STEP TETHER DYNAMICS PRELIMINARY ANALYSIS FINAL REPORT

Prepared for:

National Aeronautics and Space Administration
George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

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Prepared by: ______________________________

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1. STATEMENT OF WORK

The work performed under this contract has been directed to the tasks specified in the statement of work. These are summarized below:

SOW Task 3.1 The contractor shall modify the existing tether dynamics computer simulation, GTOSS or TSSIMR to provide the capability to model the electrodynamic tether behavior of STEP-AIRSEDS configurations for the reference mission profiles.

SOW Task 3.2 the contractor shall perform computer simulations that predict the electrodynamic performance and tether dynamic behavior for the STEP-AIRSEDS configurations for the reference mission profiles.

SOW Task 3.3 The contractor shall perform an assessment of the dynamic stability of the STEP-AIRSEDS configurations and define potential tether control strategies and concepts and the preliminary requirements such strategies would present.

2. OVERVIEW

Since GTOSS is currently more general in its ability to model multiple tether configurations and already contains the appropriate environmental models, we decided to start out using it as the tether modeling tool. Ken Welzyn/MSFC TD55 provided a version of this tool for adaptation to the PC environment. Our first step has been the conversion to the PC environment. This has been completed successfully. We now have a running version of the tether simulator GTOSS and of its post processor software called CTOSS. In addition to the software, documentation was also provided along with a running example problem from which to build/adapt the descriptive input files for the various STEP-AIRSEDS configurations.

The three body configuration (3BC) for STEP-AIRSEDS was chosen as the first configuration to model since it is the most complex and will require the multiple tether and multiple body features of GTOSS. Several 3BC have been proposed. We have chosen the one having the large central body near the system center of mass. The central body is defined as the reference body for

GTOSS. The upper end body is 6 km from the central, while the lower end body is 10 km away. These three bodies are held together by two tethers. The upper tether is assumed to be bare aluminum, while the lower is half insulated / half bare aluminum. The upper half is insulated. The initial approach to modeling this configuration was to consider each tether as consisting of two subtethers which are connected. For modeling reasons, an additional body is required to connect the subtether together. This allows for the possibility that the upper tether may be partially insulated also. Thus, the initial 3BC model consists of 4 tethers and 5 bodies. For this model, tether 1 and tether 2 are each 3 km with a mass density of 0.0132 kg/m. Tether 3 and tether 4 are each 5 km with a mass density of 0.0132 kg/m. Body 1 has a mass of 569 kg. Body 2 is the upper end body with a mass of 126 kg and body 5 is the lower end body with a mass of 74 kg. Bodies 3 and 4 are connecting bodies considered part of the upper and lower tether respectively. Each has a mass of 9.9 kg, which is approximately equivalent to one tether "bead" element.

In the process of adding the current flow model to GTOSS it was determined that modeling flow across a tether boundary added a level of complexity which was very undesirable. Additionally, it was determined that variable cross section properties could be defined for GTOSS tethers so that the original motivation for four tethers in the 3BC model was misguided. As a result of these insights the 3BC model was revised to a three body, two tether model. This is the configuration for which simulation results have been generated. The mass and tether properties previously defined are unchanged except that the connecting bodies have been eliminated and the two upper tethers have been combined and the two lower tethers also combined.

3. CONSTRUCTING THE GTOSS MODEL

The first step in constructing the GTOSS model was to define the configuration-input file. We immediately discovered that our version of GTOSS was only dimensioned for 3 finite tether solutions, although no error message informed the user that there was a problem--only strange results made this apparent. Further searching revealed that the initial delivery was set to 3 finite tether solutions but that this could be easily expanded to 9. We reset it to 4 for our case. This seemed to improve our results but tether motion still was unstable. This was thought to be due to an active current scenario, so we next investigated what output formats and what techniques were available to plot results. Initial currents were being set inadvertently because of residual settings in the template input files. These were set to zero and results improved significantly. Now just a single tether was being driven unstable. No more currents were observed so this was a puzzle. Finally, it was discovered that additional dimensions had to be reset to activate the fourth finite tether solution. Once these changes were made, the tether motion became stable. Tether solutions now seem to be normal with and without current scenarios.

4. TETHER CONTROL STRATEGIES

It is anticipated that several control strategies may be available depending on the level of electrodynamic force generated in relation to tether length and system mass magnitude and distribution. Passive strategies such as careful distribution of mass between bodies in the configuration should be sufficient for low to moderate thrust levels. Current limiting may be required to insure stability. Dampers to damp tether longitudinal and skip rope oscillations may be required. These may also be considered passive but probably involve devices with moving parts. To maximize electrodynamic thrust levels it is likely that some sort of active control combining current scheduling with attitude control and some form of vibration suppression will be required. Passive strategies will be studied first.

5. ELECTRODYNAMIC FORCES

Electrodynamic forces on a tether are produced by interaction between a current flowing in a tether and a magnetic field. The magnetic field of the earth points generally to the north. The electrodynamic force produced is perpendicular to the tether and at the same time perpendicular to the magnetic field. This same phenomenon makes an electric motor or generator work. Motor current flows entirely through solid conductors and is well understood. Current flow in a tether in space, however, is somewhat different. Tether current in space must flow along a path which is partially through the space plasma in order to realize the electrodynamic force. Accomplishing this reliably and simply is still in the research stage.

