS TOOLS IS INCOMPLETE
  - JSC AND MMAG HAVE PRIMARY ANALYSIS TOOLS (STOCS & MODEL 3)
  - TAKEUP REEL CONTROL SOFTWARE DEVELOPED BY MMAG FOR FORMAL QUALIFICATION TEST (FQT) AND INTEGRATION TEST (HSIT) HAS NOT BEEN SUBJECTED TO VALIDATION PROCEDURES

- RECOMMENDATIONS:
  - SET TARGET FOR COMPLETION OF VALIDATION ACTIVITY
  - PROVIDE ADEQUATE RESOURCES TO COMPLETE VALIDATION ON TIME
  - BROADEN SCOPE OF VALIDATION EFFORT TO INCLUDE DYNAMIC MODELS USED IN FQT AND HSIT

PANEL CONCERNS AND RECOMMENDATIONS -- 4

TEST ACTIVITIES

- THE TEST PROGRAM DOES NOT ADDRESS ALL ISSUES OF SIGNIFICANCE TO TSS
  - INSUFFICIENT PRE-TEST SIMULATION TO PREDICT PERFORMANCE, PRE-TEST RUNS MADE FOR FQT BUT NOT HSIT
  - INADEQUATE OR INCOMPLETE POST-TEST ANALYSIS OF RESULTS
  - INCOMPLETE FOLLOW-UP ON ANOMALIES NOTED DURING HSIT

- RECOMMENDATIONS:
  - COMPLETE THE ANALYSIS OF HSIT ANOMALIES AND RESOLVE ALL DISCREPANCIES
  - ASSESS ADEQUACY OF ANALYTICAL MODELS OF DEPLOYER BASED ON TEST RESULTS
  - REVIEW AND RESOLVE ANY REMAINING FRICTION OR OTHER TETHER MOTION ANOMALIES OBSERVED DURING TESTS

CONTROL DYNAMICS COMPANY

PANEL CONCERNS AND RECOMMENDATIONS -- 5

KSC TESTS

- NUMEROUS ANOMALIES AND PROCEDURAL MIX-UPS OCCURRED DURING HSIT WHICH STRESSED OR PERHAPS COMPROMISED THE HARDWARE
  - THERE WERE MIS-WIRED CONNECTORS AND OVERVOLTAGE CONDITIONS ON DELICATE HARDWARE
  - DEBRIS WAS DETECTED IN VITAL LOCATIONS IN THE DEPLOYER
  - EXCESSIVE FRICTION WAS OBSERVED DURING DRM TESTS (PROBABLY DUE TO PREVIOUS TESTS)

- RECOMMENDATIONS:
  - REVIEW AND REFINE HSIT PROCEDURES
  - REPEAT THE DRM TESTS AS PART OF THE SERIES OF TESTS TO BE PERFORMED AT KSC

CONTROL DYNAMICS COMPANY

PANEL CONCERNS AND RECOMMENDATIONS -- 6

TRAINING OF CREW

- TIMELINESS OF OPERATIONAL TRAINING
  - SAFETY DEPENDS ON CREW PERFORMANCE
  - TSS RETRIEVAL DEPENDS ON CORRECT CREW RESPONSES AND FLAWLESS ORBITER PERFORMANCE
  - SOME SKIPROPE FIXES DEPEND ON CREW
- RECOMMENDATIONS:
  - PROVIDE CREW WITH PROCEDURES AND TRAINING EARLY TO MINIMIZE RISK OF MISSION FAILURE

IMPACTS OF IMPLEMENTING RECOMMENDATIONS

- SIGNIFICANTLY INCREASED PROBABILITY OF COMPLETE MISSION SUCCESS
- ENHANCED CONFIDENCE IN TSS HARDWARE
- SOME INCREASE IN PROGRAM COST
- POSSIBLE DELAYS IN SCHEDULE

CONTROL DYNAMICS COMPANY

CONCLUSIONS

- MUCH HAS BEEN ACCOMPLISHED SINCE 1987 PANEL MEETINGS
  - CONTROL SYSTEM SIMPLIFIED
  - CONTROL SYSTEM STABILITY ANALYSES PERFORMED
  - SOFTSTOP AND RESUME LOGIC ADDED
  - SYSTEM BLOCK DIAGRAM CONSTRUCTED
  - SIMULATION VALIDATION PLAN IMPLEMENTED
  - SIGNIFICANT TEST PROGRAM ADDED, INCLUDING COMPONENT AND SYSTEM LEVEL TESTS
  - LOW TENSION OPERATIONS AND SLACK TETHER CONDITIONS INVESTIGATED
  - PASSIVE LIBRATION (YO-YO) CONTROL CAPABILITY ADDED (THOUGH LARGE FRICTION PRESENT IN SYSTEM MAKES THIS OPTION OF LITTLE VALUE)

CONCLUSIONS (CONTINUED)

- THERE IS STILL WORK TO BE DONE TO ASSURE COMPLETELY SUCCESSFUL TSS ONE MISSION
  - SKIPROPE DYNAMICS
  - FRICTION STUDIES
  - VALIDATION COMPLETION
  - COMPLETION OF TEST RESULTS EVALUATION
  - SUFFICIENCY OF KSC FINAL PRE-FLIGHT TEST PROGRAM
  - ADEQUACY AND TIMELINESS OF CREW TRAINING

APPENDIX C

NASA RESPONSE TO PANEL CONCERNS

REVIEW PANEL CONCERN
SKIPROPE SCENARIO

- Skiprope is two lateral oscillations with the proper phase between them.

- Skiprope usually develops at tether lengths greater than 5 km to amplitudes between 25 m and 150 m, usually elliptical.

- It grows slightly during retrieve to 2.4 km and often is near circular.

- It first becomes a problem near 400 m when the satellite's pitch and roll attitudes resonate with skiprope.

- This resonance takes energy out of skiprope but loses control of the satellite attitude.

- The second problem with skiprope occurs under 100 m during retrieve when the skiprope period is decreasing rapidly:

  - P @ 100 m = 12 s, P @ 10 m = 1.3 s, P @ 1 m = .13 s
  - Tension increases due to centrifugal force causing the satellite to prematurely dock

REVIEW PANEL CONCERN
SKIPROPE

- A half amp current at 20 km for 260 seconds can induce a 40 m in-plane lateral oscillation.

- Out-of-plane oscillation will grow with time if current is flowing, because the B field force changes sign.

- Skiprope will grow during retrieve to conserve angular momentum if other dissipative effects are not significant.

- Potential dissipative effects are:

  1. Orbiter roll resonance
  2. Reel motor back EMF
  3. Material damping
  4. Attach point effects
  5. Satellite pitch and roll resonance

REVIEW PANEL CONCERN
STATUS

- Italians are designing canted thrusters on the satellite to damp large rates.
  - Re-evaluation on August 25 will decide to proceed or desist
- Martin conceptualizing a scheme to damp skiprope so that premature docking will not occur. (DWG suspense 11/1/90)
- Studies to assess current flow techniques to reduce response are to be performed. (DWG suspense 8/25/90 on requested current and 11/9/90 on DWG proposal)
- Observability is being assessed using satellite sensors and a docking ring tether motion observer. (DWG suspense 10/1/90 for 20 km and 11/1/90 for 2.4 km)
- Orbiter maneuvers will be recommended if viable. (DWG suspense 10/26/90)
- Dwell at 400 m to allow satellite to absorb skiprope energy. Use satellite canted thrusters to absorb satellite energy. Preliminary results due September 1.
- Skiprope TIM September 17.

REVIEW PANEL CONCERN
SKIPROPE

- o Organization controls being implemented to make best use of resources. Martin and MSFC need reinforcements to prevent reduction in dynamics manpower.
- o ECR's to cant satellite thruster's and to damp skip at short tether lengths has been approved for assessment.
- o Skip added to MSFC's man-in-the-loop simulation to provide flight techniques development for damping satellite attitude and skip.
- o Solutions under consideration
    - Assessing maximum current
    - Reordering experiments
    - Detuning experiments
    - Orbiter maneuvers
    - Deployer-based skip damper
    - Canting satellite thrusters
    - Change Station 2 to 400 m

REVIEW PANEL CONCERN
FRICTION

- The review panel was not made aware of the tests and analyses that has been performed to characterize friction.
- Sensitivity to friction has been elevated since the hardware/software integration test anomaly.
- Thermal Balance Test performed in July reveals that a 10 N margin exists at flyaway. (Vernier motor delivers ~ 30 N.)
- A review of our models reveals that significant cost would be incurred to gain any significant fidelity. Enhancement not recommended; however, we must remain sensitive to this issue and make changes in our models when desirable.

REVIEW PANEL CONCERN
VALIDATION

- NASA Validation Plan will be complete by September 1.

    - A total of 35 simulation comparisons to the plan
    - Eighteen comparisons completed
    - Fourteen have been modified and are being re-examined
    - Three are pending re-examination

- Validation report will be completed October 15.

- The take-up reel's function is to store tether and provide outboard tension. HSIT measurements confirm an adequate tension profile thus validating the take-up reel.

REVIEW PANEL CONCERN
TEST ACTIVITIES

- Martin has provided analysis of Hardware/Software Integration Test (HSIT) data.
- HSIT Post-Mod Functional has been performed.
- Expanded test planned at KSC.
- HSIT and the Thermal Balance Test were compared with the computer simulation.
- Panel meeting held shortly after HSIT before many of the post-test activities were performed. The panel was helpful in getting additional analysis.

REVIEW PANEL CONCERN
SUMMARY

- The panel has been helpful in focusing our activities and recognizing our difficulties with limited resources.
- Solutions for skiprope are evolving.
- Since the panel convened, test results were analyzed and have been used to validate simulations.
- A comprehensive test is planned at KSC to checkout the system when in final configuration for flight.

APPENDIX C

EVALUATION OF DEPLOYER FRICTIONS THROUGH PROCESSING TEST MEASUREMENTS

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APPENDIX D

EVALUATION OF DEPLOYER FRICTIONS THROUGH PROCESSING TEST MEASUREMENTS

Interoffice Memo

MARTIN MARIETTA

August 7, 1990

To: George Cain, Doug Doubek, H. Flanders, Ron Geiger, Fred Greeb, Ray Head, E. Ress, John Tietz

From: Carl Bodley

Subject: Evaluation of Deployer Frictions Through Processing Test Measurements

---

This package describes the approach used to post-process the TSS Deployer test measurements that have been acquired from the beginning of the HSIT (with EDU DACA) series through the Post-Thermal Balance series. The purpose of this post processing is to evaluate Deployer frictions from ambient systen-level testing, such that credible predictions can be made for flight environment margins.

There are eight (8) test runs (low res.) for which I have motor current data and these runs (see Table No 1) are summarized in this memo, showing total lineal friction (for ambient temperature) and friction margin (available for extreme cold effects)

The next 5 pages show development of relationships to be evaluated for post-processing purposes. The remaining graphs of this package show results, wherin friction losses (with windage compensation) are developed and plotted, as well as projected friction margins.

Also attached is the FORTRAN code used to generate the post processed graphical results, for reference, and a complete set of graphs (including "raw, unfiltered" test measurements) is included for the HSIT, Near Field Nominal deployment test run .

Please do not hesitate to contact me if there are questions or concerns at 7-5302

Carl S. Bodley

Tethered Satellite System Test Program

Evaluation of Deployer Frictions Through Processing Test Measurements

Prepared By Carl S. Bodley

August 7, 1990

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NOMENCLATURE

ℓ_R - length of tether spooled from reel, meters

$\dot{\ell}_R$ - time derivative of ℓ_R, meters/sec

$\ddot{\ell}_R$ - 2nd time derivative of ℓ_R, meters/sec^2

ℓ_{MAX} - total length of tether on reel at launch, meters

h - sample period for this series of computations, (data recording rate)

(curr) - electric current in motor windings, amps

f_I - inboard (LTCM) tension, newtons

f_O - outboard (UTCM, coarse) tension, newtons

f_U - friction loss between LTCM & UTCM tensiometers, newtons

ρ - lineal mass density of tether, kg/meter

R - pack radius (from C/L of reel to C/L of outermost tether wrap), meters

R_0 - radius of reel arbor, meters

R_f - pack radius when reel is completely full, meters

sn - SIGN($\dot{\ell}_R$)

pw - pulse width, computed from feed-back control and sent to MCA

J - mass moment of inertia of the reel, tether pack and motor armature, kg-m^2

J_0 - mass moment of inertia of the empty reel and motor armature, kg-m^2

T_{fw} - torque loss due to windage, newton-meters

T_f - torque loss due to windage and mechanical, newton-meters

T_{fM} - torque loss due to mechanical, compensated for windage newton-meters

k_T - reel motor motor constant, newton-meters/amp

T_2/R_2 - output of the vernier motor, newtons

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Consider, with reference to the following figure and the list of nomenclature, the following relationships --

1) $$\mathrm{sn}\, f_U = f_0 + T_2/R_2 - f_1$$

2) $$\mathrm{sn}\, T_f = R f_1 - \frac{J}{R}\ddot{\ell}_R - k_T(\mathrm{curr})$$

3) $$R^2 = R_0^2 + (R_f^2 - R_0^2)(\ell_{MAX} - \ell_R)/\ell_{MAX}$$

4) $$J = J_0 + \frac{\rho}{2}(\ell_{MAX} - \ell_R)(R_0^2 + R^2)$$

and given the data values for the following parameters:

T_2/R_2	= scheduled with time and $\dot{\ell}_R$, max value of 31.4 n-m
R_0	= 0.0619125 m
R_f	= 0.181 m
ρ	= 0.00835 kg/m
k_T	= 2.028 n-m/amp
ℓ_{MAX}	= 22,000 m
J_0	= 4.18 kg-m^2

The following test data are available for processing purposes --

5) ℓ_R, $\dot{\ell}_R$, (curr), f_1, f_0 and pw

Now, the lineal acceleration is estimated as the first order difference

6) $$\ddot{\ell}_{R_1} = (\dot{\ell}_{R_1} - \dot{\ell}_{R_0})/h$$

The motor speed as used in the following equation (9), is

7) $$\mathrm{RPM} = \left|(\dot{\ell}_R/R)(60./2\pi)\right|$$

The torque loss due to windage (from Feb. 1989 SSL ETO testing) is

9) $$T_{fw} = 0.07821 + 0.0018076(\mathrm{RPM}) + 0.000026489(\mathrm{RPM}^2)$$

It now follows that the mechanical friction torque loss (having compensated for windage loss) is

10) $$T_{fM} = T_f - T_{fw}$$

The electric torque (compensated for windage) is

11) $$T_e' = T_e + sn\,T_{fw} = k_T(\text{curr}) + sn\,T_{fw}$$

The compensated pulse width is thus computed from the compensated electric torque in the standard fashion (see the attached FORTRAN listing).

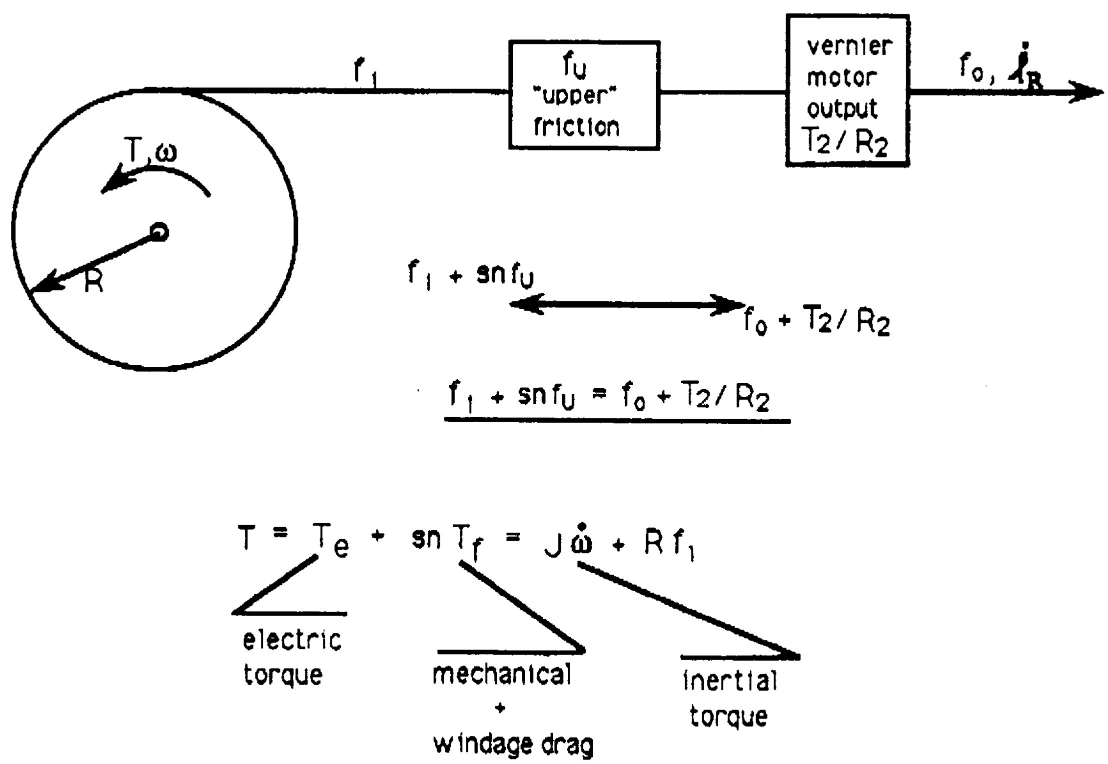

Figure 1 Schematic For Developing Friction Force/Torque Relationships

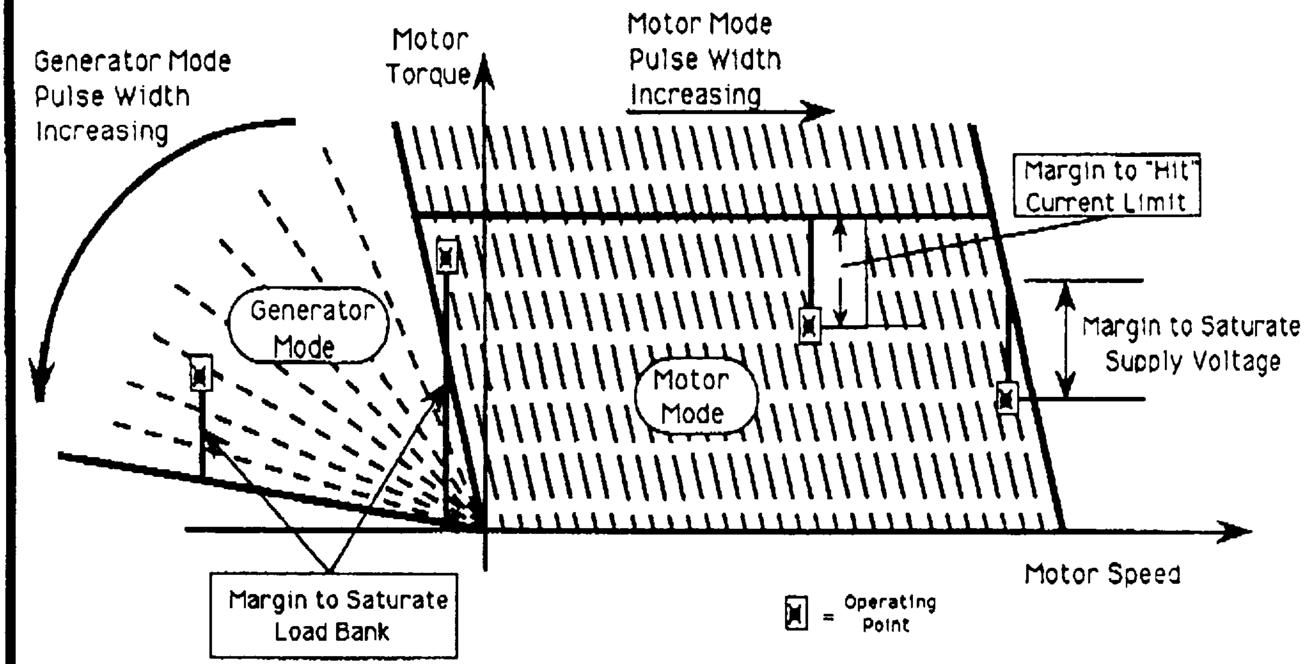

Figure 2 Torque vs Speed Showing Operating Margins

The electric torque (compensated for windage), as expressed by eq. 11, is considered as an operating point on the Torque-Speed graph, of the above Figure 2. There are 4 typical operating points indicated for 4 particular situations (two for deployment, with motor speed negative and two for retrieval, with motor speed positive). The figure clearly indicates the electric torque available (up to current limit or "saturation" of supply voltage) when in motor mode. Also the electric torque that can be "dumped" is indicated as margin to saturate the load bank.

These margins represent torque available for additional friction that would be present at extreme cold temperatures on orbit.

The summary friction graphs of this package show the equivalent lineal friction as a total loss, corresponding to ambient temperature. The total loss has included a conservative estimate of the (bugle-head) + (last outboard pulley) loss. This additional "upper-upper" loss could not be accounted for in the test setup, thus was conservatively assumed to be 7.2-newtons at max. outboard flight tension, and was linearly scheduled with measured outboard tension. Thus, the summary results (which show the difference between ambient actual and available) represent conservatively projected flight frictions, for the case of ambient temperature.

Listing of the FORTRAN Code Used to Post Process Test Measurements

```
      PROGRAM FRITA
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
C
      COMMON /VRNDTA/ TSRMP,RMPT
C
 1001 FORMAT (16I5)
 1002 FORMAT (3X,7F9.2)
 2001 FORMAT (11E14.6)
C ---
      OPEN (UNIT= 5,FILE='frita.inp')
      OPEN (UNIT= 9,FILE='frita.raw')
      OPEN (UNIT=10,FILE='frita.wrk')
      OPEN (UNIT=15,FILE='frita.t1 ')
      OPEN (UNIT=16,FILE='frita.t2 ')
      OPEN (UNIT=17,FILE='frita.t3 ')
C ---
      RV2    =      .0508
      ROW    = .00835
      ALMAX  = 22000.
ccccccc
cc  data for edu deployer sys.
      RO     = .078317
      RF     = .1879
      AKT    = 1.968
ccccccc
cc  data for flight deployer sys.
      RO     = .0619125
      RF     = .181
      AKT    = 2.028
ccccccc
C
      CURLIM = 5.5
      TRQLIM = CURLIM*AKT
C
      RESM   = 1.
      RESLB  = 35.
      TEST   = 1.D0 + RESM/RESLB
      VSUP   = 23.D0
      AJ0    = 4.18
      C0     = .07821
      C1     = .0018076
      C2     = .000026489
      PI     = DATAN2(0.D0,-1.D0)
      TUPI   = 2.D0*PI
C
      ALRD0 = 0.
      R02   = R0*R0
      RF2   = RF*RF
C ---
      READ (5,1001) NT,NA,LF
      READ (5,1002) H, TSRMP, RMPT
C
      IF (LF .EQ. 0) THEN
        CALL AVG (NA,NT)
        STOP
      ENDIF
C
      REWIND 10
C
      DO 100 I=1,NT
```

```
      READ (10,1002) T,ALR,ALRD,CURR,FI,FO,PW
      SGN = DSIGN(1.D0,ALRD)
      R2 = R02 + (RF2 - R02)*(ALMAX - ALR)/ALMAX
      AJ = AJ0 + (ROW/2.D0)*(ALMAX - ALR)*(R02 + R2)
      R  = DSQRT(R2)
      ALRDD = (ALRD - ALRD0)/H
      ALRD0 = ALRD
      CALL VRNIER (T,ALRD,T2OR2)
      SNFU = SGN*(FO + T2OR2 - FI)
      RPM = DABS(ALRD/R)
      RPM = (60.D0/TUPI)*RPM
      TFW = C0 + C1*RPM + C2*RPM*RPM
      TRMAJ = -AJ*ALRDD/R
      SNTF  = SGN*(R*FI + TRMAJ - AKT*CURR)
      TFM   = SNTF - TFW
C
      TE     = AKT*CURR + SGN*TFW
      VC = RESM*TE/AKT - AKT*ALRD/R
      MGM = 1
      OMM1 = -ALRD/R
      IF (VC .LT. 0.D0) MGM = 0
C
      IF (MGM .EQ. 1) THEN
        IPW = (VC/VSUP)*511.
        IF (IPW .GT. 511) IPW = 511
C
      ELSE
        IF (-VC .LT. .0001D0) VC = -.0001D0
        RATIO = AKT*OMM1/VC
        IF (RATIO .LT. TEST) RATIO = TEST
        RESL = RESM/(RATIO - 1.D0)
        IPW = -DSQRT(RESL/RESLB)*511.
      ENDIF
      PW1 = IPW
C
      RPM2 = (60.D0/TUPI)*ALRD/RV2
C
      IF (OMM1 .LE. 0.D0) TRQSAT = -AKT*AKT*OMM1/(RESM + RESLB)
      IF (OMM1 .GT. 0.D0) TRQSAT = AKT*(VSUP - AKT*OMM1)/RESM
      IF (TRQSAT .GT. TRQLIM) TRQSAT = TRQLIM
      IF (TRQSAT .LT.   0.D0) TRQSAT = 0.D0
      DTRQ  = TRQSAT - TE
      IF (OMM1 .LE. 0.D0) DTRQ = -DTRQ
      FRUPUP = (7.2D0/70.D0)*FO
      TREDGE = TFM + DTRQ + R*SNFU
      FREDGE = TREDGE/R
      TRFAMB = TFM + R*(SNFU + FRUPUP)
      FRFAMB = TRFAMB/R
      DELR   = TREDGE - TRFAMB
      DELL   = FREDGE - FRFAMB
C
CC    WRITE (15,2001) T,R,RPM,TRMAJ,SNFU, TFW,SNTF,TFM, PW,PW1
CC
      WRITE (15,2001) T,R, TFW,SNTF,TFM, PW,PW1
      WRITE (16,2001) T,ALRD,T2OR2,RPM2, SNFU,TE
      WRITE (17,2001) T,TREDGE,TRFAMB,DELR, FREDGE,FRFAMB,DELL
  100 CONTINUE
C
      STOP
      END
```

```fortran
      SUBROUTINE VRNIER (T,ALRD,T2OR2)
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
CC
CC    CODED BY CARL BODLEY, SPRING 1987
CC    REVISED TO INCLUDE SLOPE OF CURRENT LIMIT LEG,
CC               JUNE 1990 .....
CC
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      SAVE
C
      COMMON /VRNDTA/ TSRMP,RMPT
C
      DATA IT2, I1ST  / 1, 0 /
C
      IF (I1ST .EQ. 0) THEN
        I1ST = 1
        R2   = 0.0508
        VV   = 21.0
        AKBV = 0.326
        AKTV = 0.326
        RESV = 0.9
        AMPL = 4.896
        SLOPE = -0.00378
        T2L = AKTV*AMPL
        T2S = VV*AKTV/RESV
        ST2 = -AKTV*AKBV/RESV
      ENDIF
C
      T2OR2 = 0.D0
      IF (IT2 .EQ. 0) RETURN
C
      T2SV = T2S
      IF (T .GE. TSRMP) T2SV = T2S*(1.D0 - (T - TSRMP)/RMPT)
      IF (T .GE. TSRMP+RMPT) IT2 = 0
      OM  = ALRD/R2
      OMC = (T2SV - T2L)/(SLOPE - ST2)
      T2 = T2L + SLOPE*OM
      IF (OM .GT. OMC) T2 = T2SV + ST2*OM
      IF (T2 .LE. 0.) IT2 = 0
      IF (IT2 .EQ. 0) T2 = 0.D0
C
      T2OR2 = T2/R2
C
      RETURN
      END
```

```
      SUBROUTINE AVG (NA,NT)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      SAVE
C
      DIMENSION A(100,7), U(7), V(7)
C
 1002 FORMAT (3X,7F9.2)
C ---
      NA1 = NA - 1
      DO 20 L=1,NA
      READ (9,1002) (A(L,J),J=1,7)
   20 CONTINUE
C
      CALL AVGF (A,NA,7,V)
      WRITE (10,1002) (V(J),J=1,7)
C
      NT = NT - NA
      DO 100 I=1,NT
C
      READ (9,1002) (U(J),J=1,7)
      DO 50 L=1,NA1
      LP1 = L + 1
      DO 50 J=1,7
   50 A(L,J) = A(LP1,J)
      DO 55 J=1,7
   55 A(NA,J) = U(J)
C
      CALL AVGF (A,NA,7,V)
      WRITE (10,1002) (V(J),J=1,7)
  100 CONTINUE
C
      NT = NT + 1
      END
```

```
      SUBROUTINE AVGF (A,NA,NV,V)
      IMPLICIT DOUBLE PRECISION (A-H,O-Z)
      SAVE
C
      DIMENSION A(100,7), V(7)
C
      DO 5 J=1,NV
    5 V(J) = 0.D0
C
      DO 10 I=1,NA
      DO 10 J=1,NV
   10 V(J) = V(J) + A(I,J)
C
      DO 15 J=1,NV
   15 V(J) = V(J)/FLOAT(NA)
C
      RETURN
      END
```

Complete Set Of Graphical Results for
Near Field EMI NominalDeployment

(for reference purposes)

