Space Elevator

Dynamics Reference Manual

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in behalf of
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Contains Sections 5, 6, and 7 Only

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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*

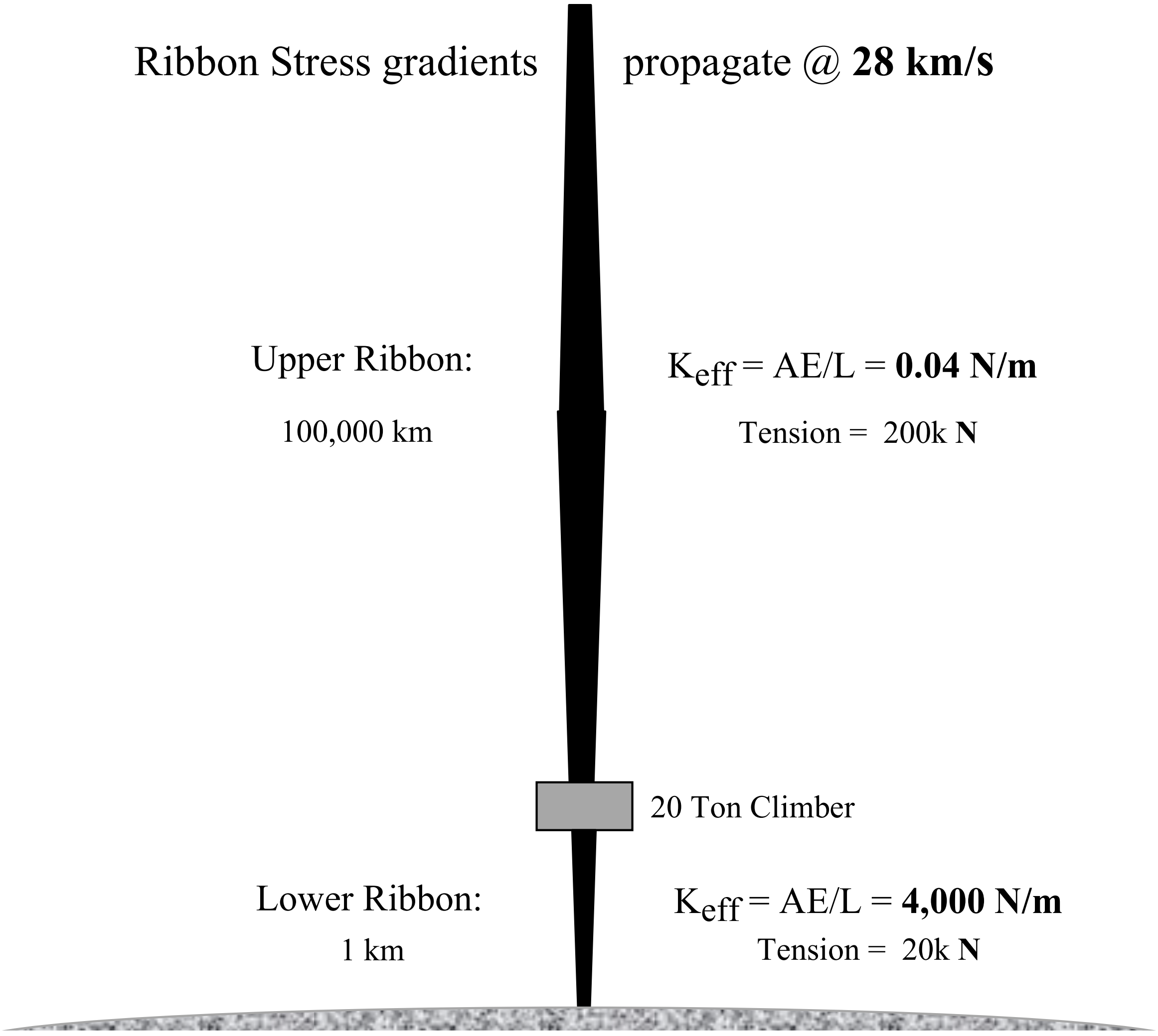
a. Thermal response
b. Climber attitude dynamics
c. Ocean wave effects on longitudinal dynamics
d. Sun-Moon tidal effects
e. Aerodynamic pull-down response
f. Breakage debris-footprints
g. General pull-down response

5.0 CLIMBER DYNAMICS

Construction and operational payload climbers traversing the ribbon, will excite transverse and longitudinal *string mode* responses and elevator libration motion (the simple pendulum-like motion of the elevator about its anchor point). Such responses will reflect all the potentially non-linear effects related to tapered ribbon design, inverse-square gravity field, centrifugal forces, Coriolis effects, atmospheric disturbance, and climber speed modulation.

The section summarizes various typical dynamic response characteristics of the SE due to the action of a climber. The rationale' and details of the simulation of this using GTOSS is presented in Appendix B. The material shown directly below can aid significantly in interpreting various un-intuitive climber response attributes

NEAR-GROUND OPERATIONS



The facts below are based on the diagram above.

5,000,000 m Upper Ribbon elong. ➡ **200,000** N Tens
5 m Lower Ribbon elong. ➡ **20,000** N Tens

1000 m of Upper Ribbon Δ elong. ➡ **0.001** % Δ Strain
1 m of Lower Ribbon Δ elong. ➡ **0.1** % Δ Strain

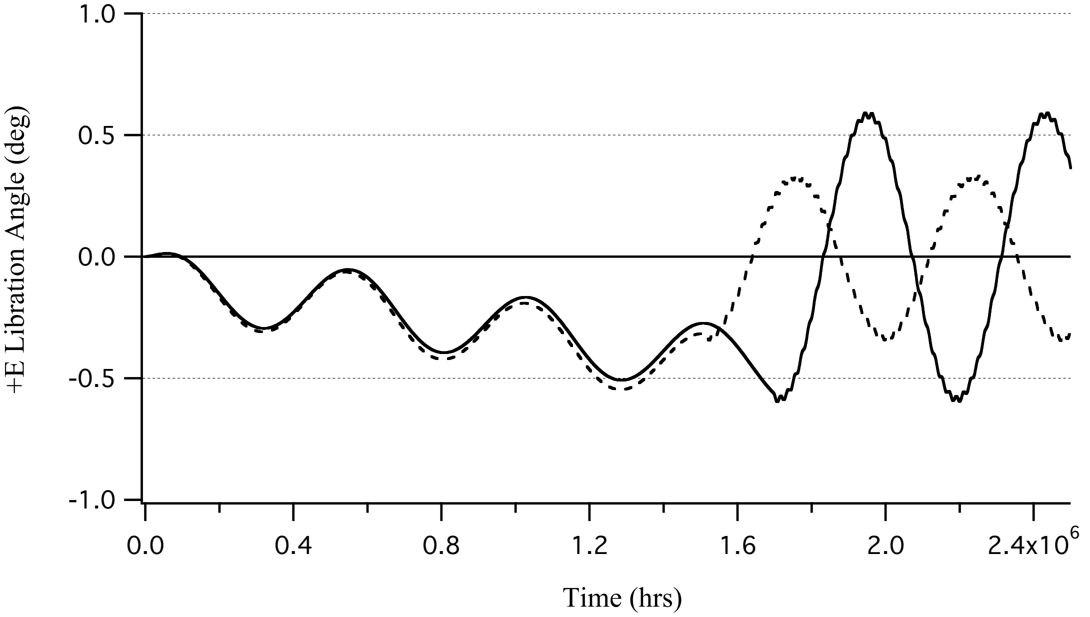
1000 m of Upper Ribbon Δ elong. ➡ **40** N Δ Force
1 m of Lower Ribbon Δ elong. ➡ **4000** N Δ Force

Elevator Ribbon nominally operates at **4** to **5**% strain

5.1 LIBRATION RESPONSE TO CLIMBING

Libration response for 200 & 400 km/hr transit to MEO
Libration response for 200 & 400 km/hr transit to GEO
Libration response for 200 & 400 km/hr transit to Ballast

Minimum-Maximum Libration -vs- transit speed MEO
Minimum-Maximum Libration -vs- transit speed GEO
Minimum-Maximum Libration -vs- transit speed Ballast



5.2 LONGITUDINAL RESPONSE TO CLIMBER LIFTOFF

Launch-liftoff response plots (Low acceleration)
Launch-liftoff response plots (Hi acceleration)

5.3 LONGITUDINAL RESPONSE TO TRANSIT RESUME

Transit Resume response @ LEO (Low acceleration)
Transit Resume response @ LEO (Hi acceleration)
Transit Resume response @ MEO (Low acceleration)
Transit Resume response @ MEO (Hi acceleration)
Transit Resume response @ GEO (Low acceleration)
Transit Resume response @ GEO (Hi acceleration)

5.4 LONGITUDINAL RESPONSE TO CLIMBING ARREST

Low acceleration arrest response Off Launch Pad
Low acceleration arrest response LEO
Low acceleration arrest response MEO
Low acceleration arrest response GEO
Sudden arrest response Off Launch Pad
Sudden arrest response @ LEO
Sudden arrest response @ MEO
Sudden arrest response @ GEO

5.5 STRESS PROFILES RELATED TO CLIMBER ACTIVITY

Identification of max stress climbing activity
Max Stress profiles

6.0 CONSTRUCTION DEPLOYMENT DYNAMICS

6.1 OVERVIEW

The purpose of this section of the handbook is not to present a solution to the initial construction deployment problem for the space elevator, but rather to expose and discuss the nature of the dynamics issues inherent in this mission, and explore the intrinsic ingredients that might constitute a successful deployment mission design.

There are currently two different approaches identified to deploying the initial elevator ribbon. Both envision the starting point as a space craft containing (either initially or via build-up by multiple courier-missions) all of the: Ribbon, Ballast mass, Ballast-end controller-craft, Anchor-end controller-craft, and required propulsion/systems capability and propellant; from a dynamics standpoint, these two approaches differ primarily in their starting point and maneuvering strategy.

The deployment scenarios are either:

(1) Start with a space-craft at GEO, thus deploying Ribbon downward from there (along with a coordinated *upward* maneuvering of the GEO craft). An overview of proposed mission details of this concept can be further explored in the book "The Space Elevator" by Bradley Edwards and Eric Westling.

or,

(2) Start with a space-craft in LEO, thus deploying the Ribbon and Ballast mass upward, creating a *combined system* with ever longer orbital period, until a configuration is attained whose geometry has grown to include GEO altitude and beyond, and manifests an "orbital period" corresponding to earth rotation rate. Details of this mission design can be explored in the paper entitled "LEO Based Space Elevator Ribbon Deployment" by Ben Shelef, Gizmonics, Inc.

Note: Bear in mind when interpreting results or speculating on dynamic behaviors for a system of the geometrical extent of the space elevator (ie ribbon lengths on the order of multiple earth radii), and moving in the inverse square central force field of the earth, the term "orbit" can loose much of its conventional significance. Previous knowledge of conventional "orbital mechanics", must be used with caution, as it is no longer clear what, if anything, is in "orbit" for the space elevator (even while in "free flight" before attachment to earth), and furthermore, contrary to what might be termed "conventional wisdom", the motion of the center-of-mass of such a system does not in fact execute a classical "Keplerian" particle trajectory, a statement whose truth is based on the easily demonstrable fact that the net force on the center-of-mass of a *system of particles* does not constitute a "central force field" (ie. a force field always directed toward a single point); solutions to a single particle's motion in this "central force field" definition is the basis for the classical Keplerian "orbital classification's" in terms of "total energy". Of course, for much conventional application, the system of particles are relatively closely allied, or clustered together (unlike the space elevator system) and the net force on the center of mass approximates a central force field.