6. ON-ORBIT OPERATIONS

The STEP-AIRSEDS two and three body configurations provide alternatives for on-orbit operations. The three body/two tether configuration allows a separate tether for orbit raising and orbit lowering. Since the three body configuration is more complex and difficult to model, it is the configuration which has been the primary focus of our development of GTOSS. The central body of the three body configuration provides the return path for electrons to the space plasma for both orbit raising and orbit lowering operations. The orbit raising tether is the lower tether and requires a high voltage power supply. This is on the central body which is assumed have the bulk of the total mass. This tether is assumed to be 10 km in total length with its upper half insulated. The non-insulated portion part of the tether picks up electrons from the space plasma, establishing an upward (away from the earth) electron flow in the tether. A large, positive voltage is required to be maintained between the middle body and the tether in order to achieve an orbit raising current. This is provided by the power supply. The voltage required varies with the tether motion emf and can be in the range from one to two thousand volts. Since power is limited to approximately one kW, currents may be as low as 0.5 amperes and seldom higher than 3. Not only are currents restricted for orbit raising but atmospheric drag must also be overcome. Thus, orbit raising will be significantly slower than orbit lowering. At the same time, such small currents will keep orbit raising relatively stable and well behaved. An example of 24 hours of orbit raising operations for a three body configuration is illustrated in figures 1-6. Figure 1 shows spacecraft (center object) voltage bias (and power supply voltage) required to drive current through the lower tether using the 1 kW of power available. Figure 2 shows the emission current at the plasma contactor. It is to be observed that according to the current model, no current is produced for significant periods of time. This is apparently because the magnetic field is not properly aligned to produce positive electrodynamic thrust in the lower tether so that no positive spacecraft bias voltage can produce a current flow. Figure 3 shows that this is not seem related to low electron density. Figure 4 shows the increase in the altitude resulting from the electrodynamic thrust. The altitude increases approximately 15 km over the 24 hours of the simulation run. Figure 5 shows the tension in the upper and lower tethers. Note that the oscillation amplitude increases but appears to approach a steady amplitude of approximately 1 N toward the end of the day. The upper curve in figure 5 is the 10 km tether which is the one carrying the current. Figure 6 shows the tether librations which are excited by the current flows. Maximum angles achieved are between 2 and 2.5 degrees and occur rather early in the day. Longer observations may be required to determine maximum libration and tension oscillation amplitudes.

Figures 7-10 show an example run with the same initial orbit conditions for orbit lowering operations. The current for this example is assumed to flow through the upper tether, which is uninsulated and assumed to be 6 km in length. The level of current is determined by control logic which attempts to maintain the spacecraft bias voltage at -20 volts. This is somewhat arbitrary but represents the action of an onboard current controller. Again, notice that current flow cannot be maintained continuously because of the occasional bad alignment of the magnetic field with respect to the tether and orbit path.

Figure 7 is the spacecraft emission current at the plasma contactor. Figure 8 is the spacecraft altitude variation with time. Notice that it changes significantly faster than the orbit raising example. This is because the current, which can be produced in the tether for orbit lowering is not limited by the 1 kW available power for orbit raising. The current oscillations are larger than observed for orbit raising. These large current oscillations cause the orbit eccentricity to double over the day. These large variations in tether current being produced by the system make the electrodynamic thrust unbalanced. This produces elliptical orbits and also aggravates tether oscillations. It is already obvious that some enhanced form of tether current control is required to minimize this observed tendency to attain precise control of orbital parameters required to achieve rendezvous with a payload spacecraft for transfer to higher or lower orbit. Figure 9 shows tether tension oscillations that are growing at a significantly faster rate than figure 5, showed. Figure 10 shows correspondingly higher libration oscillation. The sample problems run are limited to a single 24 hour period of observation and a single 3BC. The recent trends for STEP-AIRSEDS is to a two body configuration. Behavior for a two body configuration will be somewhat different but the trends shown in these results will still be applicable.

Table 1

Sample Orbit Initial Orbit Properties

Initial altitude	= 400 km,
Initial orbital latitude	= -11°,
Initial orbital longitude	= -43°,
Initial earth longitude	= -43°,
Initial sun longitude	= 180°,
— (independent of date and fixed in GTOSS option used)	
Inclination	= 35°,
Simulated Date of run start	= 10/10/2003 @ 18:00:00,
—(Used by atmosphere and ionosphere model calculations)	

