GTOSS
Generalized Tethered Object Simulation System

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A. PURPOSE OF SIMULATION

The GTOSS software system consists of approximately 410 subroutines representing 40,000 lines contained in 120 files. Code is constrained to a highly portable subset of Fortran 77, with over 700 pages of documentation describing user operation, equation derivation, and system software design. GTOSS runs on most computers (including: the Macintosh and PC's). GTOSS has been developed under the direction of the Avionics Systems Division, Johnson Space Center, NASA.

GTOSS represents a tether analysis-complex best described by addressing its *family of modules*, designed to be more or less tightly associated as a cooperative whole.

Tether dynamics: TOSS

TOSS is a portable software sub-system specifically designed to be introduced into the environment of **any** existing vehicle dynamics simulation to add the capability of simulating *multiple* interacting objects (via *multiple* tethers). These objects may interact with each other as well as with the vehicle into whose environment TOSS has been introduced. TOSS is incorporated by adherence to a straightforward set of interface rules set forth in the TOSS Interface Control Document. *Without* small motion assumption, and *with* complete generality, TOSS solves the tether dynamics problem relative to a reference point state defined for it by the host simulation.

Input is designed for easy data identification and entry, as well as to expedite parametric studies. Extensive initialization options (such as *stabilized gravity gradient start-up, Euler angle type selection*, etc.) allow user-friendly run setup.

General tethered system analysis: GTOSS

GTOSS is a ***stand-alone*** tethered system analysis program, representing an example of TOSS *having been married to a host simulation*. In order to verify the TOSS design concept and exercise the TOSS ICD ground rules, it was necessary to create a fully representative, yet easily managed simulation into whose environment TOSS could be incorporated. The resulting union was called GTOSS and has the properties of, and can be viewed as, a system tailored to the purpose of examining dynamic behavior of general tethered object configurations (space stations, constellations, etc). By contrast, TOSS has also been integrated into a Shuttle simulation (to study TSS), with the resulting association exhibiting (and rightfully so) the complexity and specificity of an Orbiter vehicle. The GTOSS *host* simulation represents a 6 DOF object with 8 tether attachment points. GTOSS has an executable code size of about 350k Bytes.

Input and initialization for GTOSS (as an entity separate from TOSS) is similar to that of TOSS. GTOSS provides output for itself as well as TOSS by invoking RTOSS (see below) to generate a Results Data Base to archive solution results for display post processing.

Solution-result archiving: RTOSS

RTOSS is the Results Data Base (**RDB**) Sub-system designed to archive TOSS simulation results for future display processing. While RTOSS was designed primarily to capture TOSS data, it offers a *Wild-Card* file which can be used by any users to capture data of their choice. For instance, GTOSS takes advantage of this feature to capture its host simulation data to an RDB for display post processing. The modular design of RTOSS requires minimal calls (from the host simulation) to invoke the creation and population of an RDB (for instance in GTOSS, this act is transparent to the user). At the end of a run, a set of files with unique names will have been created containing all pertinent time history data.

Also inherent in RTOSS are the routines which will extract data from the RDB and present it in a form most natural for display post-processing. These extraction routines *insulate* the user from structural knowledge of the RDB, thus rendering the user's display software invariant to future changes in RDB design. The RDB can be post-processed in a miriad of ways for engineering interpretation, as described below.

Simulation result display: DTOSS

DTOSS is the *first* of a growing family of display post processors designed to effectively utilize the RDB. DTOSS extracts data from the RDB for extensive multi-page printed time history displays. There are currently over 50 different display formats to choose from, each of which aggregates data selected to meet various display needs. Users are also invited to add new page formats to create output for specific needs.

Simulation result display: CTOSS

CTOSS is similar to DTOSS, but is designed to create ASCII plot files (as headers and data columns separated by delimiters). The same time history data formats provided by DTOSS (for printing) are available via CTOSS for plotting. In addition to time histories, repetitive tether shape *snapshots* can be taken in CTOSS. While the plot files are optimally configured for existing interactive graphics programs on the Macintosh computer, their plot format can be used on other PC's. Since CTOSS generates ASCII plot files (which are easily transported between different computers), it can be run on any mainframe to generate plot files for a PC or Macintosh.

Simulation result display: ITOSS

ITOSS differs from DTOSS and CTOSS in two ways. First, it generates output display data designed for 3-D *animated graphics* display of simulation results. Second, its output is targetted specifically for the IMI graphics device (a large, high resolution, fast display device).

Simulation result display: GENERAL

The above RDB post-processors not only represent a significant existing display capability for GTOSS, but also function as convenient *templates* to spawn specialized display processors. For instance, *hooks* are clearly defined, and steps are documented to modify the *existing* DTOSS or CTOSS to add new formats. These programs can also serve as a functional boilerplate structure for extracting RDB data to be post processed in any fashion you wish.