6.2 THE DEPLOYMENT VENUE

The process of deploying a ribbon the physical extension of which is on the order of the space elevator (earth to 100,000 km) is found to be a very delicate control process. Little of the knowledge base derived from actual orbital tether deployment operations has bearing on this procedure due to a host of attributes that make this process unlike any ever attempted by mankind. To understand these technical issues facing deployment, one must have a grasp of the physical factors inherent in this process, in short, the nature of the *deployment venue*.

Consider the following observations:

1. Regardless of whether such a deployment starts at LEO (progressing primarily upward initially), or at GEO (progressing primarily downward initially), the *target configuration* that must ultimately be attained for both is one of a vertical ribbon extending from near ground up to "centrifugally effective altitudes", ie. an altitude at which a net tension in the ribbon is maintained (due to centrifugal force) such that at least a condition of *neutral buoyancy* is achieved. Such a configuration (until actually attached to the earth) is also neutrally stable! Neutral stability results because any perturbation from a "balanced state" tending to move the ribbon (and its attendant end masses) upward, results in net forces that will themselves result in yet more upward motion, to wit: If the ribbon translates upward, every particle of mass becomes attracted less toward the earth by virtue of the inverse square gravity field, thus a net reduction in downward force ensues, *and by the same token*, every particle of the system as it moves away from earth is subject to less "centrifugal effect", *all said effects contributing to the initial perturbation conspiring to move the system away from earth*. Conversely, if the ribbon moves closer to earth, just the opposite of the all the above ensues, the net effect being to progressively pull the system towards earth. Of course, at the "balance point" the system will theoretically remain stationary (until perturbed).

2. Note that the "balance point depends upon the mass distribution of the system. This distribution depends upon the ribbon configuration (ie. density and taper as a function of altitude), as well as how much ribbon has been deployed. Likewise the balance point depends upon how much fuel remains in both the GEO-craft and the Deploy-end-craft at the termination of the deployment.

3. To insure stability of the final system (in preparation for anchor attachment) will require the availability of active-propulsion since there is little the system as a whole can do in terms of additional ribbon deployment to overcome an insipient move away from the balance point. Such imbalances can result from a combination of many factors, ranging from uncertainties in state-recognition (that could obscure detection of an intrinsic state-move away from balance), to, the transport time delays inherent in control effects at one end of the ribbon reaching the other end. Note that the time for tension gradients (stress wave propagation) to traverse the ribbon from earth to GEO are 20 minutes, and almost 1 hour from earth to Ballast.

4. Not only is the final configuration neutrally stable, but in order to *minimize* the need for onboard propulsion fuel, the progression of intermediate states comprising the deployment, must be delicately balanced between the gravitational attraction and the centrifugal effects, a problem that becomes increasing difficult as ribbon extension projects the end objects into the increasingly non-linear *lower* regions of the inverse square gravity field.

5. As the ribbon is extended in altitude, a tangential velocity gradient is required to maintain a vertical position initially free of libration; this amounts to a significant delta-V that must eventually be dealt with, otherwise, the ribbon configuration will have been erected with a possibly undesirable amount of residual libration motion (especially for an infant ribbon). Note that at **GEO** altitude, a point on the ribbon has **2,580 m/s** (8,460 ft/s) tangential velocity relative to the anchor point; at **Ballast** Altitude, a point on the ribbon has **7292 m/s** (23,900 ft/s) tangential velocity relative to the anchor point (note that this latter velocity is on the order of the insertion velocity required for low earth orbit).

6. These tangential velocity gradients manifest themselves as Coriolis acceleration during deployment, an effect which cannot be practically countered for *interior ribbon points*, rather only for the end-mass GEO-craft or Deploy-craft where propulsion can be practically situated. So the possibility for inducing ribbon transverse string mode oscillation also exists.

7. The ribbon must ultimately be maintained *delicately poised* between the conflicting tendencies of centrifugal and gravitational effects with virtually no outside control effectors other than (a) position state of the end-masses, (b) distributed mass within the ribbon, and (c) onboard propulsion.

8. Vast changes (*orders* of magnitude) in ribbon *effective end-to-end spring constant* are experienced over the course of this extremely long-length deployment. While for short ribbons (at deploy initiation), the end-to-end spring-rate and related natural frequencies can be quite high (stiff), near the terminal phase when vertical control at the bottom becomes critical, a ballast-to-earth length (infant) ribbon will exhibit a spring rate on the order of .004 N/m (.0003 lb/ft); for a GEO length ribbon, this will be .012 N/m (.001 lb/ft). Correspondingly, all the natural frequencies of the ribbon system change drastically over this time frame. This happens for all the natural modes of oscillation, including the end-mass bobbing modes, the longitudinal string modes, and the transverse modes. This means that control systems designed to cope with this problem will have to adapt to a vast range of frequencies; this exacerbates the problems of band-pass filtering of sensor data, and subsequent control effectiveness.

9. Small incipient departure from the neutral stability point of the configuration likely cannot be sensed directly via accelerometers since the entire system is “falling” in the gravity field, thus departure will have to be detected via a manifestation of position or velocity dispersions (GPS, while it should be useful near earth, may possibly be less effective for such a role when sensing altitude at GEO).

6.3 DEPLOYMENT STRATEGIES

Given an *unlimited supply of fuel* for the end-craft, this could be accomplished in a fairly straightforward fashion. However, in the grander sense, the economics of lofting fuel and other resources to LEO or GEO, ultimately renders this is a problem for non-linear, multivariate modern control theory and/or artificial neural-network approaches. This is because:

1. The "Plant model" is very non-linear and complex, and
2. There is a potential for (large) fuel budget requirements that reflect conventional bi-propellant propulsion, that while providing sufficient thrust levels, reflect Isp's on the order of only 450 (max) to accomplish the mission via brute force, thus requiring huge amounts of fuel to be transported to GEO (or equivalent), unless control techniques are employed to minimize total impulse (thus a need for optimal control), <u>or</u>,
3. Modest fuel budgets that reflect electro-magnetic propulsion which is typified by Isp's on the order of 1000's, <u>but</u>, very low thrust levels, in which case control will have to be optimal to allow effective usage of such minimal effectors.

<u>In overview, this control problem can be thought of as the management of the following attributes of the combined system:</u>

A. Intelligent identification of the many time-varying elastic frequencies associated with the deployment (meaning the rejection of spurious state indications related to oscillatory components),

B. Utilization of the dynamic balancing of the *total system* (upper/lower craft, and ribbon) as it is growing in length, delicately poised in the combined centrifugal and inverse-square gravity force fields, all to minimize fuel necessary to perform the deployment,

C. Management of the system libration as it traverses the Coriolis acceleration field,

D. Final balancing of the system as it is poised for anchor tie-down, which implies management of touchdown latitude/longitude (as well as on-going lat/long management during the deployment), and fine altitude rate control near touchdown.

The possible useful control effectors for this combined maneuver are then:

- Active 3-axis propulsion on Upper end-body, and
- Active 3-axis propulsion on Lower end-body, and
- The ribbon deployment-scenario (essentially deployment rate -vs- time).

The possible sensors are:

- Amount and Rate of ribbon deployed,
- Ribbon Tension at either (or both) ends of ribbon,
- Position, velocity, and acceleration at either (or both) ends of ribbon.

6.4 RIBBON/DEPLOY-CRAFT SIMULATION CONFIGURATION

This section describes the geometry of the system being studied for the deployment simulations. When parked at GEO, the initial configuration contains all the ribbon to be deployed (100,000 km) as well as the GEO-craft (destined to be the Ballast Mass), and the Deploy-craft that guides and controls the bottom end of the ribbon, destined to be *grappled* at the ground anchor. At separation prior to deployment, the Deploy-craft (while connected to GEO-craft by the ribbon) becomes independent of the GEO craft.

6.4.1 Initial Conditions of Simulation

After defining and verifying the overall system geometry and configuration, all GTOSS ribbon deployment simulation runs were started with the same initial conditions (with the exception of Deploy-craft initial separation rates, that were dependent upon chosen deployment scenarios). Thus, mainly what was varied were control system modes and strategies (and attendant gains, limits, dead bands, etc, within those selected control system scenarios), and the ribbon deployment scenarios. Initial runs to determine basic system tendencies were made with no control system modes invoked, and employed a constant deploy rate throughout.

Since the GTOSS tether model uses a fixed number of nodes, there typically arises a numerical efficiency issue associated with the start of a deployment simulation. This is because the node-count specification for the tether must be sufficient to describe the tether dynamics when the tether is *fully deployed*, which means that when the tether is initially deployed, the node density will be much greater than required. Since, high nodal density results in high inherent natural frequencies, this in turn dictates smaller numerical integration step sizes, thus high CPU load to advance the simulation solution time (initially).

This is usually not an insurmountable problem, but is somewhat exacerbated for the space elevator deployment due to the many orders-of-magnitude change in ribbon length during elevator ribbon deployment. The solution is to start a deployment with an *initial amount of tether* already deployed in conjunction with user-specified integration step-size staging to advance the deployment initially with small step size but, while quickly reducing step size as deployed length increases (note: doubling deployed length usually allows a doubling of step size).

For this reason, this deployment simulation starts with an initial 10 km of ribbon already deployed (between the GEO-craft and Deploy-craft situated directly below). This initially deployed ribbon is such a miniscule proportion of the fully deployed ribbon (plus representing a mission phase easily accomplished by an un-eventful maneuvering of the Deploy-craft, in conjunction with a benign deployment of ribbon), it is safely judged to have no bearing on the outcome of the full deployment (that of which, is indeed a significantly challenging process).

6.4.2 GEO-Craft Configuration

The GEO-craft (TOSS Object 3 in the simulations) initially has a mass of approximately 69 metric tons (69,000 kg, =152,000 lbm, =4700 slugs). This initial mass includes the entire initial ribbon to be deployed (about 40 metric tons). The remaining 29 tons (69 - 40 = 29) represents the fuel, mechanisms, propulsion systems, and reflects a ribbon-to-ballast ratio of about 1.364, a current base-line elevator design point. The difference between 69 tons and 54 tons (54 = 1.364 x 40) represents expendables that will <u>not</u> ultimately end up at ballast altitude. During the course of the deployment, mass will be lost from the GEO-craft both due to ribbon deployment as well as propulsion expendables. The GEO-craft is simulated as 3 DOF point mass.

6.4.2.1 GEO-craft control systems

Control in both the vertical direction as well as the horizontal plane will likely be required for the deployment of the ribbon and ballast mass, hence numerous control modes were developed in the attempt to deploy and stabilize the configuration. Note that these are simplistic control modes, and in no way represent an engineering approach that would be acceptable for *final* vehicle/mission design; rather these modes were provided to examine the nature of the control dynamics problems that will likely be confronted in the system design. The modes implemented in GTOSS to accomplish this examination were:

Vertical Control: Vertical control of (both of) the “end-Craft” for the elevator deploy mission has the following two main tasks to accomplish:

(1). <u>Maintain Altitude -vs- Time profiles</u> that will result in a dynamic balancing of the vertically extending elastic system delicately poised between the gravity-well forces and the centrifugal force field as ribbon grows in length. Failure to accomplish this task will result in either the entire system flying off into a useless “orbit”, or “crashing to earth”. Furthermore, inefficiency in performing an effective balancing act, while surmountable by copious application of propulsion, can render the entire proposition impractical due to the large values of total impulse that can result; note that such a deployment when transpiring at deployment rates on the order of 200 km/hr can easily take a week of operation (and likely longer to achieve practical control). Constant active propulsive make-up of control-inadequacies for such an undertaking has vast implications on total impulse required.

