Space Elevator

Dynamics Reference Manual

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Contains Appendices Only

TABLE OF CONTENTS

INTRODUCTION

This manual is a preliminary work aimed at providing a source of convenient dynamics-related information for those involved with all aspects of space elevator (SE) development and design. For some, this manual may serve as a primer of SE dynamics, for all, it is a source of specific constants, attributes and SE behaviors. This manual is a work in progress as much remains to be addressed as work proceeds on the project. Each section of the manual addresses a special aspect of information pertaining to the SE.

The dynamics attributes have been mostly derived from the time-domain simulation called GTOSS (Generalized Tethered Object Simulation). An outline of GTOSS is included (in Appendices A through D, etc) to allow the user to assess the pertinence of this simulation in providing such results for each aspect of SE dynamics. Related materials s re-organized and derived from these studies by the author appear in the papers listed among the references.

***General Note**: Some items below should be included for future efforts*

a. Thermal response
b. Climber attitude dynamics
c. Ocean wave effects on longitudinal dynamics
d. Sun-Moon tidal effects
e. Aerodynamic pull-down response
f. Breakage debris-footprints
g. General pull-down response

APPENDIX A: GTOSS OVERVIEW

The **G**eneralized **T**ethered **O**bject **S**imulation **S**ystem is a time-domain dynamics simulation code, first developed in 1982 to provide NASA with the capability to simulate the dynamics of combinations of space objects and tethers for flight safety certification of the Shuttle Tethered Satellite System (TSS) missions. Since then, GTOSS has undergone continuous evolution and validation, being applied at some stage in the formulation of virtually every US tethered space experiment flown to date; more than 25 aerospace organizations have employed it. The design criteria for GTOSS featured generality, thus allowing its current use in simulating space elevator behavior. Below is an overview of its features.

• Multiple rigid bodies, with 3 or 6 degree of freedom, connected in arbitrary fashion by multiple tethers, all subject to natural planetary environments, including sophisticated models for earth attributes as well as more rudimentary models for the other planets.

• Tethers represented by either *massless* or *massive* models. The *massive* tether model is a "point synthesis" approach employing a constant number of up to 500 nodes, specifiable by tether (500 is a system configurable limit).

• All tethers can be deployed from, or retrieved into, objects by means of user-definable scenarios. The deployment/retrieval dynamics model includes momentum effects of mass entering or leaving the domain of the tether itself, and produces related forces on objects deploying and retrieving the tether material.

• Tethers can be defined to have length dependent non-uniform material properties. Elastic cross section, aerodynamic cross section, and lineal mass density are independently specified for up to 15 separate regions. Properties at sub-nodal points within each region are determined by interpolation. Each region can have its own modulus of elasticity and material damping attributes.

• Tethers are subject to distributed external forces arising from these environmental effects: aerodynamics in the subsonic and hypersonic; electrodynamics due to the interaction of current-flow with the Earth's magnetic field using current-flow models that incorporate the earth magnetic field and effects of an insulated or bare-wire conductor interacting with the orbital plasma environment model. Note, with an appropriate ribbon-to-plasma electron contact model, this could simulate grounding-current in a conducting elevator ribbon.

• Tethers can experience longitudinal thermal expansion and contraction. A tether gains heat under the influence of direct solar radiation, earth albedo, earth infrared radiation, aerodynamics, and electrical currents; heat loss occurs through radiative dissipation.

• Tethers can be severed at multiple locations during simulation.

• Objects and tethers can be initialized in many ways, including creating a stable configuration for extremely long tether chains, attached to and rotating with a planet (a space elevator) with due consideration for non-uniform tether properties and the concomitant longitudinally varying strain distribution of elastic tether material.