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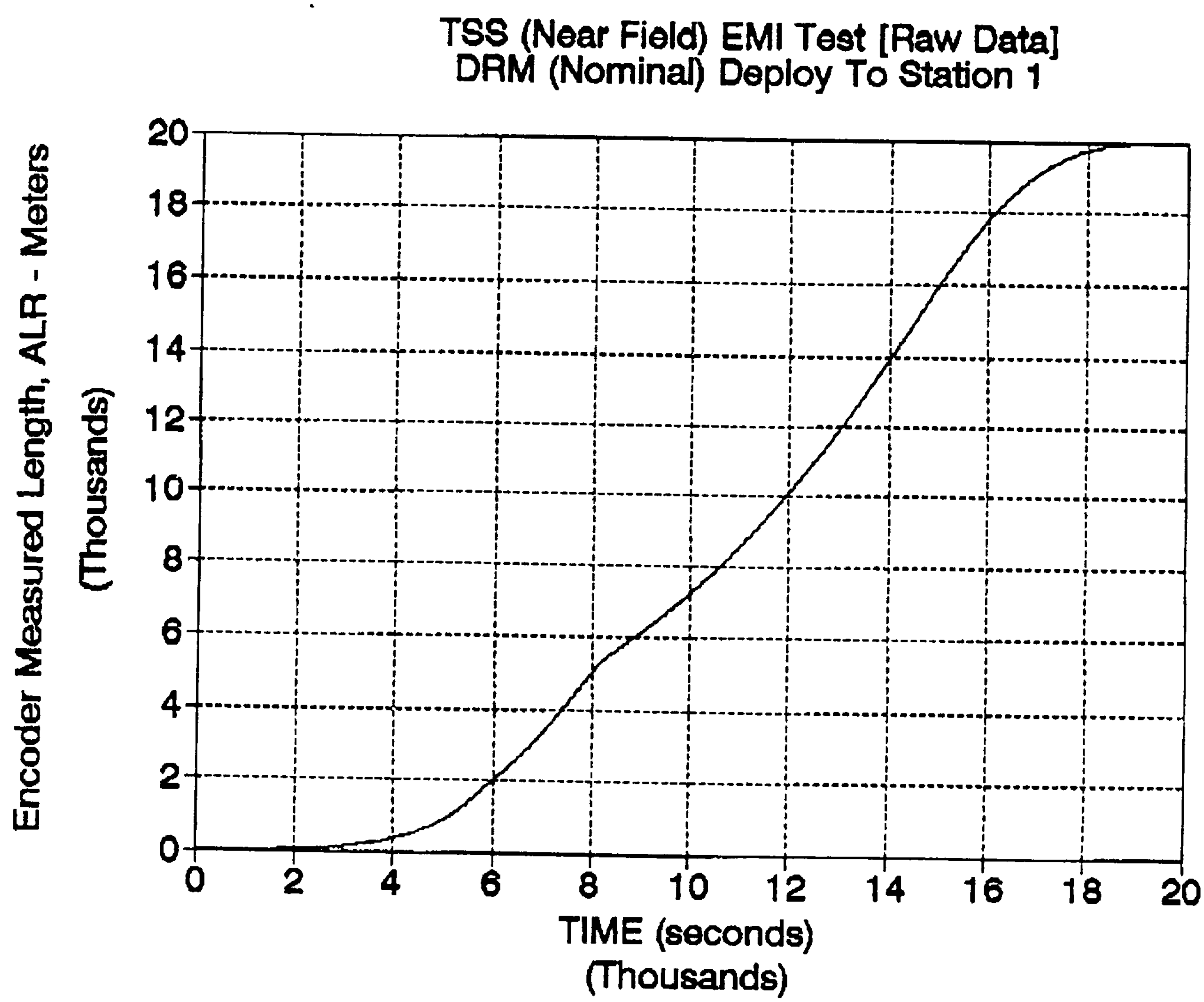
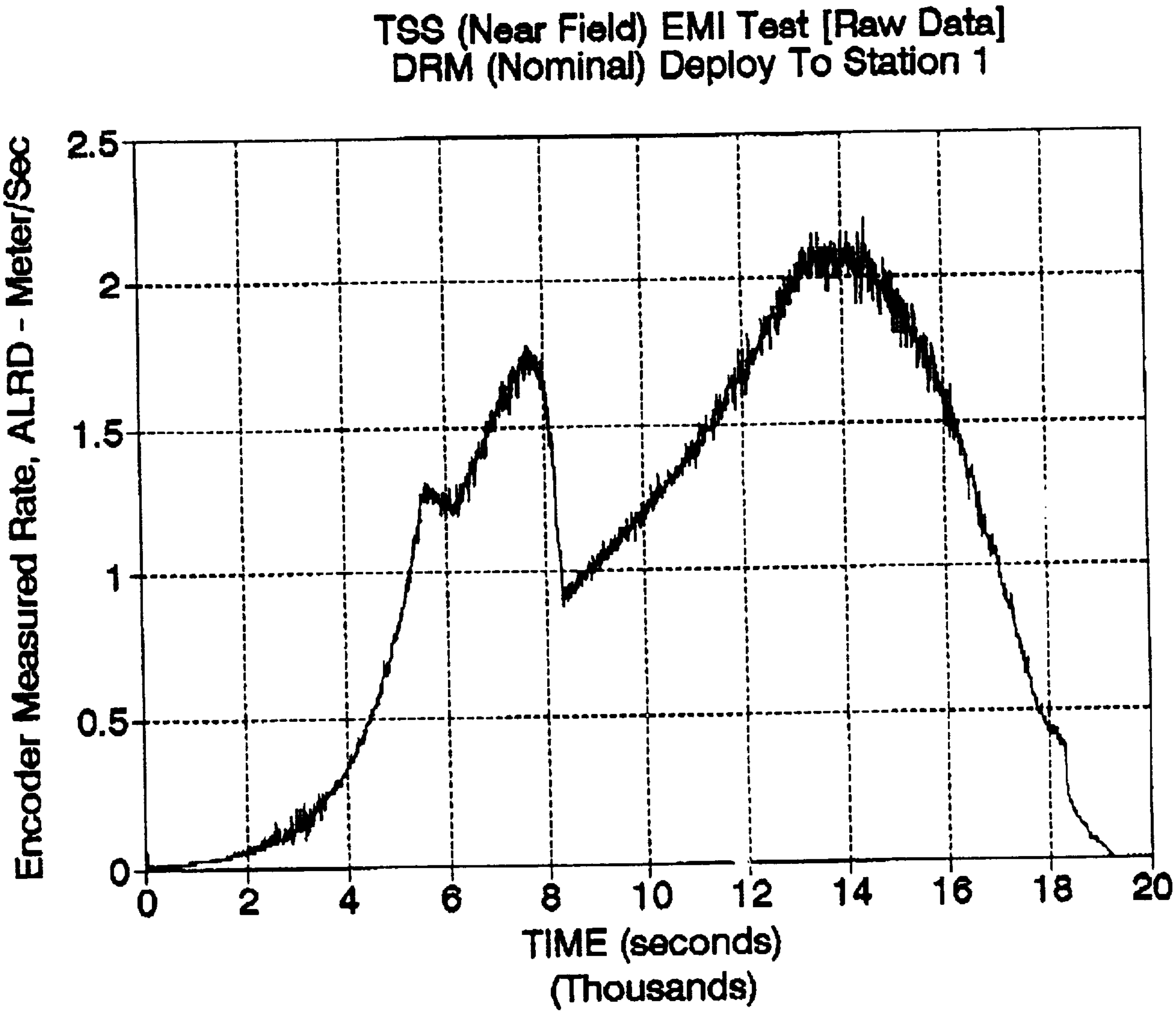
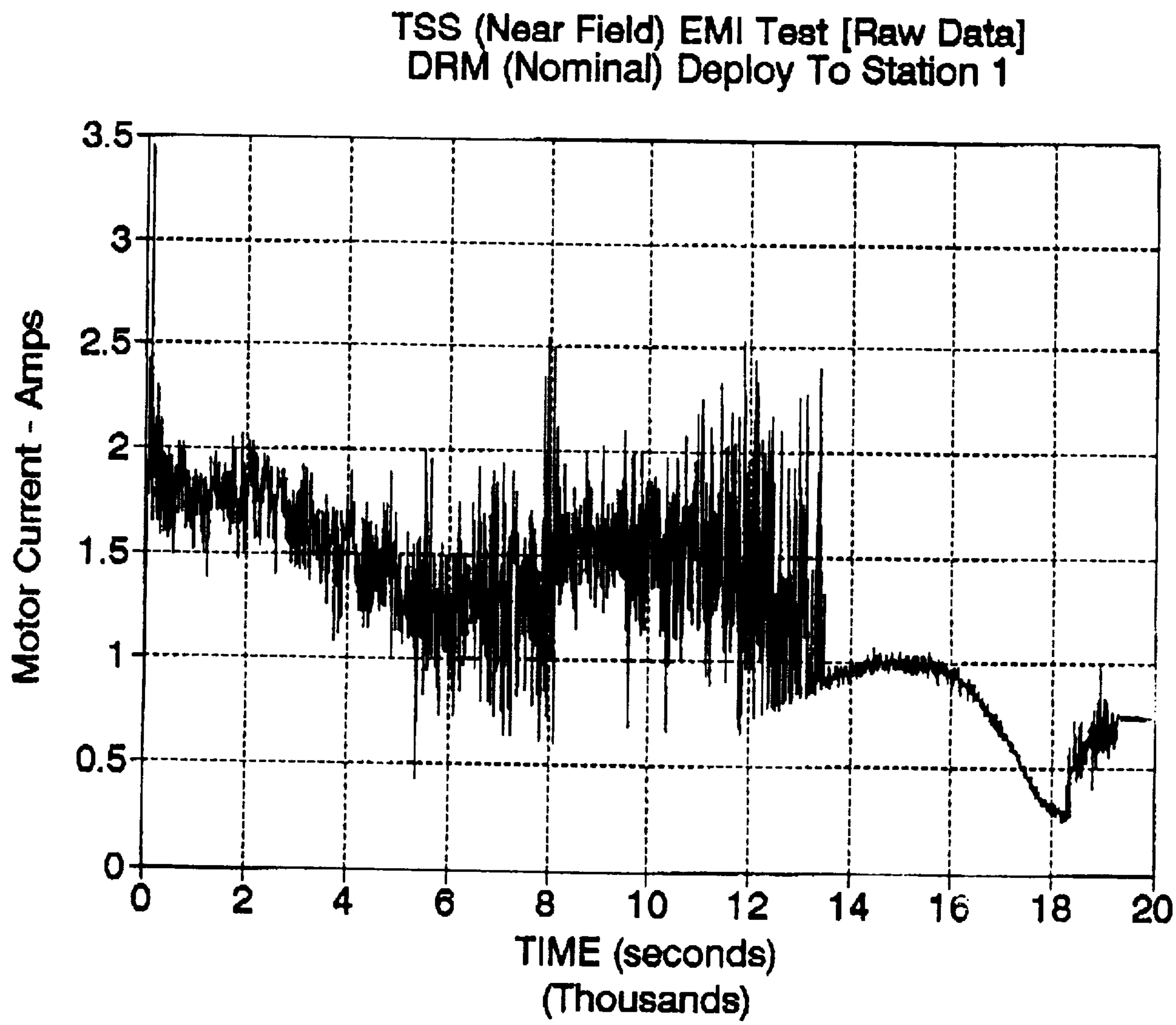
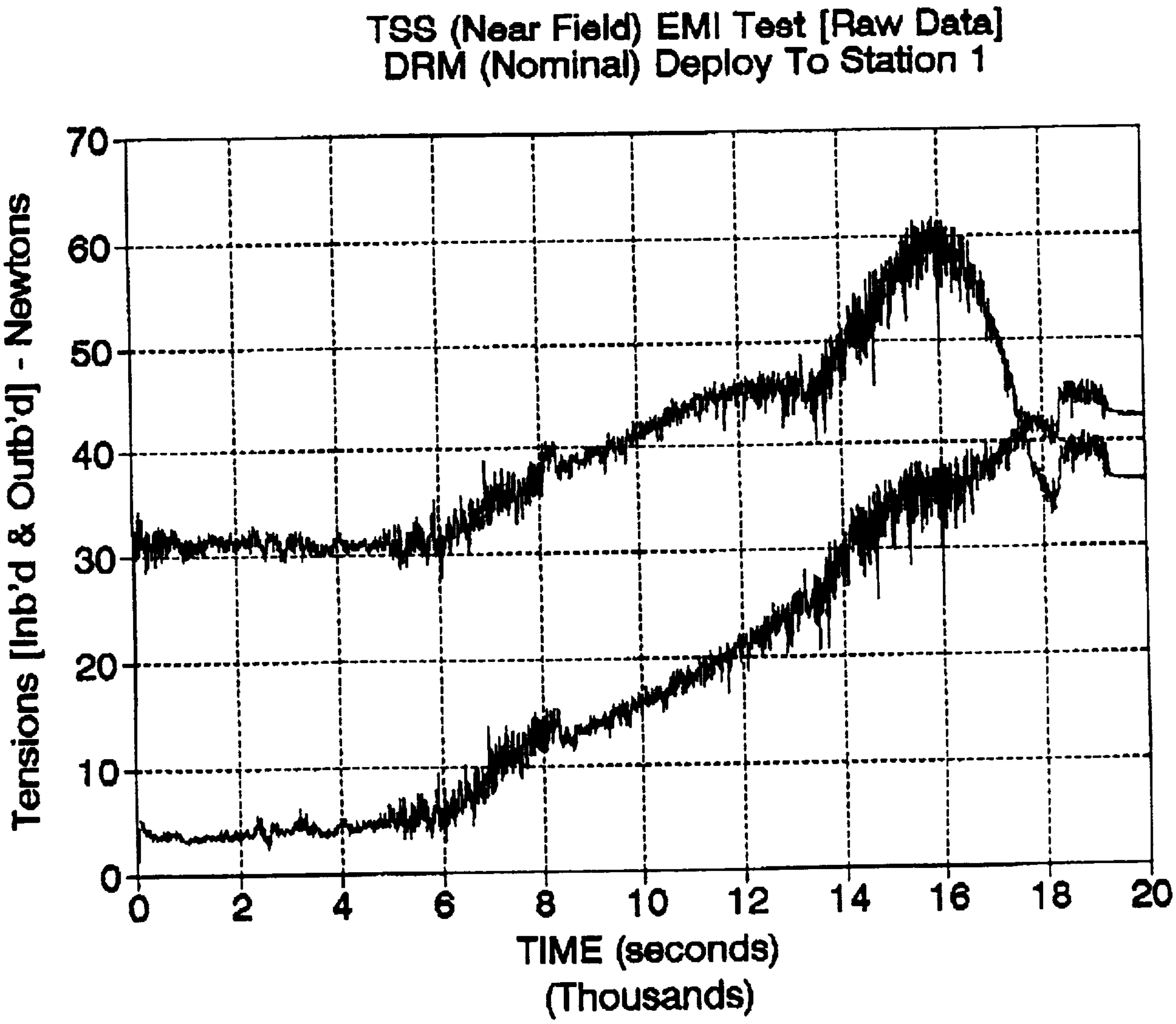
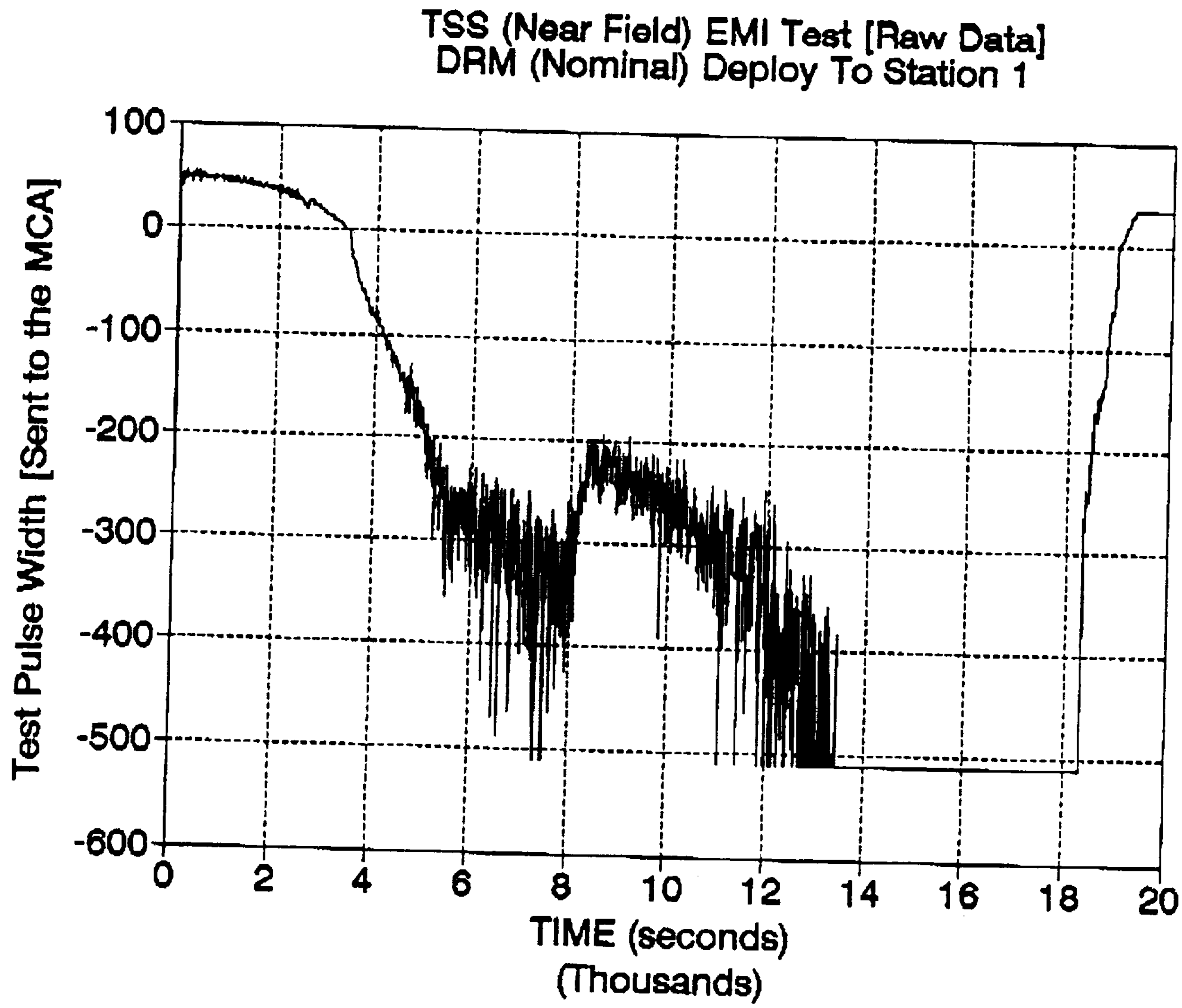

TSS (Near Field) EMI Test [Raw Data]
DRM (Nominal) Deploy To Station 1
Encoder Measured Length, ALR - Meters
(Thousands)
0
2
4
6
8
10
12
14
16
18
20
TIME (seconds)
(Thousands)

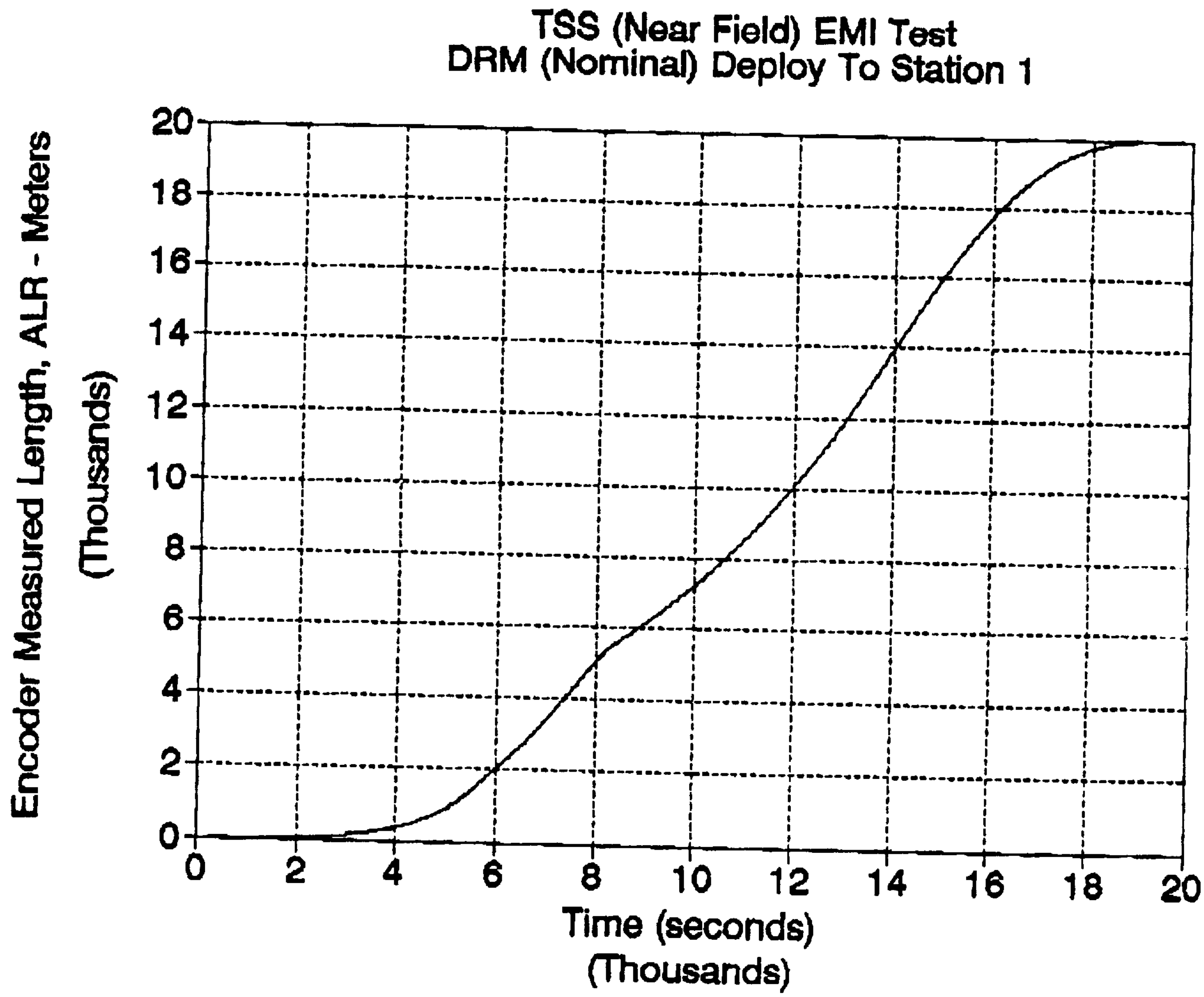

TSS (Near Field) EMI Test [Raw Data]
DRM (Nominal) Deploy To Station 1
Encoder Measured Rate, ALRD - Meter/Sec
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
TIME (seconds)
(Thousands)

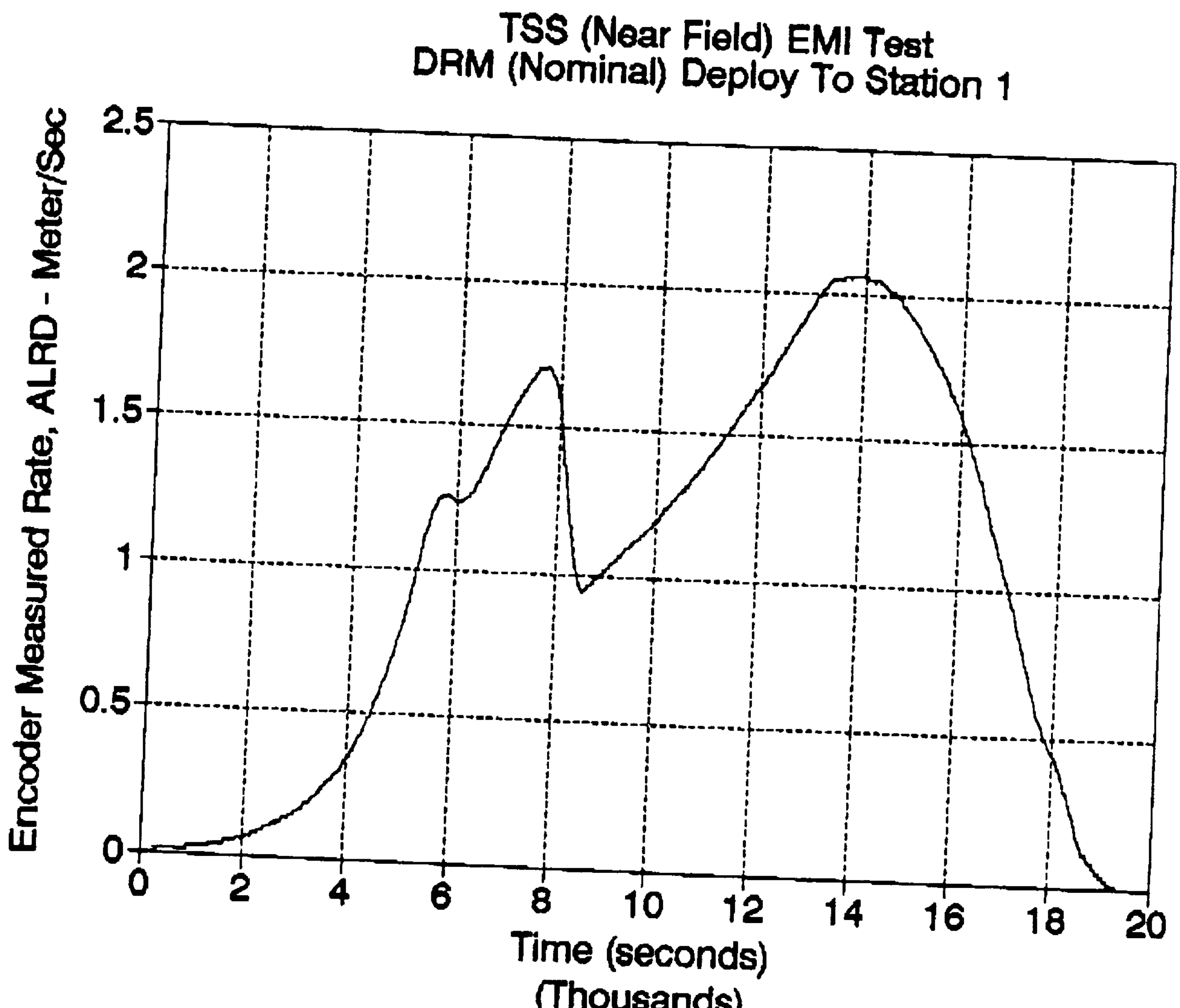


TSS (Near Field) EMI Test [Raw Data]
DRM (Nominal) Deploy To Station 1
Motor Current - Amps
3.5
3
2.5
2
1.5
1
0.5
0
0 2 4 6 8 10 12 14 16 18 20
TIME (seconds)
(Thousands)


TSS (Near Field) EMI Test [Raw Data]
DRM (Nominal) Deploy To Station 1
Tensions [Inb'd & Outb'd] - Newtons
70
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
TIME (seconds)
(Thousands)

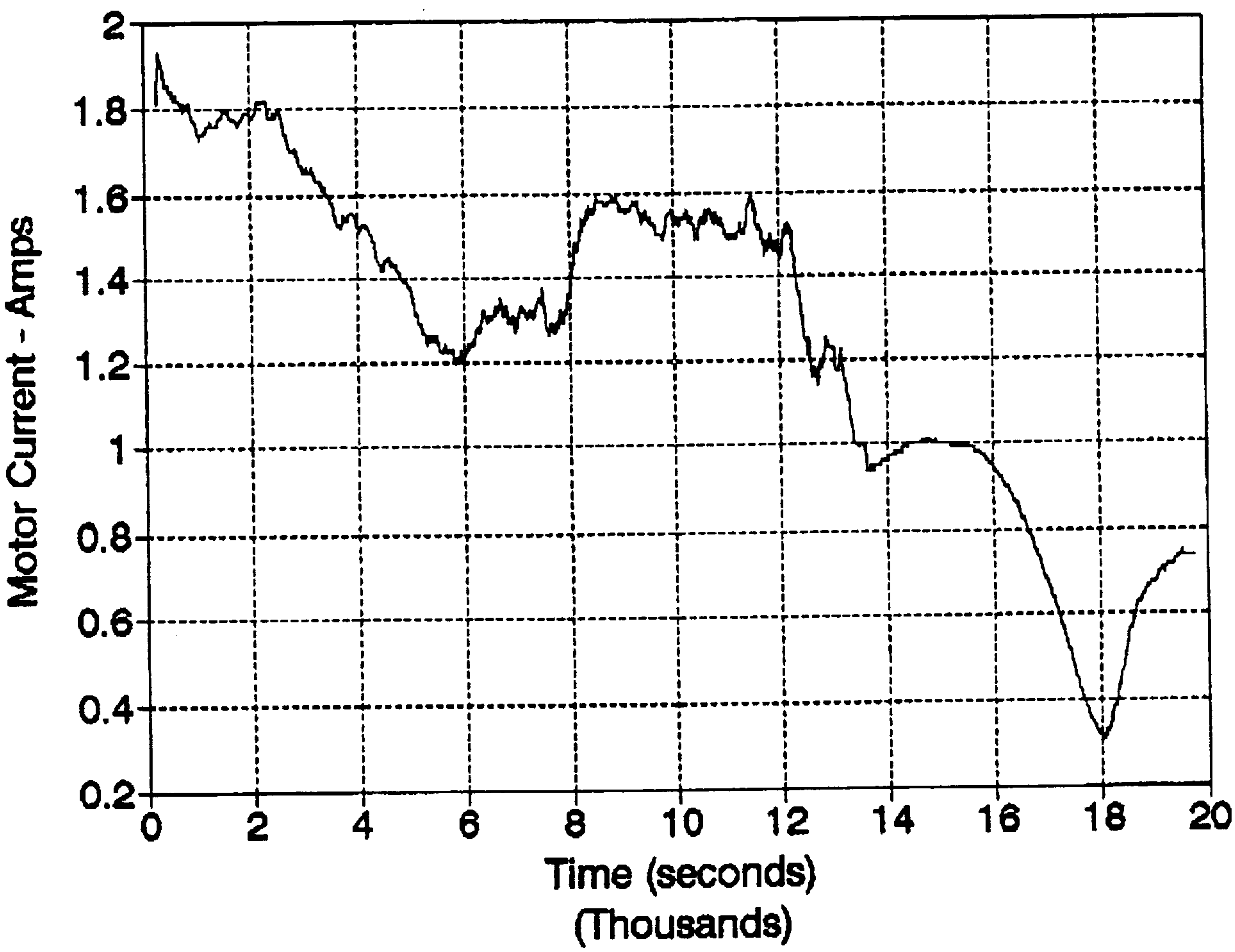

TSS (Near Field) EMI Test [Raw Data]
DRM (Nominal) Deploy To Station 1
Test Pulse Width [Sent to the MCA]
100
0
-100
-200
-300
-400
-500
-600
0
2
4
6
8
10
12
14
16
18
20
TIME (seconds)
(Thousands)

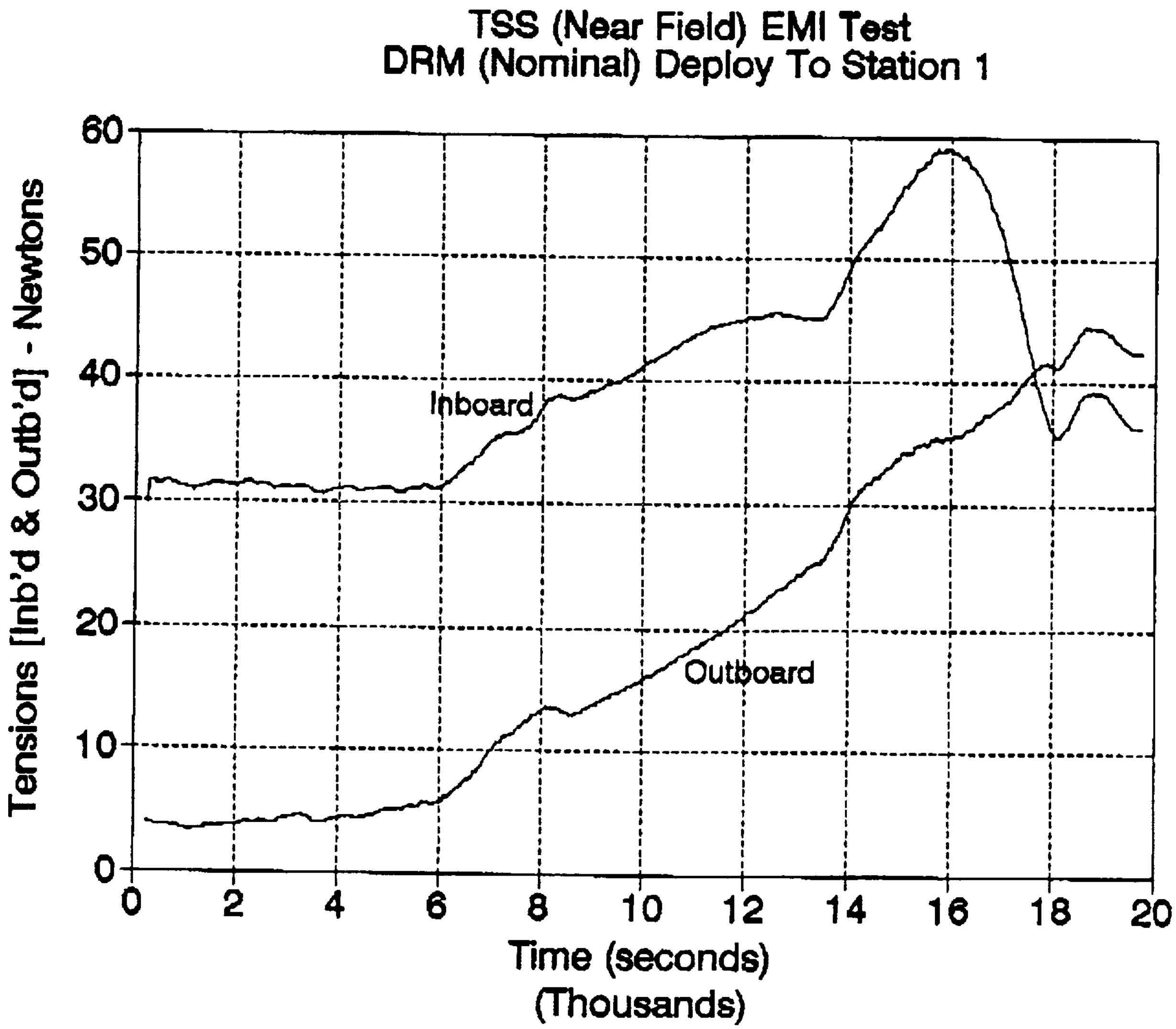

TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Encoder Measured Length, ALR - Meters
(Thousands)
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)