B. COORDINATE SYSTEMS and DEGREES of FREEDOM

Coordinate Systems

The following coordinate systems are used in TOSS:

A. *TOSS Inertial Frame.* The user is allowed to *arbitrarily define this frame*, however, its relationship to the planet-fixed frame must be explicitly stated in the standard TOSS routine invoked to transform inertial frame vector components to the planet-fixed frame. This routine (and its inverse-routine) can describe an arbitrarily complex relationship between inertial and planet-fixed frames. *As delivered*, the TOSS inertial frame is defined as one which is aligned with the planet-fixed frame at zero simulation time.

B. *Planet-fixed Frame.* This is typically an earth-fixed frame, and also the one in which all planetary environment calculations are defined. The user is allowed to *arbitrarily define this frame*, however, its relationship to the inertial frame must be explicitly stated in the TOSS routine which transforms planet frame vector components to the inertial frame, and environment calculations must be consistent with its definition. *As delivered*, GTOSS environment routines assume an earth-fixed frame, the +X axis of which is presumed to pass through the Greenwich meridian, +Z axis through the geocentric North pole.

C. *Topocentric Frame.* This is a frame aligned along local spherical longitude, latitude, and radius vector to the planet center. It is used for state initialization options and result interpretation.

D. *Orbital Frame.* This frame is defined by the kinematic state of a point, and is similar to the topocentric frame except the local longitude/latitude vectors are aligned to the current plane of Keplerian motion. Any TOSS entity can have an associated orbital frame, which is used for state initialization options and result interpretation.

E. *Body Axis Frame.* A body-fixed frame (and a body station reference point) is associated with each 6 DOF object. The frame and body station are arbitrary, but must be consistently used for defining all body attributes (CG location; tether attach-points; aerodynamic reference point; etc). This frame is the reference for body attitude interpretation.

F. *Tether Frame.* Each *finite* tether has its own tether frame. The X axis of this frame is aligned along the line of sight between the tether's attach points. The Z axis is orthogonal to the first, but lies *in the orbital plane* (of a preferred kinematic point). The Y axis is defined to complete the triad. This frame hosts the tether dynamics coordinate solution, and is used for both initialization options and result interpretation.

Degrees of Freedom (DOF)

Many of the DOF are modifiable via procedures included in the manuals. The nominally delivered GTOSS configuration provides:

1. Up to 9 bodies (each with up to 6 rigid-body DOF's).

2. A 3 DOF *particle dynamics option* to eliminate rotational dynamics overhead (for efficient study of overall topological behavior).

3. Concurrent simulation of up to 25 different tethers.

4. Tether inter-connection in *any conceivable fashion* at up to 8 attach-points per body. Each attach point is specified by its coordinates in an arbitrary body axis frame.

5. No practical constraints on tether/attach point connectivity.

6. Tether dynamics simulation as your mixed choice of:

    - Massless models (ie. linear springs and dash pots).

    - Modal Synthesis finite models (on a tether-by-tether, and axis-by-axis basis, up to 15 *modal* coordinates *per each* of 3 axes, with the evaluative resolution of each generalized force type specifiable at up to a maximum of 30 uniform spatial intervals). Tension is optionally evaluated either in terms of material strain, or Lagrangian multipliers.

    - Point Synthesis (ie. Bead) type finite models (on a tether-by-tether basis, up to 48 collocation points *per* tether; with 3 DOF *per* point). Tether can break on tension limits, or be severed at multiple points.

7. Five *length-rate*, and five *tension-profile*, data-driven deployment scenarios:

8. Five *power-profile* (*amp-limited*) data-driven, power generation scenarios:

    - All deployment and power scenarios can be arbitrarily assigned to any one or more tethers (a tether also has its own scenario *scaling factors*).

C. ENVIRONMENTAL MODELS

Planetary Environment

Subroutine calls to the planetary environment models are standardized within TOSS so that any level of environmental sophistication (you have available) can be easily incorporated into TOSS. Calling arguments to an environment model are: a sophistication-level flag; and, a position state in the planet-fixed (earth) frame. Vector results are returned in the planet-fixed frame. Currently delivered with GTOSS are the following:

- o Gravitational Field Model: Earth; Inverse square central force field; also an Oblateness model with 2 anomaly terms.
- o Globe Shape Geometry Model: Earth; Spherical globe.
- o Atmospheric State Model: Earth; 1976 Standard earth density, speed of sound, and temperature model (3% accuracy to 1000 KM).
- o Atmospheric Kinematics Model: Earth; Rotating atmosphere (with local wind perturbations currently zero).
- o Magnetic Field Model: Earth; Tilted, shifted, vector dipole.
- o Inertial Frame Model: Planet centered inertial point, with inertial frame aligned to planet-fixed frame at zero time.