(2). <u>Damp vertical oscillations</u> that arise due to various aspects of the vertical maneuvering and deployment. For instance, vertical maneuvering required to maintain the vertical balance between the gravity field and centrifugal field during deployment will tend to stimulate vertical modes of oscillation. These modes can be a combination of end-body bobbing modes as well as longitudinal elastic ribbon modes. Another form of vertical response arises due to the continuing accommodation of the ribbon end-to-end effective-stiffness time-gradient to the ever increasing gravitational attraction during deployment; this can induce end-body bobbing response.

The following vertical control modes were added for (all) TOSS Objects to facilitate examination of the vertical control issues for this deployment,

GTOSS Object: Vertical Control Modes:

- Maintain constant vertical thrust
- Maintain constant vertical velocity
- Maintain constant vertical acceleration
- Maintain vertical thrust -vs- time-profile
- Maintain vertical velocity -vs- time-profile
- Maintain centrifugal counter-force altitude to equilibrate tether tension
- Maintain a factor times vertical velocity of another object
- Maintain vertical velocity greater than a specified velocity
- Maintain vertical velocity less than a specified velocity
- Maintain altitude -vs- time-profile
- Maintain vertical greater than a velocity -vs- time-profile
- Maintain vertical velocity within a dead-band of zero
- Maintain altitude-profile of vertical velocity

Horizontal Control: Vertical control of (both of) the “end-Craft” for the elevator deploy mission has the following three main tasks to accomplish:

(1) Limit Total System Libration to within practical design margins (this necessitates horizontal thrusting designed to more or less negate the induced Coriolis acceleration associated with the deployment along a local vertical).

(2) Maintain Earth Longitude/Latitude to within limits to effect a practical rendezvous of the Deploy-craft with the anchor station for initial grappling. This control requirement, while related to the requirement (1) above, goes beyond that requirement since the precision of this final rendezvous far exceeds the requirements associated with general libration response of the elevator system as a whole.

(3) Dampen (or otherwise manage) transverse ribbon response that may be excited by various aspects of the deploy mission (such as horizontal accelerations of the GEO- and Deploy-craft, wind disturbances once into the atmosphere, etc).

The following horizontal control modes were added for (all) TOSS Objects within GTOSS to facilitate examination of the horizontal control issues for this deployment,

GTOSS Object: Horizontal Control Modes:

- Maintain constant Horizontal thrust
- Maintain constant Horizontal velocity
- Maintain constant Horizontal acceleration
- Maintain Horizontal thrust -vs- time-profile
- Maintain Horizontal velocity -vs- time-profile
- Maintain constant earth Latitude/Longitude with Dead Band
- Maintain constant negative Coriolis acceleration
- Maintain constant earth Lat/Long within dead-band + neg. Coriolis acceleration
- Maintain constant earth Lat/Long w/proportional control

Note: The above defined GTOSS control system implementations are in no way to be construed as ideal or optimal for final mission design, nor have they been implemented as such. They are mainly intended to provide a primitive level of stability to assist in demonstrating the possibility of, and exploring problems inherent in, performing such a deployment mission.

6.4.3 Deploy-Craft Configuration

The Deploy-craft, residing at the bottom end of the ribbon, is largely an unknown entity at this point in the space elevator design cycle. Its control agenda is similar to, yet different from that played by the GEO-craft. The Deploy-craft vehicle is primarily a thrusting controller, whose job it is participate in maintaining overall stability and quiescence of the system as it elongates, and finally to effect a precise earth latitude-longitude homing maneuver for terminal rendezvous with the anchor station. Depending on what (other functions) one imagines the role of this vehicle to play, a range of masses could be assigned. For the purpose of this study, a middle-of-the-road value of 1500 kg (100 slugs, =3200 lbm) was used. This vehicle is being simulated as a 3 DOF object in GTOSS.

6.4.3.1 Deploy-craft control systems

Control in both the vertical and horizontal plane will be required for the Deploy-craft. If for nothing else, this will be necessary to effect a graceful terminal rendezvous with the anchor station. All the various control modes implemented in GTOSS to accomplish control tasks associated with the GEO-craft (see section 6.4.2.1 above) were also available for the Deploy-craft.

6.4.4 Ribbon Configuration

The initial space craft configuration parked at GEO contains all the ribbon to be deployed. In a current nominal deployment mission scenario, this ribbon is envisioned to be in the form of two 20 (metric) ton spools of ribbon. These would be deployed simultaneously as one ribbon of 10 cm width. It is assumed that this infantile ribbon would have the identical longitudinal design-taper configuration as the mature elevator configuration (whose taper and other attributes are fully defined in an earlier section of this Dynamics Handbook).

The ribbon properties for the initial deployment mission is thus derived as a “scaled-down” version of the mature ribbon. This is done by noting that the mass of the mature elevator ribbon is 825 tons (1,820,000 lbm, =56,572 slugs), so calculating the mass ratio between the initial 40 ton ribbon and the mature ribbon would provide the ratio between the lineal density (ρ) of the initial ribbon and the mature ribbon. This is:

$$\frac{\rho_i}{\rho_m} = \frac{M_i}{Mm} = \frac{40}{825} = 0.0485$$

Where:

ρ_i is the Initial construction ribbon density

ρ_m is the Mature ribbon density

M_i is the Initial construction ribbon total mass

Mm is the Mature ribbon total mass

So would the elastic area of the two ribbons exhibit this same ratio, thus:

$$\frac{A_i}{Am} = 0.0485$$

Where:

A_i is the Initial construction elastic cross sectional area

Am is the Mature ribbon elastic cross sectional area

D_i is the Initial construction effective elastic diameter

Dm is the Mature ribbon effective elastic diameter

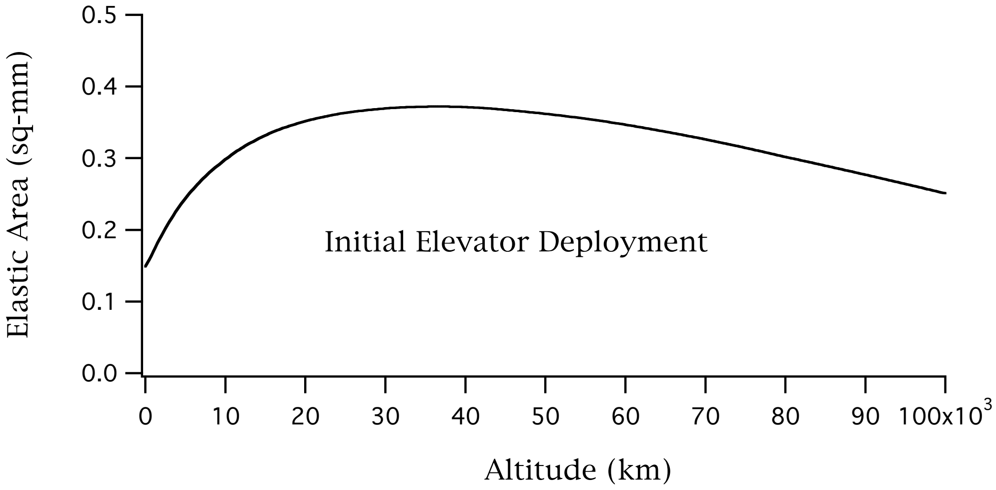
Then, since GTOSS requires an equivalent elastic diameter, note that the ratios of elastic area relates to elastic diameter as per:

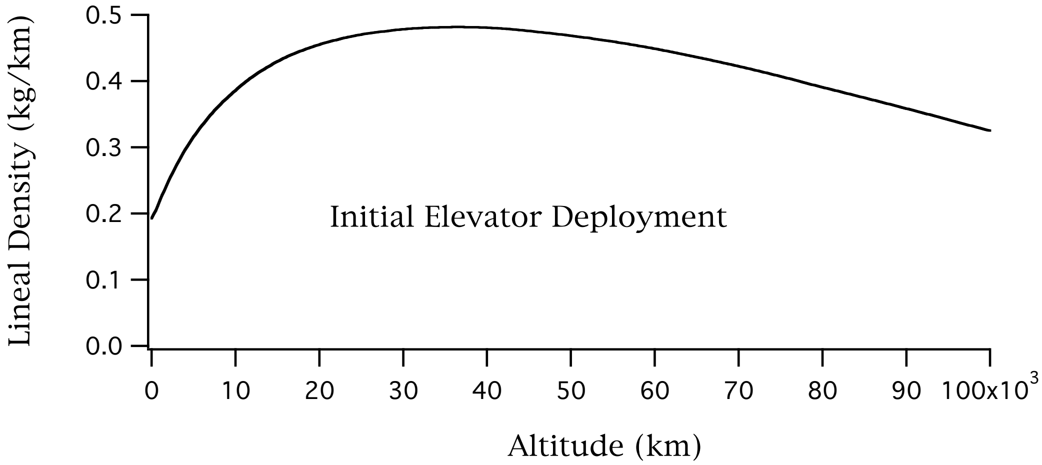
$$\frac{D_i}{Dm} = \sqrt{\frac{\rho_i}{\rho m}} = \sqrt{0.0485}$$

This then provides all that is needed define a new tapered ribbon specification for use within GTOSS.

6.4.4.1 Tapered ribbon deployment topology

Within GTOSS, all the ribbon is initially contained within the GEO-craft and is deployed downward with respect to the GEO-craft. This means that the ribbon taper definition within the GTOSS non-uniform tether data protocol must be defined such that the *first* part of the ribbon to emerge upon deployment will be that part destined to be grappled at the anchor station, and the *last* portion of ribbon to be deployed must be that destined for the Ballast altitude. Note that this is true only for the mission in which everything deploys downward with respect to a GEO-craft (for the LEO mission deployment scenario, *exactly the opposite* would be true). The definition of this required ribbon data for the GEO mission will be found in the associated input data files for GTOSS. Below are graphs of the length-varying longitudinal properties of the initial deployment ribbon used in the GTOSS simulations of the initial deployment mission.





The table below (and continued on next page) represents an optimal approximation to ribbon length-varying parameters for initial deployment ribbon configuration (when quadratic interpolation is used).

Lineal Density (kg/km)	**Cross Section** (mm^2)	**Region Δ Length** ΔL (km)
0.189	0.146	<= value at Earth
		3048
0.273	0.212	
		3048
0.333	0.258	
		3048
0.377	0.290	
		4572
0.421	0.324	
		4572
0.448	0.345	
		3048
0.460	0.355	

		6096
0.476	0.366	
		6096
0.482	0.371	
		6096
0.481	0.371	
		6096
0.477	0.366	
		9144
0.460	0.355	
		9144
0.439	0.338	
		15240
0.355	0.273	
		12192
0.326	0.250	
		8656.32
0.326	0.250	<= value at Ballast

6.4.4.2 Tether/Object topology

The simulation runs employ the planet-fixed Reference Point option within GTOSS. In this scheme:

- the Reference Point (fixed in earth) is **Object 1**
- the Deploy-craft (the space vehicle at the *bottom end* of the ribbon) is **Object 2**
- the GEO-craft (destined to arrive at Ballast altitude) is **Object 3**.