Figure 1

Orbit Raise Example

Constant 1 kW Spacecraft Power Supply

Supply Voltage

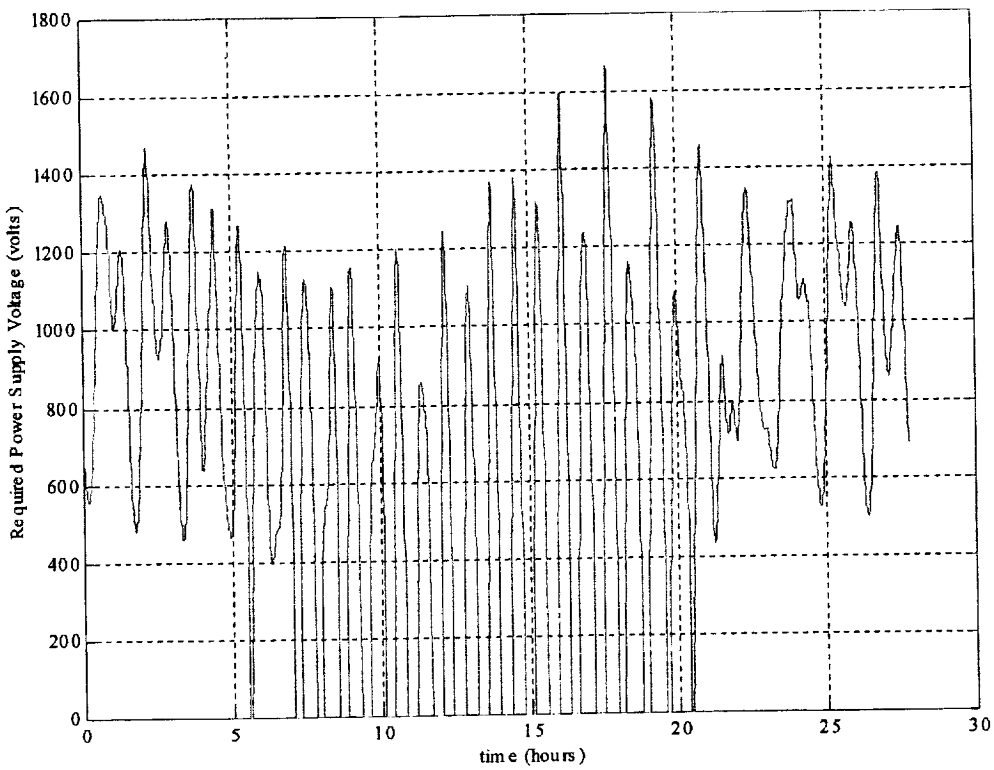


Figure 2

Orbit Raise Example

Tether current, lower tether (amperes)