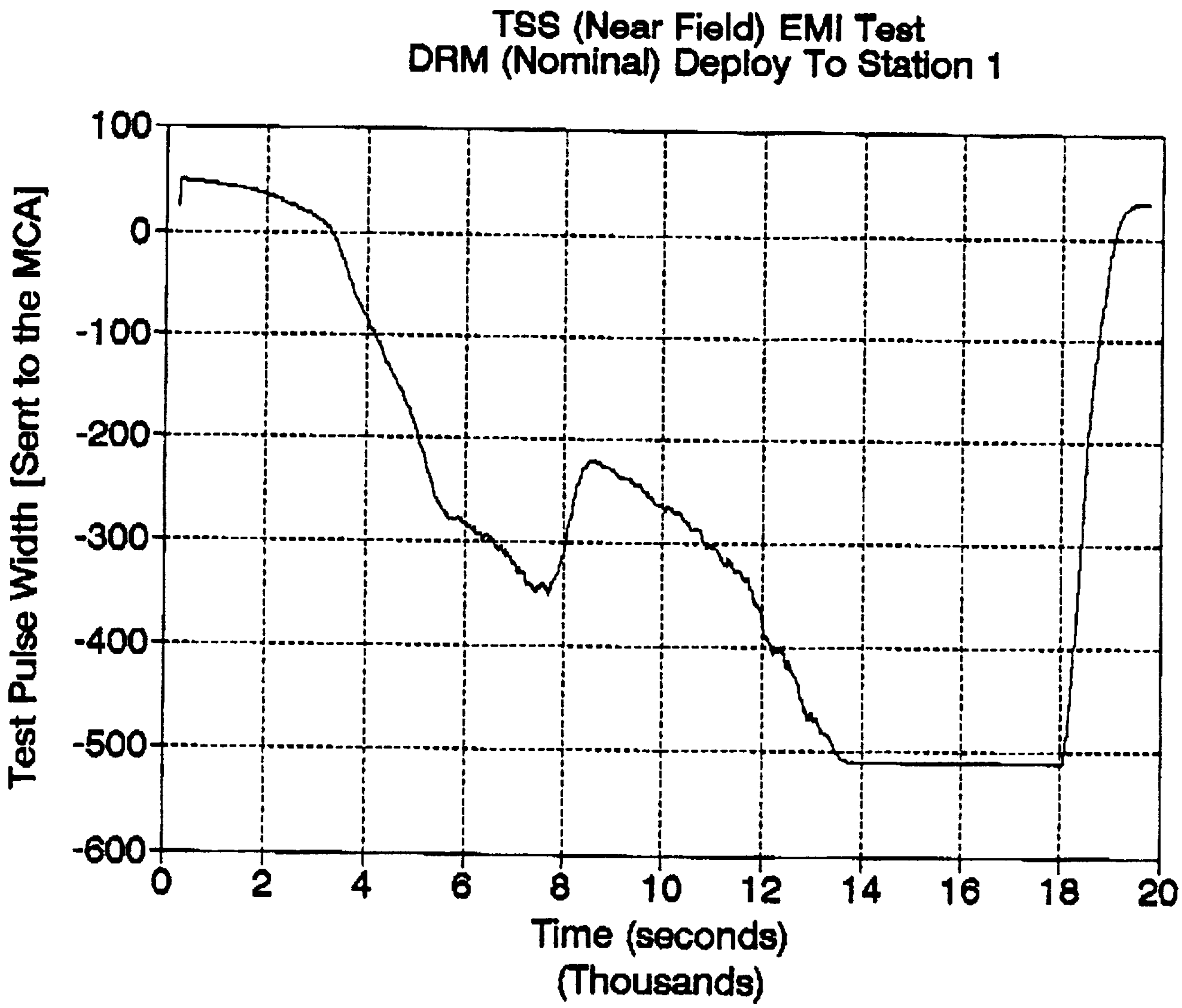


TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Encoder Measured Rate, ALRD - Meter/Sec
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)

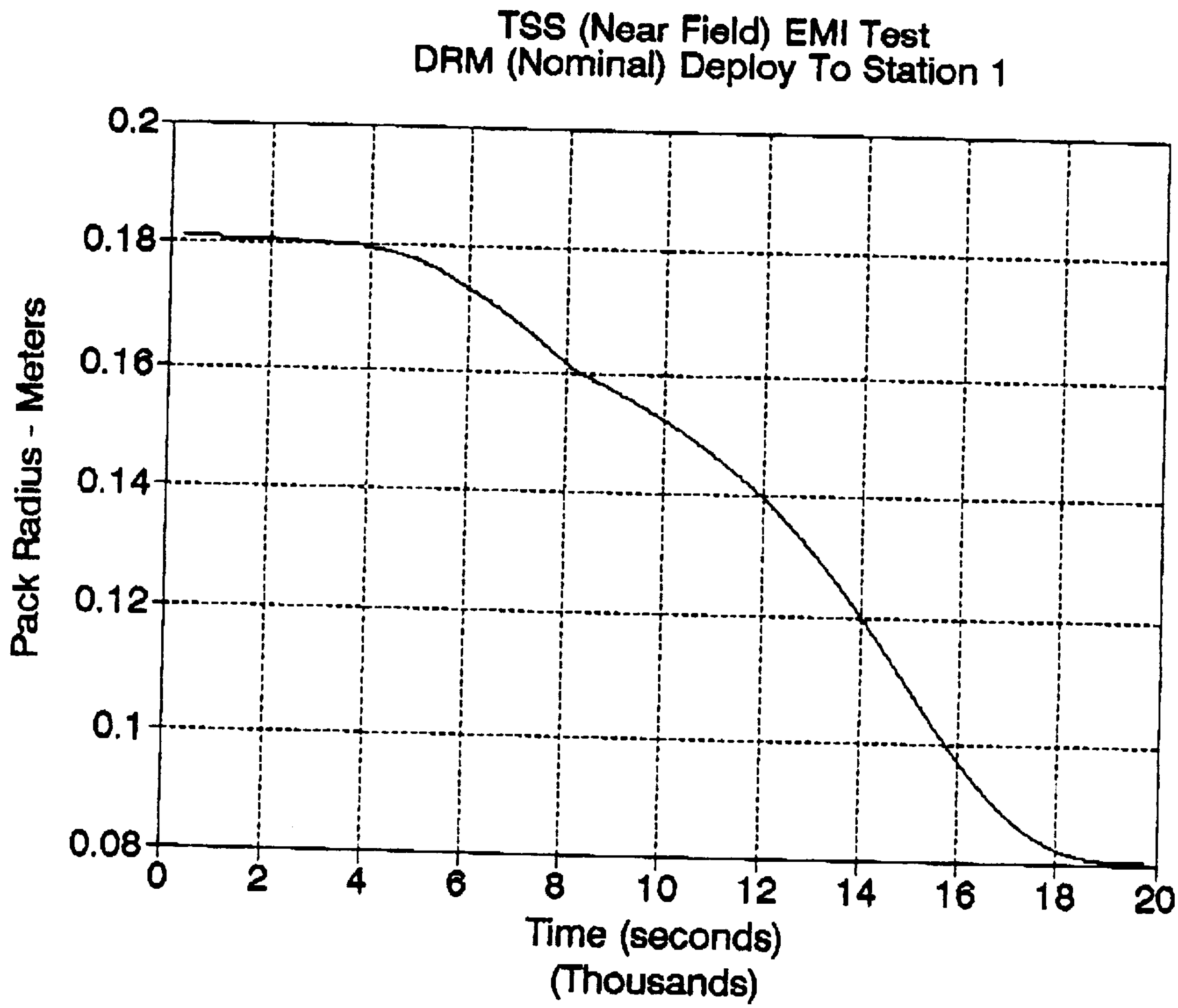
TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1

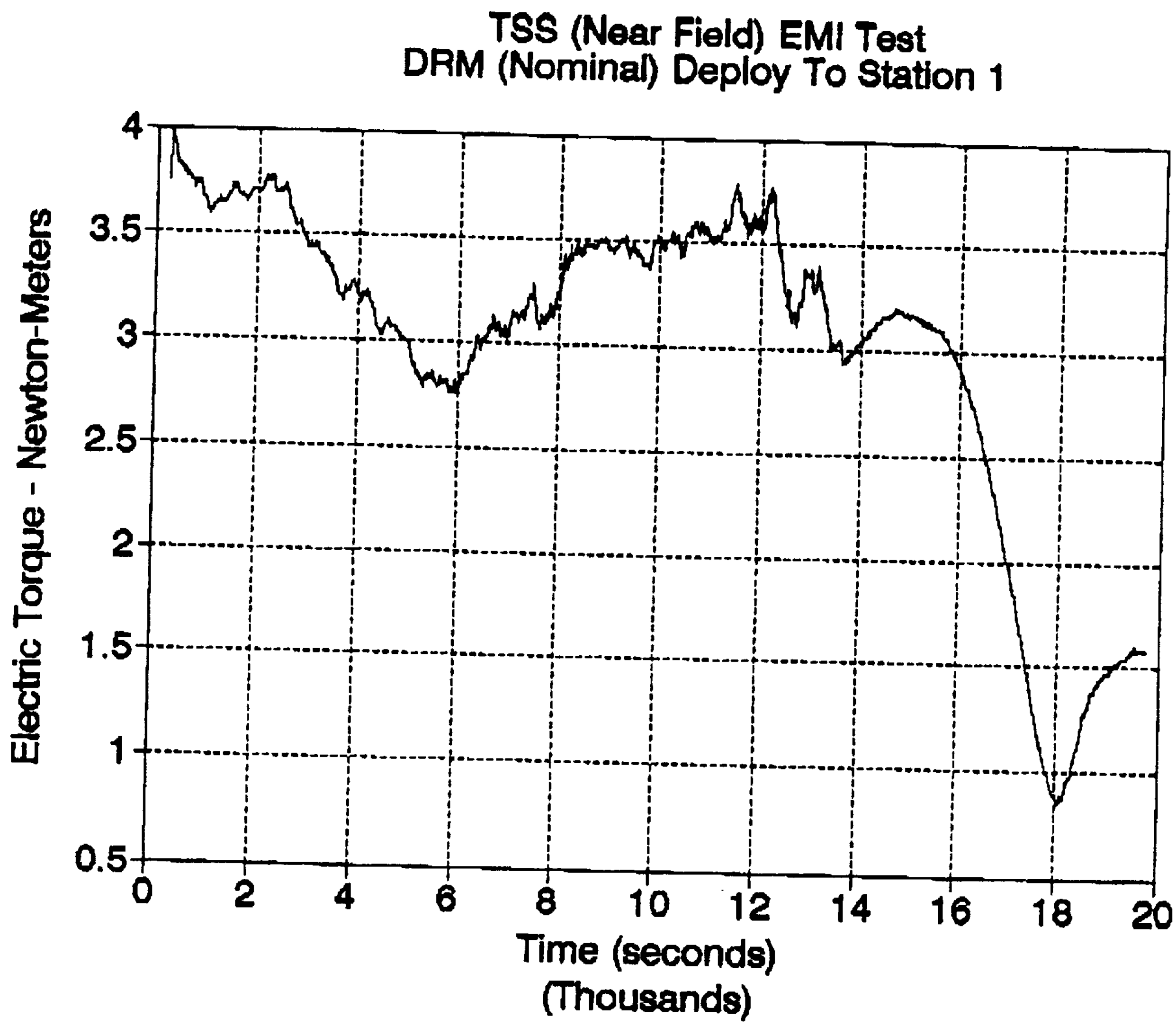



TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Tensions [Inb'd & Outb'd] - Newtons
Time (seconds)
(Thousands)
Inboard
Outboard
0
10
20
30
40
50
60
0
2
4
6
8
10
12
14
16
18
20

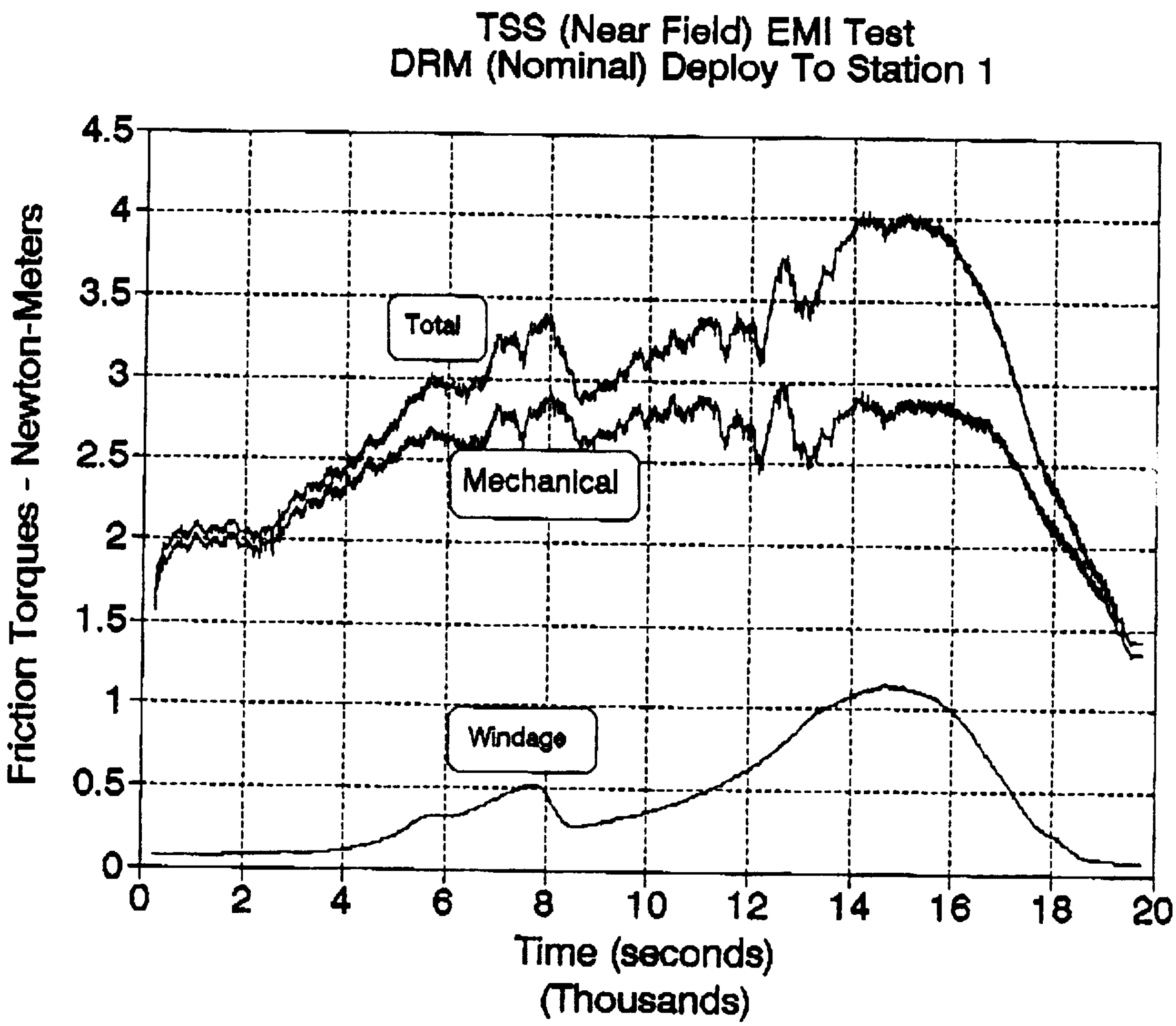


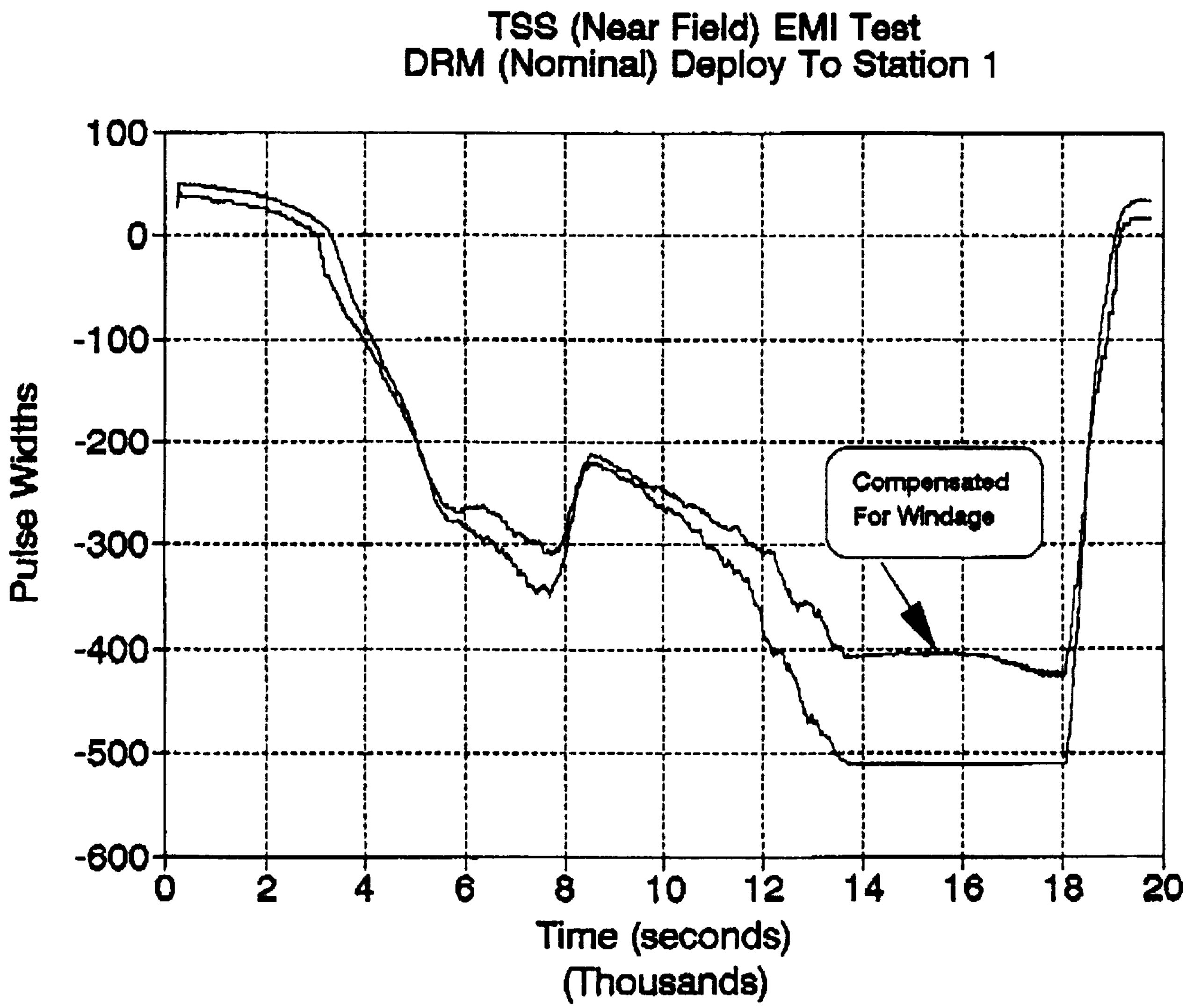
TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Test Pulse Width [Sent to the MCA]
100
0
-100
-200
-300
-400
-500
-600
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)


TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Pack Radius - Meters
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)

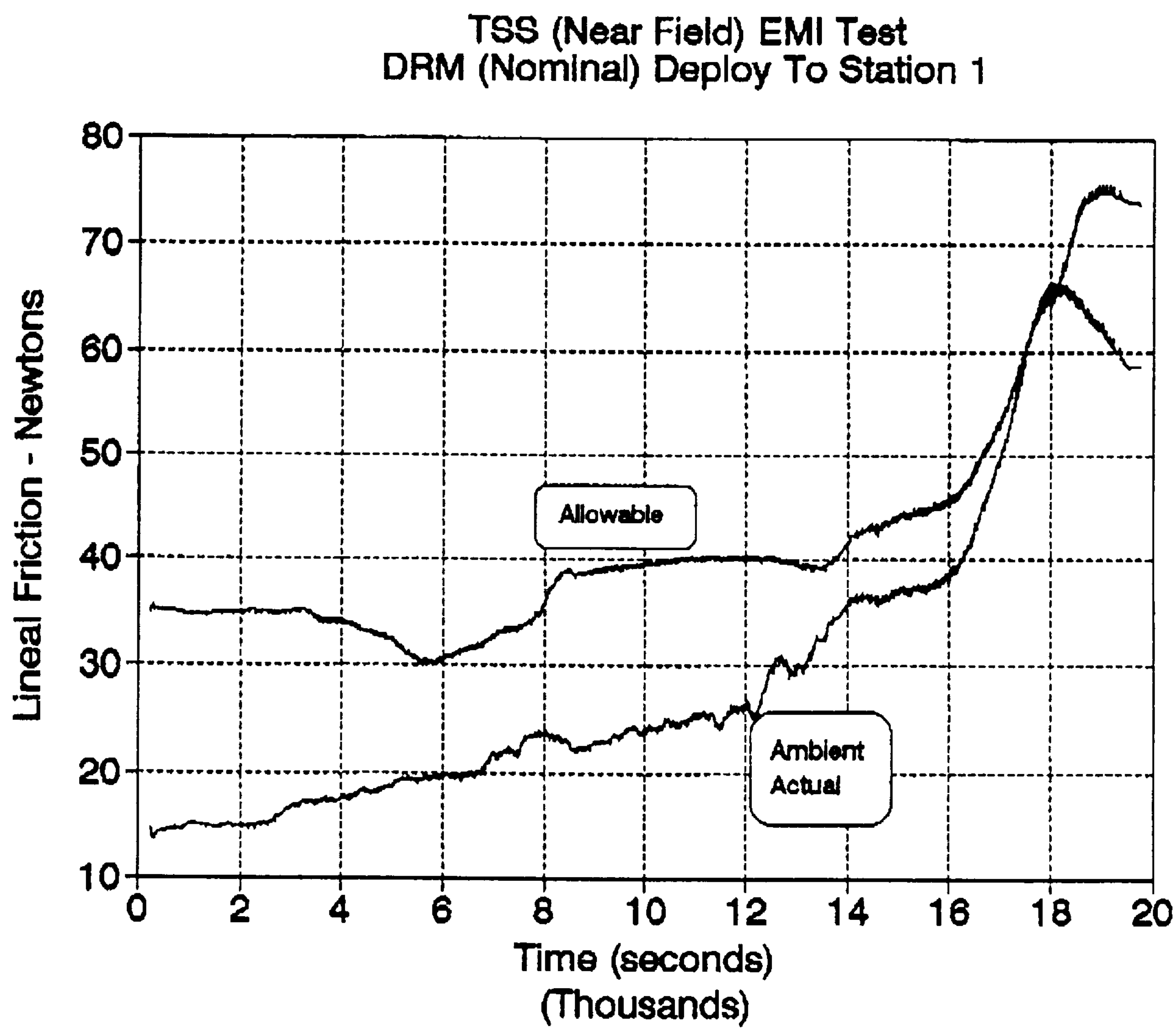


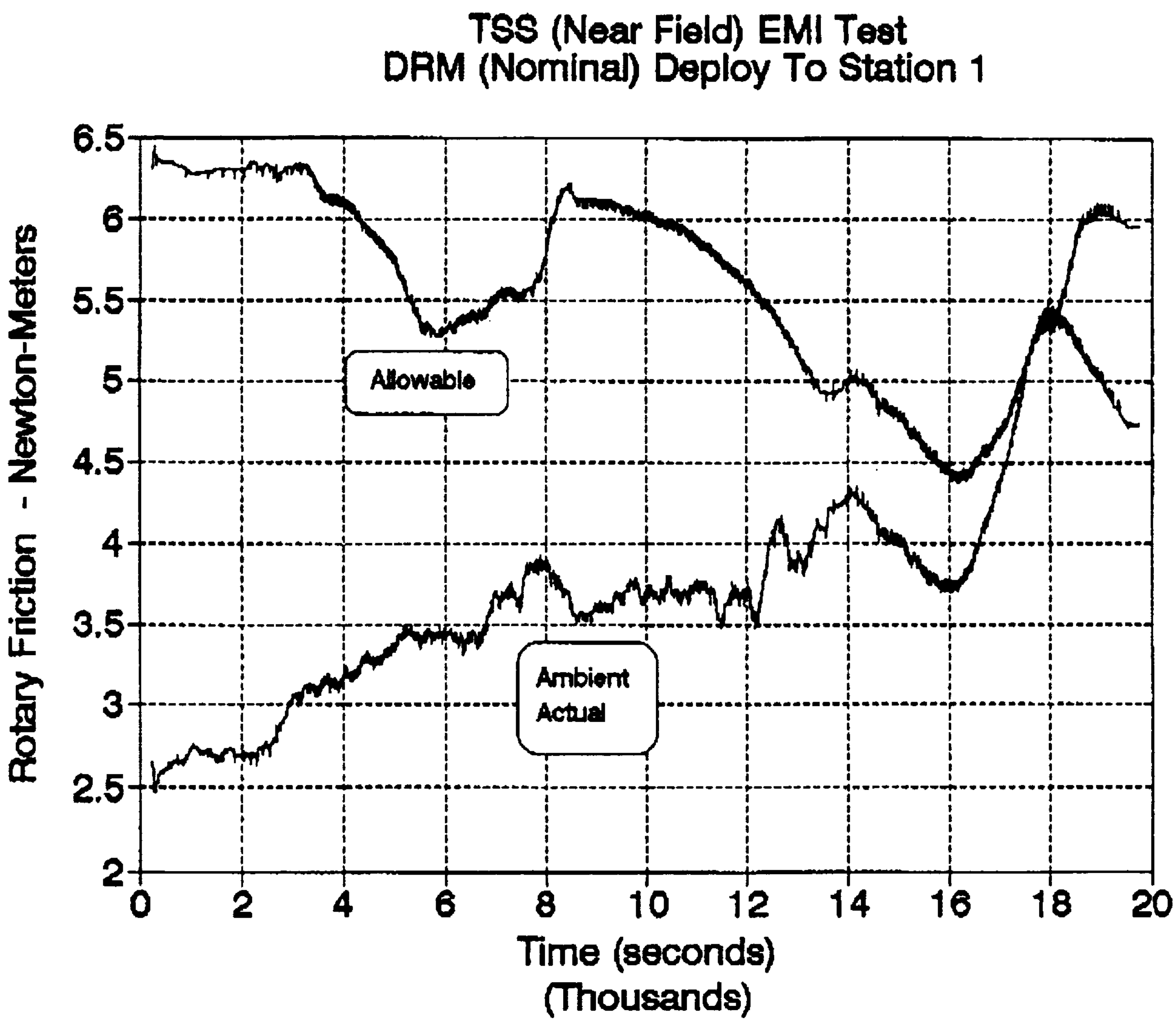
TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Electric Torque - Newton-Meters
4
3.5
3
2.5
2
1.5
1
0.5
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)


TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Friction Torques - Newton-Meters
Time (seconds)
(Thousands)
Total
Mechanical
Windage
0
0.5
1
1.5
2
2.5
3
3.5
4
4.5
0
2
4
6
8
10
12
14
16
18
20



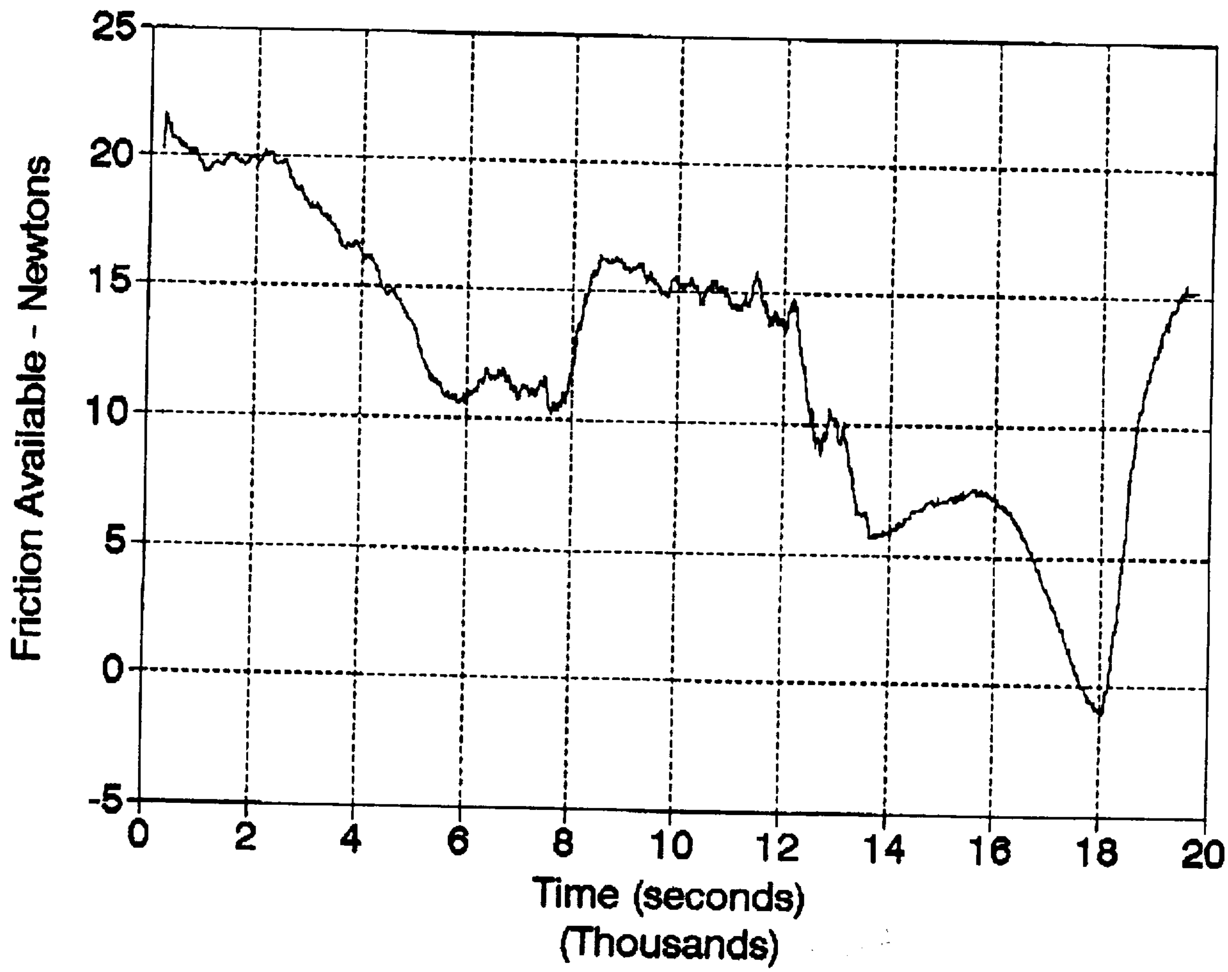
TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Pulse Widths
100
0
-100
-200
-300
-400
-500
-600
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)
Compensated
For Windage

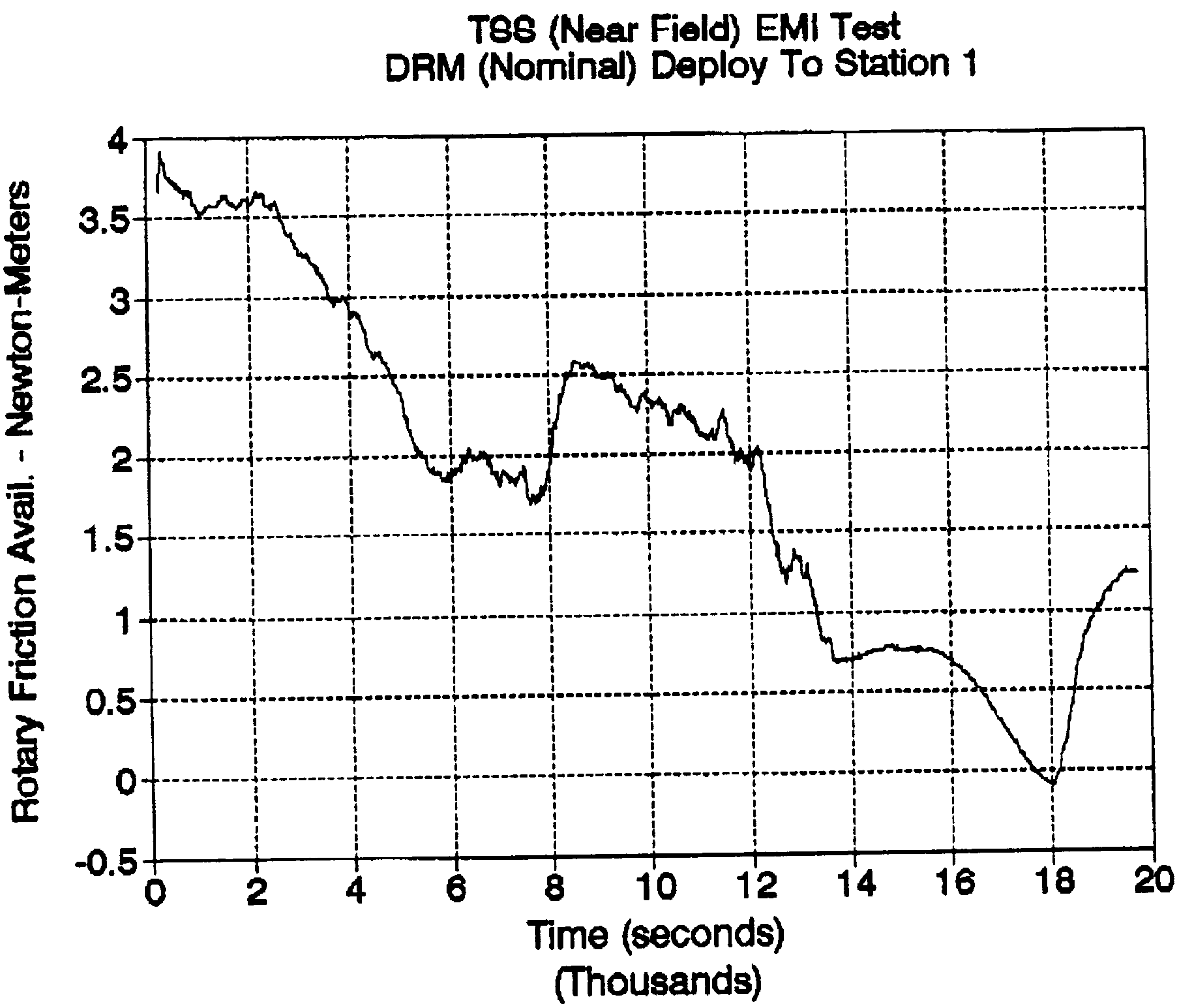

TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Lineal Friction - Newtons
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)
Allowable
Ambient
Actual



TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Rotary Friction - Newton-Meters
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)
Allowable
Ambient
Actual

TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1




TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Rotary Friction Avail. - Newton-Meters
4
3.5
3
2.5
2
1.5
1
0.5
0
-0.5
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)

Summary Results for the Eight Long-Term (Low-Res.) Test Runs

Projected "Available" Friction

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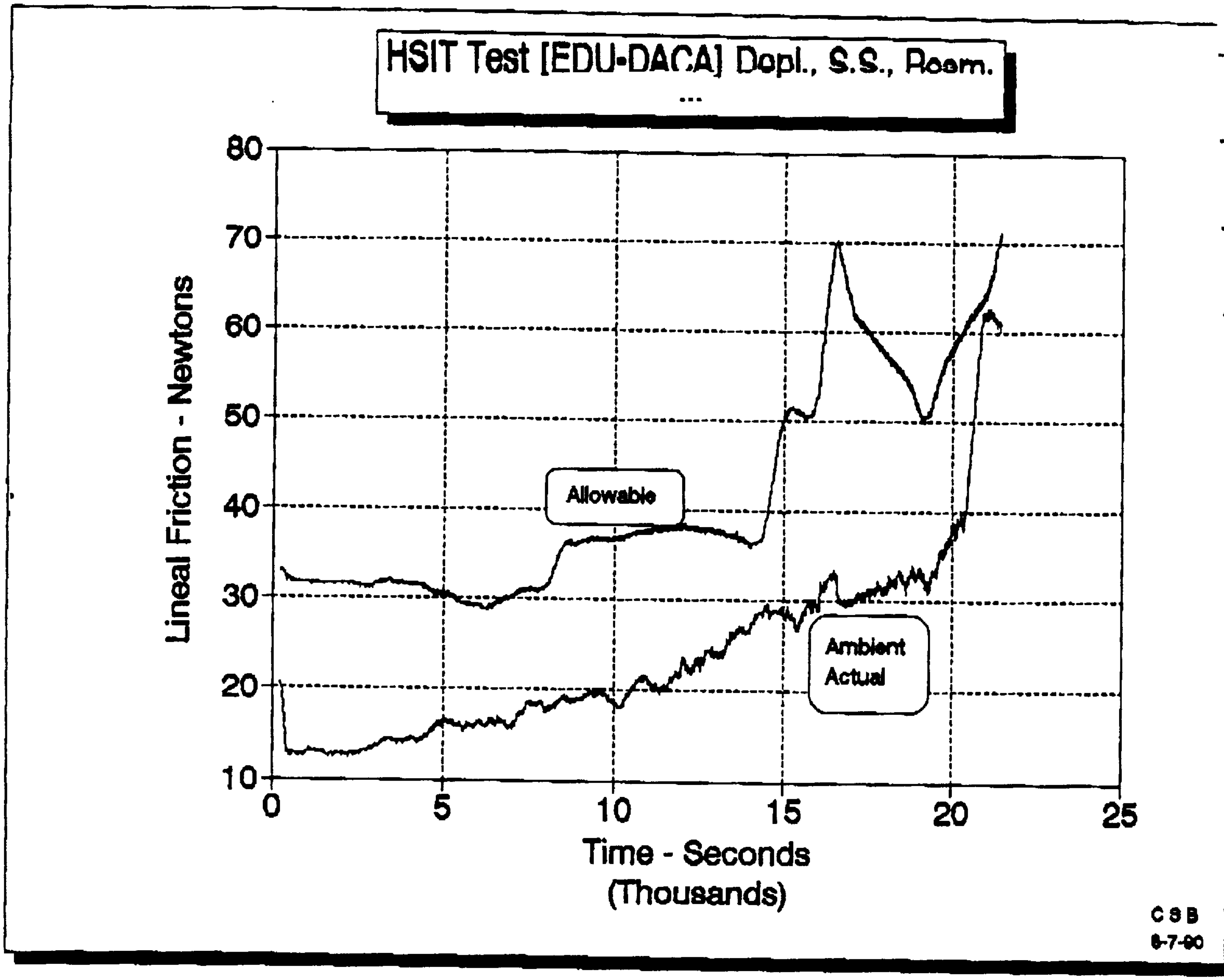
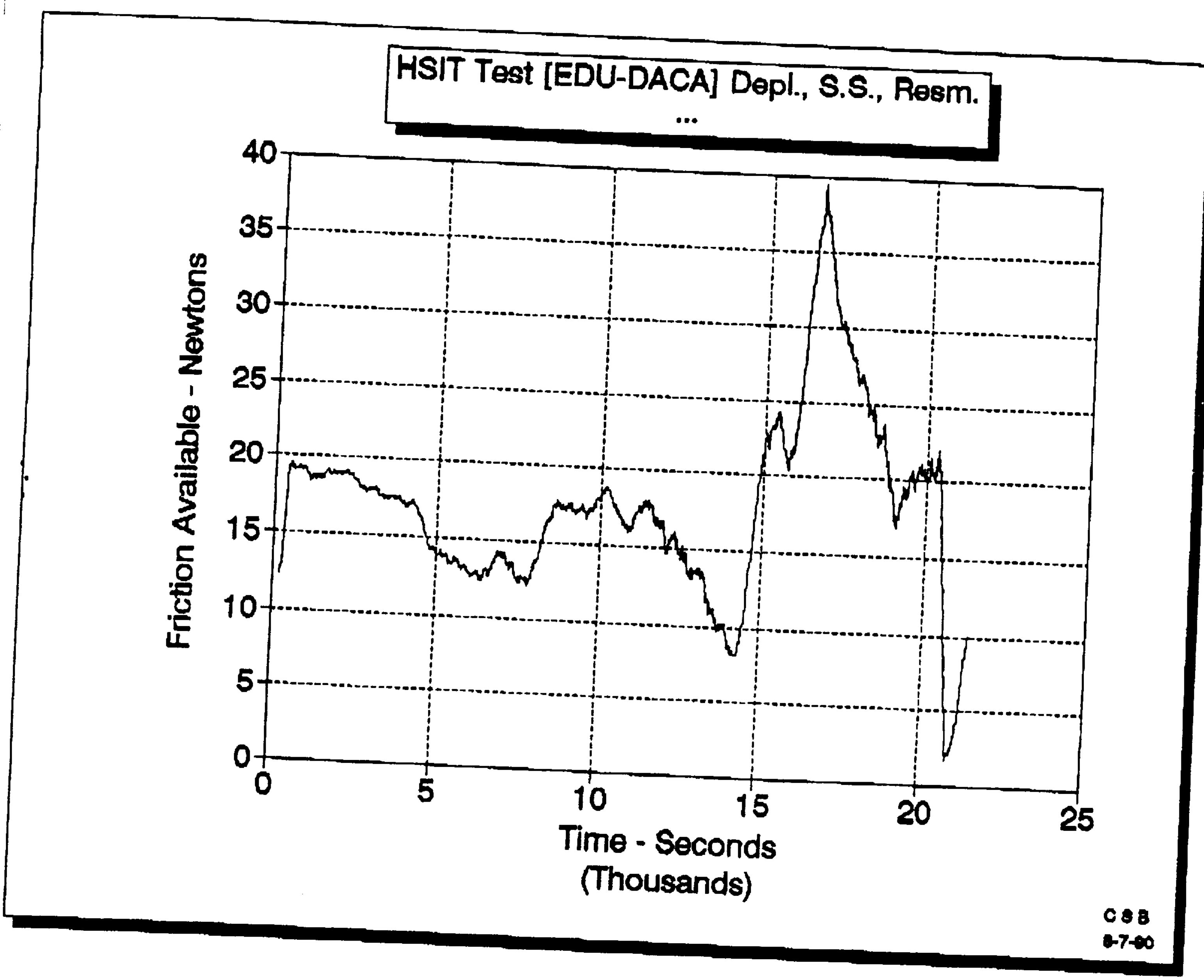
Table No. 1

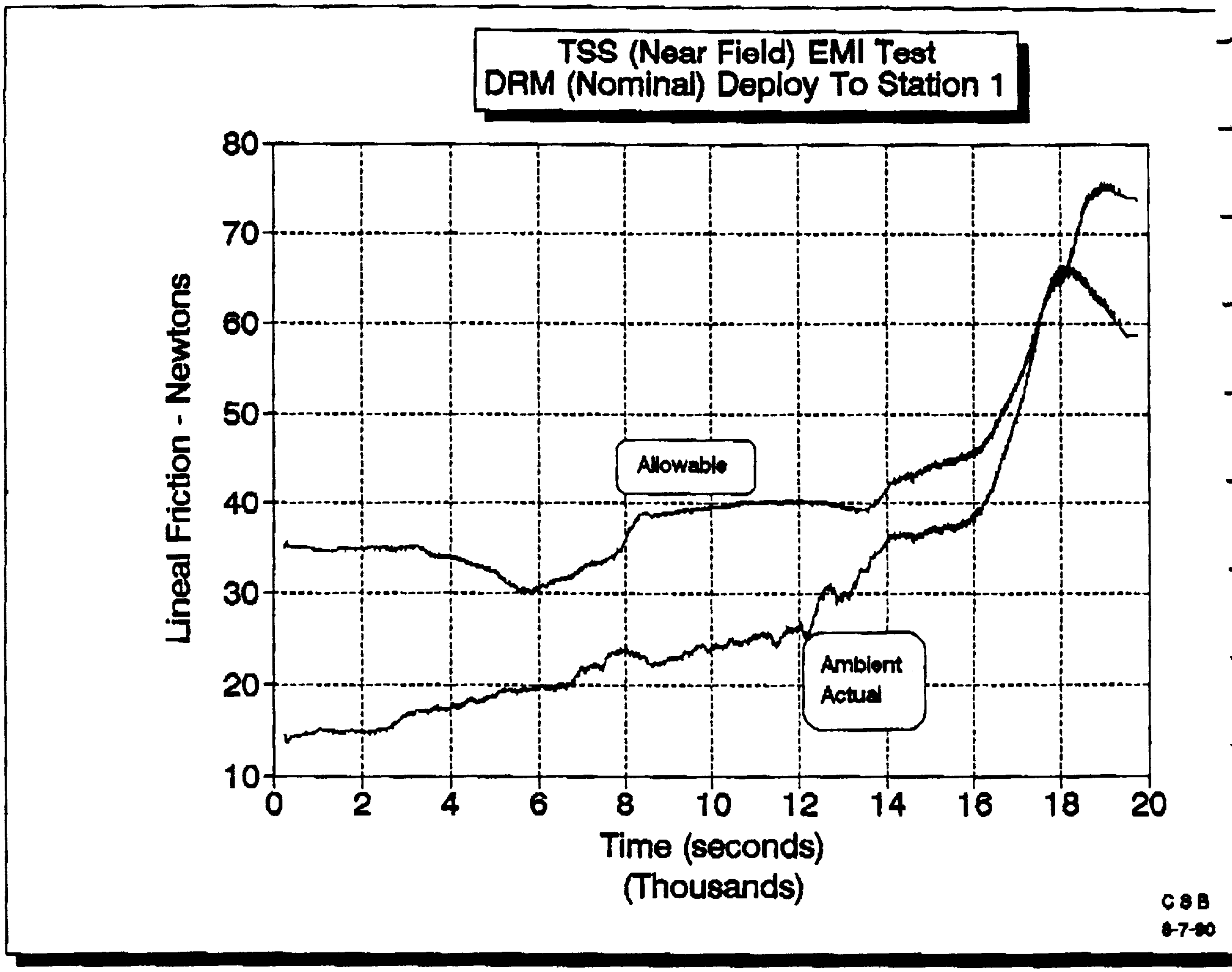
This Is a List of Test Runs Processed to Evaluate Available Friction

csb_

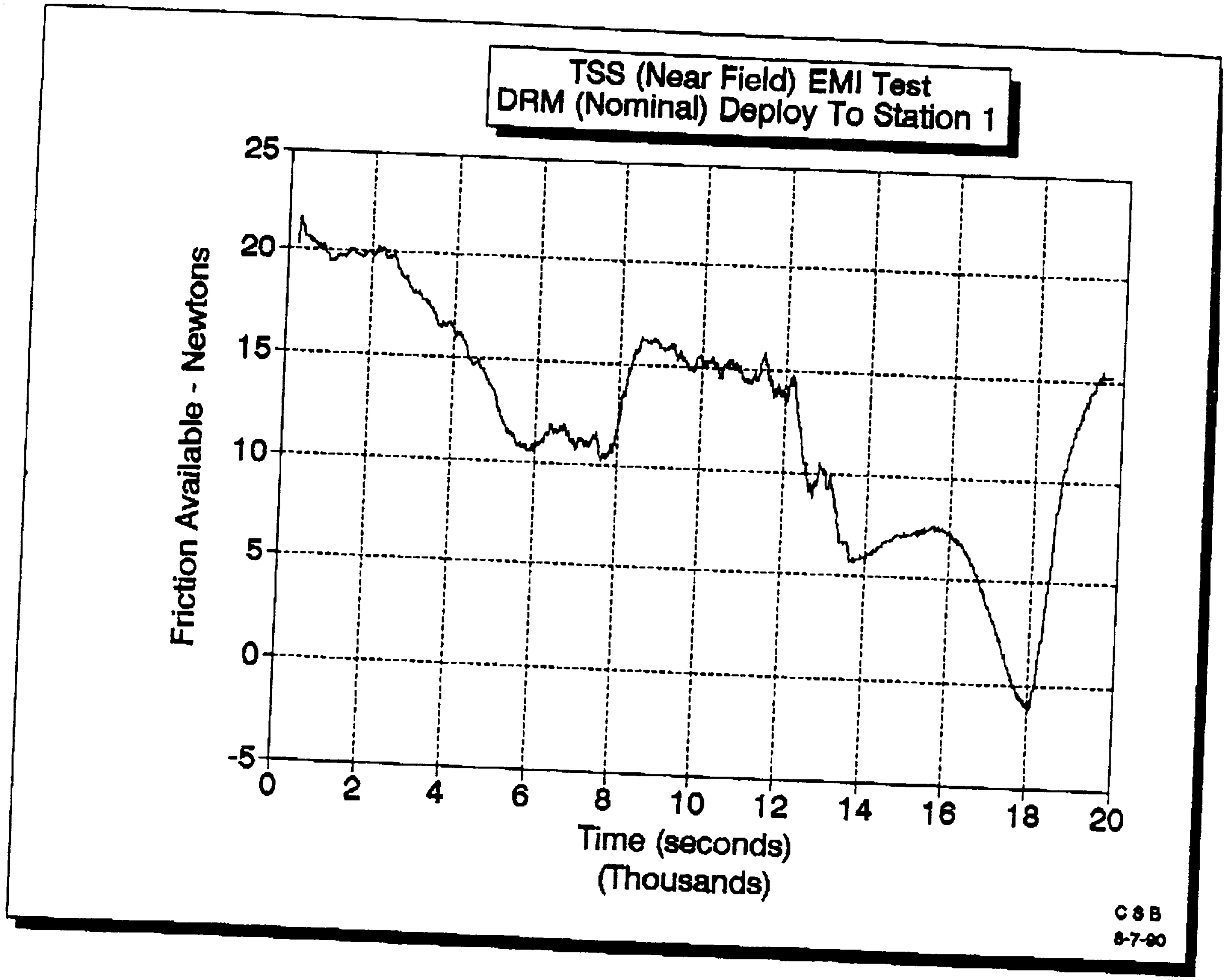
1)	HSIT Test, EDU DACA, New Gains, Deploy, Soft Stop, Resume to Sta. 1
2)	TSS (Near Field) EMI Test, DRM (Nominal) Deploy to Sta. 1
3)	TSS (Near Field) EMI Test, DRM (Nominal) Retrieve to Dock
4)	TSS Post Mod. Test, Deploy, Soft Stop, Resume to Sta. 1
5)	TSS Post Mod. Test, Retrieve, Soft Stop, Resume to Dock
6)	TSS Post Mod. Test, Short Retest, Dep., Soft Stop at 5,600-m
7)	TSS Post Thermal Balance Test, Deploy, Soft Stop, Resume to Sta. 1
8)	TSS Post Thermal Balance Test, Retrieve, Soft Stop, Resume to Dock


HSIT Test [EDU-DACA] Depl., S.S., Ream.
...
Lineal Friction - Newtons
80
70
60
50
40
30
20
10
Allowable
Ambient
Actual
0
5
10
15
20
25
Time - Seconds
(Thousands)
CSB
8-7-90

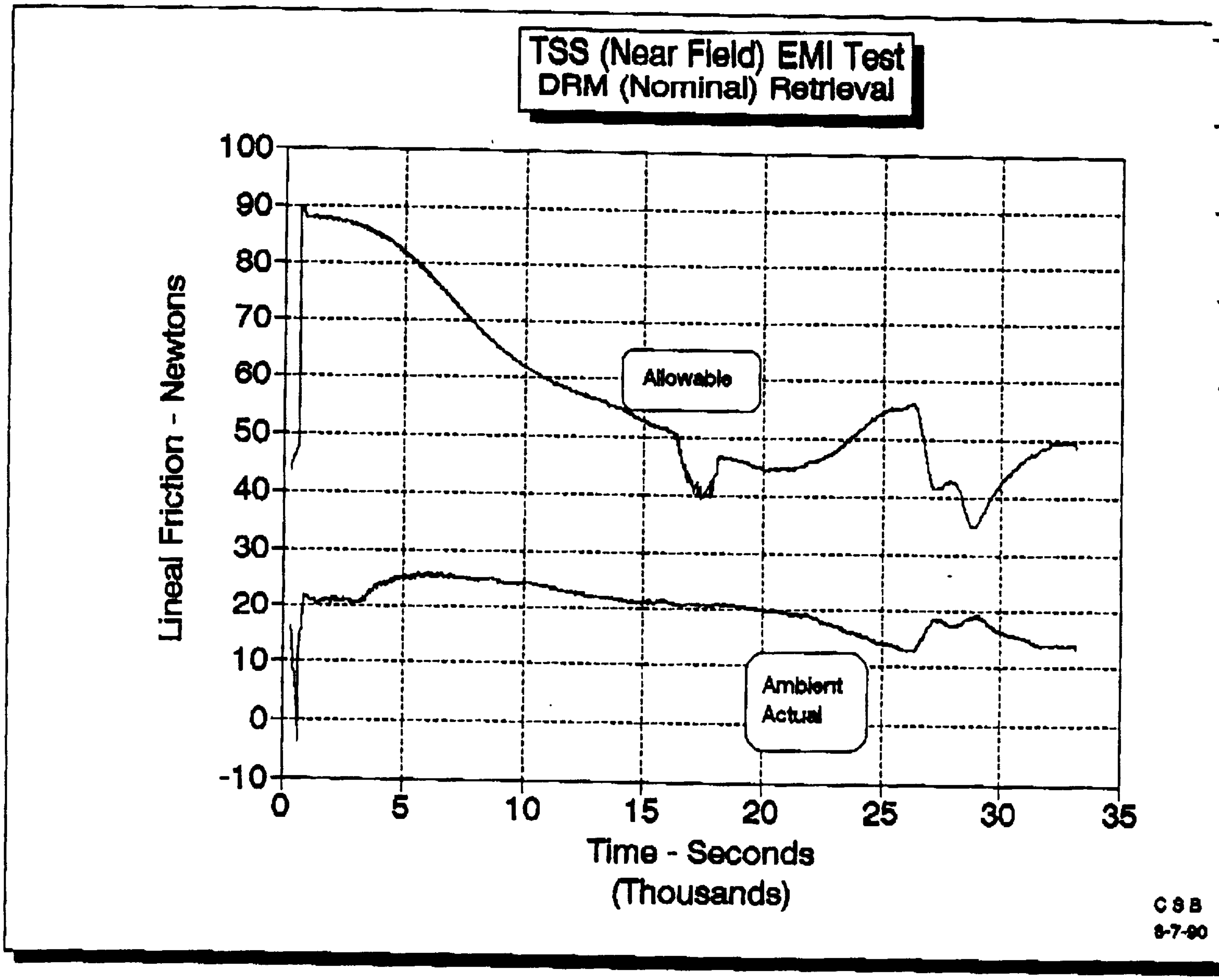

HSIT Test [EDU-DACA] Depl., S.S., Resm.
...
Friction Available - Newtons
40
35
30
25
20
15
10
5
0
0
5
10
15
20
25
Time - Seconds
(Thousands)
CSB
8-7-90

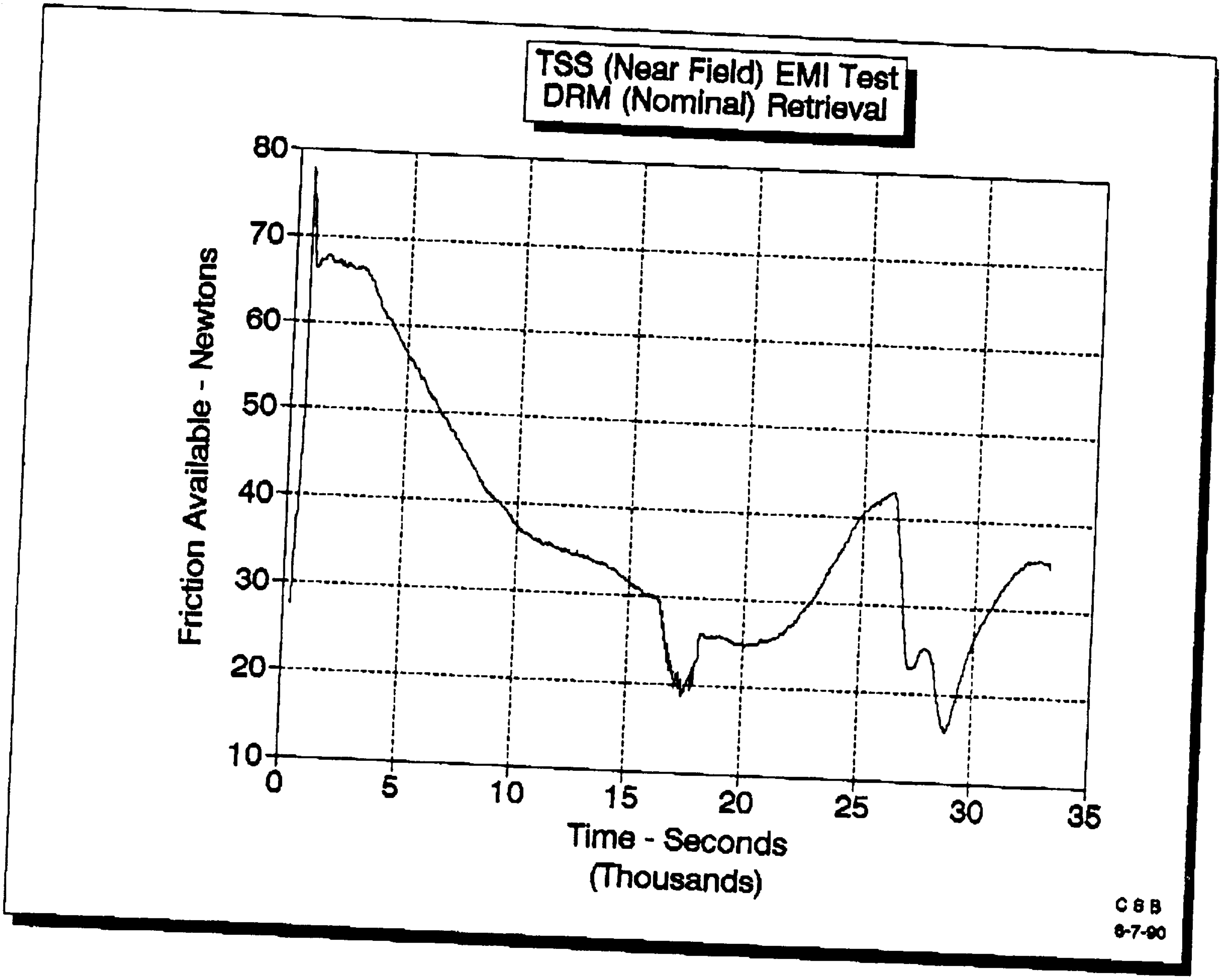


TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Lineal Friction - Newtons
80
70
60
50
40
30
20
10
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)
Allowable
Ambient
Actual
CSB
8-7-90

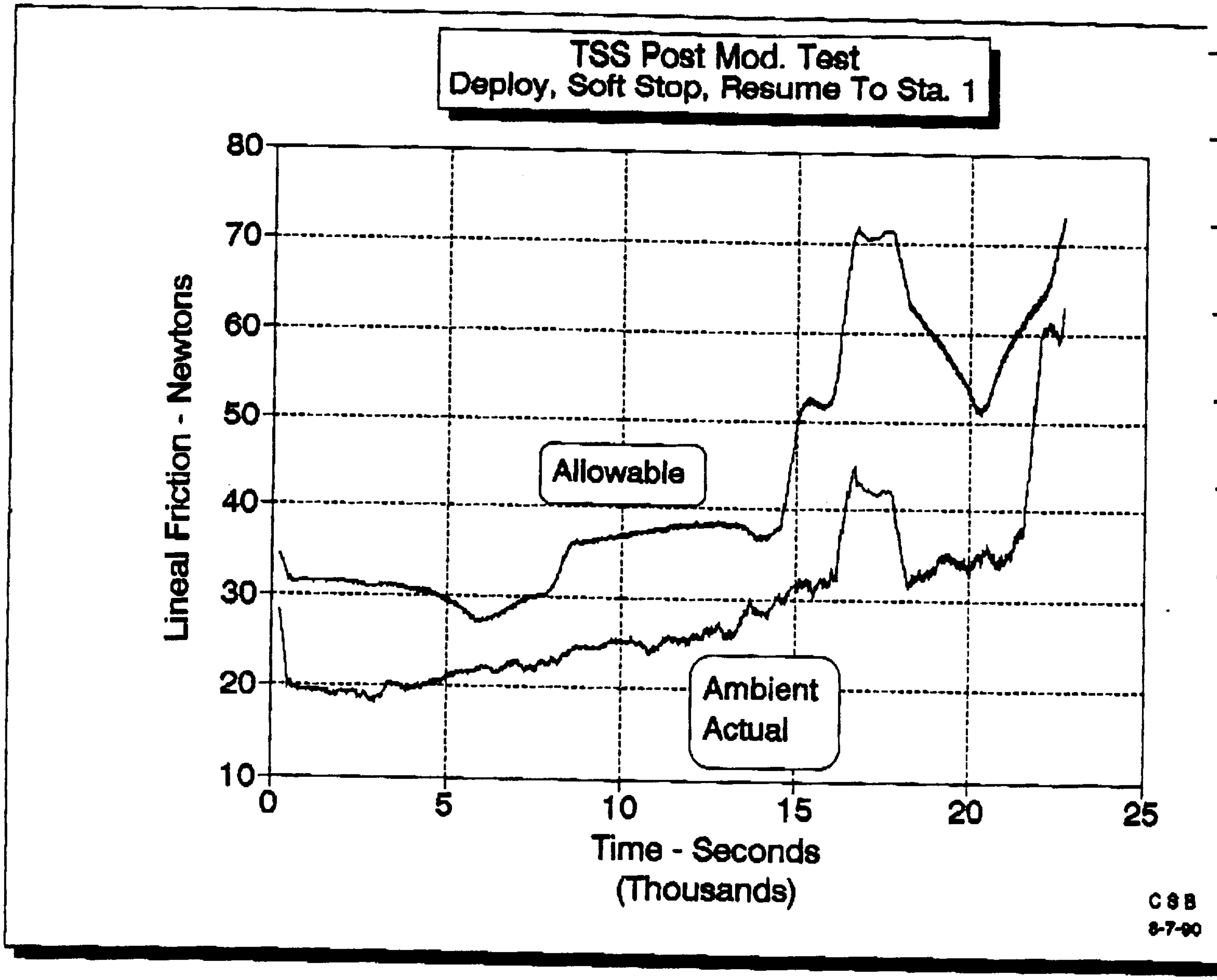

TSS (Near Field) EMI Test
DRM (Nominal) Deploy To Station 1
Friction Available - Newtons
25
20
15
10
5
0
-5
0
2
4
6
8
10
12
14
16
18
20
Time (seconds)
(Thousands)
C S B
8-7-90

C-2

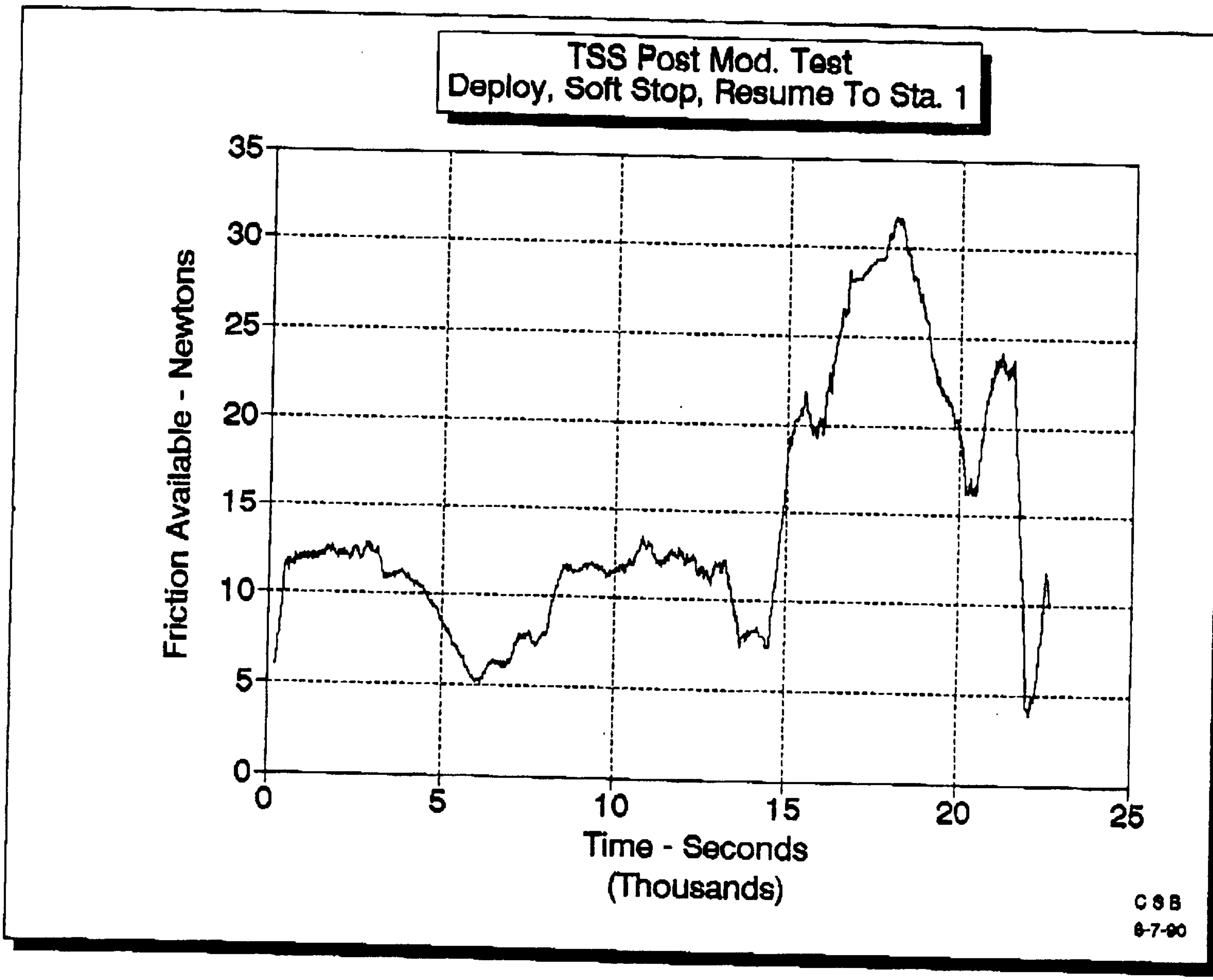

TSS (Near Field) EMI Test
DRM (Nominal) Retrieval
Lineal Friction - Newtons
100
90
80
70
60
50
40
30
20
10
0
-10
0
5
10
15
20
25
30
35
Time - Seconds
(Thousands)
Allowable
Ambient
Actual
CSB
8-7-90