The tether undergoing deployment is TOSS tether number 1; this tether is connected between Objects 2 and 3 with the X-end (deployment/emission end of tether) located at the upper (GEO) object.

Important Note: There is yet **one more tether** being employed in this deployment simulation. This is TOSS tether number 2 that extends between the Deploy-craft and the earth-fixed Reference Point (the anchor station). This tether is a massless tether (thus exerting no inertial loading on the dynamics of the solution) and is initially given a length that is so long as to render its tension zero throughout the full deployment. Its purpose is to effect an eventual grappling of the Deploy-craft at the anchor station, thus allowing for simulation of the tie-down of the elevator ribbon to the anchor point. This is accomplished by specifying a Tension-command scenario for this massless tether, that will be enabled at the time that the deploy-craft is sufficiently near the anchor point. This tension command will immediately define a new deployed length for this tether that will produce the specified tension level needed to secure the ribbon. At this point, continued upward deployment of the GEO-craft could ensue, except now under the conditions of an anchored lower ribbon end.

6.4.4.3 System mass balance

Both the GEO-craft and the Deploy-craft can loose mass during the deployment operation.

The GEO-craft looses mass due to:

- Deployment of the ribbon (ie. up to 40 tons when full deployment has occurred if the GEO-craft arrives at nominal Ballast-altitude),
- Propulsion.

The Deploy-craft looses mass due to:

- propulsion only (since ribbon is exclusively deployed from the GEO-craft).

To enable mass loss effects, GTOSS must be instructed specifically to allow this to occur. Deployment and propulsion mass changes are enabled independently of one another.

To enable mass change due to Deployment, a general TOSS input control flag that specifically enables such mass changes, must be set.

To enable mass loss due to Propulsion, a non-zero value of Isp must be specified (since Isp occurs in the denominator of the mass-flow calculation); failure to specify a non-zero value of Isp while it will inhibit mass loss due to propulsion, will not disable calculation of "total thrusting impulse" that will still be available for post processing examination.

6.5 NATURAL SYSTEM TENDENCIES

This section examines the natural tendencies of a system in which an object is deployed from GEO towards the earth without the benefit of any control intervention. While this is a unique behavior simply reflecting the response of a greatly-extending system of particles embedded in an inverse square central force field, it nevertheless is found to manifest some interesting tendencies that are indicative of what a controller must deal with to successfully deploy an elevator ribbon. This particular simulation run starts with both craft at GEO, and starts the Deploy-craft towards the earth at a speed of 200 km/hr; the tether also deploys at this same rate throughout the simulation. These runs are made using first a massless tether, then a distributed mass tether, to obtain information about the effects of distributed mass on the system dynamics.

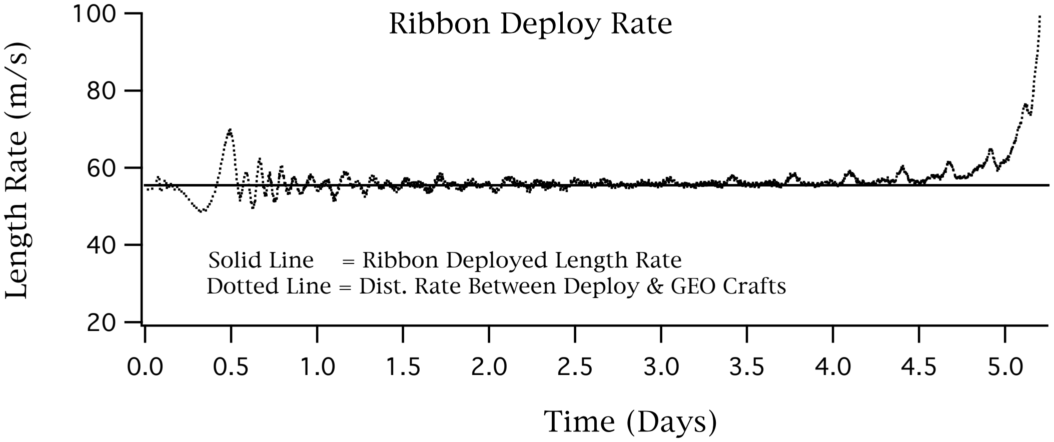
Massless Ribbon Simulation

In the massless case, the GEO-craft looses no mass during the deployment (since the deploying ribbon has no mass related to it). Both deployments take about 5 days. With the exception of tension gradients and transients that are attendant to the longitudinal mass distribution and elastic modes inherent in the distributed mass model, in this simplified, no-control case, the behavioral trends were *similar* between the massless and distributed mass ribbon cases. The massless simulation was done primarily as a *ballpark verification* of the higher fidelity massive-ribbon simulation. It is clear that due to the significance of 40 tons of ribbon mass immersed in the gravity field, that a massive ribbon model is required to thoroughly examine the nature of this deployment problem.

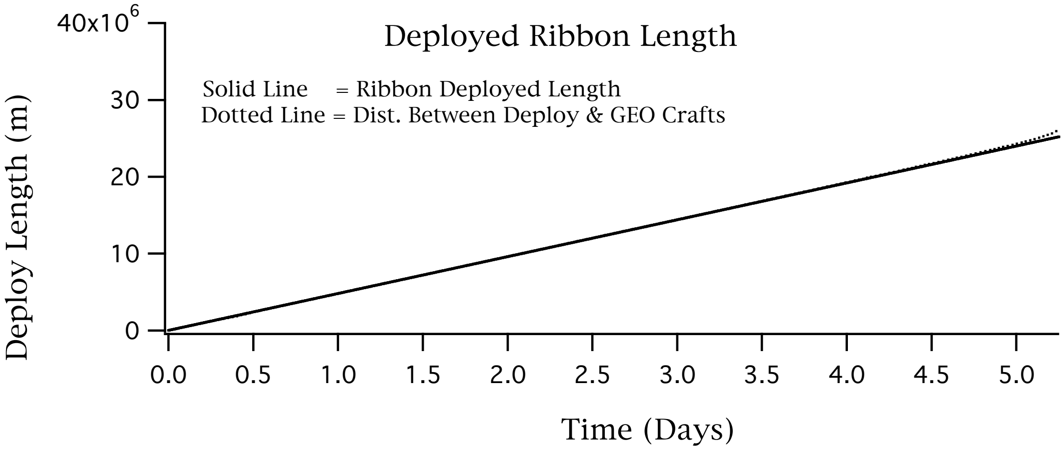
Massive Ribbon Simulation

The results of this uncontrolled deployment is shown below. The initial hours of deployment are essentially tension-free, so the Deploy-craft (hooked on the end of the ribbon) having been given an initial vertical velocity is just behaving as it should (essentially Keplerian orbit moving posigrade wr/t the GEO object), all-the-while the GEO craft essentially sits at GEO (as it should). Now, *as soon as tension manifests itself*, the deploy-craft (smaller mass) starts to librate noticeably (typical tether behavior). The onset of tension (too small to be evident in the tension graph shown farther on in this section) manifests itself in relative range-rate as shown in the graph below

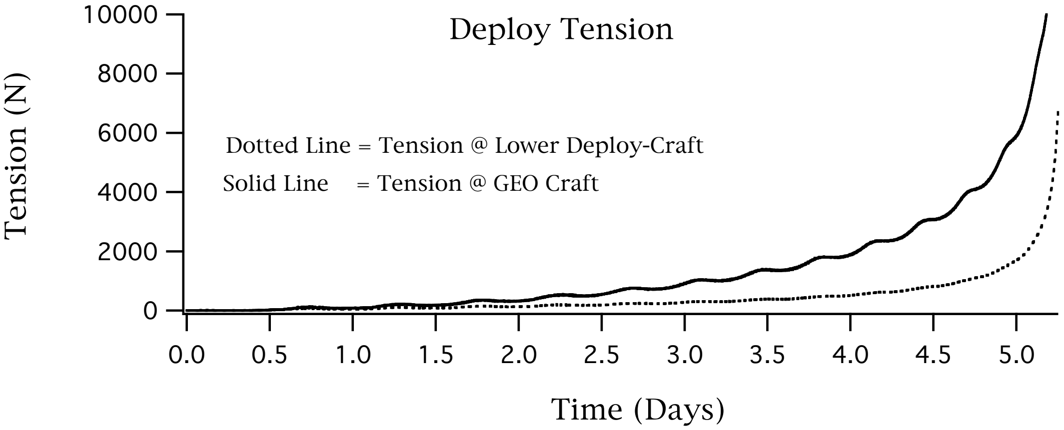
The first graph compares the constant 200 km/hr deploy rate to the range-rate between the GEO-craft and Deploy-craft. The transient appearing at about ½ day into the deployment relates to the initial impact of the Deploy-craft with the ribbon as it's recession rate "catches up" to the amount of ribbon having already been deployed (ie the "slack" is being removed from the system); the ribbon is intentionally deployed at a rate slightly in excess of the initial separation rate of the two vehicles, so as gravity slowly accelerates the Deploy-craft away from the GEO-craft eventually, this slack removal results in a minor impact loading event. Following this impact event, the range rate between the Deploy-craft and GEO-craft become essentially congruent with ribbon deployment until near the end of the deployment, when other effects come into play.



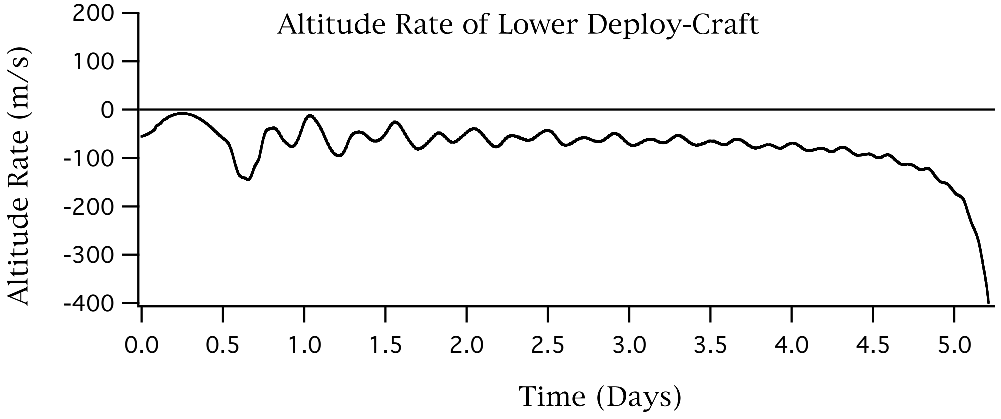
The graph below simply shows the resultant deployed length resulting from the constant deploy rate being commanded.