Entity Attribute Environment

As delivered, all TOSS objects can experience simple aerodynamic drag. Tethers experience distributed aerodynamic lift and drag. Tethers carrying electric current experience electromagnetic forces.

TOSS is designed to facilitate incorporation of any degree of entity attribute simulation.

D. SYSTEM MODELS

The design philosophy of TOSS has been to provide a useful array of built-in system simulation features such as *data driven scenarios* for: control forces and moments, tether deployment, and electromagnetic power generation; as well as default aerodynamics options; etc. In addition, TOSS supports *arbitrarily complex* simulation of mass properties, control systems, aerodynamics, tether deployment, and power generation, etc. through its documented user-interface data structures, modularized code, and logical *hooks* which invite and assist in user modification.

Of course, when TOSS is incorporated into a host simulation, all the system models present in the host then function in the tether environment provided by TOSS.

E. LIMITATIONS

The following summarizes the currently known limitations to the use of GTOSS/TOSS (also see section below entitled: *What should be done next*).

a. Tether Frame Definition: The orientation of the Tether Frame is undefined if attach point line-of-sight becomes *exactly perpendicular* to an associated *orbital* plane. Near this state, frame orientation rates can become large, inducing large apparent rates of change of finite tether coordinates. This can be avoided in the Point synthesis model by integrating coordinates in the inertial frame (thus using the tether frame for interpretation *only*). To date, this has not been a *practical* restriction (due to the nature of engineering applications); If required, this restriction can be removed.

b. Modal Synthesis Finite Tether Model: This model is only valid during motions for which the distance between attach points is greater than the deployed tether length (a state of *intrinsic tension*). Furthermore, cases in which cyclic slack/taut states are a significant element of behavior may not be simulated well. In short, while the Modal synthesis model has some advantages, the Point synthesis (bead) model is significantly more robust and should be used to establish truth datum.

c. Stabilized Gravity Gradient Initialization: Currently this feature applies only to *simple chains*, limited to 3 objects and 2 tethers (as a mixture of massless and Point synthesis models). *Multiple* disconnected chains *are* allowed.

d. Certain Environmental Effects (for example, solar pressure effects) are not incorporated into TOSS.

F. VALIDATION METHODS

Validation of TOSS/GTOSS involves three distinct areas: Classical techniques (for those cases which are simple enough to be described by classical closed form solution); Comparative techniques (for those cases which defy classical substantiation); and Official techniques (to verify site installation and validate evolutionary changes to GTOSS).

Classical Verification

Offical solution verification of TOSS has been accomplished from many directions. First, the simulation of the rigid body TOSS objects are verified via classically known solutions to Euler's rotational equations and Newton's law. Overall translational dynamics is further verified against classical Keplerian motion. Massless tether dynamics are verified against known gravity gradient as well as *bolo type* motions. Finite tether wave propagation and shape verification has also been accomplished against classical string theory.

Comparative Verification

Finite tether dynamics have been verified by comparing both the TOSS Modal Synthesis (MS) and Point Synthesis (PS, ie. bead model) against *each other* and against a bead model *independently developed* by NASA JSC. These comparisons have addressed aerodynamic response, wave propagation, and slack/taut behavior. Electrodynamic finite tether response has been officially compared only internally to TOSS (between the MS and PS models).

There are at least 5 known, actively used, installations of GTOSS. When GTOSS is installed, users invariably compare its results to independent tether solutions previously verified by the installation. To date, there are no unexplained anomalies in result comparisons of this type.

Installation Verification

Delivered with GTOSS are 18 different input run decks (along with corresponding *official* results) which test all aspects of GTOSS. A user site compares the output of the newly installed GTOSS to these official results to verify site installation.

6. WHAT SHOULD BE DONE NEXT

The following features are either planned, or recommended for future GTOSS/TOSS development:

1. Non-uniform point spacing for the Point Synthesis (PS) finite tether model: This will allow more efficienct use of degrees of freedom for solving certain type finite tether problems.

2. Non-uniform material properties for the PS finite tether model: This will allow simulation of tethers which are purposely constructed of different materials as a function of length.

3. Auto-transition (on user defined criteria) from finite to massless to finite tether models: This will allow full mission simulation *continuity* without the large computation overhead associated with very short tethers.

4. Improved aero force model for finite tethers: The current model does not represent the consensus standard for distributed air loads on tethers

5. Flexible boom attachment simulation: This will allow a certain amount of attach structure flexibility without full involvement in simulating body flexibility of a TOSS object.