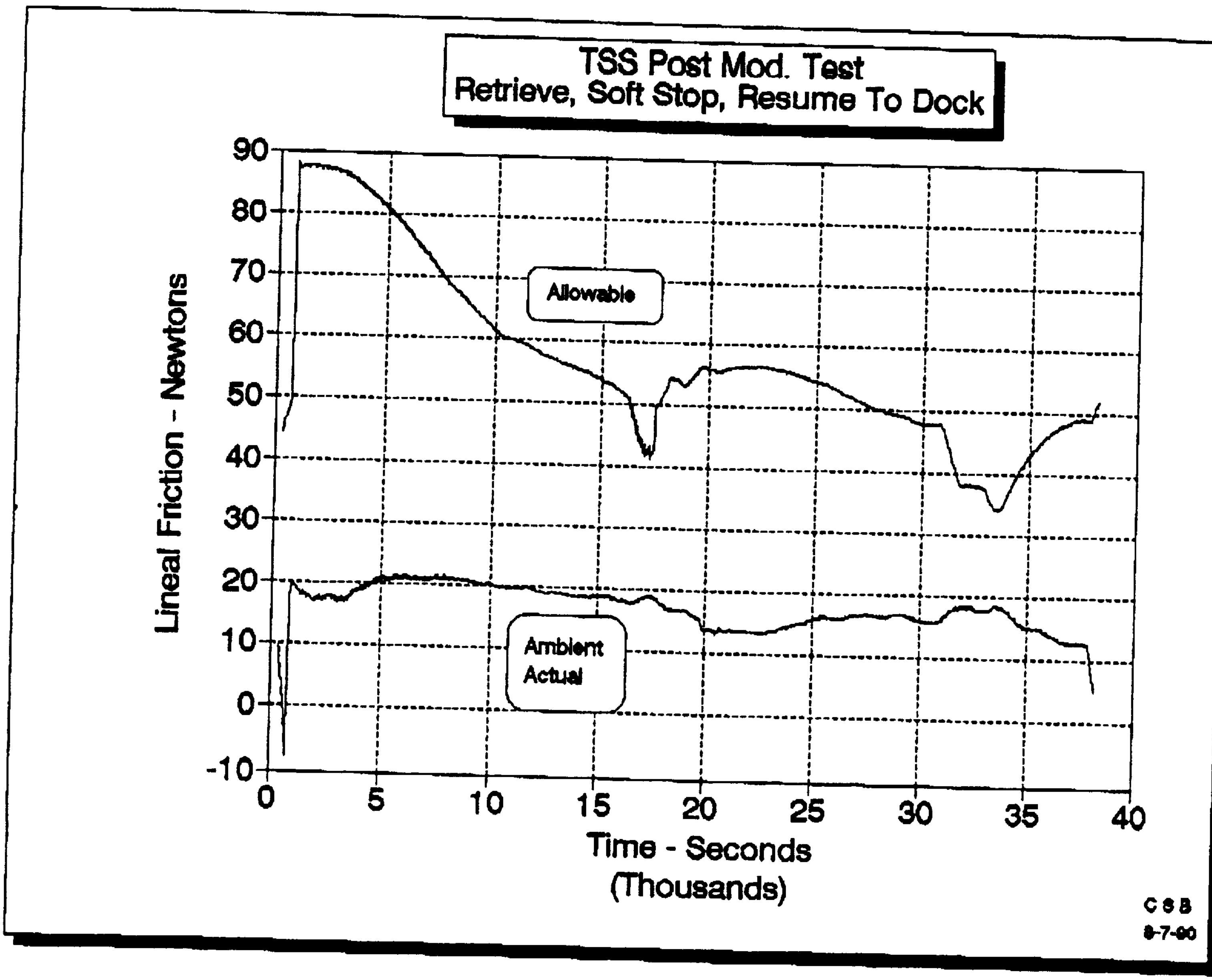


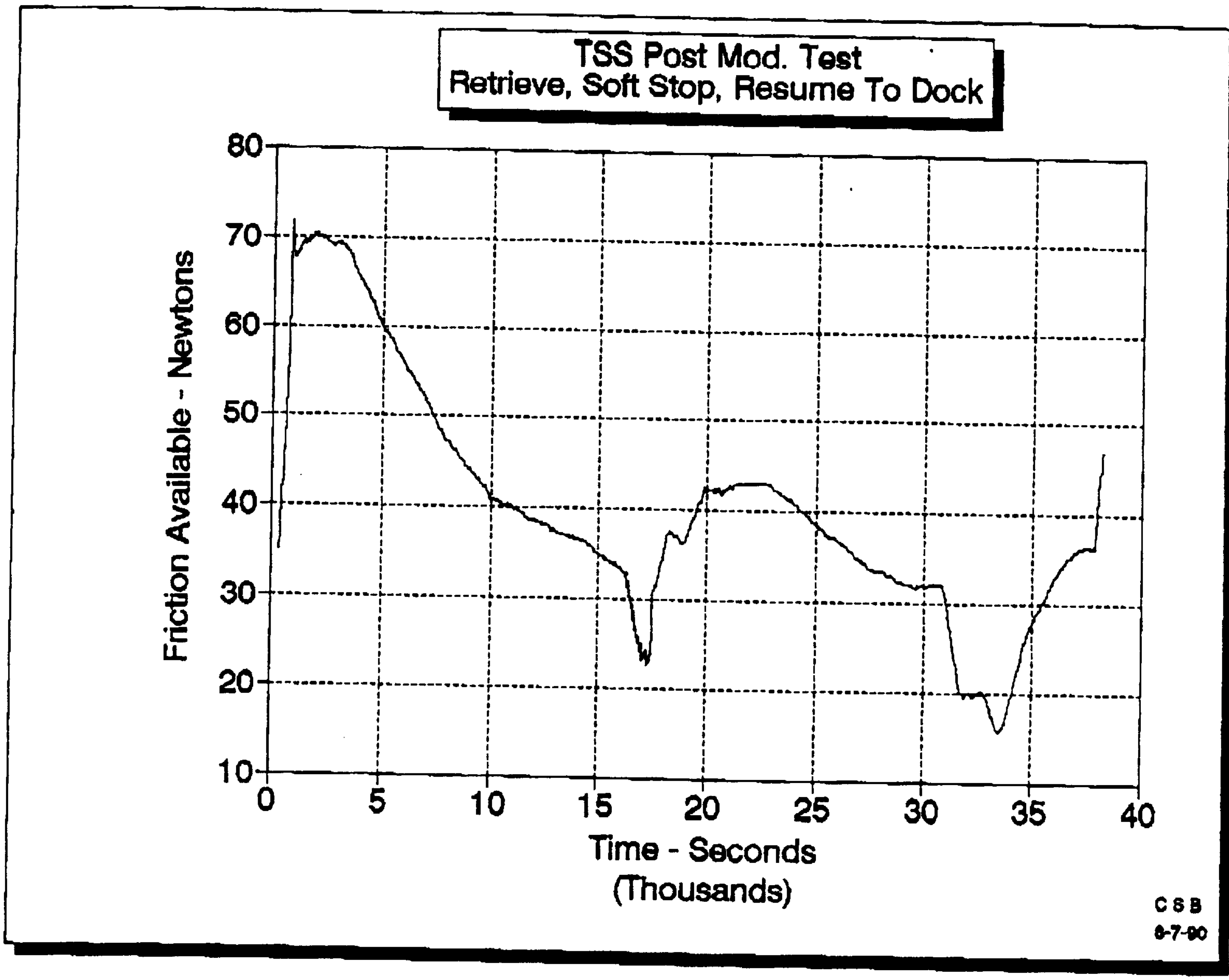
TSS (Near Field) EMI Test
DRM (Nominal) Retrieval
Friction Available - Newtons
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
Time - Seconds
(Thousands)
C S B
8-7-90



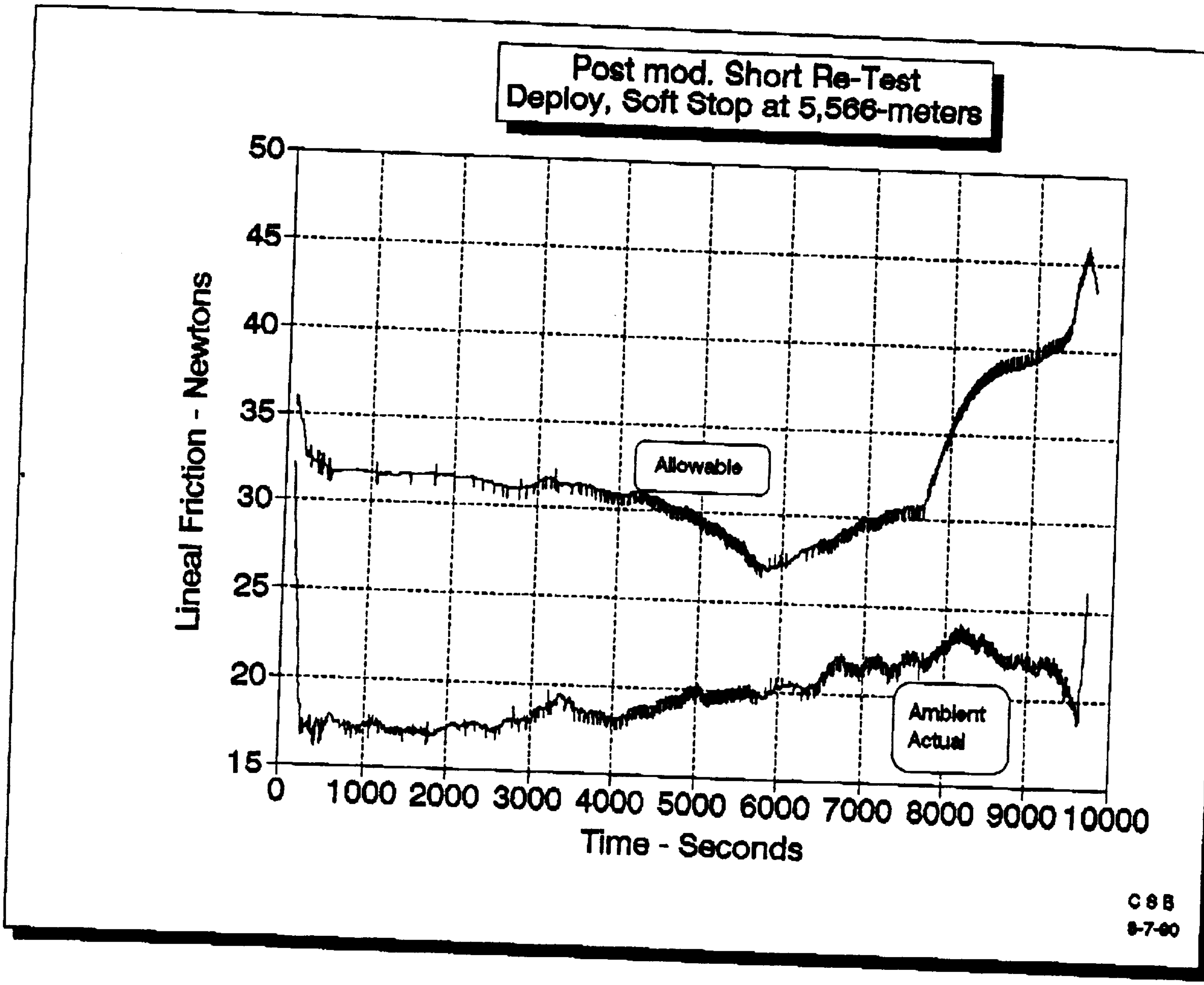
TSS Post Mod. Test
Deploy, Soft Stop, Resume To Sta. 1
80
70
60
50
40
30
20
10
Lineal Friction - Newtons
Allowable
Ambient
Actual
0
5
10
15
20
25
Time - Seconds
(Thousands)
CSB
8-7-90

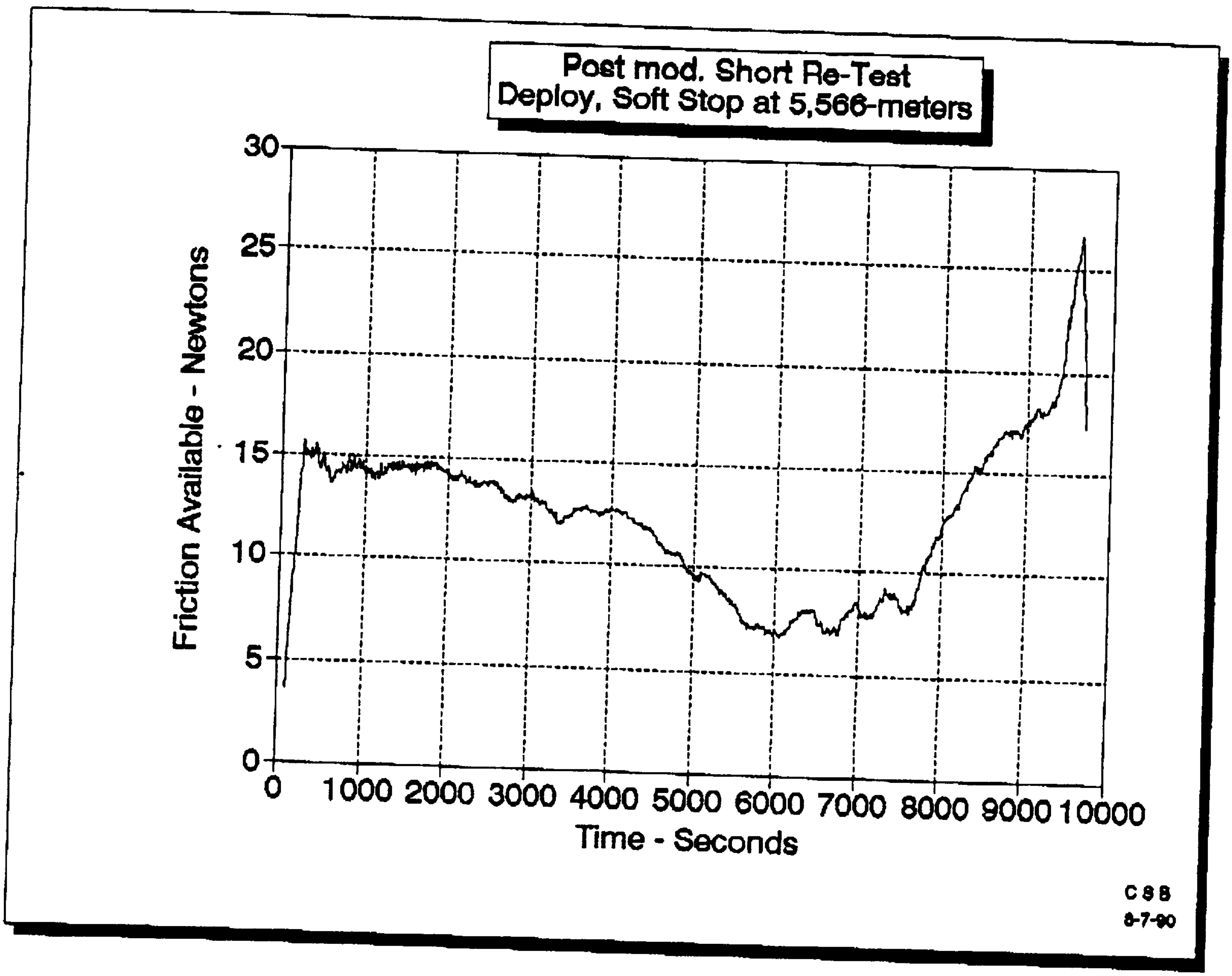

TSS Post Mod. Test
Deploy, Soft Stop, Resume To Sta. 1
Friction Available - Newtons
35
30
25
20
15
10
5
0
0
5
10
15
20
25
Time - Seconds
(Thousands)
CSB
6-7-90

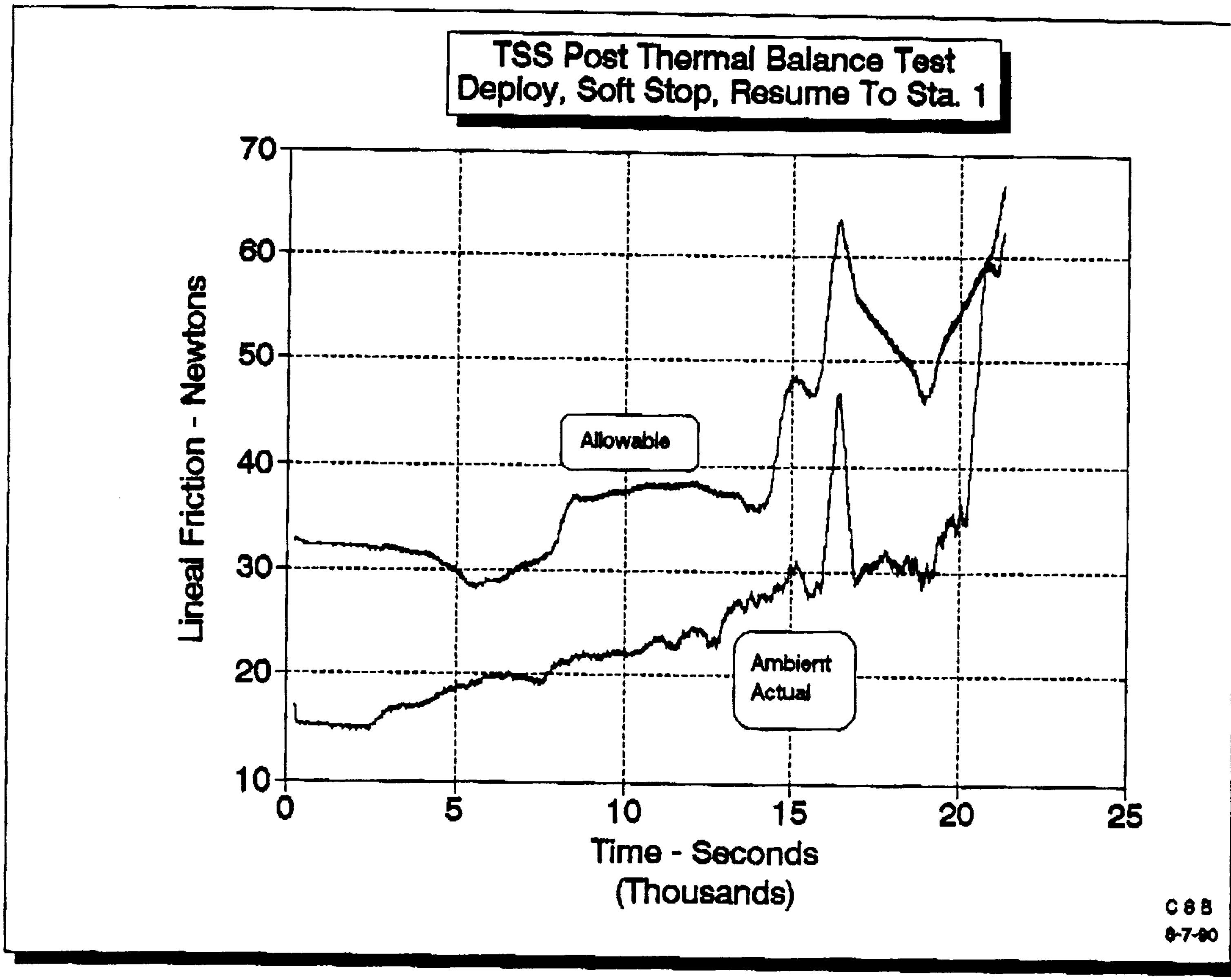

TSS Post Mod. Test
Retrieve, Soft Stop, Resume To Dock
Lineal Friction - Newtons
90
80
70
60
50
40
30
20
10
0
-10
0
5
10
15
20
25
30
35
40
Time - Seconds
(Thousands)
Allowable
Ambient
Actual
C S B
8-7-90

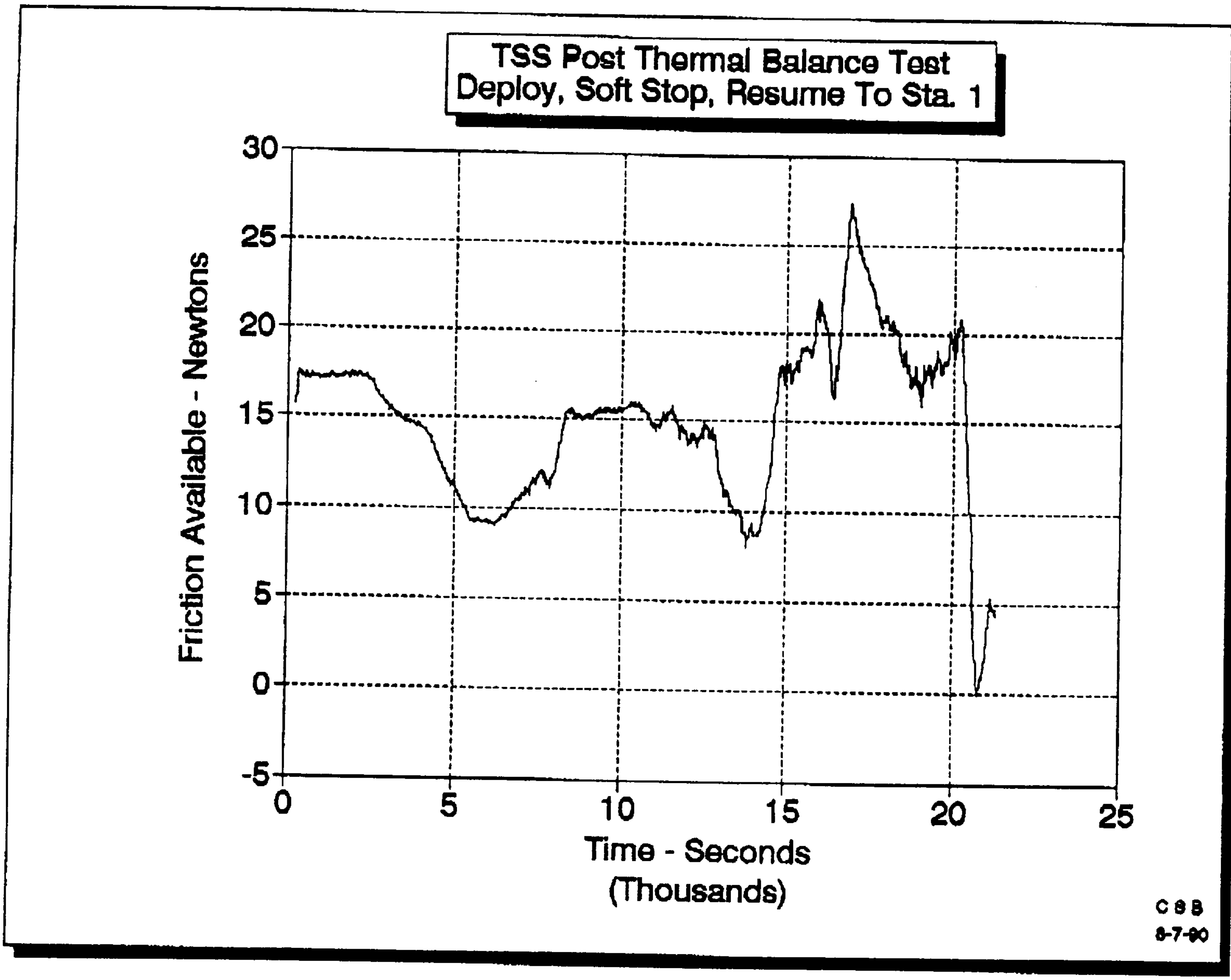


TSS Post Mod. Test
Retrieve, Soft Stop, Resume To Dock
Friction Available - Newtons
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
Time - Seconds
(Thousands)
CSB
8-7-90

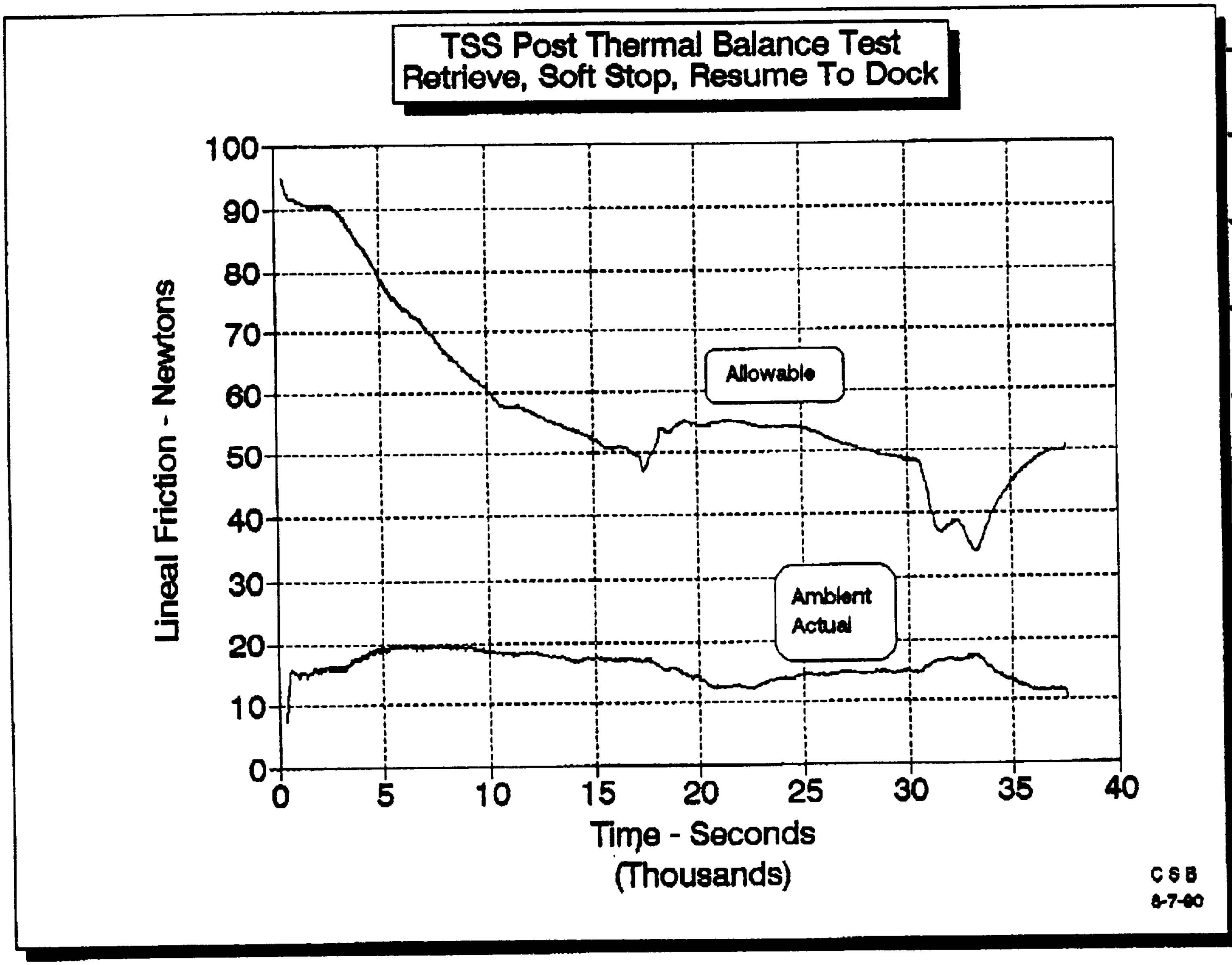

Post mod. Short Re-Test
Deploy, Soft Stop at 5,566-meters
Lineal Friction - Newtons
50
45
40
35
30
25
20
15
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Time - Seconds
Allowable
Ambient
Actual
CSB
9-7-90


Post mod. Short Re-Test
Deploy, Soft Stop at 5,566-meters
Friction Available - Newtons
30
25
20
15
10
5
0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000
10000
Time - Seconds
CSB
8-7-90

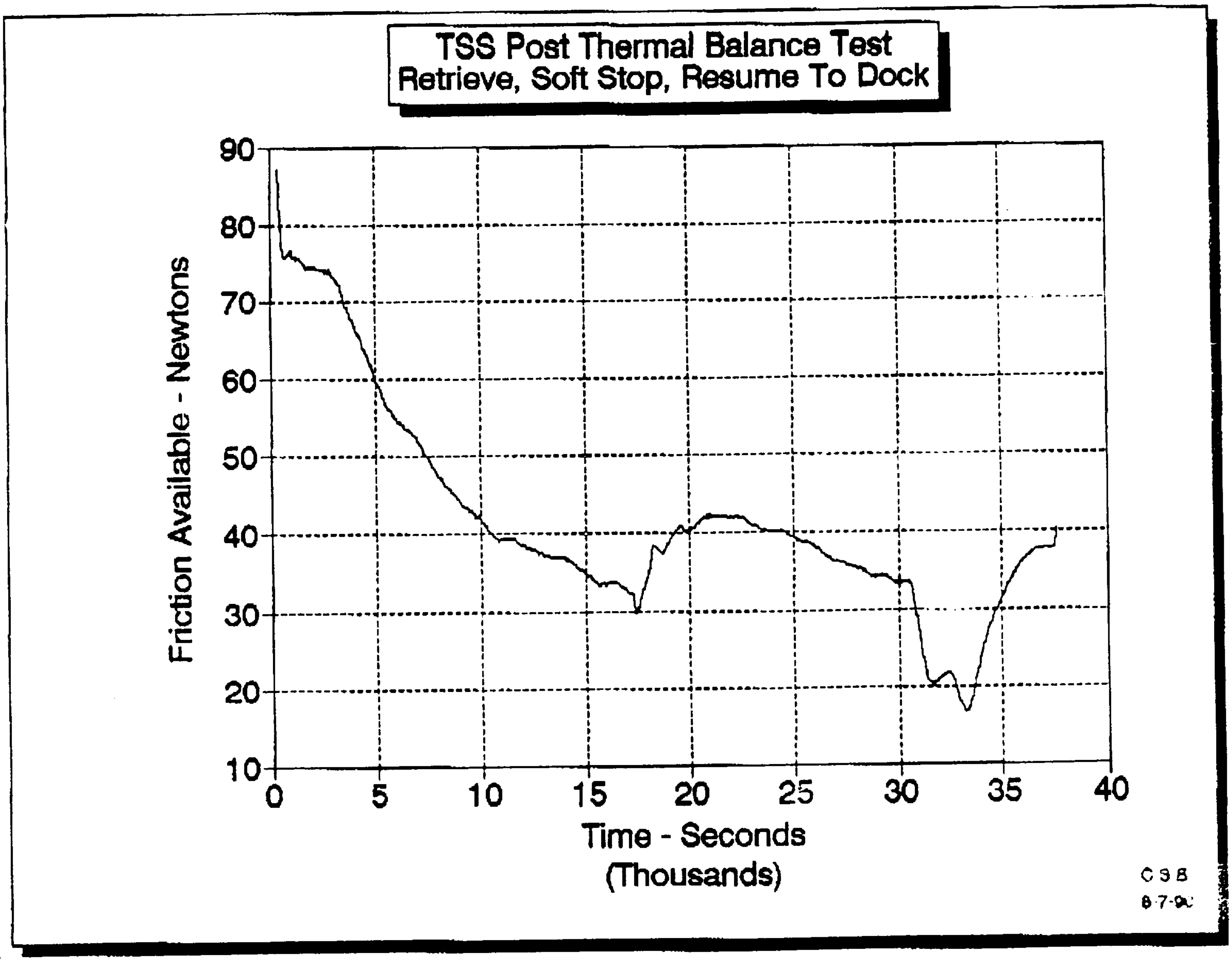

TSS Post Thermal Balance Test
Deploy, Soft Stop, Resume To Sta. 1
Lineal Friction - Newtons
Time - Seconds
(Thousands)
70
60
50
40
30
20
10
0
5
10
15
20
25
Allowable
Ambient
Actual
C S B
8-7-90



TSS Post Thermal Balance Test
Deploy, Soft Stop, Resume To Sta. 1
Friction Available - Newtons
30
25
20
15
10
5
0
-5
0
5
10
15
20
25
Time - Seconds
(Thousands)
C S B
8-7-90



TSS Post Thermal Balance Test
Retrieve, Soft Stop, Resume To Dock
Allowable
Ambient
Actual
Lineal Friction - Newtons
100
90
80
70
60
50
40
30
20
10
0
0
5
10
15
20
25
30
35
40
Time - Seconds
(Thousands)
CSB
8-7-90



TSS Post Thermal Balance Test
Retrieve, Soft Stop, Resume To Dock
Friction Available - Newtons
90
80
70
60
50
40
30
20
10
0
5
10
15
20
25
30
35
40
Time - Seconds
(Thousands)

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APPENDIX E

STATUS OF CDy SKIP ROPE MODE ANALYSIS

6-29-89

Status of CDy Skiprope Mode Analysis
6-28-89

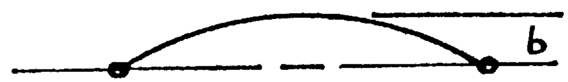
- Introduction & Overview
- Current Results
- Animation
- Conclusions

INTRODUCTION

SKIPROPE MODE:

A type of tether motion in which each tether element travels in an orbit about an axis approximately along the line connecting the end masses.