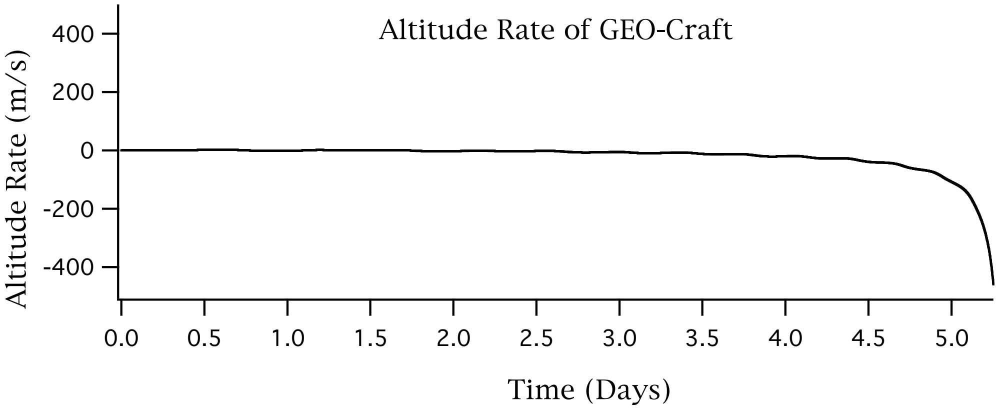


The steady increase in tension at both ends of the ribbon is seen in the graph below. The higher tension at the GEO-craft is responsible for pulling the GEO-craft earthward and the resulting significant posigrade motion of the GEO-craft with respect to its initial geosynchronous state. The sharp tension increase at the Deploy-craft near the end of deployment is due to its diving ever more rapidly into the inverse-square gravity-well.

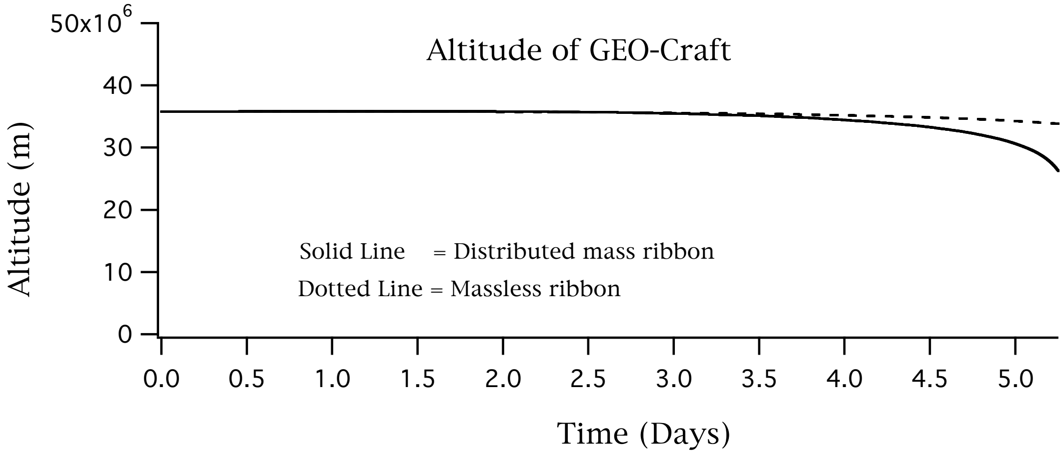


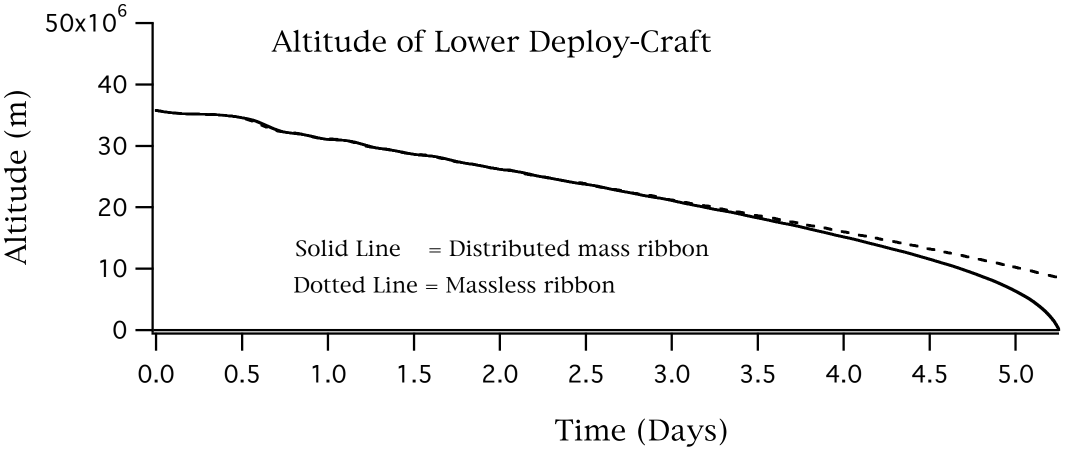
Altitude rates of both end-objects, shown in the two graphs below, expose the sharp increase at 4.5 days of the Deploy-craft's accelerating encounter with gravity, *dragging everything down with it.*



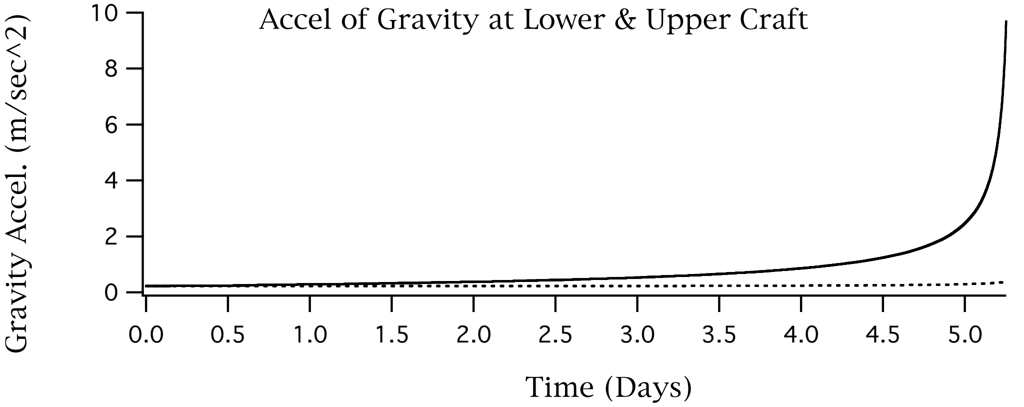


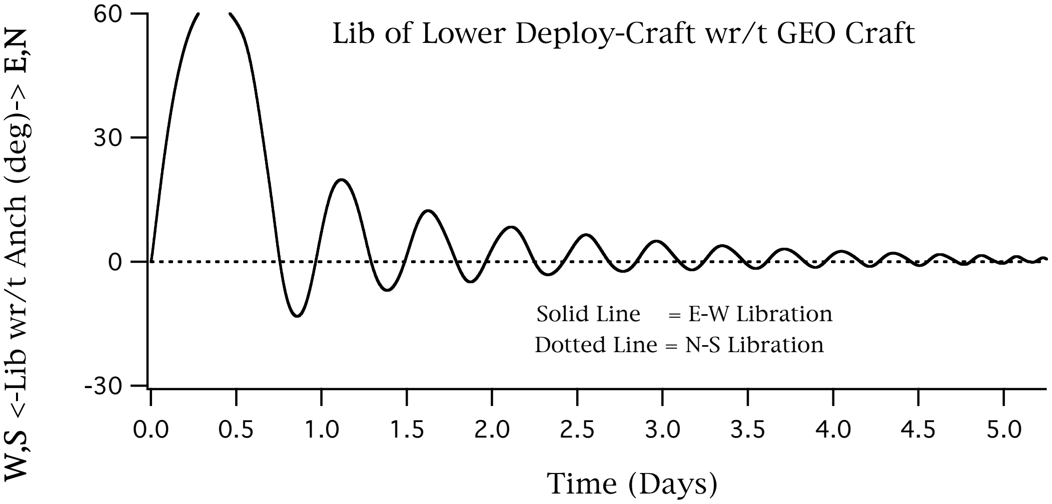
The two graphs below compare the altitude response between the *massless ribbon* and the *distributed mass ribbon* models. In general, it is seen that the GEO-craft and Deploy-craft both loose altitude considerably more and/or faster for the distributed mass case than the massless case. This phenomenon is attributable to different reasons for each object. For the GEO-craft it is because the mass of the ribbon has come into play as it moves into the gravity well. On the other hand, for the Deploy-craft, it is because as the massive ribbon is drawn into the gravity-well *in its own right*, the Deploy-craft is progressively deprived of its *supporting-spring*.

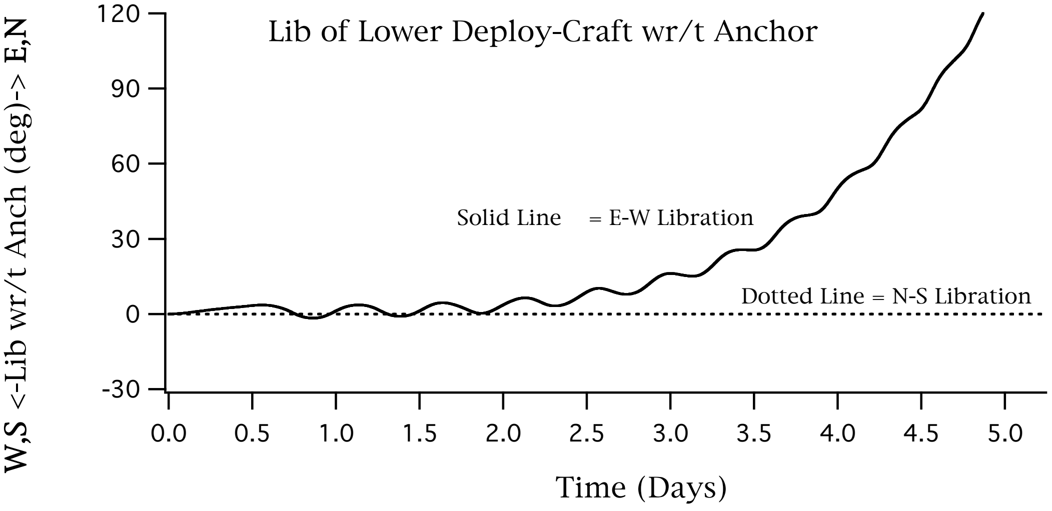


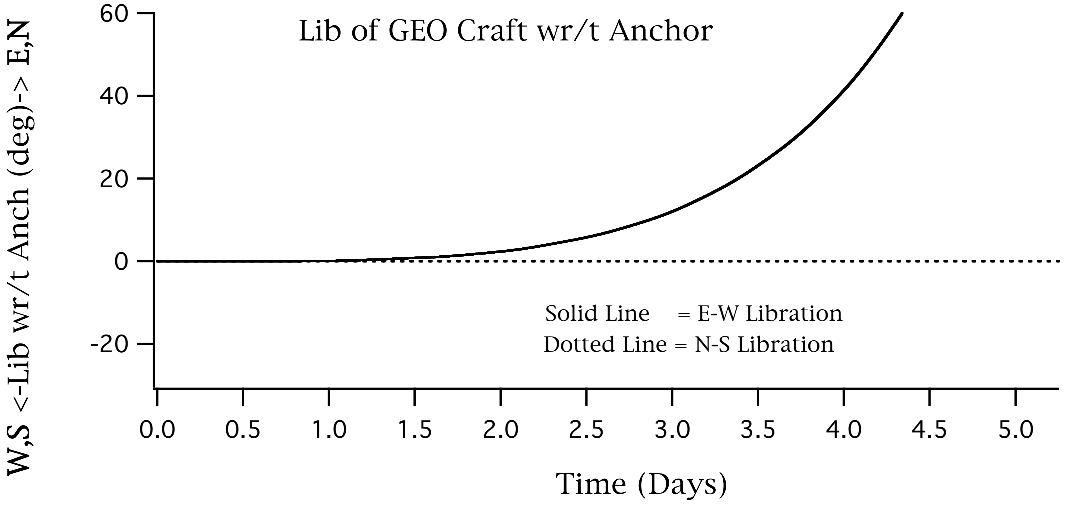


The pronounced increase in gravity on the Deploy-craft at 4.5 days is shown below.