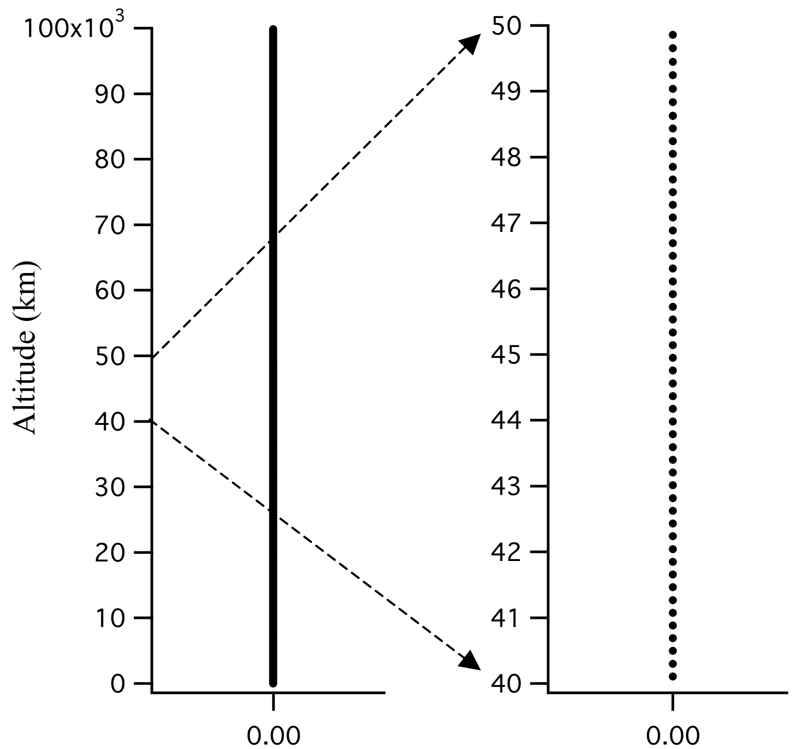
• GTOSS creates a database containing the response to user-defined configurations, initialization specifications, and environmental options; this permanent data base can then be *post processed* to produce a wide variety of result displays, from tabular data, to graph plots, to animations. In addition to the above, certain handbook section-specific information concerning GTOSS analytical models is provided as appropriate.

Finite Element Resolutions

Dual levels of finite element spatial resolution (nodal spacing) has been used to obtain most of these results due to the impracticality of employing (throughout the entire ribbon length) the same resolution level necessary in the certain regimes of interest. For example, for wind response studies, the spatial resolution in the atmosphere is about 300 times finer than that used for the ribbon above the atmosphere. Either a climber mass was interposed between the two regions of nodal resolution, or, in the absence of a climber, a small mass on the order of a nodal mass. Note: results do not appear to be sensitive to interior mass selections within this nodal mass range.