6. While the latest version of TOSS reflects an emission-end-sensitive *plunging* aspect of tether deployment (under small strain), the author does not admit to knowledge of an ultimate expression for deployment kinematics or dynamics. TOSS will be continually improved in this area as understanding is gained.

H. CASE STUDY EXAMPLES

Examples of Host/TOSS Integration

There are two different instances of TOSS having been successfully introduced into a host simulation environment: the first of these is GTOSS (described above); the second is called STOCS (Shuttle Tethered Object Control Simulation). The host simulation for STOCS is a full engineering fidelity flight control simulation of the Orbiter. STOCS is being used to perform mission verification tasks for the TSS experiment (under the responsibility of NASA JSC). STOCS is an excellent example of complex control systems (TSS on-board control) becoming associated with a TOSS object (which represents the TSS), as well as the introduction of specialized tether deployment systems (TSS deployer) into TOSS.

Examples of TOSS/GTOSS Application

TOSS has been used to study enumerable engineering applications of tethers. Some of these are:

1. TSS mission study (STOCS/TOSS, 2 rigid-bodies, both massless and bead model tethers).
2. A spinning, orbital station (6 rigid-bodies, 15 massless tethers).
3. Gravity gradient/Gyroscopic orienting spinning dumbell (2 particles, 1 massless tether).
4. Electrodynamic day/night power generation/orbital boost with tethered counter balance (3 particles, 1 bead model and 1 massless tether).
5. Real-time Shuttle Engineering Simulator (SES) verification (comparison runs made with both GTOSS and STOCS).
6. Planetary exploration maneuvers using a slingshot mechanism.
7. Electrodynamic pulse maneuvers (2 particles, 1 bead model tether).
8. Space Station docking devices (3 particles, 2 massless tethers).
9. Orbiting, spinning *carousel* (3 rigid-bodies, 1 massless, 1 modal synthesis, and 1 bead model tether).
10. Gravity gradient stabilized orbiting platform (3 rigid-bodies, 1 modal synthesis and 4 massless tethers).
11. *Simulated* bead model by chain-connecting 9 TOSS rigid-bodies with 8 massless tethers (for bead model verification study).
12. Comparative solution verification studies between GTOSS and an independent bead model simulation (wave propagation, aerodynamic response, symmetrical slack/taut gravity gradient behavior of a system exhibiting TSS physical properties)