Lib of GEO Craft wr/t Anchor
W,S <-Lib wr/t Anch (deg)-> E,N
60
40
20
0
-20
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Time (Days)
Solid Line = E-W Libration
Dotted Line = N-S Libration

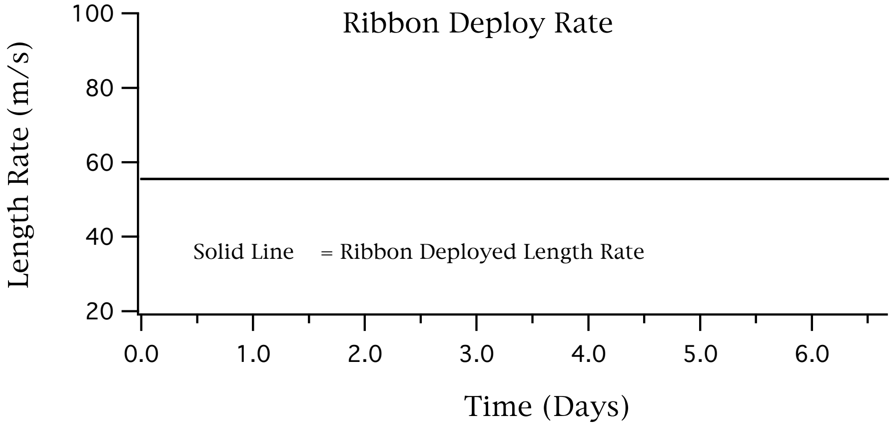
6.6 UNDER-EQUILIBRATED SYSTEM (FALL-DOWN)

This simulation is the first in this series using the various end-object control modes that were developed in GTOSS to examine this problem (the detail definitions of these control modes can be seen in the addenda to the Dynamics Handbook). The outcome of this particular simulation does not represent a successful deployment mission, but rather illustrates a potential failure mode when the GEO-craft's vertical control mode fails to properly equilibrate the increasing tension as the ribbon plunges into the gravity-well.

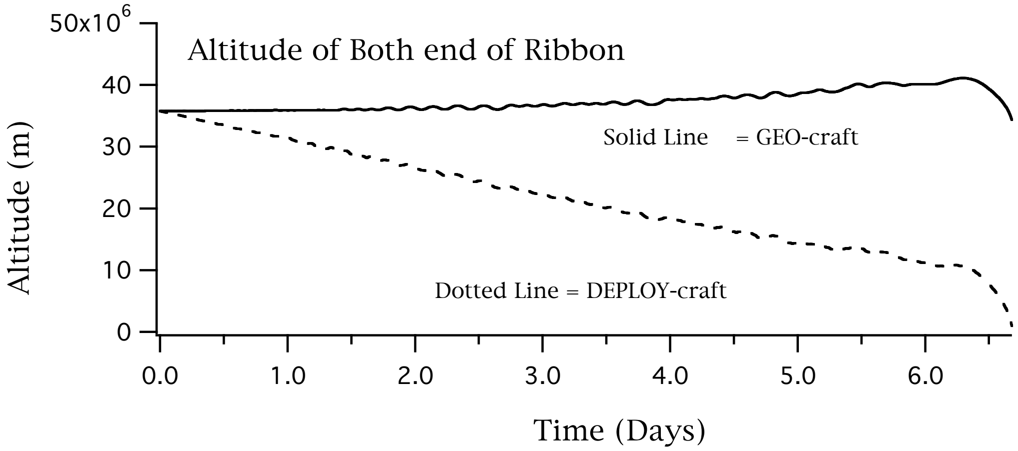
Ribbon was deployed with a Type 1 deployment scenario (deploy rate a linear function of time), and simply generated a constant rate of deploy of 200 kh/hr. The GEO object was controlled in the vertical axis by a type 6 control mode (that attempted to equilibrate net tension, via altitude increase); the various control parameters and gains failed to allow this to occur sufficiently to preclude the system from being dragged down to earth. Horizontal axis control was accomplished via a type 9 controller, that simply held (via feedback proportional control) a constant latitude and longitude. Gains for this mode were too high, resulting in noticeable transverse string-mode excitation in the ribbon, especially early in the deployment when tension was low, and any over-thrusting in the horizontal direction could easily excite ribbon displacements.

As the Deploy-craft starts to come under the influence of the increasing "gravity well", the low spring rate of the long length of ribbon, that has been deployed under almost no tension, *presents almost no resistance to stretch*, and (depending upon the mass of the Deploy-craft) it can dip increasingly into the 1/R**2 gravity, rapidly developing a "dive to earth" in the final hours of deployment. This of course is not appropriate mission design, and clearly points out the need to modulate ribbon deployment consistent with raising the altitude of the GEO-craft to equilibrate tension, as well as curtailing deployment rate late in the mission to insure a state of vertical equilibrium exists between gravity and the ribbon elasticity as gravity onset rate becomes great; this of course speaks for a long mission duration.

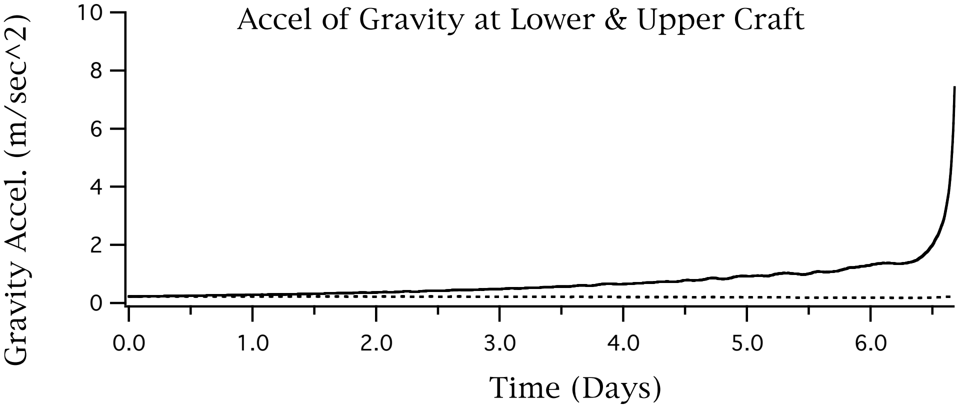
Ribbon deploy rate is shown below:



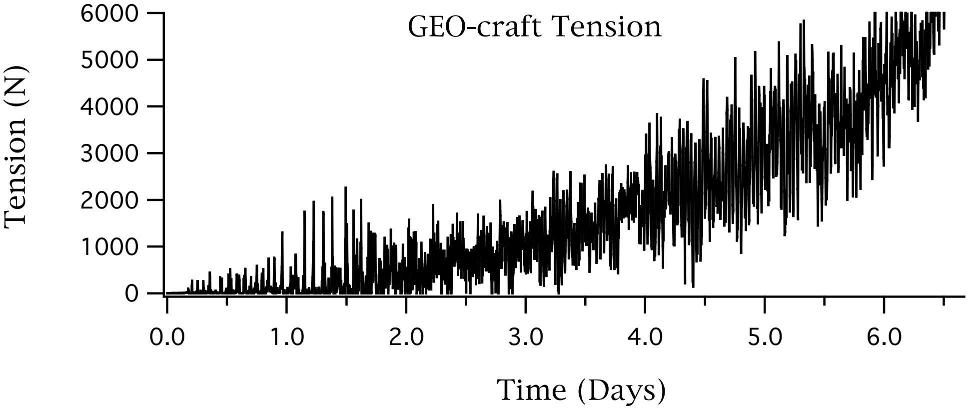
Altitude history of the top/bottom of the ribbon is shown below. The GEO-craft is rising, attempting to equilibrate tension, however, control mode settings are not aggressive enough to effectively counter tension. Also, the effect of the (over deployed) ribbon's low spring rate can be clearly seen in the diving plunge to earth of the Deploy-craft. For effective mission design, the GEO-craft should exhibit a noticeably progressive acceleration of altitude-rate starting about mid-deployment.



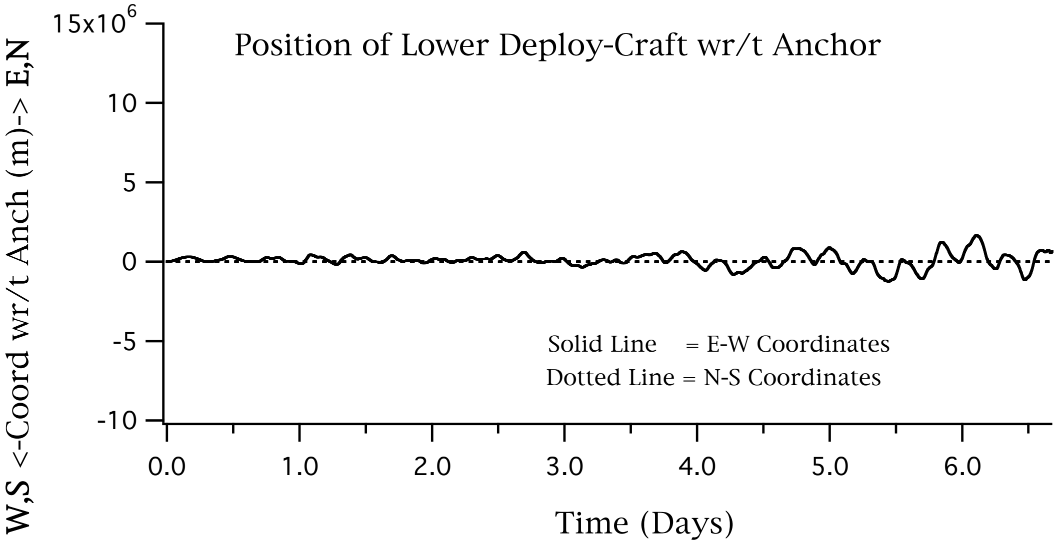
Rapidly increasing gravity at both ends of ribbon is evident below, GEO-craft is dotted.



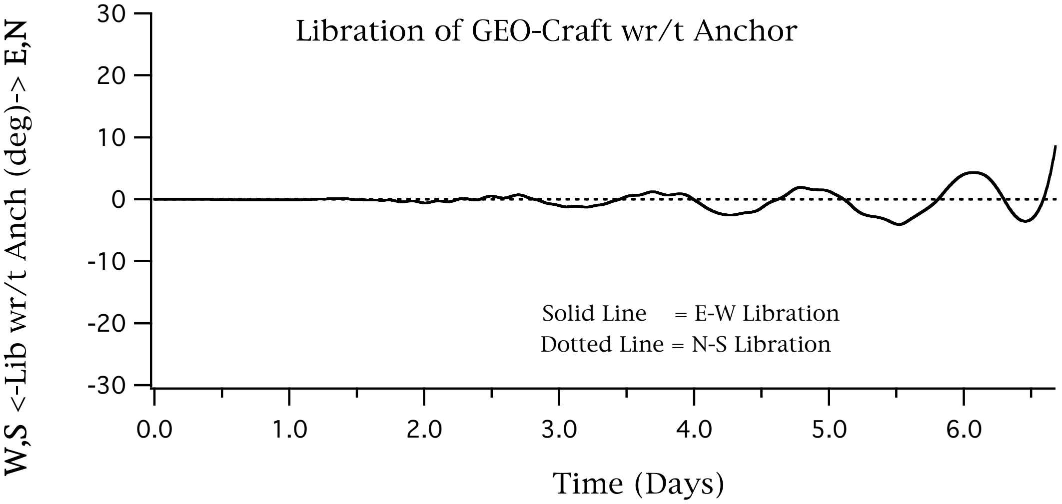
The tension below betrays inappropriate control system settings and gains that are exciting the ribbon and system.