OVERVIEW



- Radius at midpoint: $b = \sqrt{\dfrac{2h}{\pi\sqrt{\mu T}}}$

- Frequency of skiprope: $\omega_s = \dfrac{\pi}{L}\sqrt{\dfrac{T}{\mu}}$

- Steady state hang angle vs retrieval rate:
  $\Theta_0 = -\frac{1}{2}\,\mathrm{Sin}^{-1}\dfrac{4\alpha}{3\omega_0}\,; \quad \alpha = \dfrac{\dot{L}}{L}$

- Tether deflection due to magnetic field: $b = \dfrac{1}{8}\dfrac{i B L^2}{T}$
  (field normal to tether, steady current)

- Coriolis offset: $b_0 = \dfrac{\mu\omega_0 \dot{L} L^2}{8\,T}$

SUMMARY OF RESULTS TO DATE

SAO:

- o Predicts that skiprope mode once created will grow in amplitude during retrieval (L ^ -1/4).
- o Negligible damping of skiprope mode

JSC:

- o Negligible damping in skiprope for constant length tether
- o Significant damping during retrieval (Unknown source)
  - Damping not caused by reel motor, orbiter DAP, satellite yaw, aerodynamic forces or electromagnetic forces.

SUMMARY

MMDA:

- o Simulation of full system
  - Results show amplitude decay
  - Concluded skiprope not a concern

CDy:

- o Results similar to SAO results
- o Amplitude growth during retrieval predicted analytically and by simulation

CONCLUSIONS

- o CDy analysis shows skiprope mode passively undamped
  - Results agree with SAO results -- David Arnold
  - Results disagree with JSC & MMDA
- o Disagreement between simulations needs to be resolved
  - Currently working with David Lang, author of GTOSS used by JSC in STOCS, to pursue source of discrepancies
  - Recommend we continue until differences understood or impasse reached

SAO COMPARISON CASE

- o Case 1 from SAO quarterly report # 15, page 18ff

  m1 (satellite) = 500 kg

  m2 (orbiter) = 100,000 kg

  L = 20,000 m

  initial inplane angle = 8.53 degrees

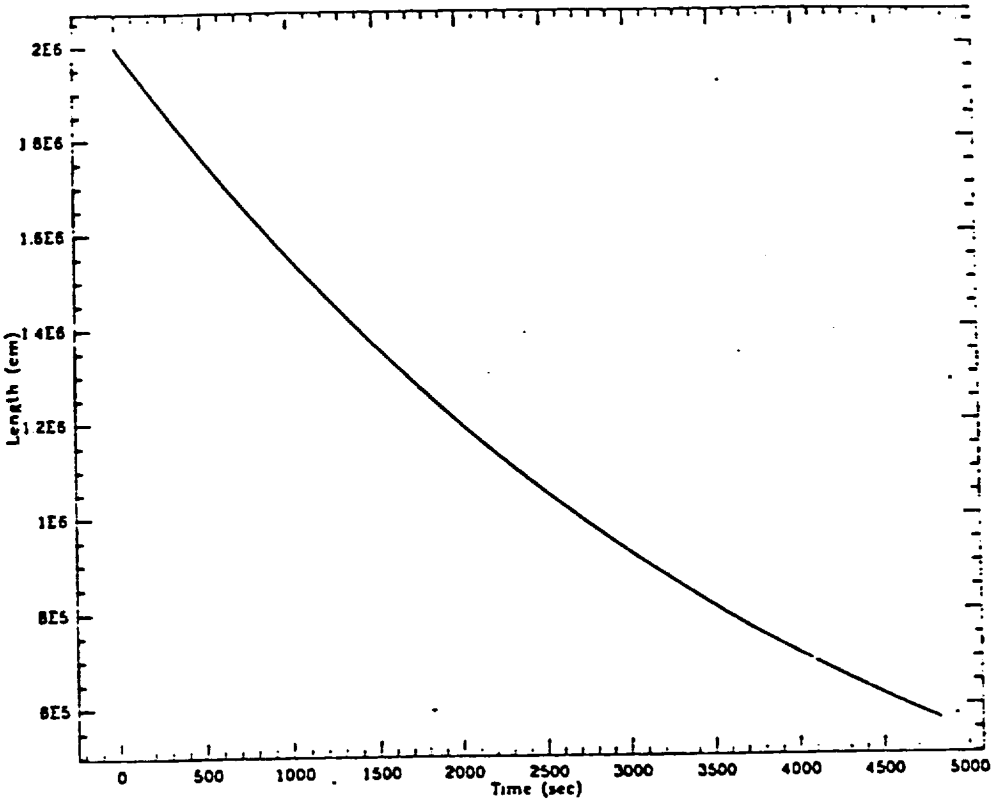
  stop time = 4840 sec

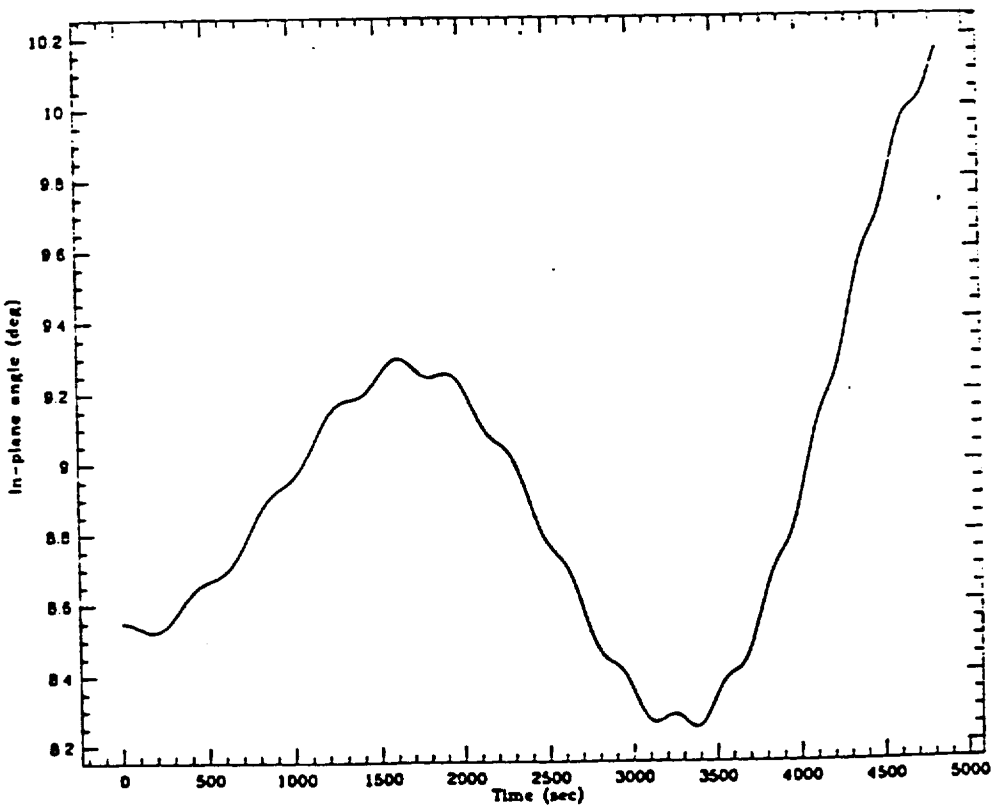
  Tether midpoint velocity = 1.46 m/sec

  TSS orbit, no drag, spherical earth gravity

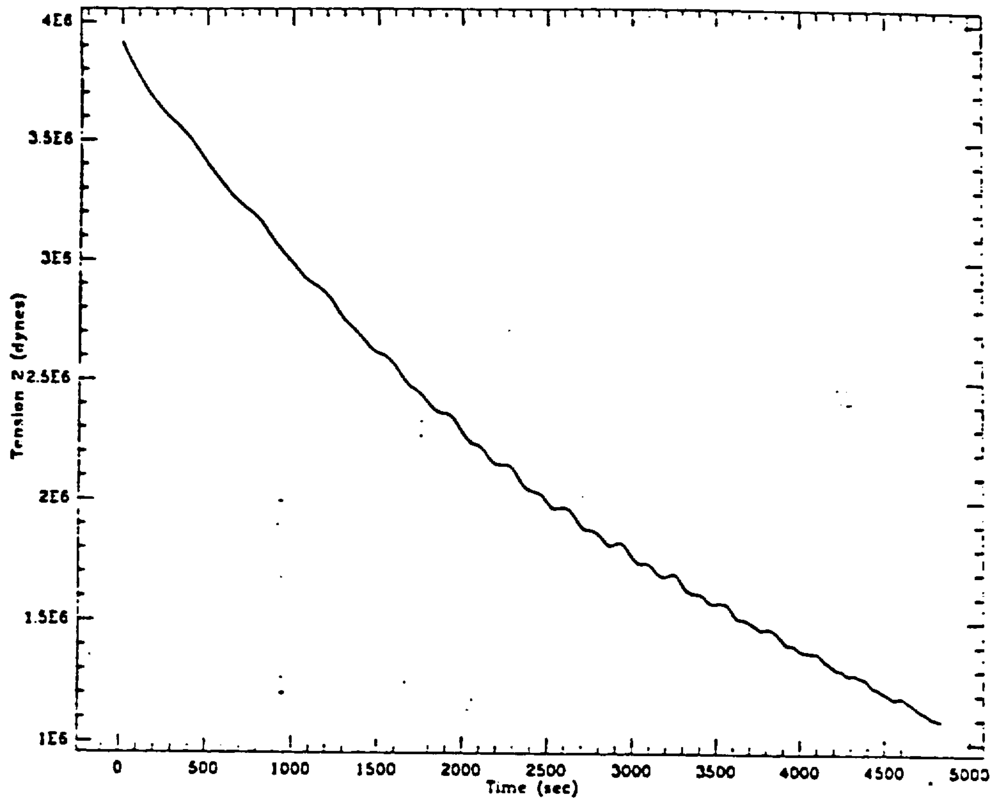
SAO RESULTS FOR CASE 1

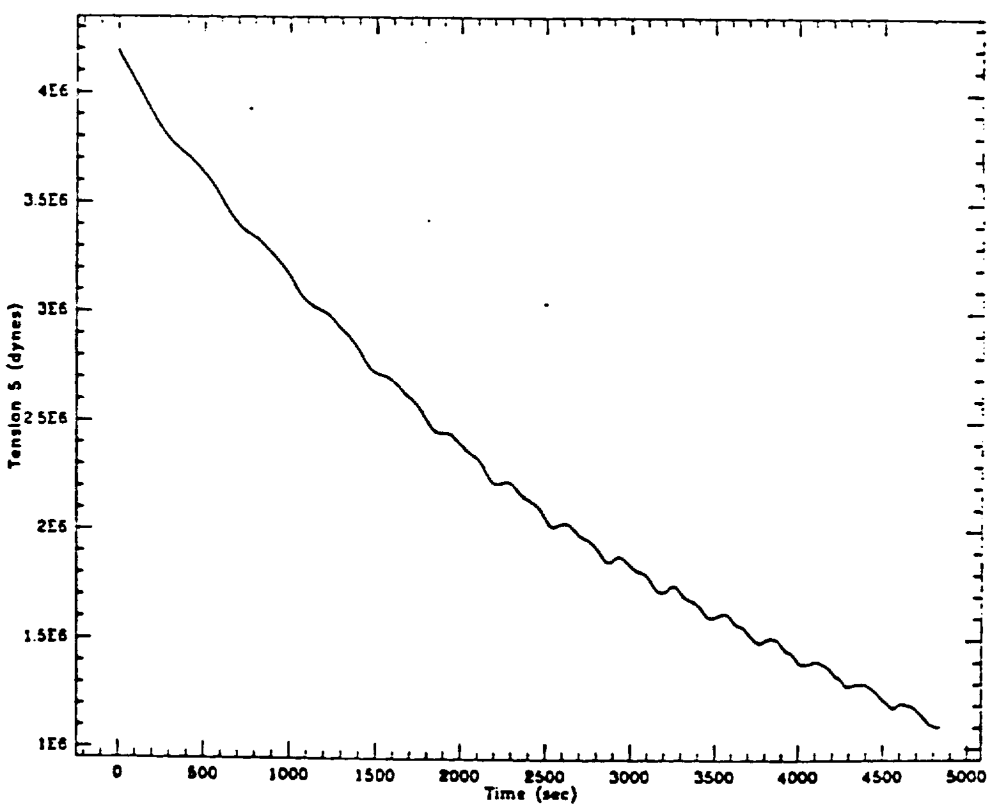
- Open loop, exponential retrieval
- 20,000 > l >5800
- 5 mass bead model of tether
- Longitudinal frequency tuned to skiprope (lateral fundamental), damping critical
- Skiprope amplitude observed to grow with time



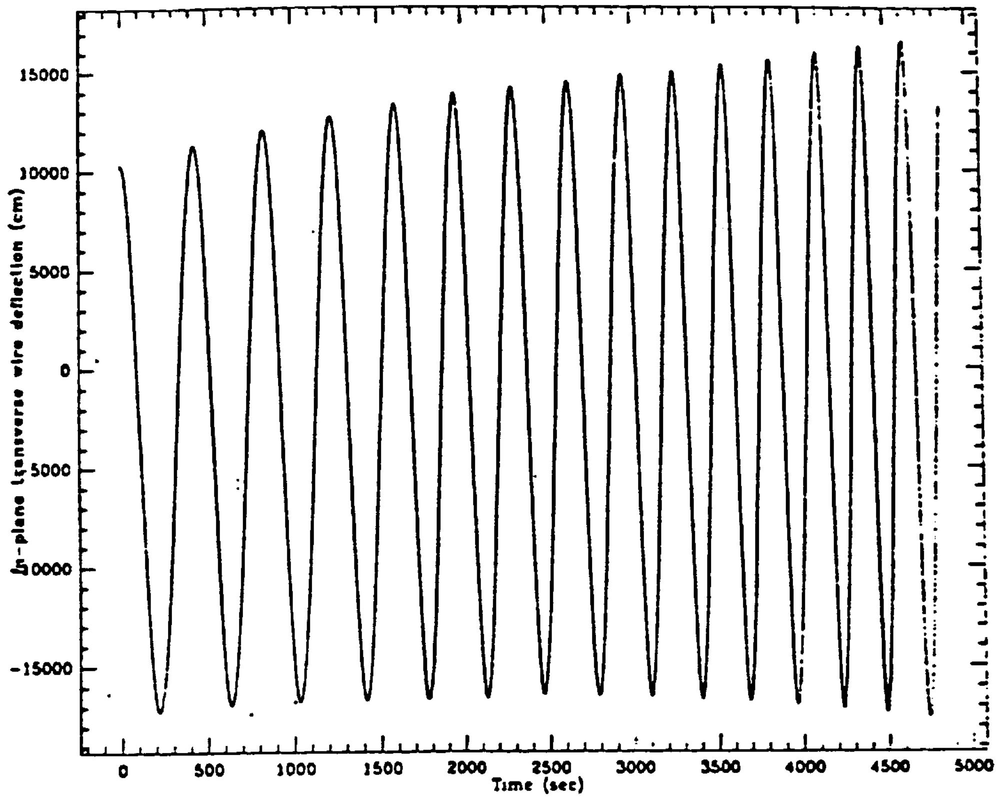


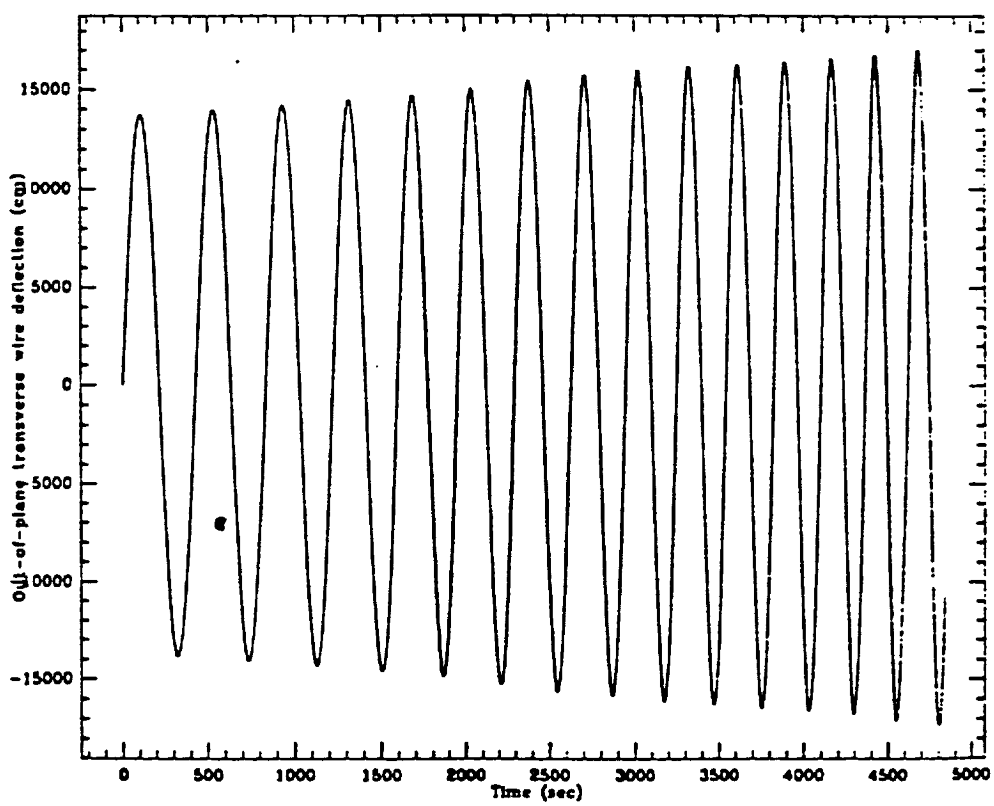
Figures 1a and 1b.





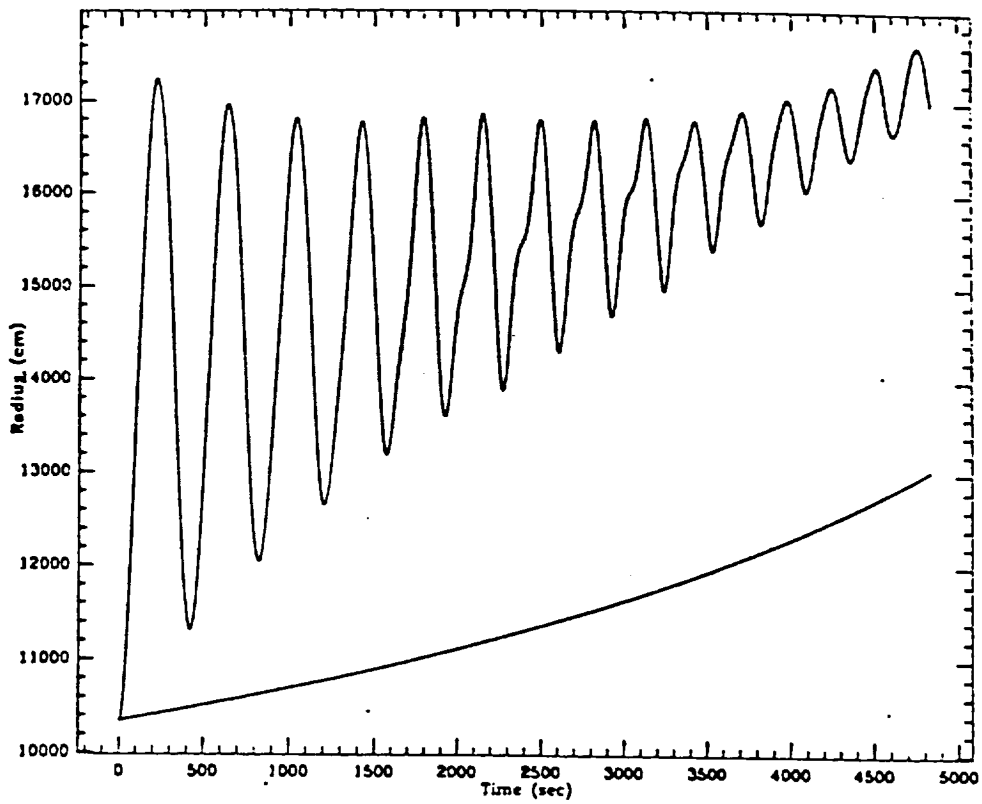
Figures 1c and 1d.

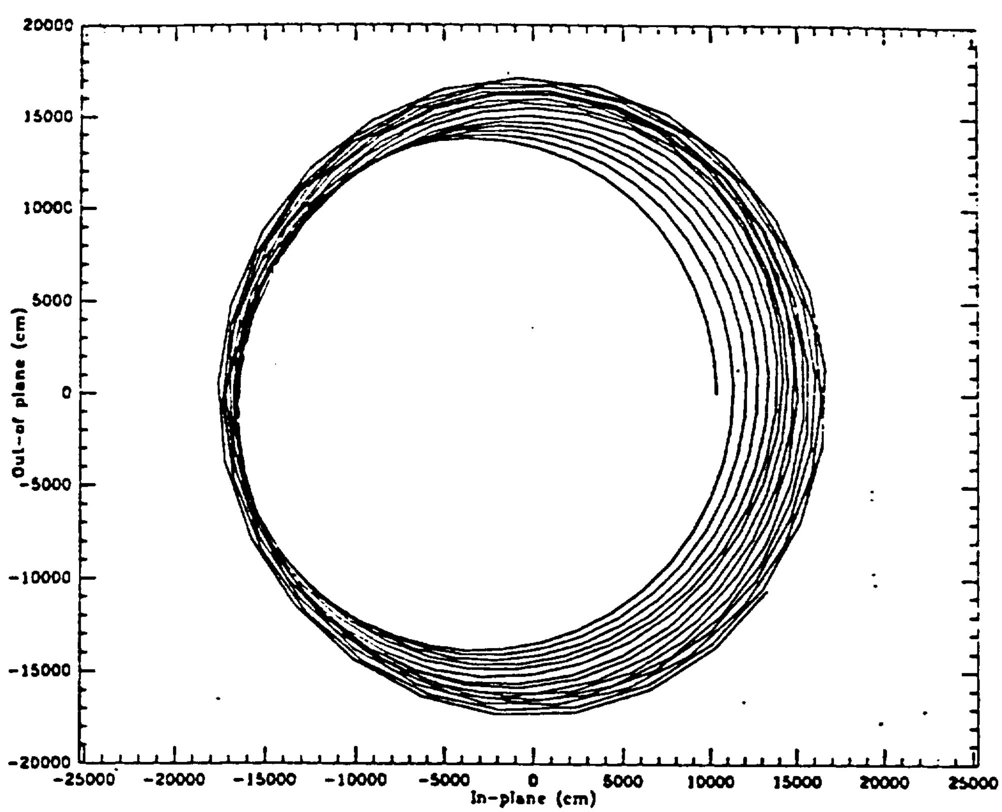




Figures 1e and 1f.

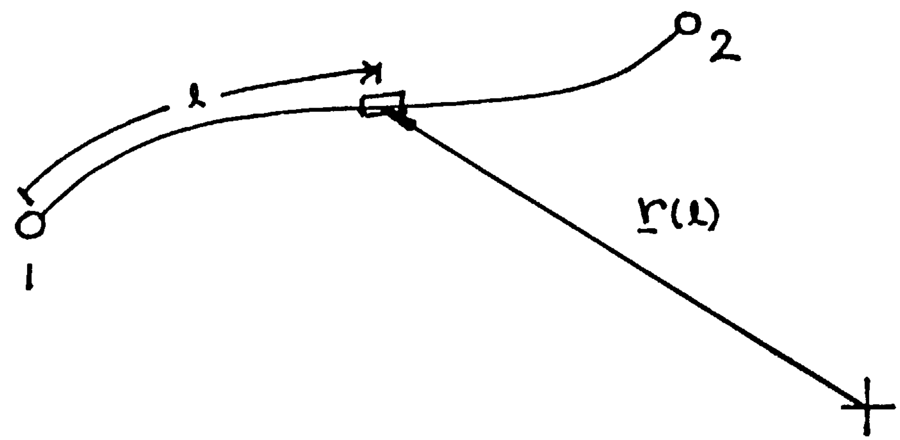
[redacted]


Radius (cm)
10000
11000
12000
13000
14000
15000
16000
17000
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Time (sec)


Out-of plane (cm)
-20000
-15000
-10000
-5000
0
5000
10000
15000
20000
-25000
-20000
-15000
-10000
-5000
0
5000
10000
15000
20000
25000
In-plane (cm)

ACM/CDy Tether Simulation

- Based on PDE $\mu \ddot{\underline{r}} = \underline{f} + \frac{\partial}{\partial \ell}(\underline{T} + \underline{Q})$

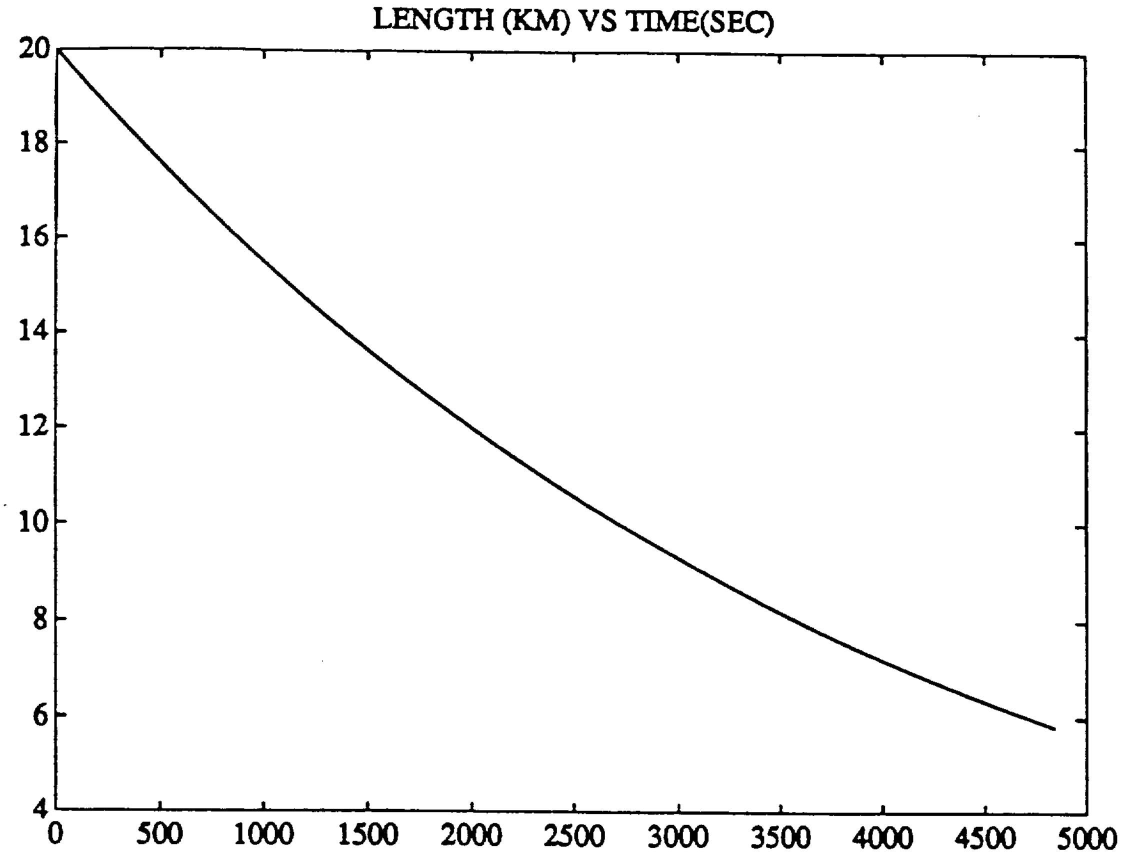


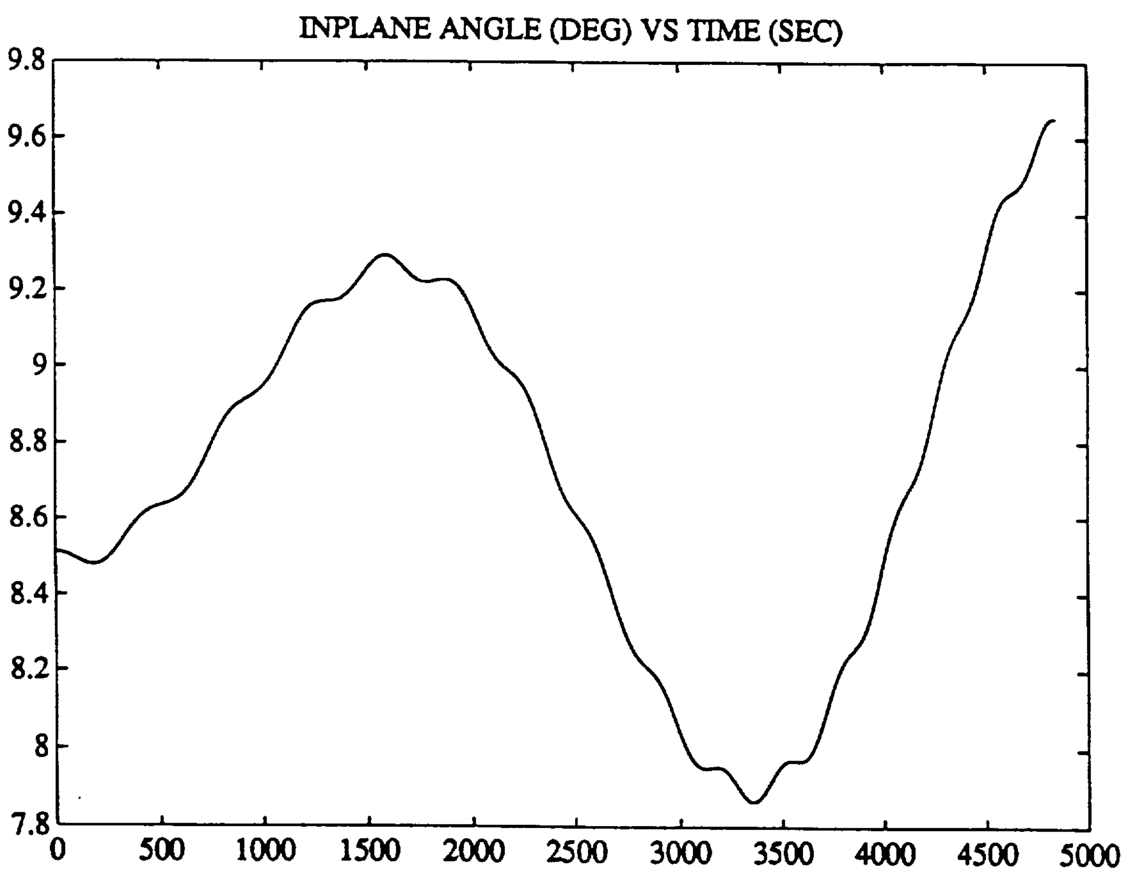
$\underline{r}(\ell)$ – Position of element at ℓ (natural length)
$\underline{f}(\ell)$ – External force per unit natural length at ℓ
$\underline{T}(\ell)$ – Tension at ℓ
$\underline{Q}(\ell)$ – Shear force at ℓ

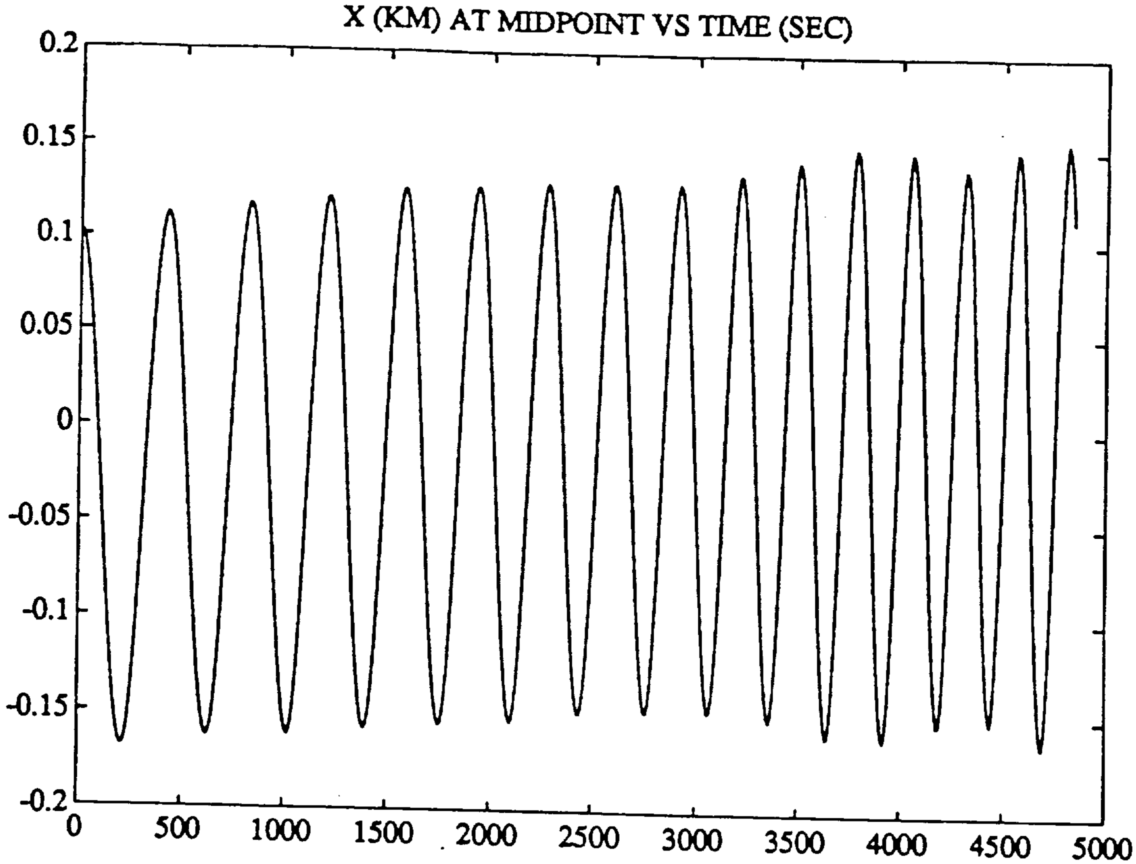
- PDE is transformed for numerical solution using $\ell = \xi L$