GTOSS TERMINOLOGY

TOSS ☞ **T**ethered **O**bject **S**ub-**S**ystem

GTOSS ☞ **G**eneralized **T**ethered **O**bject **S**imulation **S**ystem

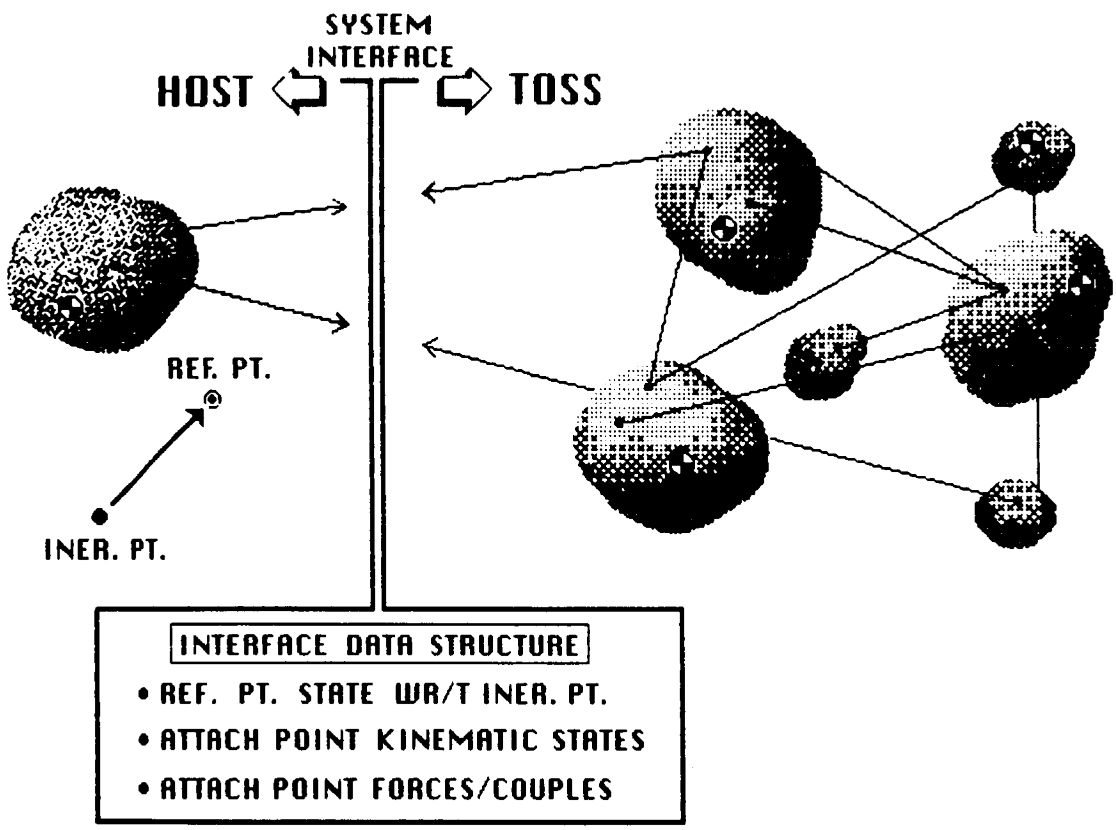
RTOSS ☞ **R**esult Data Base sub-system

DTOSS ☞ **D**isplay print RDB post-processor

CTOSS ☞ **C**hart/Graphics RDB post-processor

ITOSS ☞ **I**mi graphics RDB post-processor

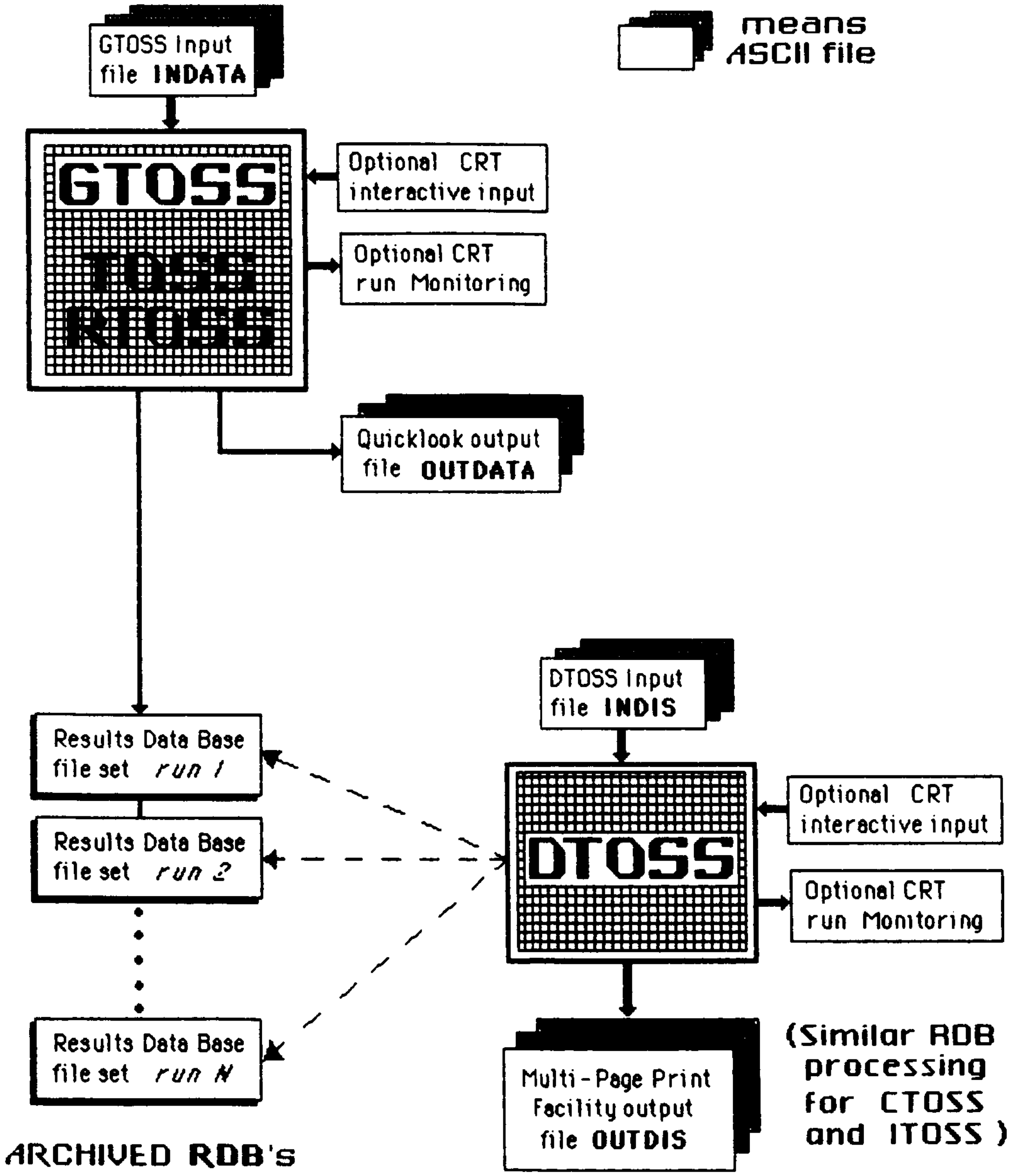
INTERFACE CONCEPT



☞ **No Orbital State Assumptions**

☞ **No Small Motion Assumptions**

GTOSS OPERATION



DEGREES OF FREEDOM

9 Bodies (3 or 6 DOF)

25 Different Tethers

8 Tether attachment points per body

Totally General *Connectivity*

Tether models, your mixed choice of:

- Massless
- Modal Synthesis (3-D)
  - Up to 15 Modal Coordinates (Legendre) *per axis*
  - Up to 30 *Generalized Force* evaluation intervals
  - Tension via *strain* or *Lagrangian multipiers*
- Point Synthesis (3-D)
  - Up to 50 *collocation points* per tether
  - 3 DOF per collocation point
  - Tether sever (on time) or break (on tension)

Data-driven, arbitrarily assignable scenarios

- 5 length-rate deployment scenarios
- 5 tension control deployment scenarios