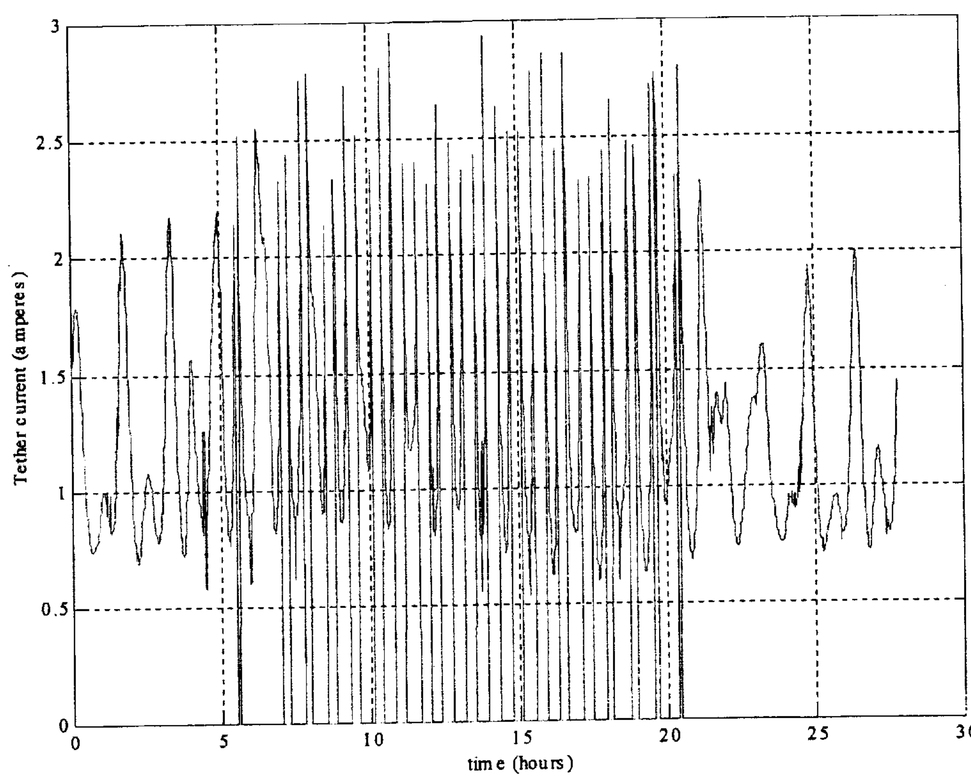


Figure 3

Orbit Raise Example

Electron density

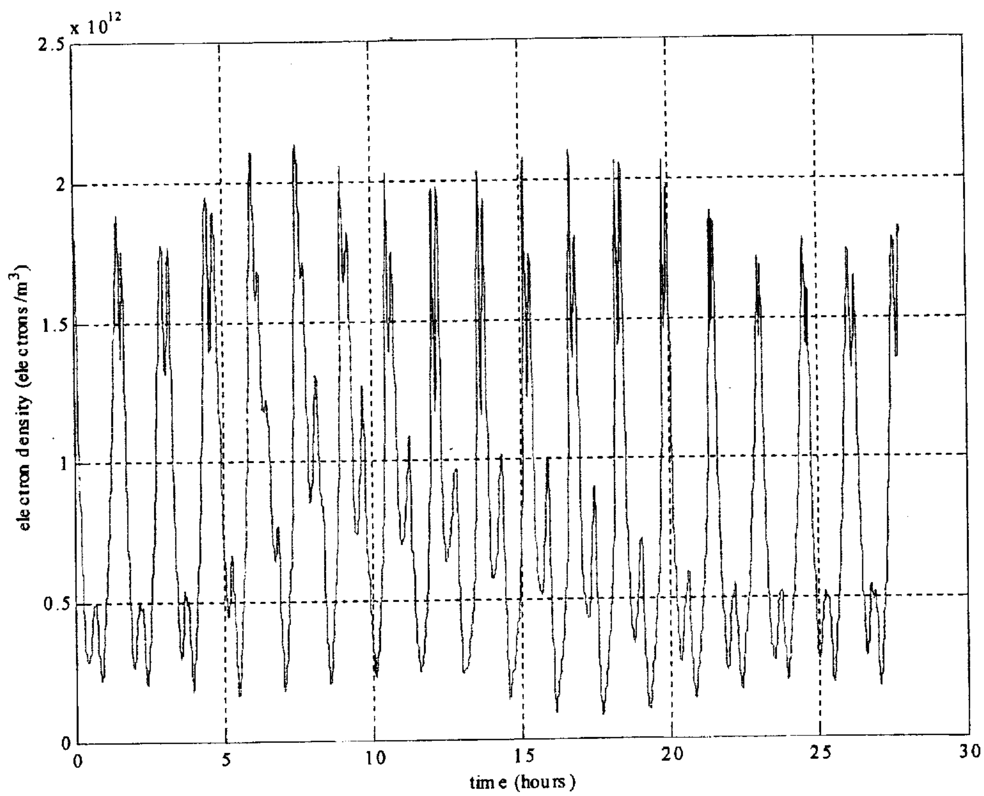


Figure 4

Orbit Raise Example

Central body altitude (km)

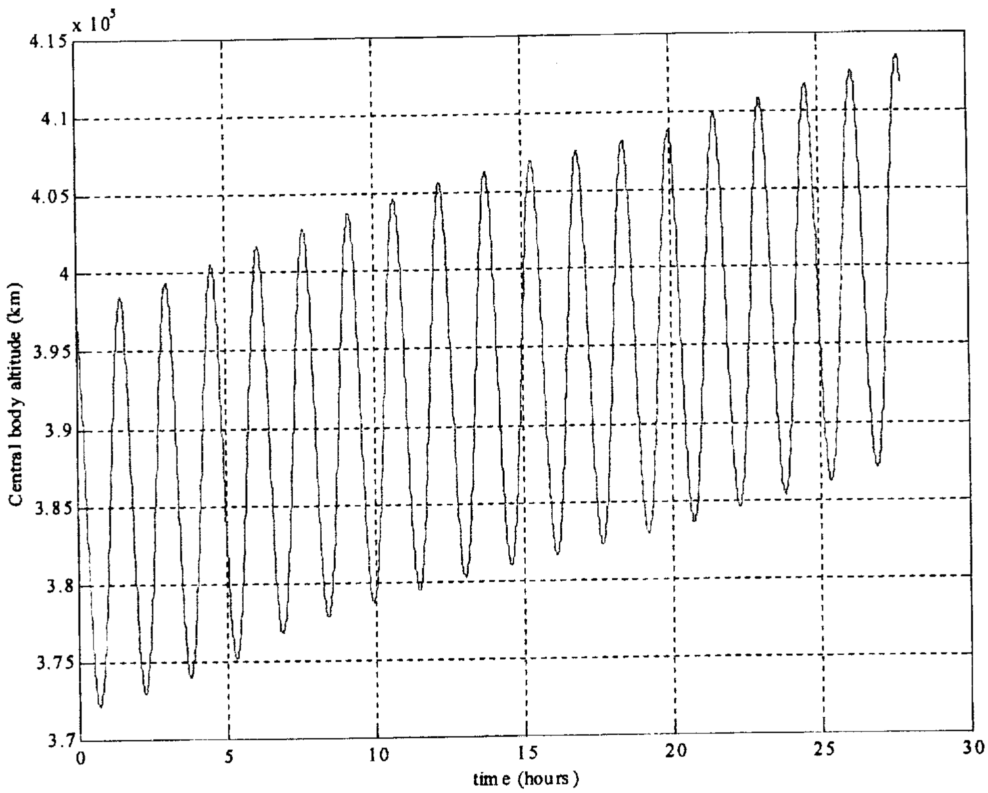


Figure 5

Orbit Raise Example

Tether tension at central body (N)

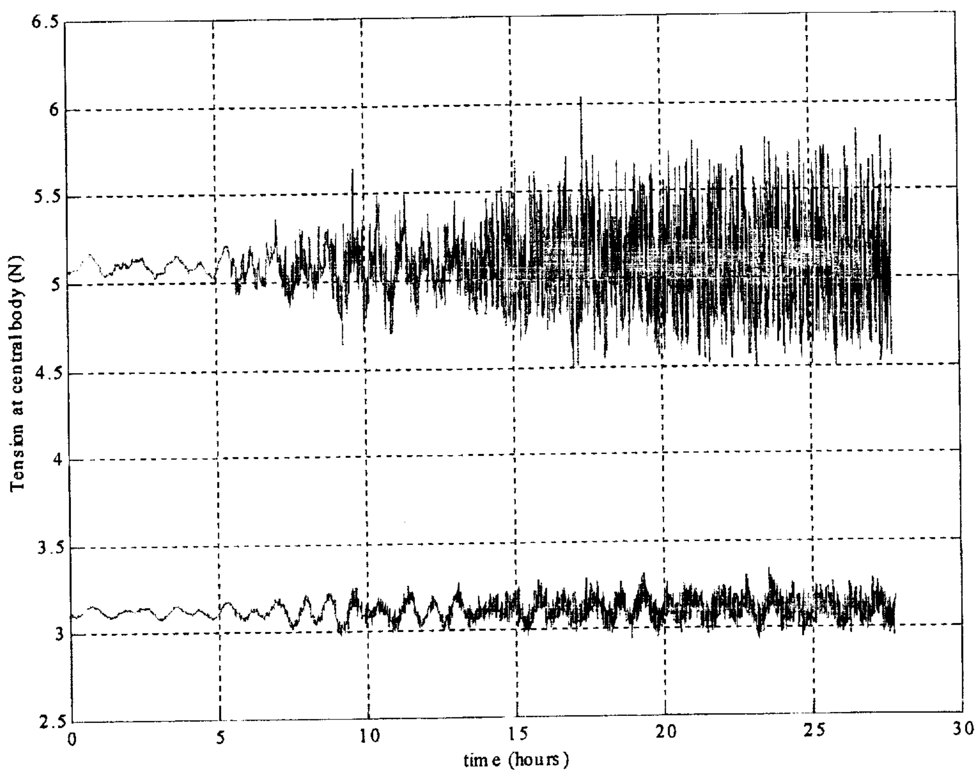


Figure 6

Orbit Raise Example

Tether librations at central body (degrees)