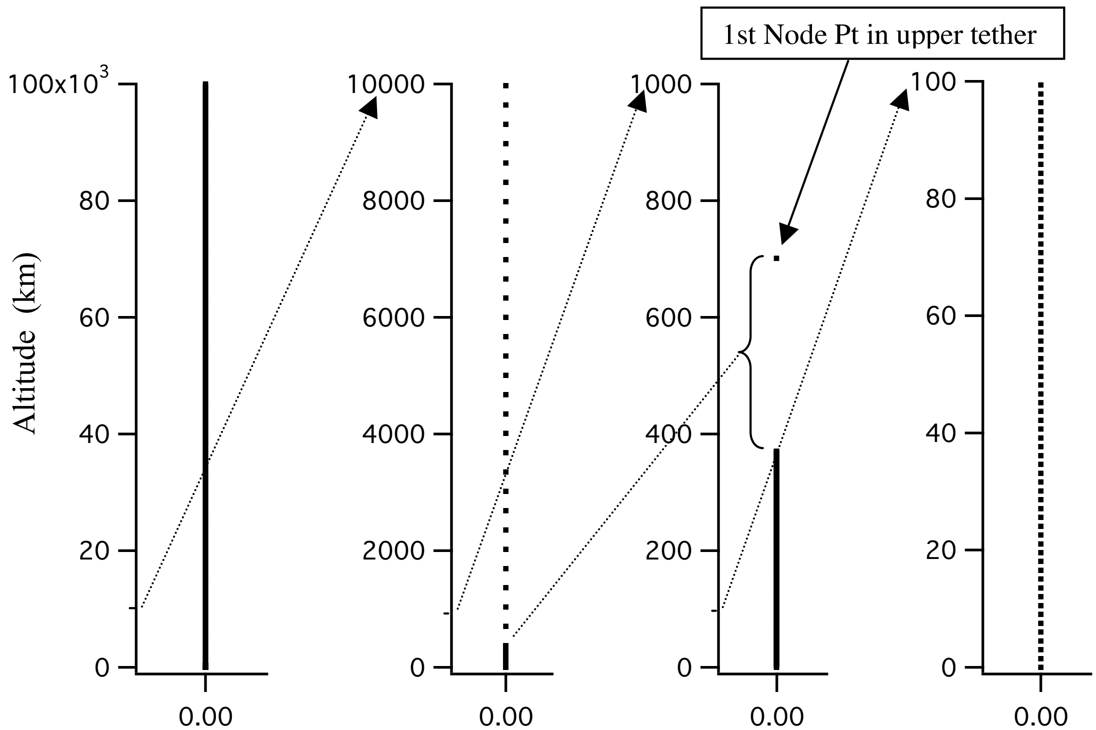
Climber Configuration

Shown below are nodal resolutions typical of **climber simulation configurations**. These depictions are <u>comprised of dots at each nodal point</u>, thus on the scale of the SE's full length (on the left), the dots are so dense as to appear as a solid line; a subsection, when exploded to a larger scale allows the nodal resolution to become apparent (on the right).



Aerodynamic Response Configuration

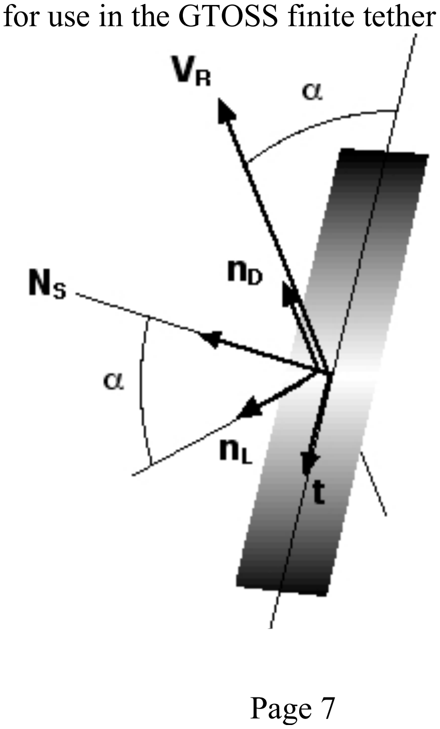
Shown below are nodal resolutions typical of **aerodynamic response simulation configurations**. These depictions are comprised of dots at each nodal point, thus on the scale of the SE's full length (graph on the left), the dots are so dense as to appear as a solid line; a subsection of that graph, when exploded to a larger scale, then allows the nodal resolution to become more distinct (graph on the right). Notice that the high nodal resolutions required to resolve atmospheric wind loads within the atmosphere, need 4 levels of graphical down-scaling (starting from full ribbon length) to enable nodal point discreteness to be visually discerned.



APPENDIX B: GTOSS AERODYNAMICS MODEL

Air loads are calculated separately for each nodal segment, considering for each segment: its relative wind; its effective aerodynamic cross sectional area; and its atmospheric density. The tether's effective aerodynamic cross sectional area is a function of the position along the tether, specified independently of the elastic cross sectional area and mass density variations. The relative wind vector comprises contributions from both the wind disturbance and the tether's motion. Based, on this model, aerodynamic lineal-load-density is determined from which total air load can be calculated on a nodal segment. Note that TOSS does not model a *twisting* degree of freedom (rotation about the *longitudinal* axis of the tether), thus, this model effectively presents the ribbon's full aerodynamic cross section to the relative wind at all times. If the relative wind changes in *azimuth*, then the tether will accordingly accommodate by assuming *a virtual twist* thus producing air loads corresponding to presentation of its maximum area to the wind; hence effects such as rotary flutter, twisting, and *differential windup* are not simulated.

This model is based on calculations often used to simulate kite aerodynamics, derived from a flat plate aerodynamics model. No aerodynamic interaction is assumed to take place between a ribbon segment and its adjacent segments, thus downwash precipitated by one segment does not induce effects on the adjacent segments. A raw *magnitude* of the total air load is found as the product of the dynamic pressure (derived from total relative wind) and the *effective projection* of the segment's surface area *normal* to the *direction* of the relative wind vector; this magnitude is multiplied by a flat-plate drag coefficient (typically between 1 and 1.5) to form the total air load. This resultant air load is assumed to act *normal* to the surface of the segment; segment orientation is derived from a tangent vector to the ribbon and the relative wind. Drag and lift are normal to one another (drag being aligned along the relative wind vector), with both lying in the plane defined by the relative wind vector and a tangent to the ribbon. Thus, the total air load vector is resolved into components *parallel* to and *normal* to the relative wind vector to calculate segment drag and lift densities for use in the GTOSS finite tether code.