- 5 power profile (amp limited) generation scenarios

INTRINSIC ENVIRONMENT

Input to all TOSS environment routines:

1. Fidelity level flag
2. Simulation Time
3. Position in Planet-fixed frame

To evaluate this environment, use	standard routine
Inertial Frame Model	EFTEI, EITEF
Gravity Model	GRAV
Globe Shape Model	GEOD
Magnetic Field Model	GAUSS
Atmospheric State Model	ATMOS
Atmospheric Kinematics Model	WINDS

CURRENT LIMITATIONS

- Tether-Frame is Un-defined when line of attach points is 90 degrees <u>out</u> <u>of</u> the *orbital plane*

- Modal Synthesis model valid only for a state of *intrinsic tension*

- Modal Synthesis model <u>dubious</u> for cyclic *slack-taut states*

- Stabilized Gravity Gradient start-up valid only for *simple chains* of up to 3 bodies and 2 tethers (mixed bead and/or massless)

VERIFICATION METHODS

CLASSICAL VERIFICATION

- Keplarian/Newtonian behaviour
- Classical String Theory

COMPARATIVE VERIFICATION

Participants:

- JSC developed bead model
- GTOSS bead model
- GTOSS modal synthesis model

Study parameters:

- TSS Type Parameters
- Aero Response
- Transverse Wave Response
- Symmetrical, Un-forced Response