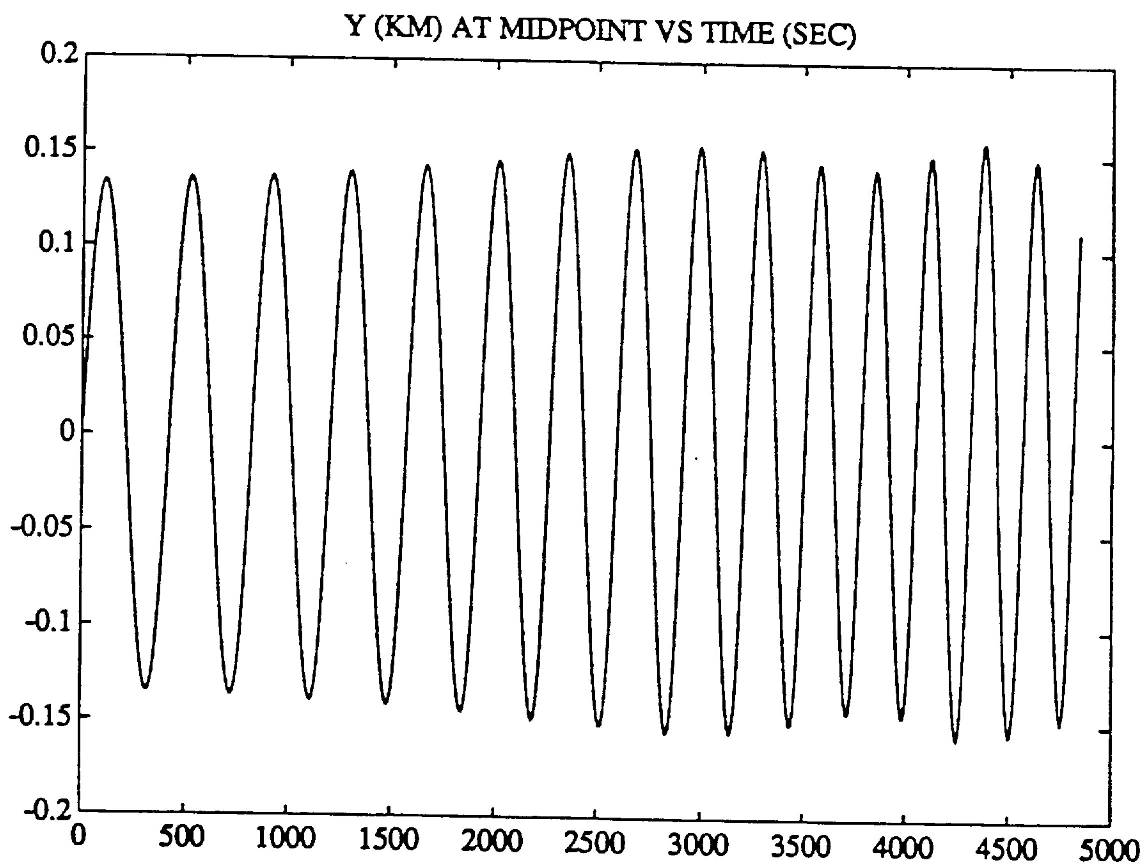
CDy COMPARISON RESULTS

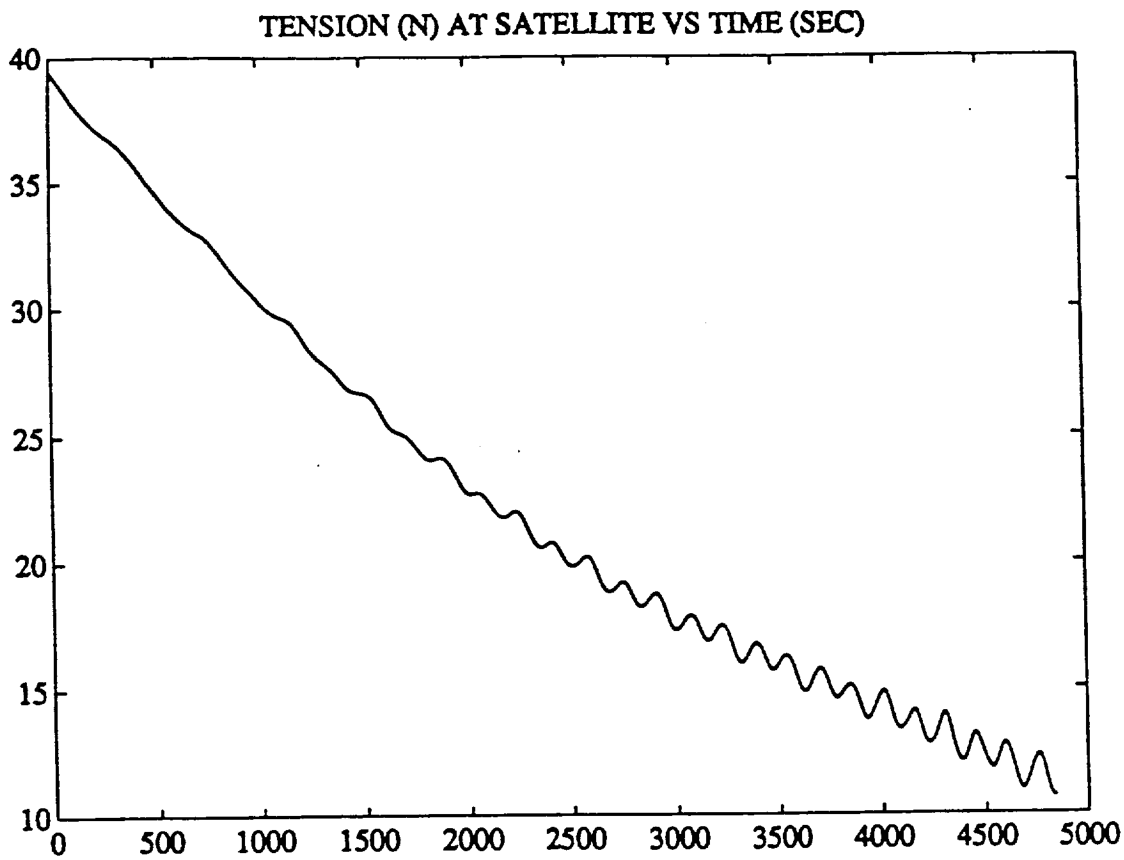
- o First attempt run with inextensible tether option
- o All other conditions set to SAO case 1 values
- o Tether skiprope started by initial conditions
  - No attempt made to match ic's at each node

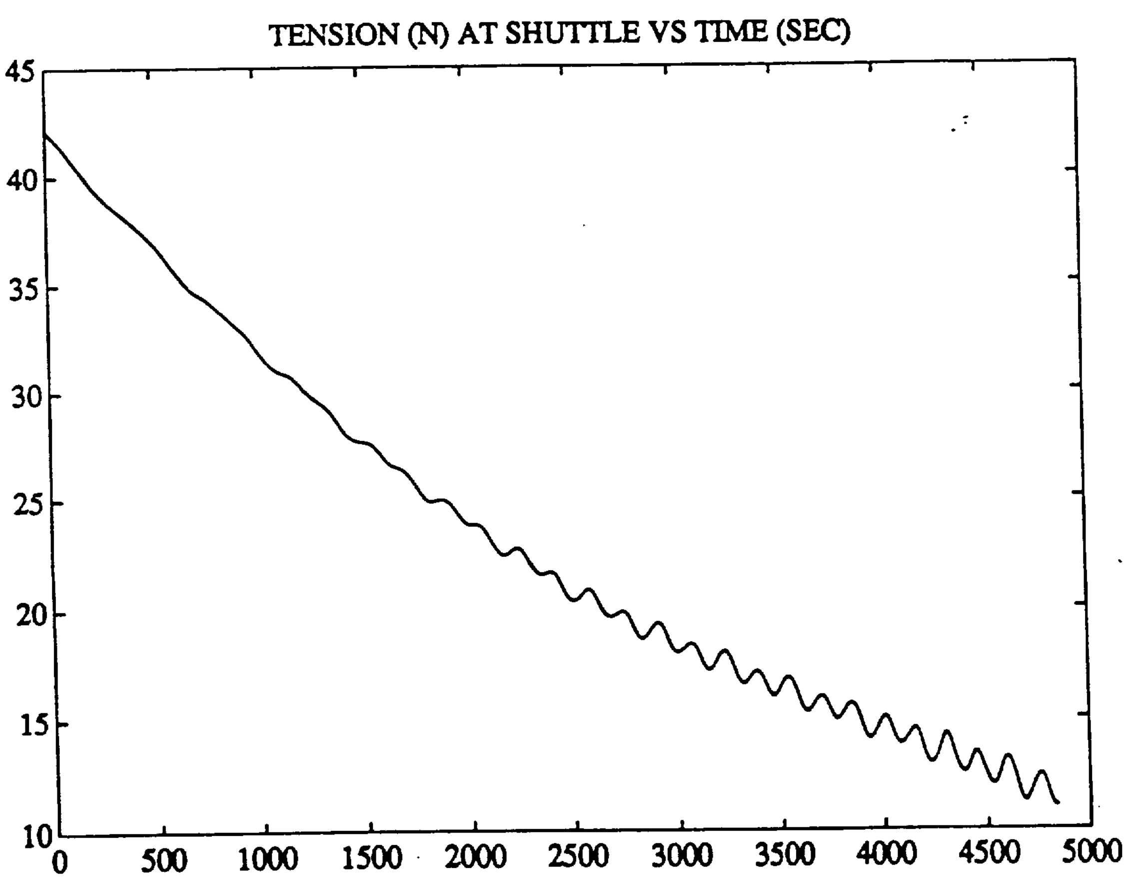

LENGTH (KM) VS TIME(SEC)
20
18
16
14
12
10
8
6
4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

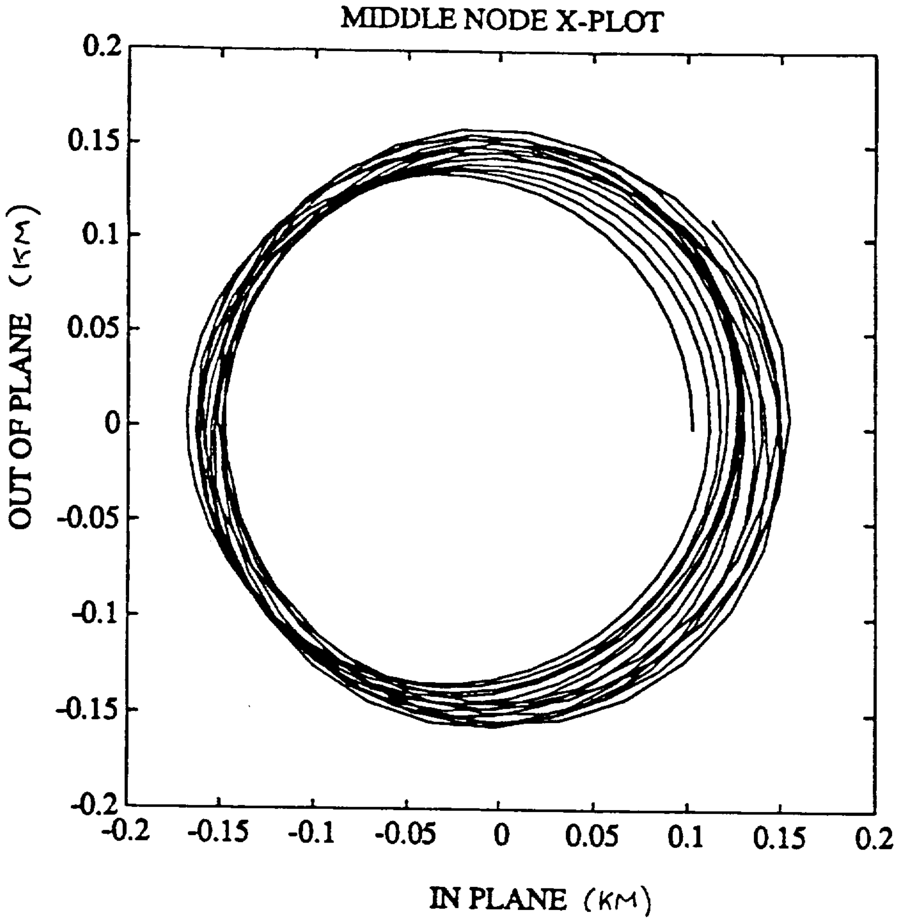

INPLANE ANGLE (DEG) VS TIME (SEC)
9.8
9.6
9.4
9.2
9
8.8
8.6
8.4
8.2
8
7.8
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


X (KM) AT MIDPOINT VS TIME (SEC)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


Y (KM) AT MIDPOINT VS TIME (SEC)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


TENSION (N) AT SATELLITE VS TIME (SEC)
40
35
30
25
20
15
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


TENSION (N) AT SHUTTLE VS TIME (SEC)
45
40
35
30
25
20
15
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000



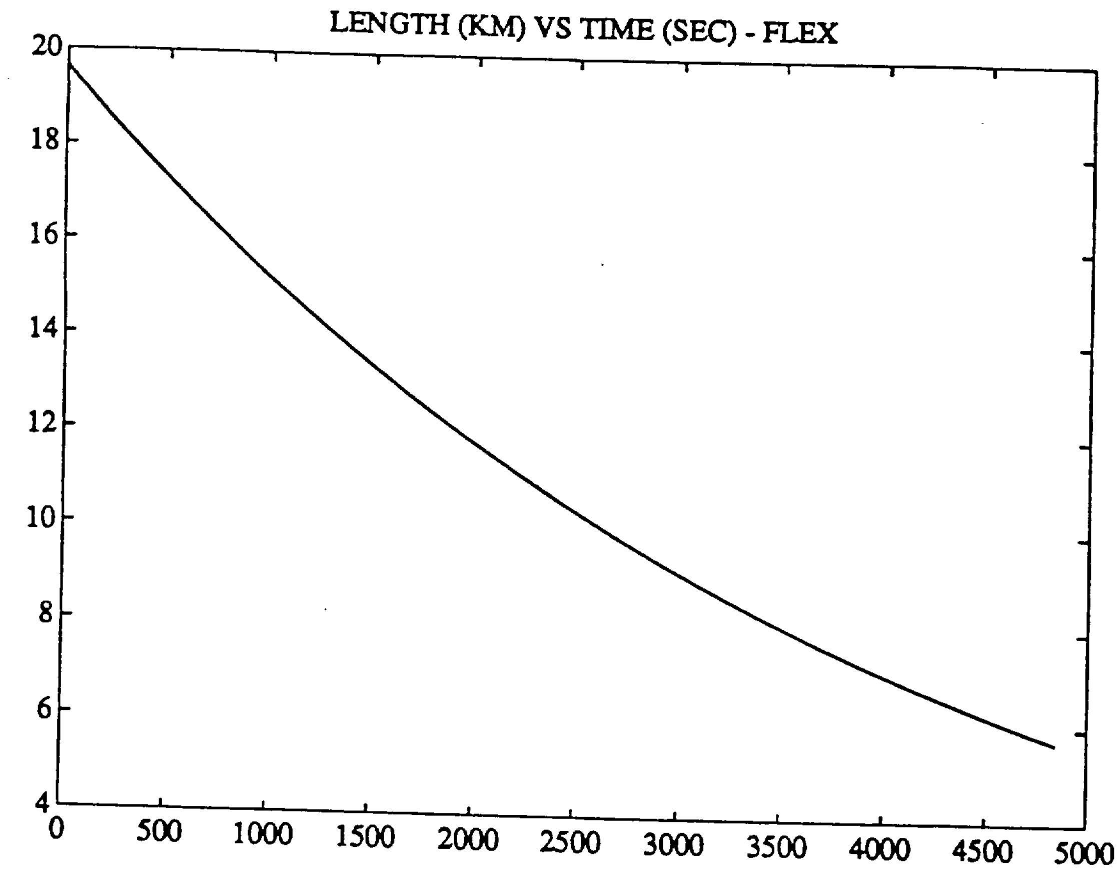
MIDDLE NODE X-PLOT
OUT OF PLANE (KM)
IN PLANE (KM)
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2

CDy COMPARISON RESULTS

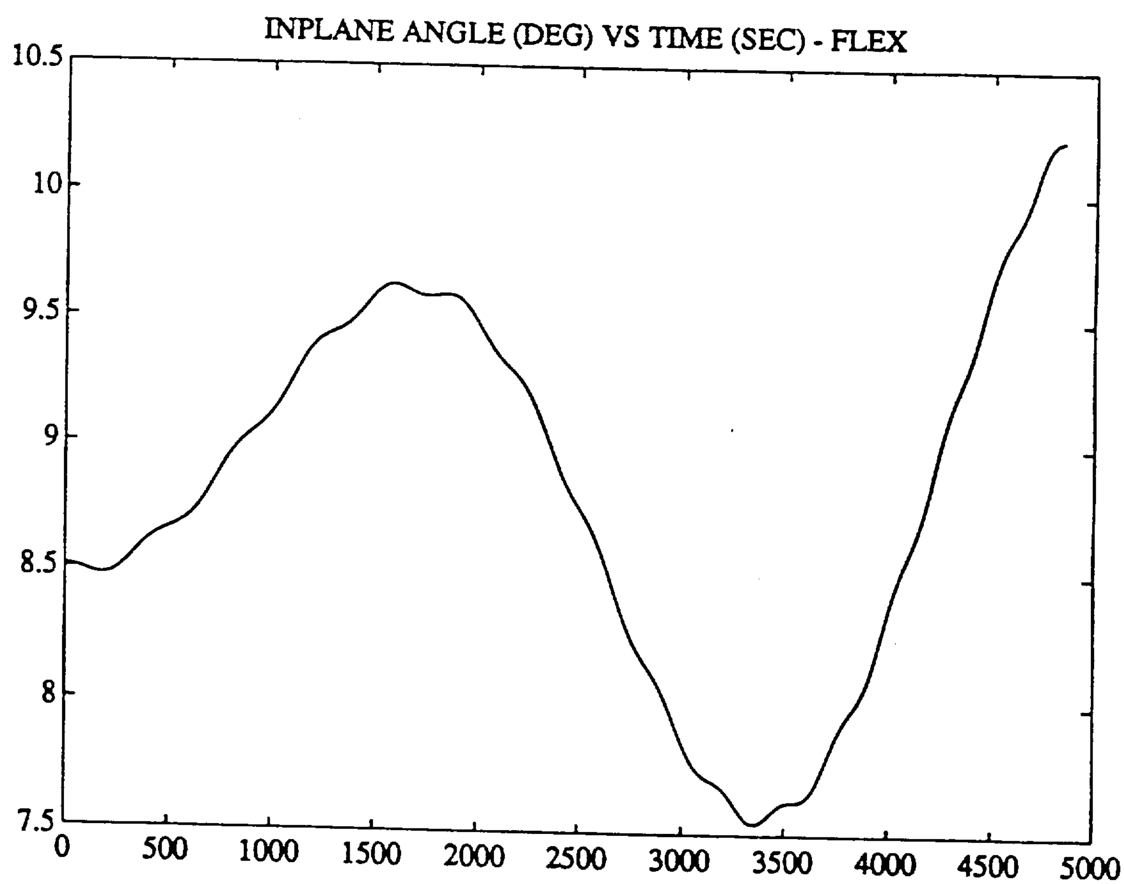
- o Second attempt run with fully extensible tether option

- o Conditions match SAO case 1 as well as is known except for initialization of node positions and velocities

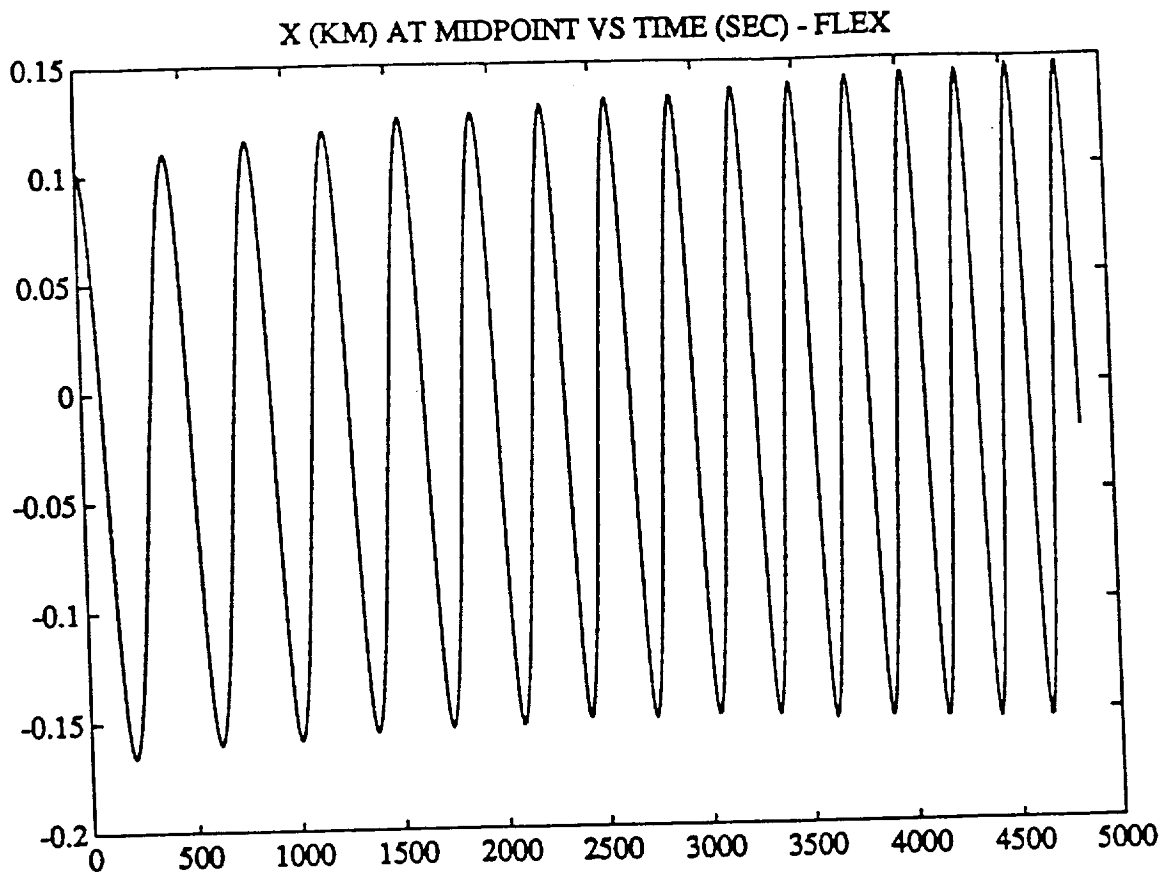
- o Skiprope initialized as in inextensible case

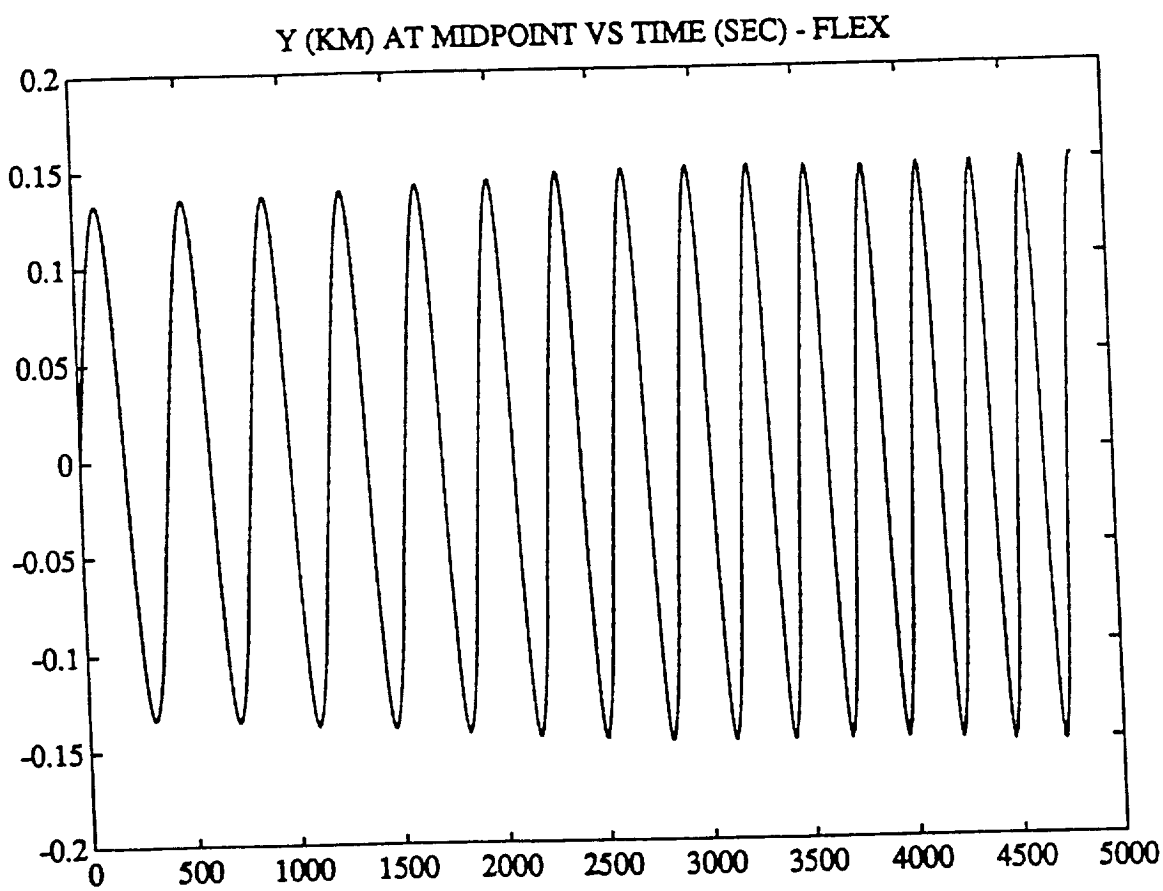


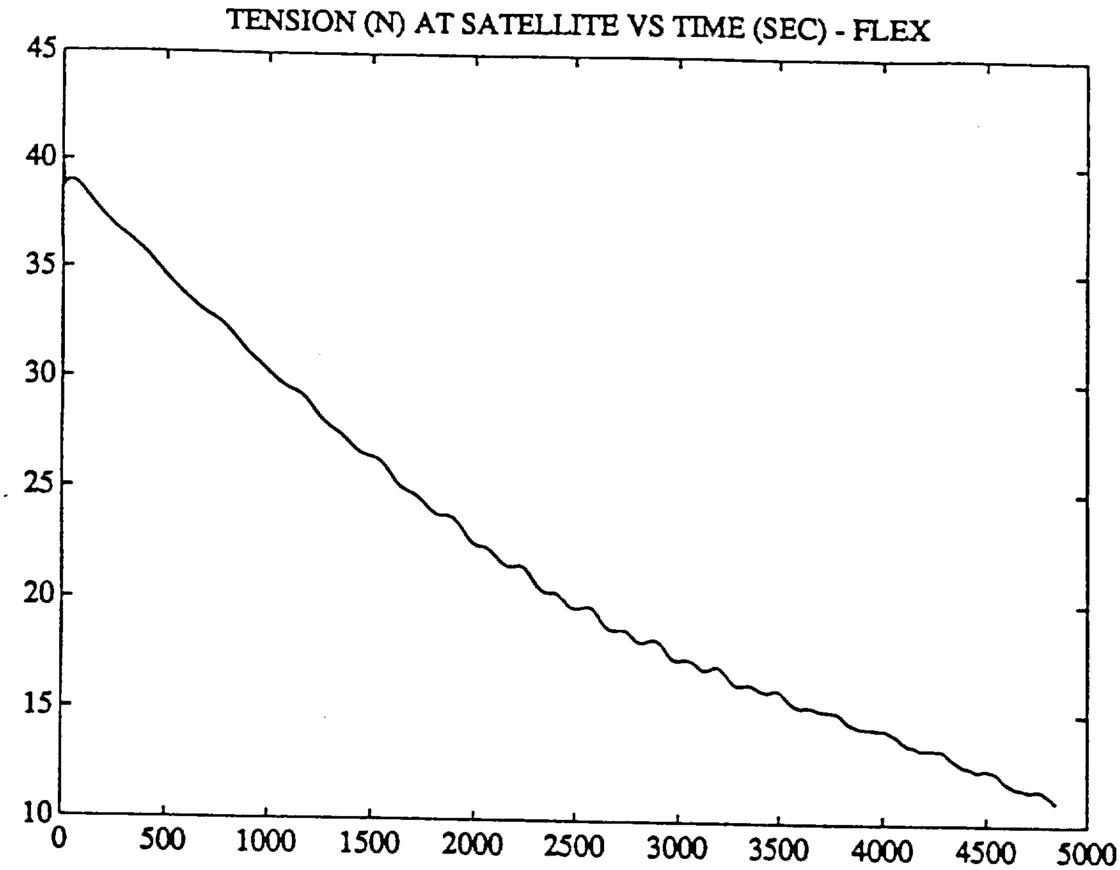
LENGTH (KM) VS TIME (SEC) - FLEX
20
18
16
14
12
10
8
6
4
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