The figure above depicts an element of the ribbon acted upon by the relative wind vector, $\mathbf{V}_R$. Below is an overview of the analytical relationships for this aerodynamic model.

$\mathbf{V}_R$ = relative wind vector acting at the ribbon element
$\mathbf{n}_D$ = unit vector in the direction of $\mathbf{V}_R$
(by definition = unit vector in the direction of Drag)
$\mathbf{n}_L$ = unit vector defining the direction of Lift
(by definition = unit vector normal to Drag)
α = angle between $\mathbf{V}_R$ ribbon tangent vector
$\mathbf{t}$ = unit vector tangent to the ribbon element
$\mathbf{Ns}$ = unit vector normal to the ribbon element
A = area of the ribbon element
$\mathbf{A}$ = directed vector area of the ribbon element (= A Ns)
A_n = component of the element's area facing normal to V_R
q = dynamic pressure
C_D = effective drag coefficient
F_A = magnitude of the total air load on the ribbon element
$\mathbf{F}_A$ = total air load vector on the ribbon element (= F_A Ns)
L = Lift on the ribbon element
D = Drag on the ribbon element

From these definitions and the geometry, it follows that,

$$\mathbf{Ns} = \text{unit}[\,\mathbf{t} \times (\mathbf{n}_D \times \mathbf{t})\,] \tag{1}$$

The component of area normal to the relative wind is,

$$A_n = \mathbf{A} \bullet \mathbf{n}_D \tag{2}$$

$$= A \sin\alpha \tag{3}$$

The total air load vector is,

$$\mathbf{F}_A = C_D\, A_n\, q\, \mathbf{Ns} \tag{4}$$

Lift and Drag is then (in terms of "normal area component"),

$$L = \mathbf{F}_A \bullet \mathbf{n}_L = C_D\, A_n\, q \cos\alpha \tag{5}$$

$$D = \mathbf{F}_A \bullet \mathbf{n}_D = C_D\, A_n\, q \sin\alpha \tag{6}$$

Finally, Lift and Drag is,

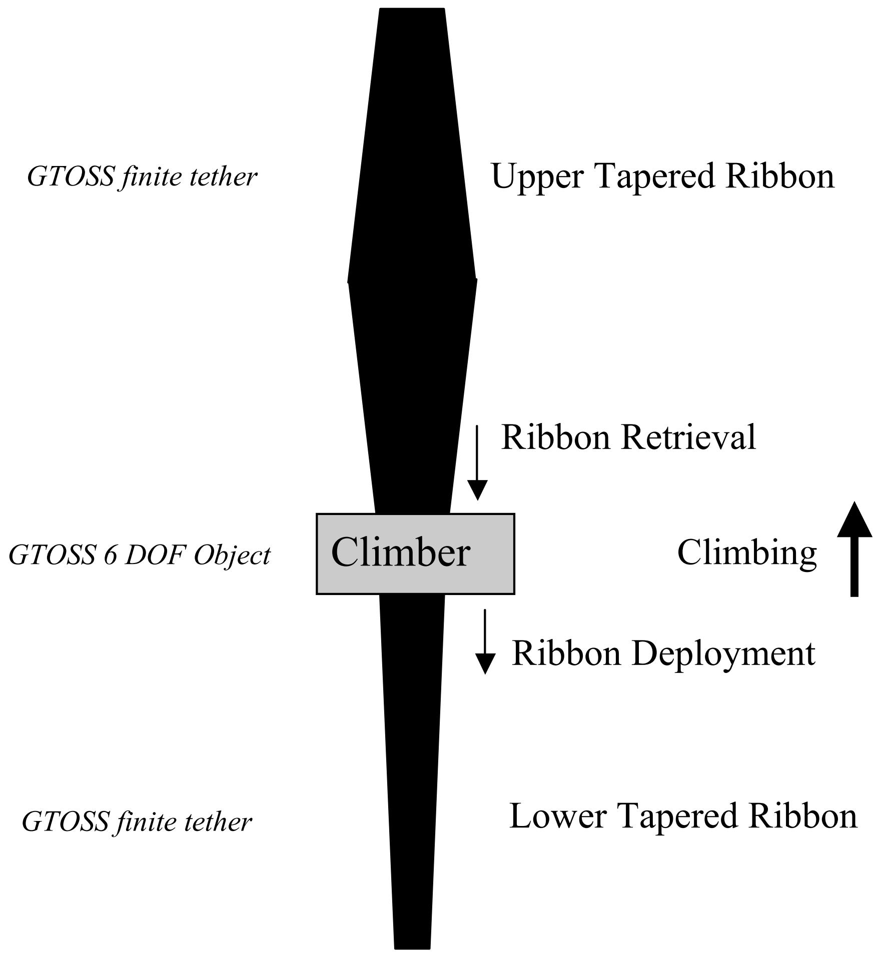
$$L = C_D\, A\, q \sin\alpha \cos\alpha \tag{7}$$