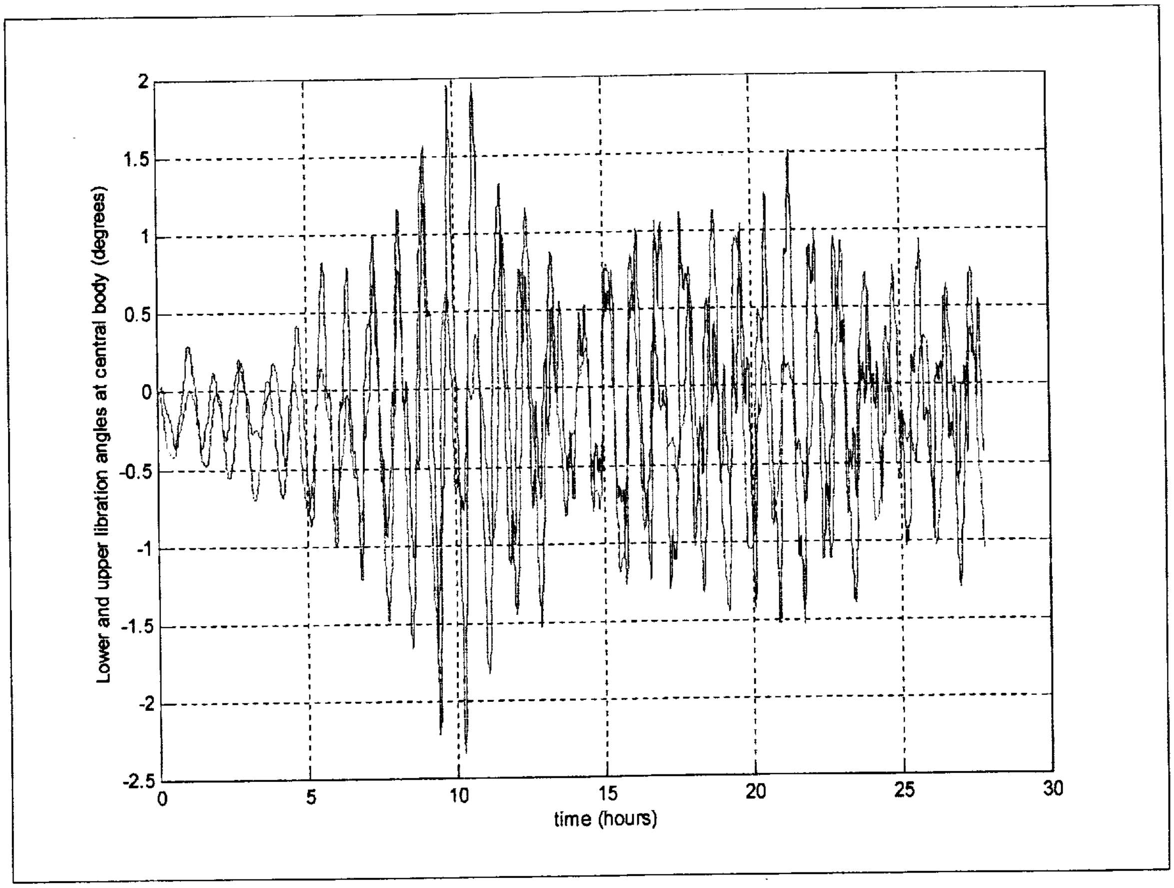


Figure 7

Orbit Lower Example

Current in lower tether (amperes)