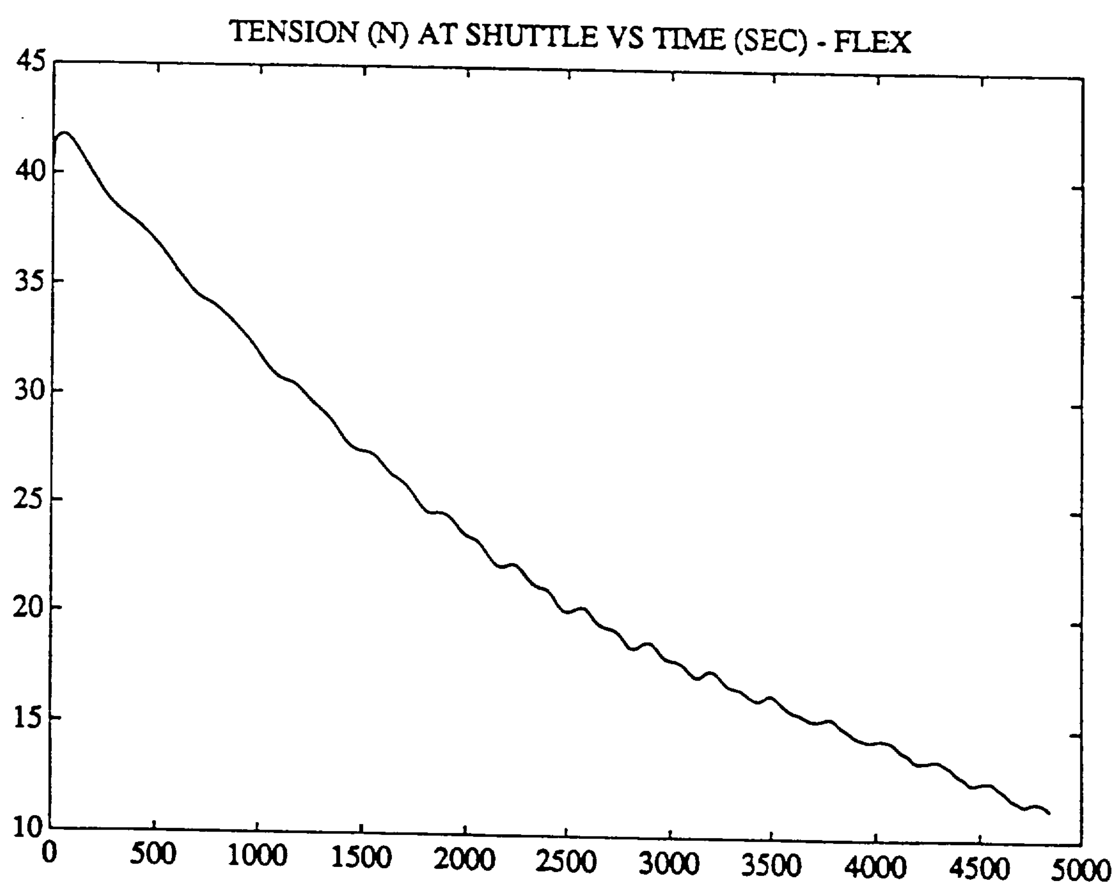


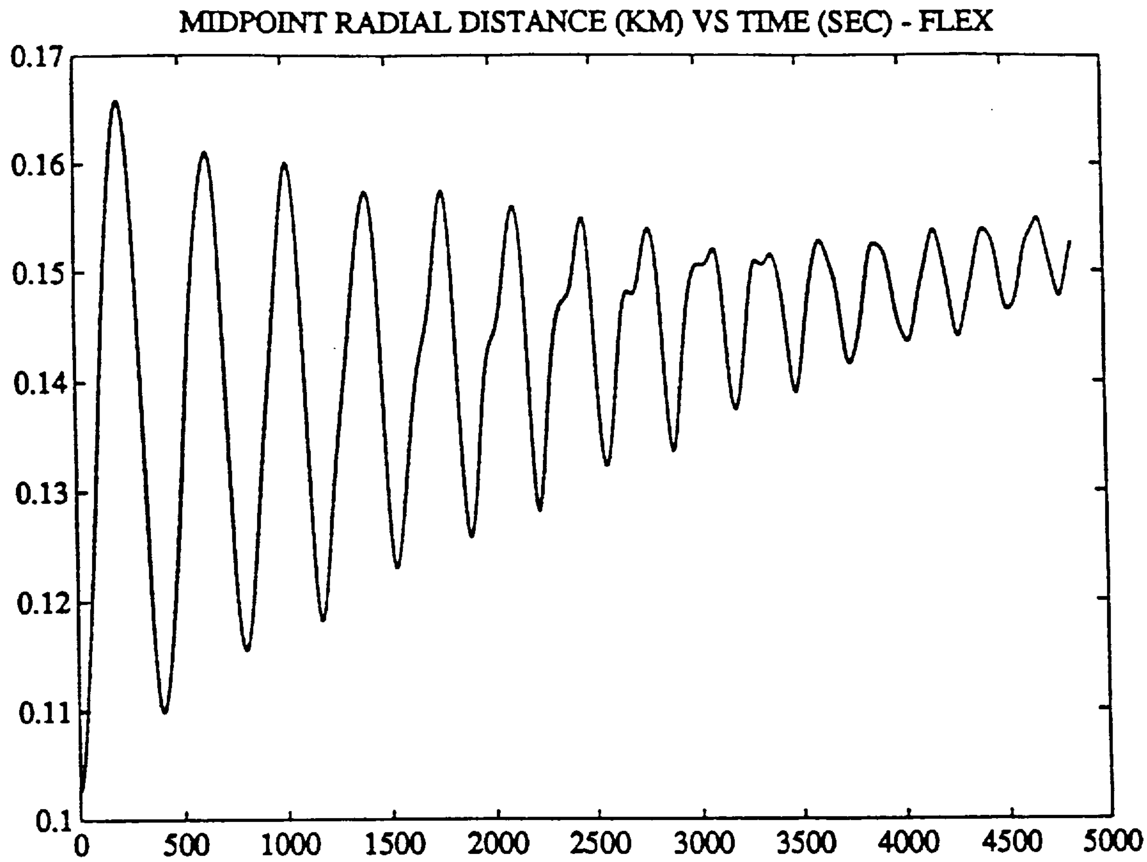
INPLANE ANGLE (DEG) VS TIME (SEC) - FLEX
10.5
10
9.5
9
8.5
8
7.5
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

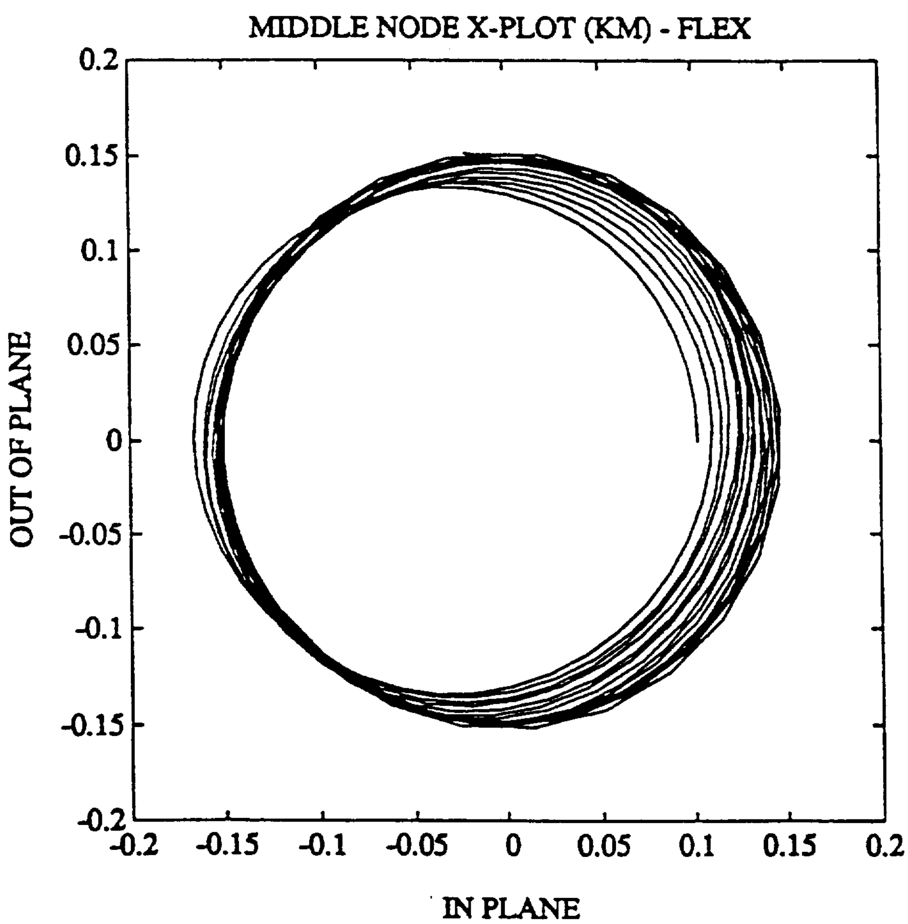

X (KM) AT MIDPOINT VS TIME (SEC) - FLEX
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


Y (KM) AT MIDPOINT VS TIME (SEC) - FLEX
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000


TENSION (N) AT SATELLITE VS TIME (SEC) - FLEX
45
40
35
30
25
20
15
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

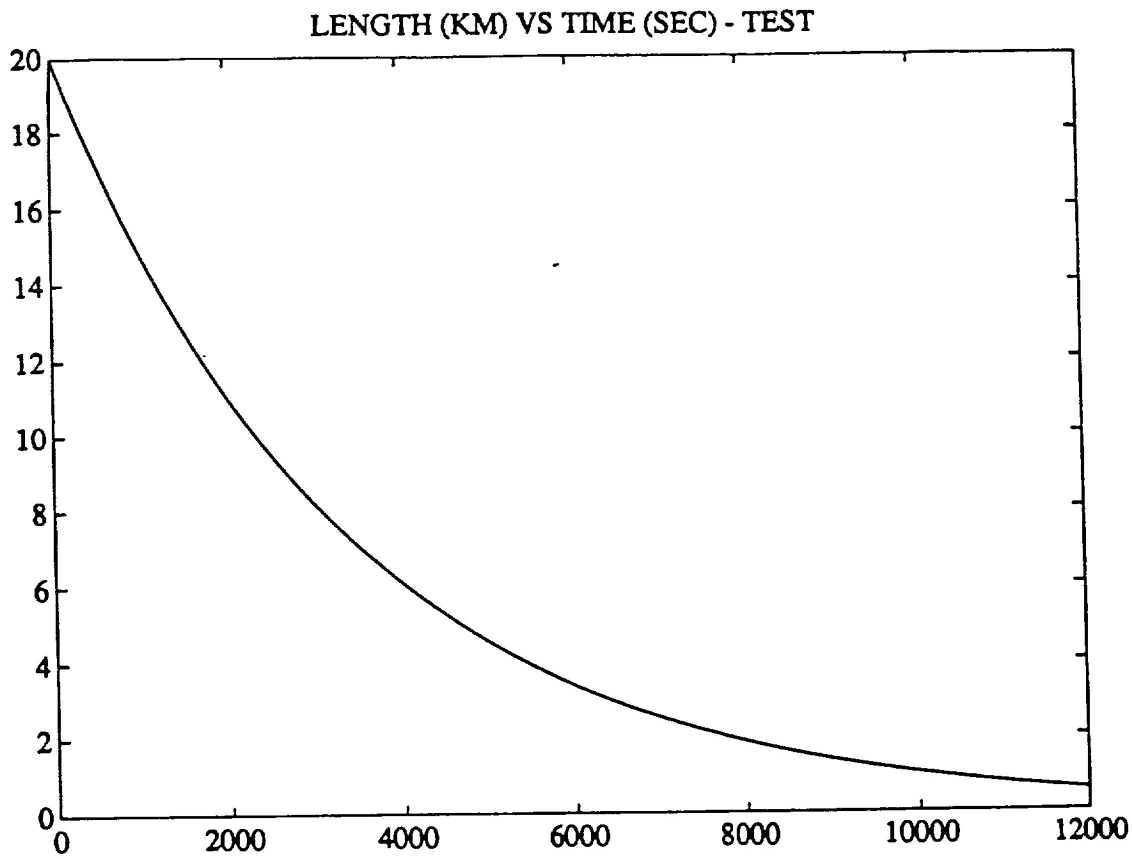

TENSION (N) AT SHUTTLE VS TIME (SEC) - FLEX
45
40
35
30
25
20
15
10
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

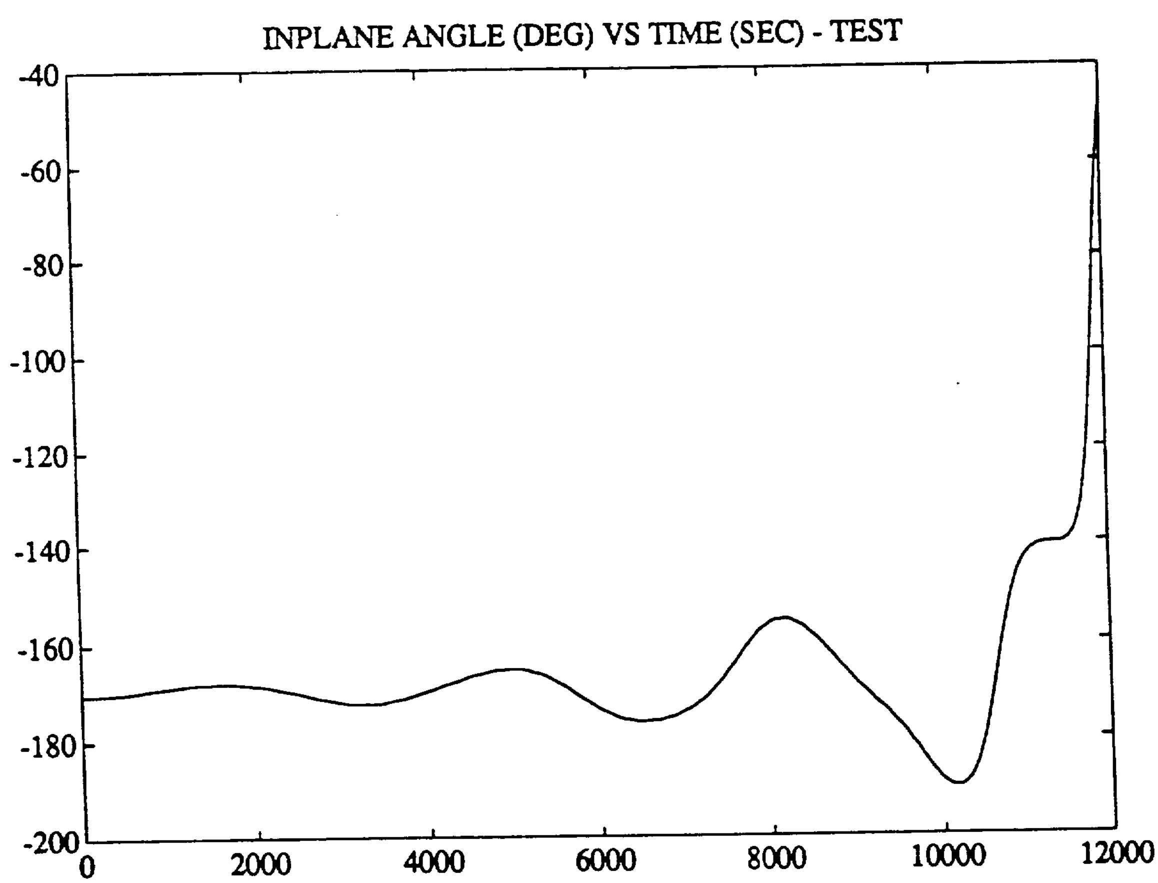

MIDPOINT RADIAL DISTANCE (KM) VS TIME (SEC) - FLEX
0.17
0.16
0.15
0.14
0.13
0.12
0.11
0.1
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000

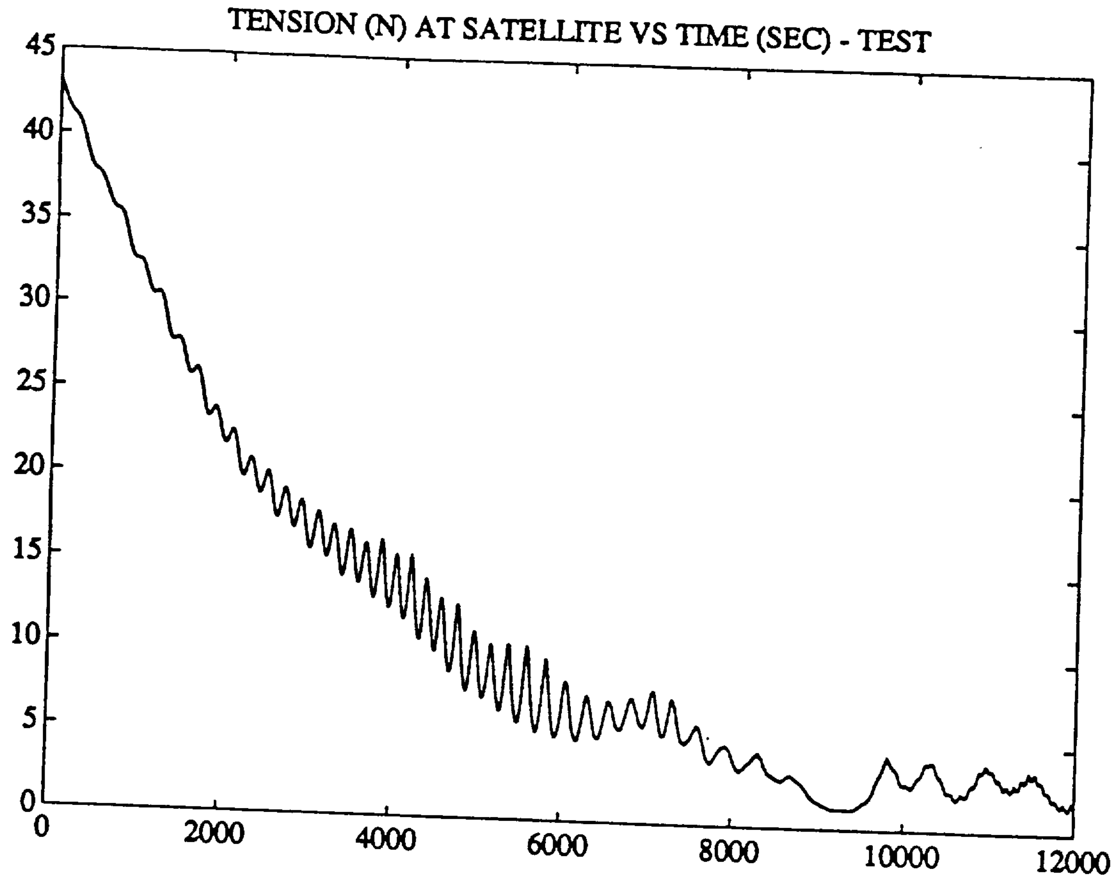

MIDDLE NODE X-PLOT (KM) - FLEX
OUT OF PLANE
0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2
IN PLANE

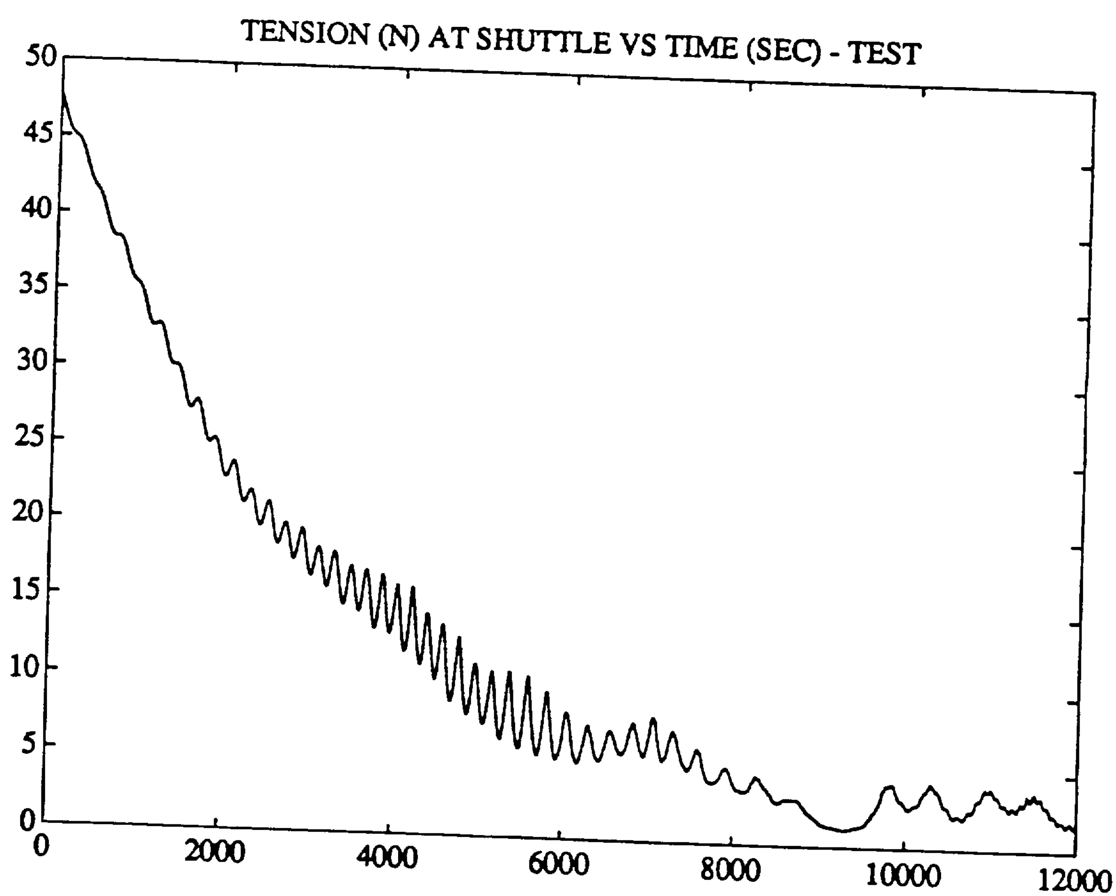
TSS RETRIEVAL TEST CASE

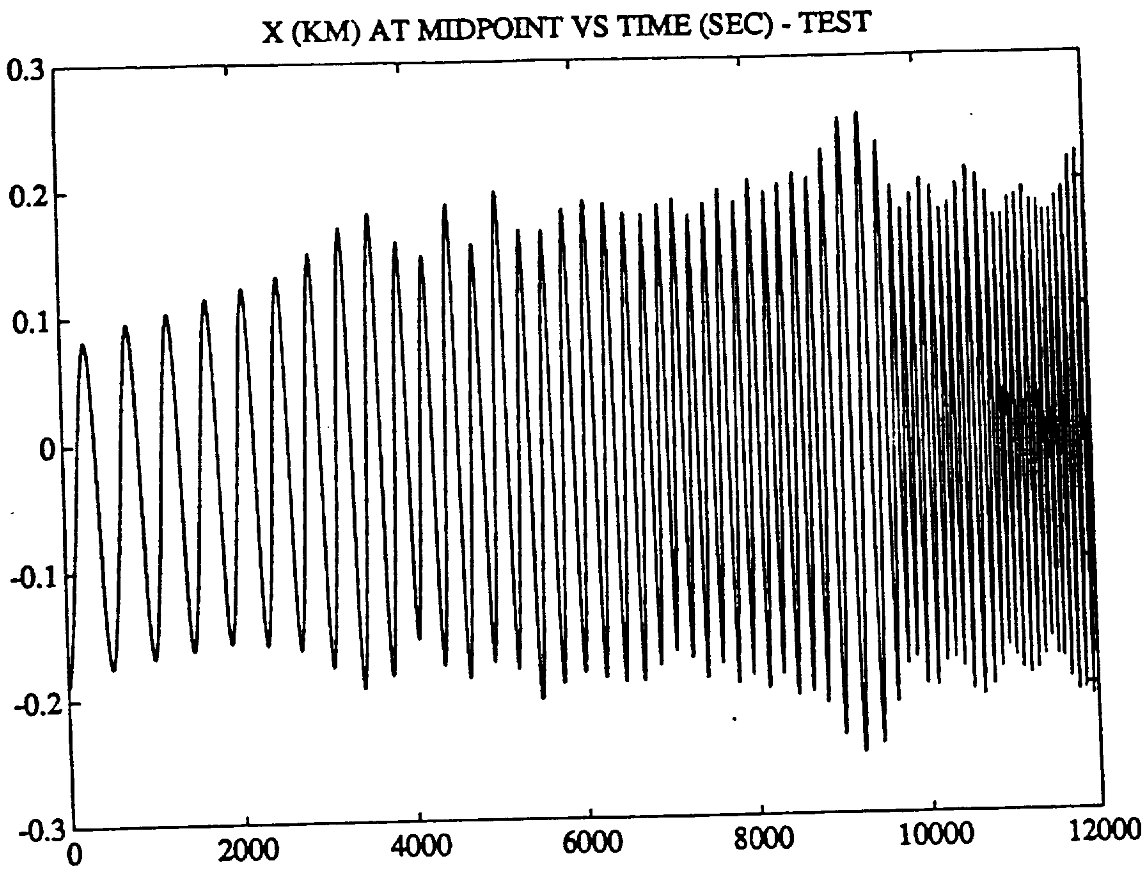
- Inextensible tether
- 10 degrees inplane angle, exponential retrieval
- 20,000 > L . 600

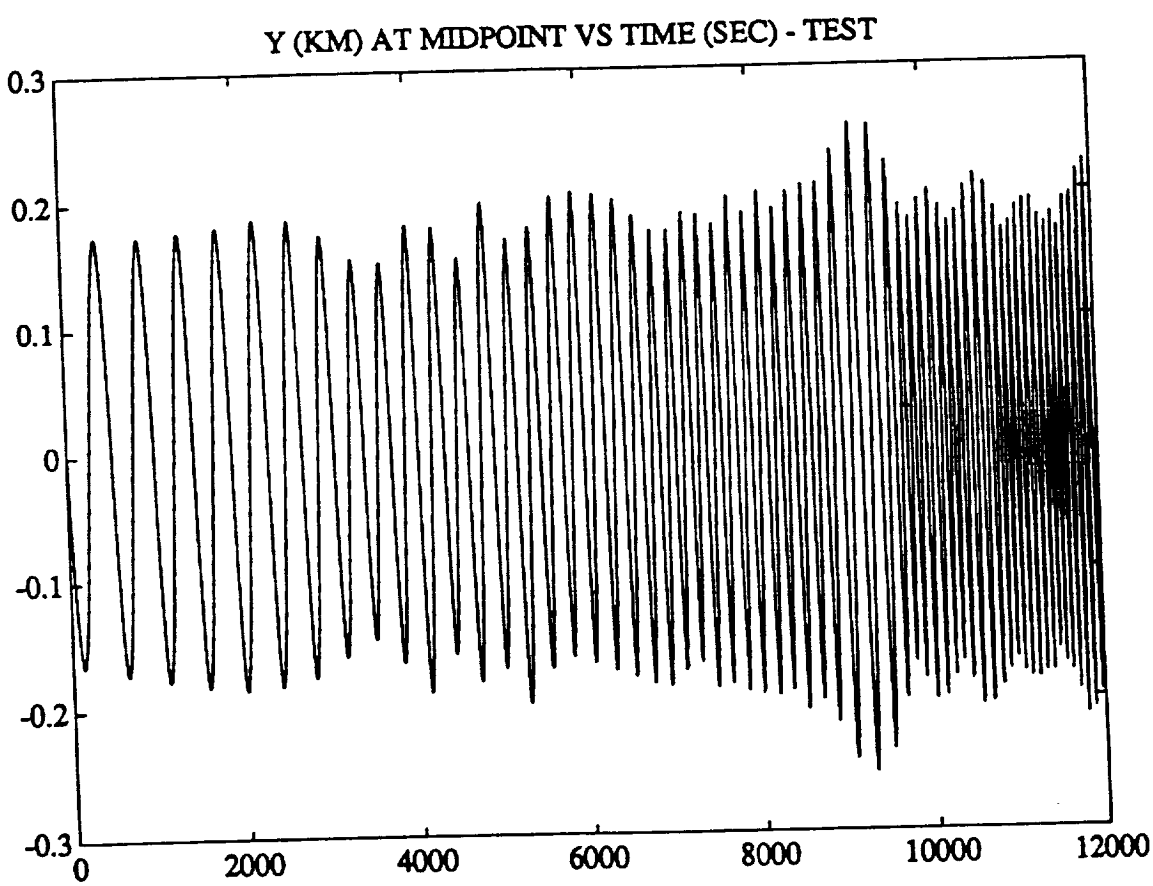

LENGTH (KM) VS TIME (SEC) - TEST
20
18
16
14
12
10
8
6
4
2
0
0
2000
4000
6000
8000
10000
12000

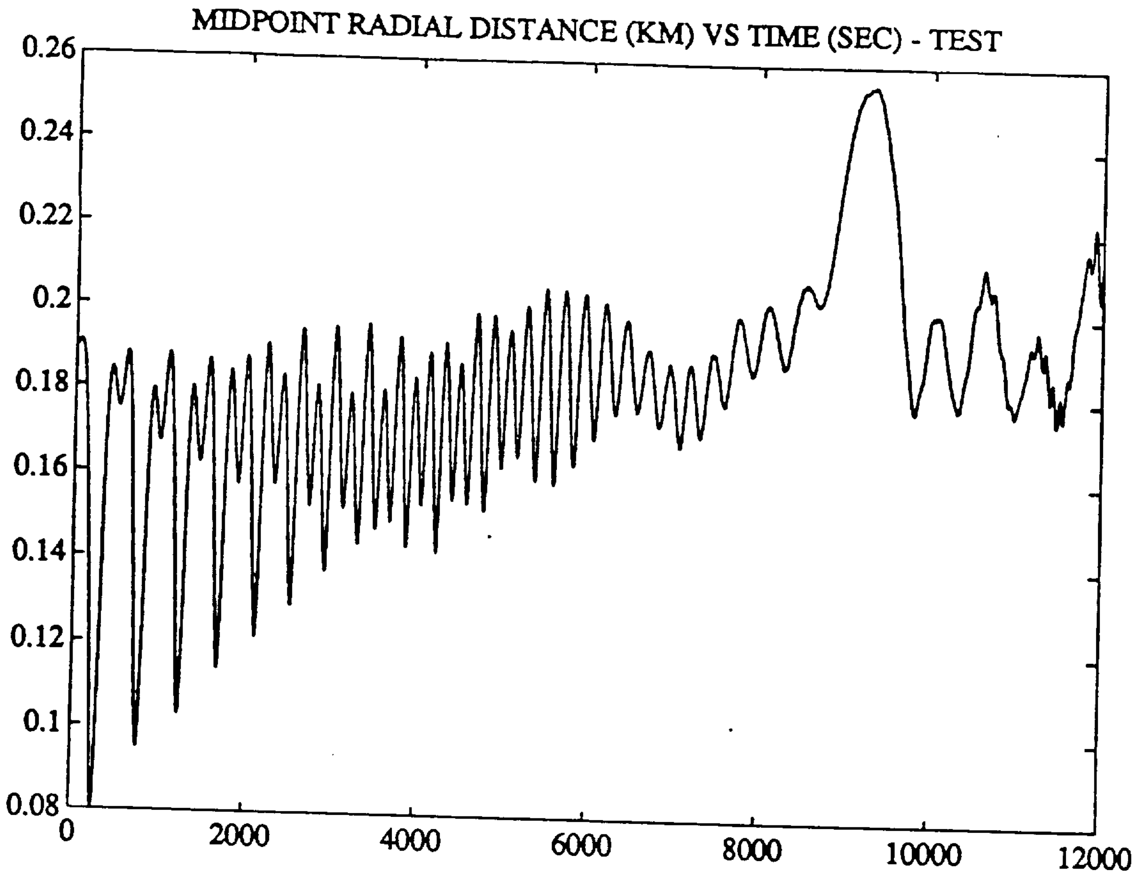

INPLANE ANGLE (DEG) VS TIME (SEC) - TEST
-40
-60
-80
-100
-120
-140
-160
-180
-200
0
2000
4000
6000
8000
10000
12000

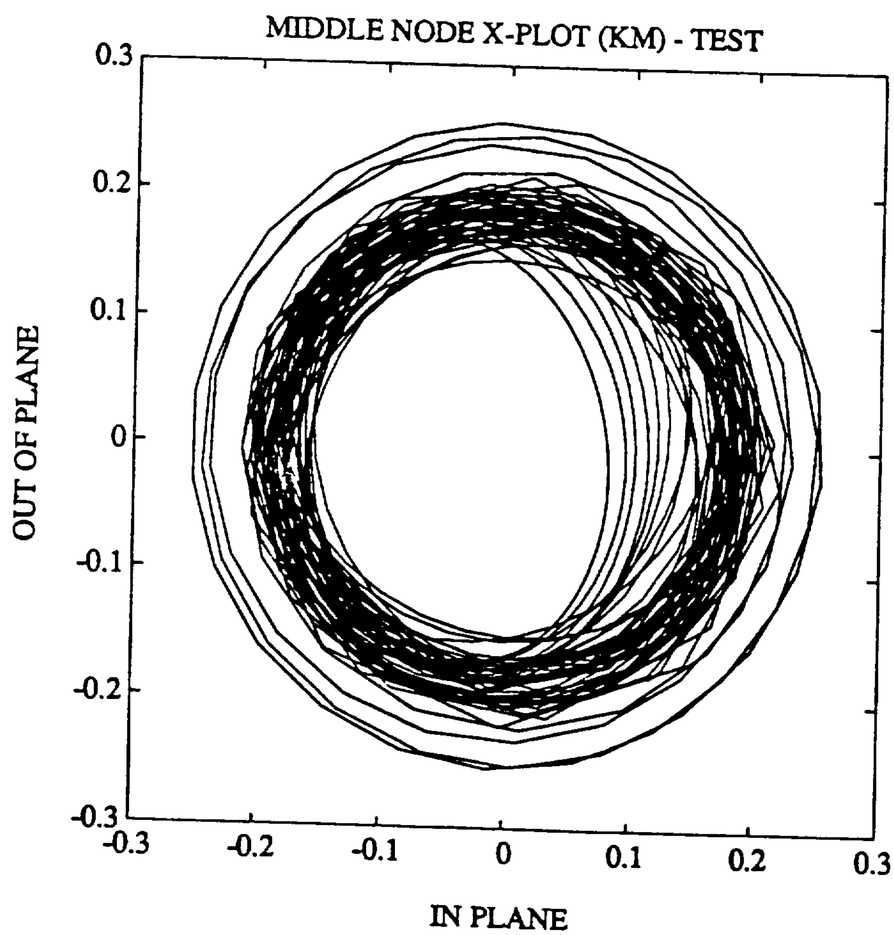

TENSION (N) AT SATELLITE VS TIME (SEC) - TEST
45
40
35
30
25
20
15
10
5
0
0
2000
4000
6000
8000
10000
12000


TENSION (N) AT SHUTTLE VS TIME (SEC) - TEST
50
45
40
35
30
25
20
15
10
5
0
0
2000
4000
6000
8000
10000
12000


X (KM) AT MIDPOINT VS TIME (SEC) - TEST
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
2000
4000
6000
8000
10000
12000


Y (KM) AT MIDPOINT VS TIME (SEC) - TEST
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
0
2000
4000
6000
8000
10000
12000


MIDPOINT RADIAL DISTANCE (KM) VS TIME (SEC) - TEST
0.26
0.24
0.22
0.2
0.18
0.16
0.14
0.12
0.1
0.08
0
2000
4000
6000
8000
10000
12000


MIDDLE NODE X-PLOT (KM) - TEST
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
OUT OF PLANE
-0.3
-0.2
-0.1
0
0.1
0.2
0.3
IN PLANE