$$D = C_D\, A\, q \sin^2\alpha \tag{8}$$

This model, while not sophisticated, should provide a first approximation to the aerodynamic loading on the space elevator. This model presents the tether's maximum aerodynamic area to the relative wind at all times; this can be thought of as differential weather-cocking along the ribbon's length to meet this assumption. This clearly disallows effects such as flutter; besides, such would require unsteady aerodynamics and torsional degrees-of-freedom for the tether, neither of which are included in the present TOSS model.

APPENDIX C: GTOSS CLIMBER SIMULATION

GTOSS possesses the ability to simulate a climber's transit of the ribbon by modeling of *chains* of multiple objects and tethers. The climber would be an object in a *chain* with two adjacent tethers, the earth-side tether undergoing appropriate *deployment*, while the ballast-side tether undergoes complimentary *retrieval* (for upward climbing).



An argument in behalf of this approach starts with the fact that once an element of ribbon enters the "domain of the climber" (ie. gets clenched-in and/or threaded-through rollers, etc.), and until it emerges, that element is within the domain of the climber itself, thus, not a participant in the free dynamic motion of the ribbon lying outside the climber. Such a state of affairs appears to meet all the pertinent criteria for application of a tether deployment/retrieval simulation. So that which is true in nature is extant within GTOSS to simulate climber action. In further affirmation of this viewpoint, note that ribbon strain distribution internal to the climber will, in general, be unlike that of adjacent external ribbon because unique strain states can be imposed upon the ribbon within the climber; indeed, exceeding limit-strain within the climber may be a factor in climber traction designs that engage the ribbon through overlapping roller schemes to take advantage of *capstan effects*. Intuitive reasoning based on a priori knowledge of ribbon continuity must be tempered by the fact that as far as <u>external</u> ribbon dynamics are concerned, there could just as well be a recycling plant within the climber ingesting ribbon from above, re-synthesizing it to make a new ribbon, and deploying it out the bottom.

For climber studies, the GTOSS configuration consists of a climber containing two reels of ribbon, both of which characterize the ribbon's dual taper design. Earth-side deployment occurs such that the earth-end-taper would emerge first, while for the upward deployed ribbon, the ballast end would emerge first. In this way, no matter where the climber is positioned, the ribbon below and above properly portray the total earth-to-ballast profile.

Conventionally, *deployment* conjures up images of a reel positioned at altitude, with ribbon being dropped down; that is <u>not</u> what is occurring during climber operations. To clarify, consider two points, P1 and P2, between which ribbon is to be dispensed. Two distinct processes can accomplish this, process A and B. In process <u>A</u>, the reel is positioned at P2 remaining stationed there with the ribbon spooled-off and dragged to P1. In process <u>B</u>, the reel starts at P1, and is then transported to point P2, with ribbon being *laid-down* between P1 and P2. These are dynamically distinct processes, in that if observed from a location fixed between P1 and P2, the following would be noted: in process A, there would be a continuous *parade* of different ribbon particles traversing by, while for process B, a single particle of ribbon would appear at the observation point, and remain there throughout the deployment. Process B is realized by GTOSS climber simulation both above and below the climber.