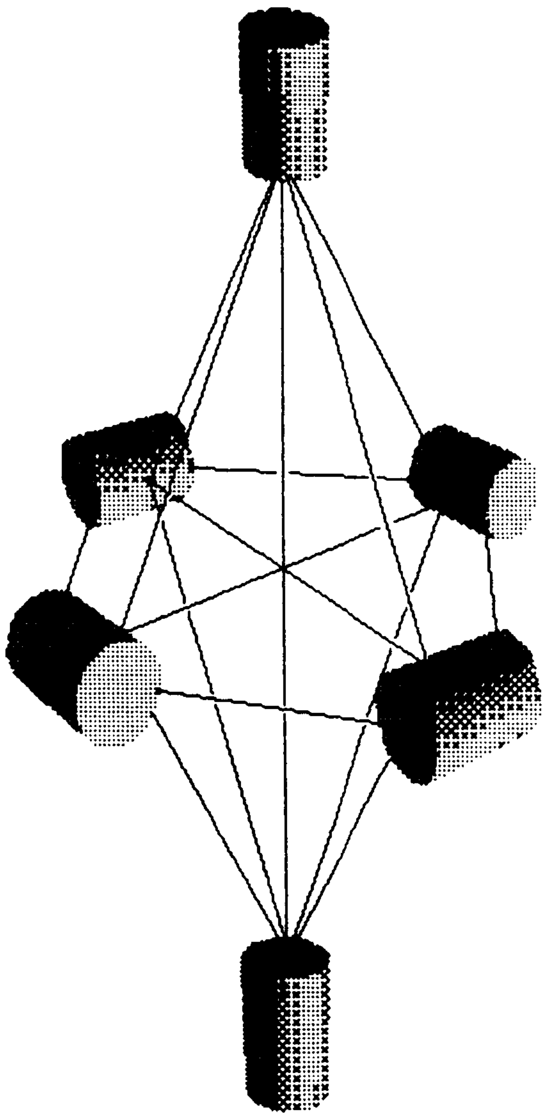
OFFICIAL VERIFICATION

UN-OFFICIAL VERIFICATION

TOSS/GTOSS APPLICATION

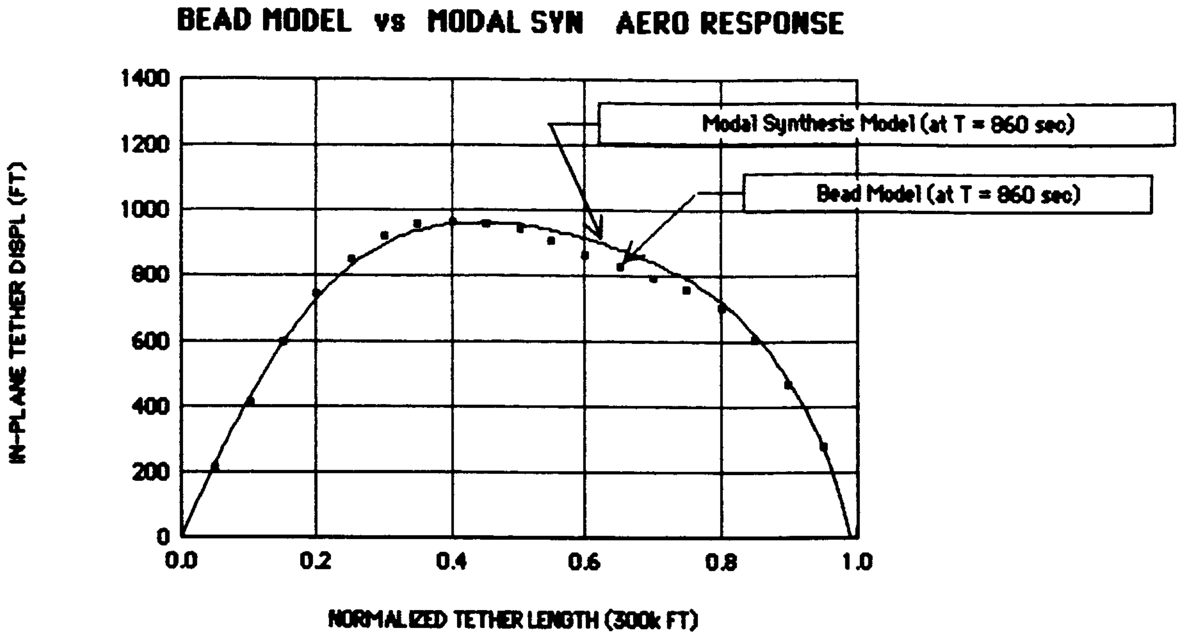
- TSS/Orbiter Compatibility (2 RB, 1 TH)
- Spinning, Orbital station (6 RB, 15 TH)
- Gravity gradient/Gyro dumbell (2 P, 1 TH)
- Day/Night electro pwr gen (3 P, 2 TH)
- SES verification (GTOSS/STOCS)
- Planetary exploration studies
- Electro pulse maneuvers (2 P, 1 th)
- Space Station docking device (3 P, 2 TH)
- Orbiting spinning carousel (3 RB, 3 TH)
- Gravity gradient platform (3 RB, 5 TH)
- 9 Body equivalent bead model (8 TH)
- Verification studies (20 - 50 beads)