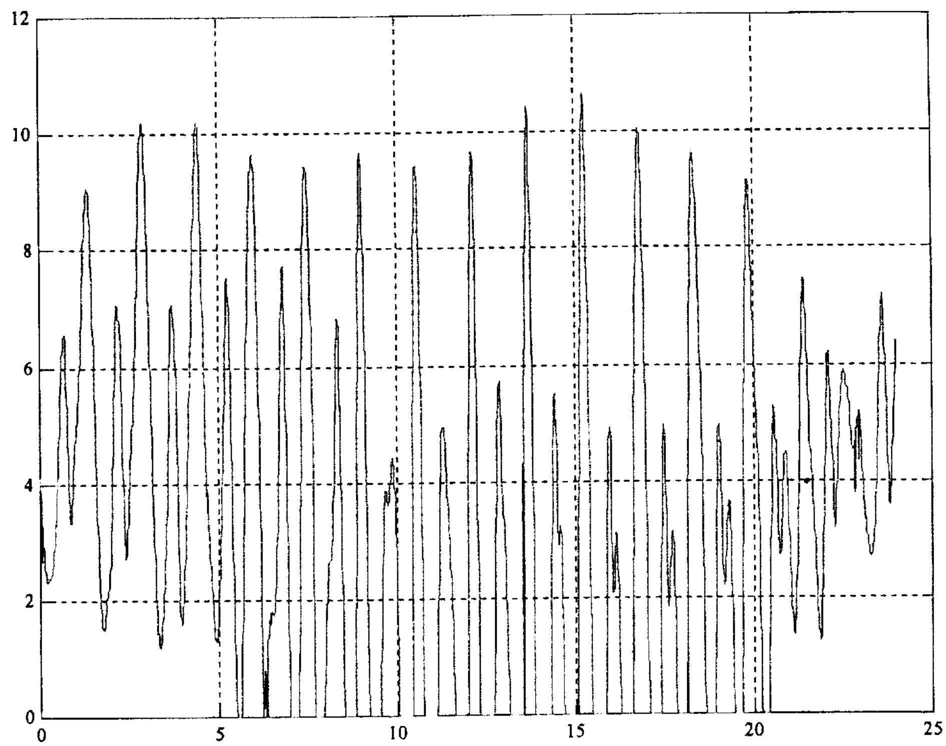


Figure 8

Orbit Lower Example

Central body altitude (km)

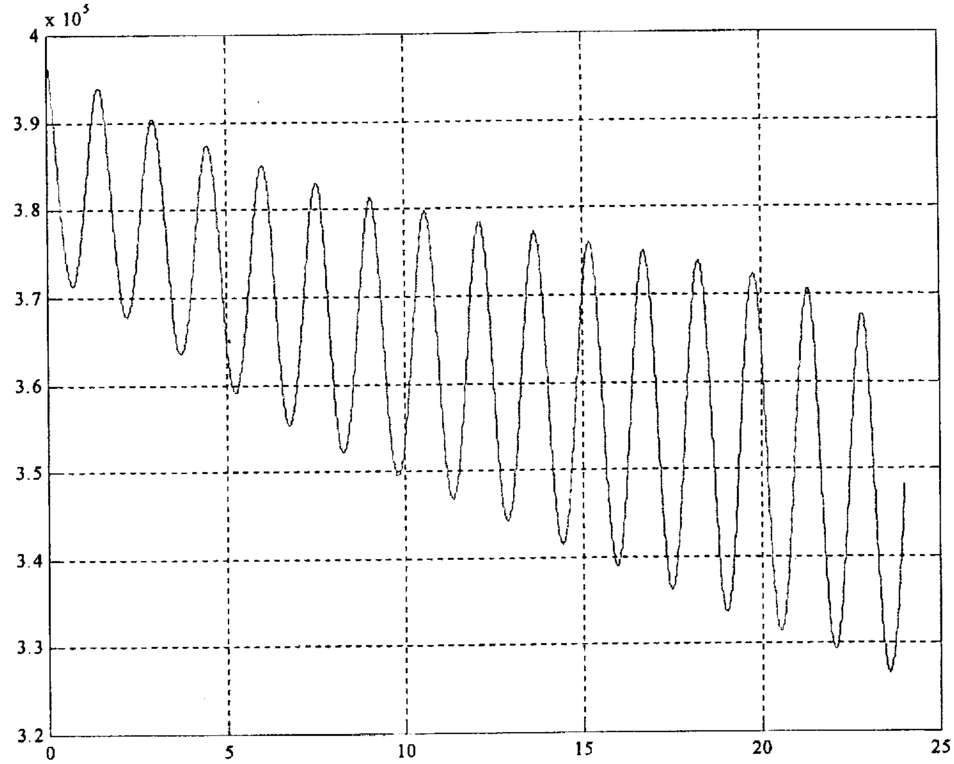


Figure 9

Orbit Lower Example

Tether tension at central body (N)