APPENDIX D: GTOSS RIBBON SIMULATION

GTOSS allows a ribbon to have 15 regions of taper definition. These studies employ all 15 regions, and invoke an option to use a quadratic interpolation to define taper attributes interior to a ribbon. The data plots shown for the material attributes of the ribbon reflect this use of 15 regions.

There are two elevator configurations used by GTOSS for these handbook studies; they will be referred to as the ***occupied*** and the ***unoccupied*** configurations. Both share the same *intrinsic* physical property description of the elevator ribbon. Within GTOSS, the unoccupied configuration logically constitutes of a single tether and two objects, the objects being a ballast and a *pseudo object* (fixed to the planet serving as the anchor point). In the case of occupied configurations, an intermediate mass representing a climber is introduced on the ribbon; the occupied configuration is represented by two tethers and three objects, referred to in GTOSS parlance as a *tether chain* manifesting itself as a simple topological chain consisting of Object-*tether*-Object-*tether*-Object. By using appropriate definitions of tether properties above and below the *interior* object, the ribbon properties reflect that of the elevator's tapered design profile along the entire ribbon length.

A variation of the occupied configuration is used within GTOSS for purposes besides representing a climber. Since each finite tether model can have independent properties, assigning a different number of nodes to each tether can achieve dissimilar nodal resolutions at different regions of ribbon. For instance, in the case of aerodynamic studies, the nodal spacing required to provide proper resolution of wind profiles extending over the first 20 km, if used over the entire 100,000 km length of ribbon, would result in an impractical number of nodes. In this use, the *interior* object becomes a transition element within the chain, being assigned a mass commensurate with the nodal masses of the two adjacent tethers. It should be pointed out that tether frequency response characteristics is dependent upon its natural frequencies, and is proportional to its number of degrees of freedom, that in turn depends upon the node count. So the interface between two such tethers has the potential to be a band-pass filter, affecting transmission of disturbances. The power spectrum of response to disturbances can be examined, and if they are within the frequency response of both tethers, this should present no problem.

Unoccupied Elevator Configuration

Data characterizing the elevator configuration varies with length and comprises: mass density, elastic area and modulus, aerodynamic area, and damping properties corresponding to a preliminary baseline ribbon design described in References 1 and 2. A ballast mass of 634,000 kg, at a nominal radius of 100,000 km, produces 200,000 N tension at the ground. The elevator's dual tapered ribbon is nominally initialized by GTOSS to a stable vertical state with a ribbon longitudinal strain distribution that was in equilibrium with gravity and centrifugal loading. The dual tapered ribbon is designed for optimally efficient material usage by achieving a uniform stress distribution over its entire length at a level of approximately half of the ultimate stress capability of 120 giga

Pascal anticipated for an operational ribbon. GTOSS confirms this design objective as shown by the stress profile produced by the simulation (see section 1.2).

Occupied Elevator Configuration

The occupied elevator configuration requires the definition of two ribbon profiles, one ribbon deployed down to the earth, the other up to the ballast mass. GTOSS allows ribbon attributes to be assigned independently, so the *interior* object becomes the source object, from which two ribbons are *deployed* in opposite directions. One tether's deployed profile can be thought of as complementary to the other; thus, the end that would have emerged first downward corresponds to the earth end, while, that first deployed upward corresponds to attributes at the ballast end. Only for occupied elevators in which a climber is in transit would these tethers actually be undergoing time-dependent deployment. For static situations, the deployed ribbon length is automatically determined at initialization to produce a stable configuration. For all cases employing a "nominal reference ribbon", the ribbon is assumed to have an *effective* aerodynamic width of 5 cm; this is referred to as an *effective* width to point out that it can relate to the actual ribbon width to factor-in design attributes such as wind permeability.

Occupied configurations are used (almost) exclusively in studies for this handbook to allow both dissimilar nodal resolutions and enable the study of effects of climber presence on ribbon aerodynamic response. The climber has been assigned a mass corresponding to the nominal 20 ton design; an area of 18 m^2 is assumed in assessing the effects of drag on a climber. Due to its unknown attributes and preliminary design status, the climber has been simulated with 3, rather than a 6, degrees of freedom for this study.

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