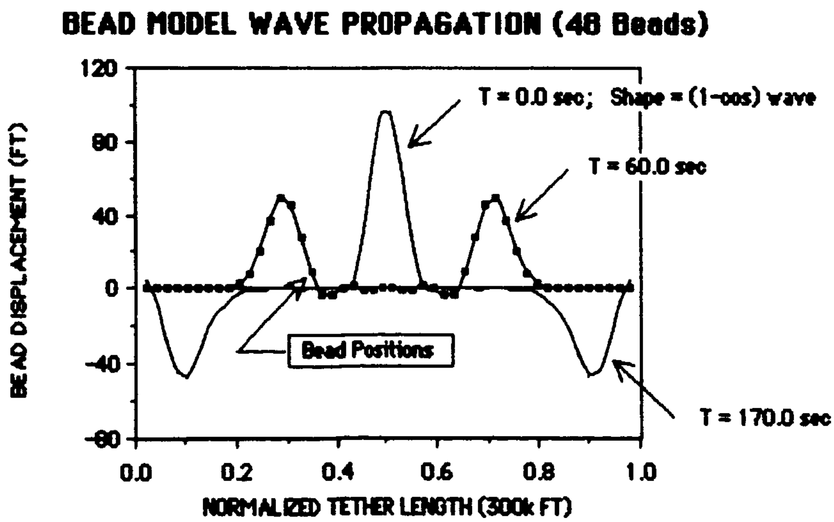
WHIRLING DERVISH



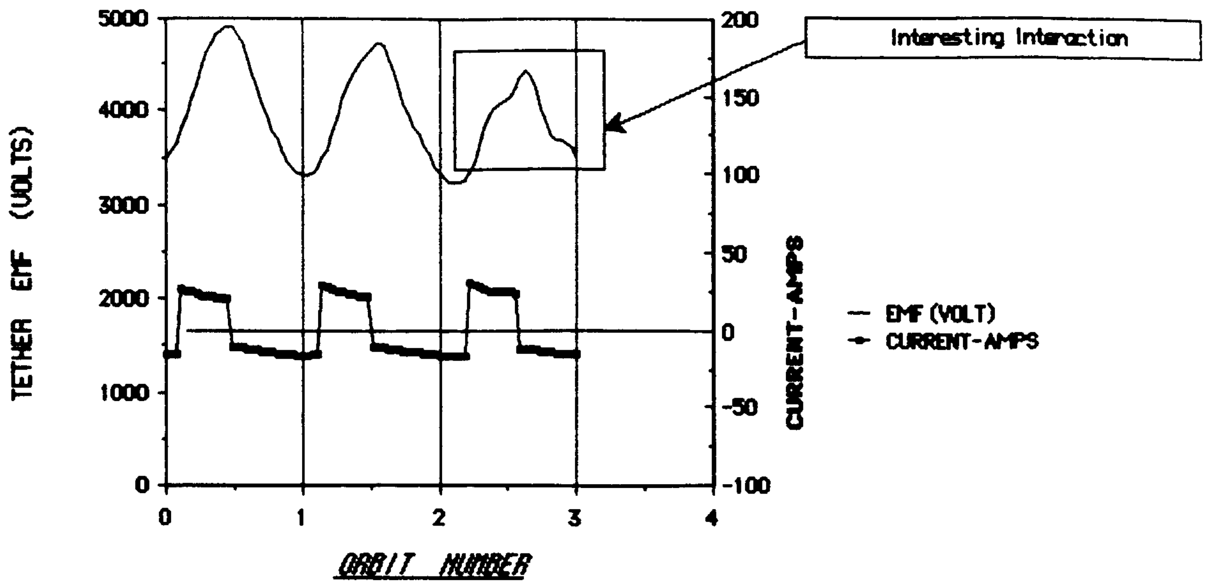
FUTURE GTOSS PLANS

- Non-uniform Point Spacing
- Non-uniform Tether Properties
- Auto-phase transition
- Improved aero-force model
- Flexible boom simulation
- Improved deployment fidelity
- Expert, Friendly User interface

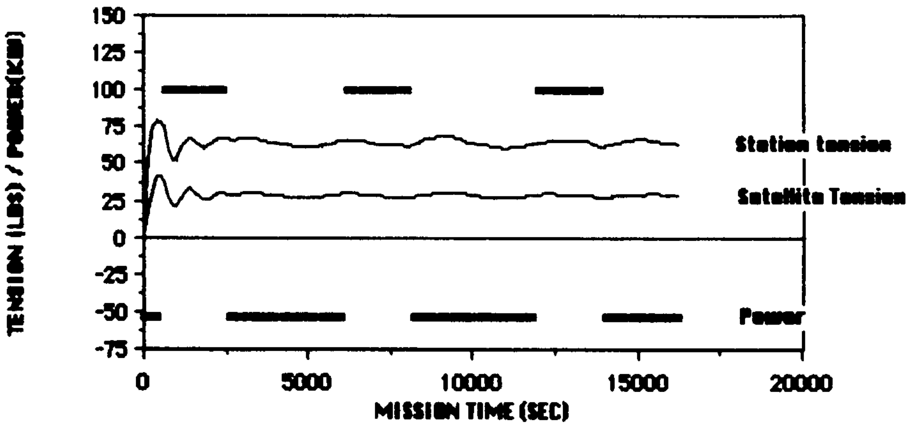

BEAD MODEL vs MODAL SYN AERO RESPONSE
Modal Synthesis Model (at T = 860 sec)
Bead Model (at T = 860 sec)
IN-PLANE TETHER DISPL (FT)
NORMALIZED TETHER LENGTH (300k FT)


BEAD MODEL WAVE PROPAGATION (48 Beads)
T = 0.0 sec; Shape = (1-cos) wave
T = 60.0 sec
Bead Positions
T = 170.0 sec
BEAD DISPLACEMENT (FT)
NORMALIZED TETHER LENGTH (300k FT)

DAY/NITE POWER GENERATION (65k LENGTH)



DAY/NITE POWER GENERATION



TETHER ANG vs SATELLITE ANG at STATION