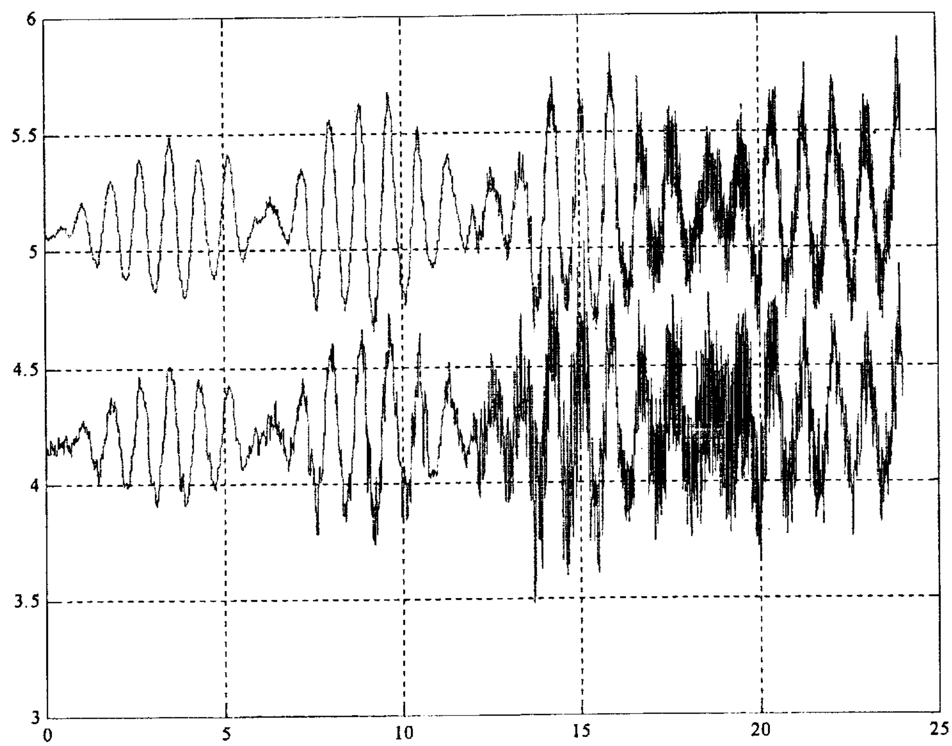
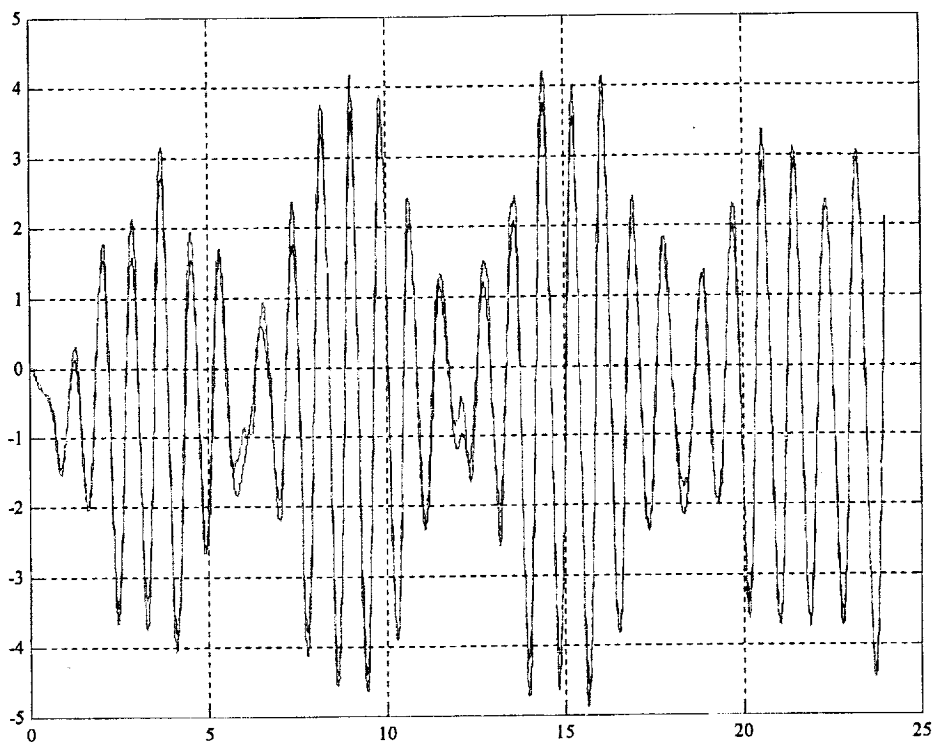


Figure 10

Orbit Lower Example

Tether tension at central body (N)



7. STEP-AIRSEDS Current Flow Model

A brief discussion of the current flow model implemented in GTOSS for STEP-AIRSEDS is appropriate. The current flow in a segment of the tether is determined by the current flowing into the segment from adjacent segments and by the electrons and ions flowing into the segment from the space plasma. Dr. Robert Estes/SAO has provided an equation describing electron and ion transfer to bare tethers in space in the orbital motion limit condition.

$$\frac{dI}{ds} = -N_e \frac{P}{\pi}\sqrt{\frac{2e^3 V_b}{m_e}} + N_i \frac{P}{\pi}\sqrt{\frac{2e^3 V_b}{m_i}}$$

The quantities in the current equation on the previous slide are

- I tether current
- s distance along deformed tether
- N_e and N_i electron and ion densities
- P tether perimeter
- e electron charge
- m_e and m_i electron and ion masses
- V_b bias voltage (potential relative to space plasma)

Since the electron mass is so much smaller than typical ion masses, ion contribution to tether current is normally taken to be negligible. The voltage bias is the difference between the tether and space plasma potentials. The potential in the conducting tether V_t is determined by current flow and Ohm's law, resistivity ρ, while the space plasma potential V_p is determined by motion emf through the magnetic field. This is determined by tether velocity v_t, the magnetic field B and the unit vector along the tether u_t. These are determined by the following equations:

$$\frac{dV_T}{dl} = -\varrho I$$

$$\frac{dV_P}{ds} = -\bar{u}_T \cdot \bar{v}_T x \bar{B}$$

Tether bias voltage $V_b = V_t - V_p$ is determined by combining the two voltage equations and solving. The quantity l is the unstretched length along the tether and is used as a position parameter for the tether. The quantity s is the deformed length along the tether and is normally only slightly different from l. For our model this difference is ignored. We state it to make our assumptions clear. The model equations are:

$$\frac{dI}{dl} = -N_e \frac{P}{\pi} \sqrt{\frac{e^3}{m_e} V_b}$$

$$\frac{dV_b}{dl} = -\varrho I + \bar{u}_T \cdot \bar{v}_T x \bar{B}$$

The variation of resistivity with tether temperature is modeled by GTOSS and this effect is included in the tether current model. Tether thermal behavior is also modeled by GTOSS. The differential equations of this model are approximated by finite difference equations for tether segments. The number of segments is a user selected multiple of the number of beads of the finite tether solution. This is currently set to 5 and requires a coding change to modify. Linear interpolation is used to determine the various environmental quantities at the intermediate points. Since electron flow is assumed to be toward the central body, current flow is assumed to be zero at the opposite end of the tether. Bias voltage of this point is adjusted starting at zero to achieve the desired spacecraft bias voltage or power as required. This condition is solved iteratively to find the tether current in each segment and to find the spacecraft emission current. This solution has not been thoroughly tested and verified but only at the equation level. Additional testing and comparison to other solutions is needed to gain additional confidence. Observed behavior is consistent with other reported solutions and intuitively expectations.