The graphs below shows that the horizontal mode control of the GEO-craft and Deploy-craft were functioning to maintain a semblance of tracking on the specified latitude and longitude of zero. This position of the Deploy-craft is clearly not tight enough to effect an operational rendezvous with the anchor, but the Coriolis effects are seen to be effectively countered (in terms of gross libration of the system).



It can be seen below that the elevator as a whole built up libration oscillation as the deployment neared termination.



Conclusion:

This case illustrates a semblance of control in the horizontal plane, but is significantly lacking in the vertical axis, in short it is catastrophically failing to equilibrate the system during ribbon extension. The next case will illustrate the extreme in the opposite direction.

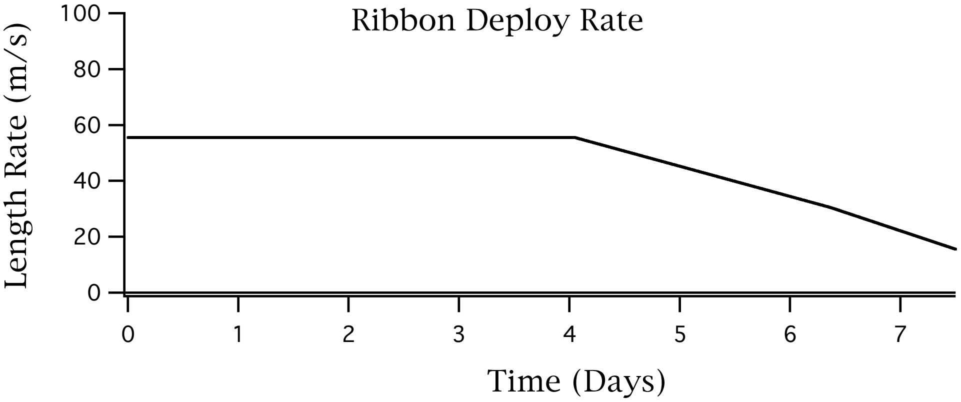
6.7 OVER-EQUILIBRATED SYSTEM (FLY-AWAY)

The outcome of this particular simulation does not represent a successful deployment mission, but rather illustrates another potential failure mode when the GEO-craft's vertical control mode becomes over-aggressive in equilibrating the increasing tension as the ribbon plunges into the gravity-well.

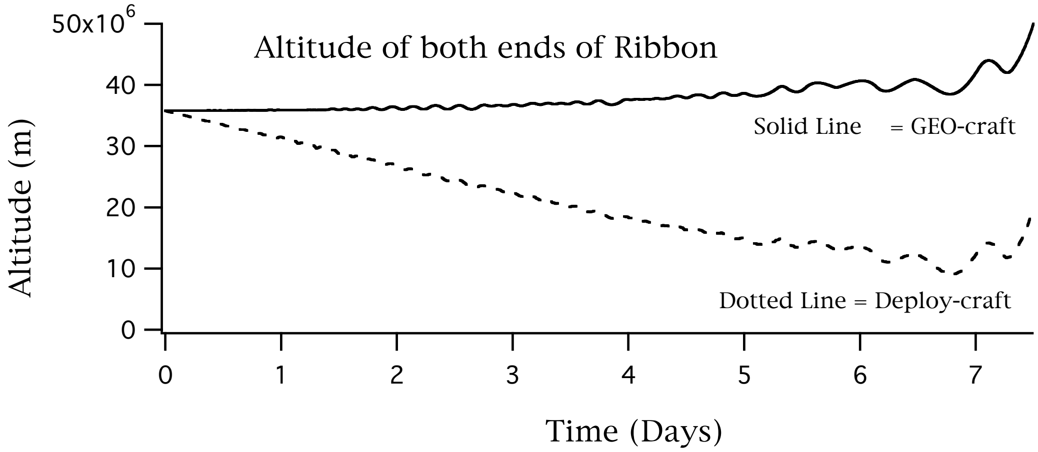
Ribbon was deployed with a Type 1 deployment scenario (deploy rate a linear function of time) starting with a rate of 200 kh/hr, but then slowly reducing this rate over time as the ribbon is lowered. The GEO object was controlled in the vertical axis by a type 6 control mode (that attempted to equilibrate net tension, via altitude increase); the various control parameters and gains resulted in an over-equilibration of the system, which subsequently hurtles off to ever higher altitudes. Horizontal axis control was accomplished via a type 9 controller, that simply held (via feedback proportional control) a constant latitude and longitude; gains for this mode were too high, resulting in noticeable transverse string-mode excitation in the ribbon, especially early on when tension was low, and any over-thrusting in the horizontal direction could easily excite ribbon displacements.

As the Deploy-craft starts to come under the influence of the "gravity well", the vertical equilibration algorithm starts a slow vertical/horizontal oscillation mode as a result of interaction of the vertical control with the Coriolis effects due to the ever increasing vertical velocity. It is at the apex of one of these vertical oscillations that the system becomes over-equilibrated to an extent that the thrust effectors can no longer contain the net vertical impetus and the system departs from earth-bound flight.

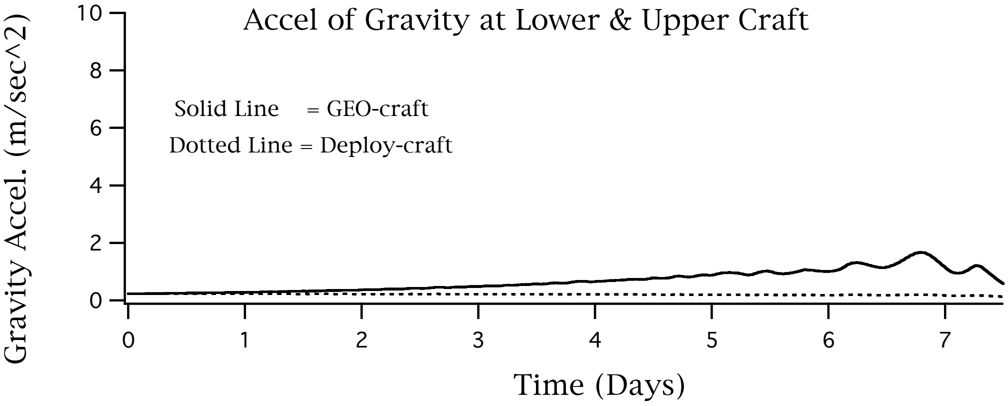
The graph below shows the ribbon deployment rate, illustrating the tail-off in rate as the altitude reduces (note, this is rate as a function of time however, so any rate-altitude relationship is an implied one, which is an important distinction, since near the end, the altitude of the Deploy-craft starts to actually increase in time, a problem which is more successfully countered in the example simulation of Section 6.9).



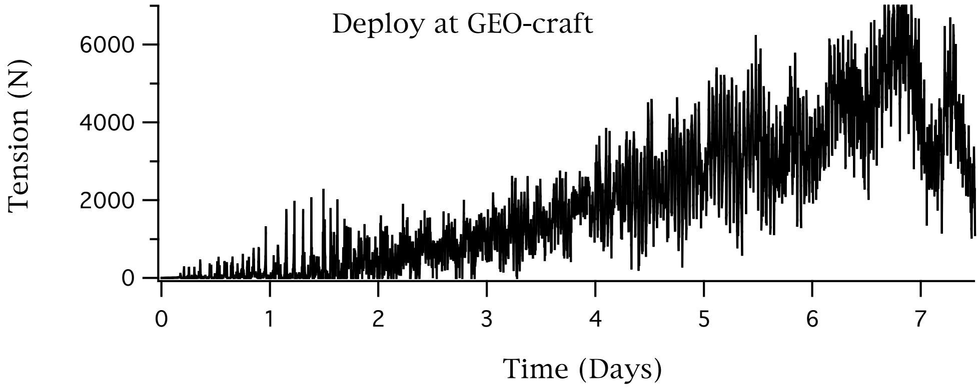
The ultimate failure of this deployment mission is clearly seen in the GEO- and Deploy-craft altitude histories shown below. The GEO-craft is rising, attempting to equilibrate tension, but at about 6 days into the mission, a vertical instability starts manifesting itself, and after a few cycles of this, the system's acceleration field instability overwhelms the control effectors, and the system irretrievably departs controlled flight!



In the graph below, it is seen that the system as a whole has failed to "bite into the gravity well" sufficiently to prevent a centrifugal departure.

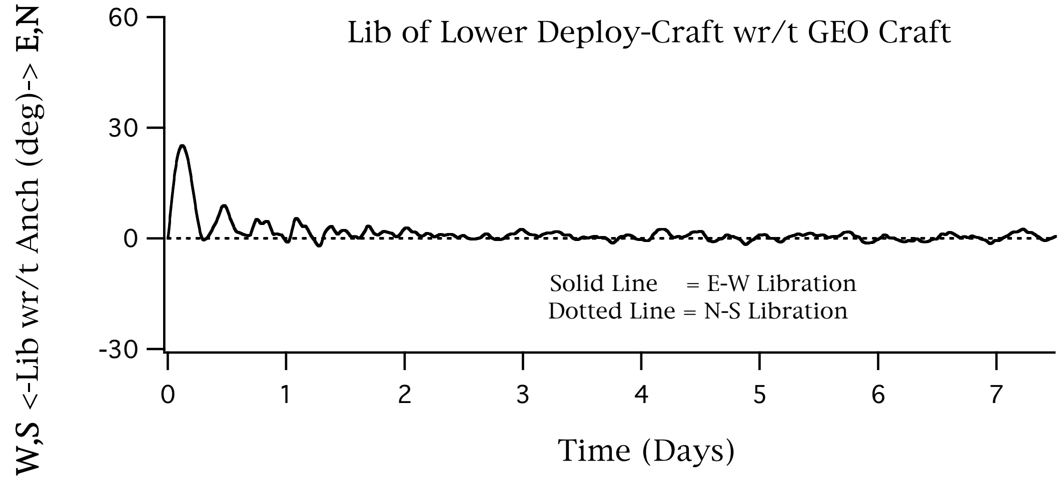


The tension below betrays inappropriate control system settings and gains that are exciting the ribbon and system.