8. CONCLUSIONS

The General Tethered Object Simulation System (GTOSS) has been successfully converted to the PC environment. GTOSS has been run under Microsoft Windows 95, 98 and NT4.0 with no problems noted. Adaptation to the PC environment and definition of the 3 three body configuration required resizing some of the GTOSS internal data arrays.

To allow studies of the tether dynamics accompanying electrodynamic thrust, a tether current flow model has also been developed for GTOSS. This model includes effects due to the earth's magnetic field and ionosphere, tether conductivity, temperature, motion, shape and available power.

Sample cases have been defined for a proposed STEP-AIRSEDS three body configuration. This required definition of a 6^{th} power scenario for GTOSS. This power scenario allows a user to specify whether orbit raising or orbit lowering is to be performed by selecting the number of the tether. Orbit raising and orbit lowering sample cases have been run successfully. Results from these runs have been included in this report.

Results have only been generated so far for a three body configuration. Only point end masses have been represented. No attitude dynamics have been included. Initial results suggest that tether current can have significant and detrimental effects on tether dynamics and provisions will have to be made for control of it. This control will have to be considered in connection with desired target orbits for electrodynamic thrusting, as well as end body attitude control, momentum management of proposed control moment gyros, solar array pointing. All of these items will interact and thus, any system simulation will have to have each of these effects modeled in sufficient detail to display these interactions. Future work on GTOSS and other simulation tools for STEP-AIRSEDS will have to add attitude dynamics and momentum management control. Attitude dynamics is a built-in option but momentum management control techniques will have to be developed. Control laws to control end body attitude and maneuvering will also have to be developed. Tether deployment and retrieval operations also have to be studied and will interact with the systems defined above. To summarize, there are many fruitful areas here for future study.

9. APPENDIX

Changes and Additions to GTOSS for PC Version

The following changes and additions have been made to GTOSS/CTOSS during the process of conversion to PC and implementation of STEP-AIRSEDS model:

9-30-99

CTOSS:

* Eliminated warning messages from "yfm47.f.

1. RTD referenced but not set. Replaced RTD by RTDALL to be consistent with rest of program

2. QTIME referenced but not set. Added INCLUDE 'EQU_TOSS.INC' to include statements at beginning of subroutine.

GTOSS:

* Eliminated warning messages from cmode2.f, cmode3.f, cmode4.f: ILFDUM referenced but not set. Fixed these by replacing these routines taken from toss subdirectory by routines with same name taken from toss\cmodes subdirectory.

* Eliminated warning message from jachia.f by adding INCLUDE 'CM50EF.INC' to includes at beginning of subroutine.

* Eliminated warning message from tossh4.f by changing DO 2200 ... 2200 CONTINUE loop with DO ... ENDDO loop, 2200 CONTINUE statement remains but is not outside do loop.

* Noted warning on inconsistent structure in call to VECSUM in tosae.f. This refers to an argument in the subroutine call that is repeated (GDB). After thinking about this am satisfied that it is OK.

** According to Ken Welzyn, the versions of cmodel-4 and curcal in the toss subdirectory are the proper ones to use so I restored the pointer to those in the file list.

1-3-00
GTOSS/CTOSS:
* Increased number limiting finite solutions from 3 to 4 in HDR\COM_FOSS due to need. 4 required to simulate 3 body configuration (as originally thought).
Modified TOSS\TOZGGV.F to remove a potential divide by zero condition.

1-25-00

GTOSS/CTOSS:

*Increasing number of finite solutions from 3 to 4 was not enough. Also had to increase NFJ4 from 5 to NFJWSZ and NFD4 from 1 to NFDWSZ to handle increased memory.

2-15-00

GTOSS:

* Added bare_wire subroutine to calculate current flow model for bare wire current collection. Bob Estes supplied a model of current collection by a bare wire in the motion limited regime. John Glaese implemented the model and added it to GTOSS. Added tossh6 subroutine to call bare_wire routine for a new power scenario 6.

2-16-00

GTOSS:

*ModifiedTOSSH6.F file by combining bare_wire subroutine with it. This is specific to 3 body configuration. Two body will require slight mods.

2-16-00

CTOSS:

*Modified source file PULBSB.F so that segment current output for non active tethers is set to zero. Was not being zeroed and was being output as a nonzero value which was confusing me. Made me think some of my coding changes were putting spurious values into program. Added "else" section to if block where CURRTS is being assigned.

*Added YFM052.F format definition source file to output parameters for STEP-AIRSEDS.

GTOSS:

*Modified TOSSH6.F to add body bias voltage (power supply voltage) and power supply power to common EQU_FOSS.INC.

Used equivalences to replace output for power scenario number 5 (proseds) with output for power scenario number 6 (STEP-AIRSEDS).

*Modified RDBOPN.F to correct counting error which undercounts power scenario data array when power scenario is not in finite tether number 1. Inserted loop on finite solution number to determine maximum data count over all finite tethers rather than just solution number 1 and set counter to maximum value so determined. This is to be tested for adequacy. Initial tests seem OK. Changed to 3 body, 2 tether configuration to eliminate this problem. Requires a variable cross section tether number 1. GTOSS supposed to be able to do this.

2-16-00

GTOSS:

Modified TOSSH6.F, changing the convergence test attempting to minimize or eliminate convergences with extra large current or voltage. Changed from test on "power" error to delta voltage at Y end. This may still need work.