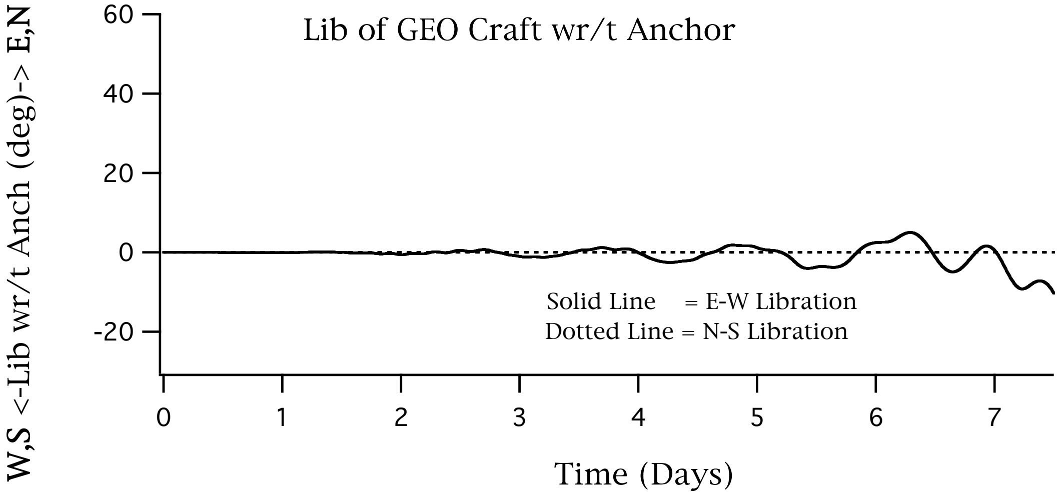


The tension variations seen above are indicative of the need for any elevator ribbon deployment control system design to be able to properly reject "noise" in the tension signal so as to deduce the intrinsic tension level, against which the GEO-craft must fly a compensating equilibrium-altitude maneuver.

The libration of the Deploy-craft relative to the GEO-craft shown below illustrates the potential for minimal control of libration of the Deploy-craft during its deployment; tether deployment tends to be stable (the inverse of tether retrieval, an intrinsic tendency that is a manifestations of the well known "skaters-effect").



The libration of the GEO-craft relative to the earth anchor point shown below shows that the departure of the system from controlled flight is attended by increasing angular disturbance as well as increasing altitude, and effect consistent with gravity field dynamics.

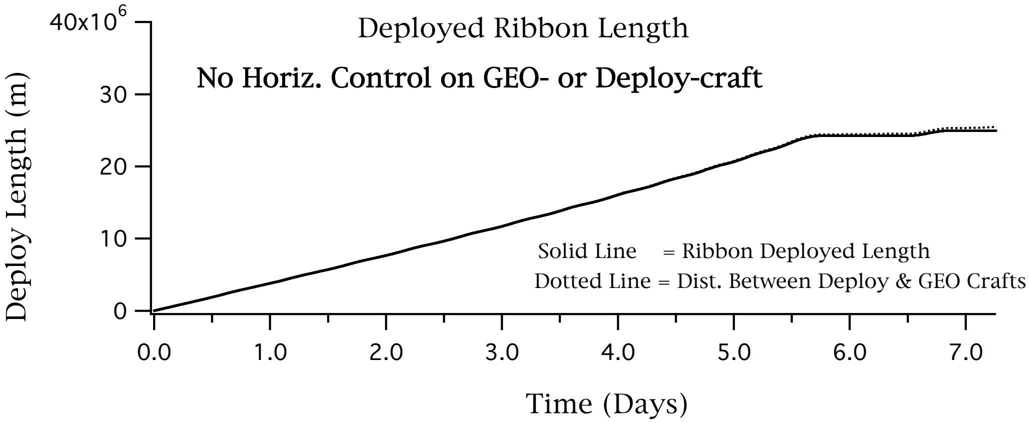


6.8 END-BODY LIBRATION CONTROL EFFECTS

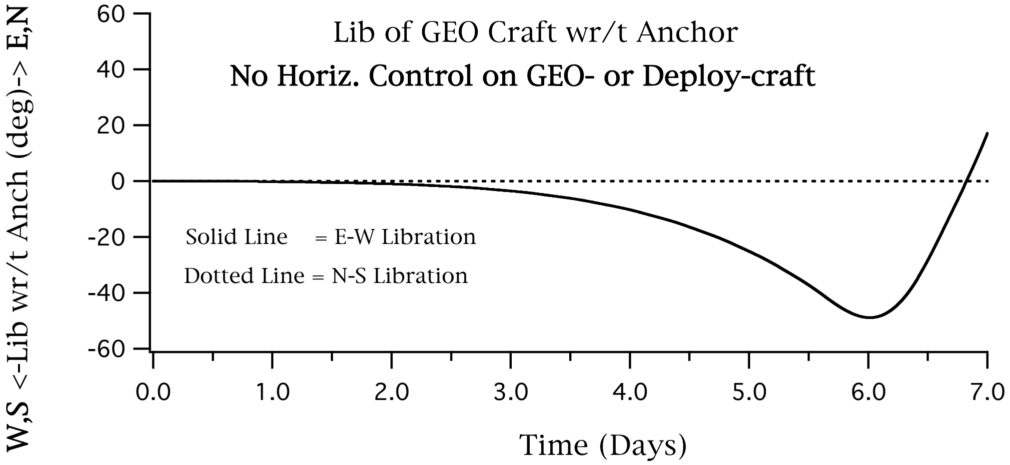
This examination centered on determining the effects of enabling/disabling Horizontal control for the ribbon's end objects (GEO-craft and Deploy-craft). Horizontal control took the form of various types of algorithms for this study, ranging from direct control of earth referenced latitude/longitude coordinates, to simple tangential velocity make-up (to counteract Coriolis effects), and combinations of these with various control logic implementations (dead-band based on-off control, classical proportional control, etc). Note that algorithms controlling longitude, also then *indirectly* serve to control tangential velocity, thus performing a tangential velocity make-up (counter-Coriolos) maneuver.

6.8.1 No Libration Control on Either Upper or Lower Craft

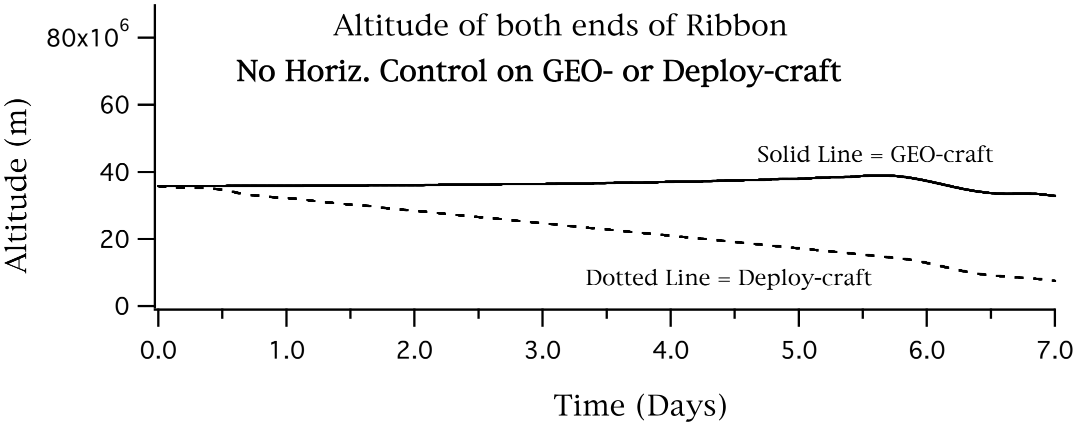
Here, the deployment took place with no Horizontal control being enabled on any of the end-craft; this means no attempt is made to track an earth fixed point, nor, to compensate for Coriolis effects. Below is the deployed ribbon time history (typical of all the following series of Horizontal control runs).



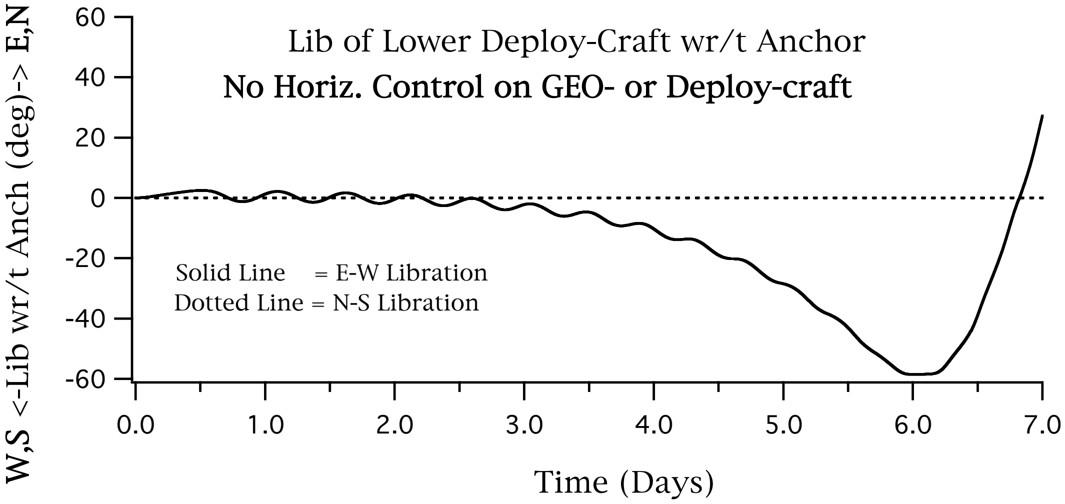
The graph below shows the Libration of the GEO craft as viewed from the anchor station. It is clear that large and impractical angular dispersions are occurring in this case.



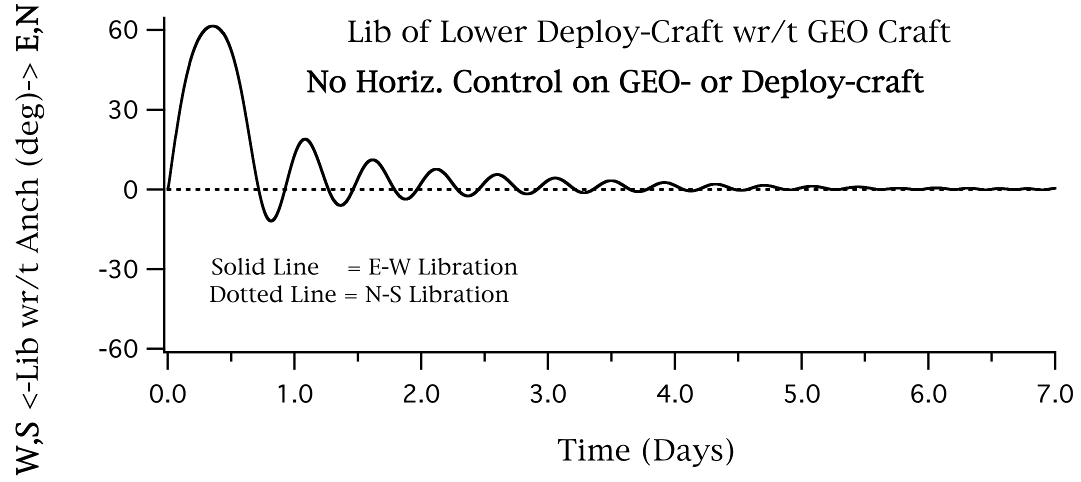
The altitude response of both end-objects are shown below. In this case, the vertical control was not aggressively attempting to raise the altitude of the GEO craft to compensate for the rising tension; had it done so, much greater positive altitude rates would have been realized, that would have exacerbated the GEO-craft libration (shown above), since the Coriolis acceleration is directly proportional to the altitude rate.



The Libration of the (lower) Deploy-craft relative to the anchor (shown below) is seen to follow the GEO-craft trend fairly closely.



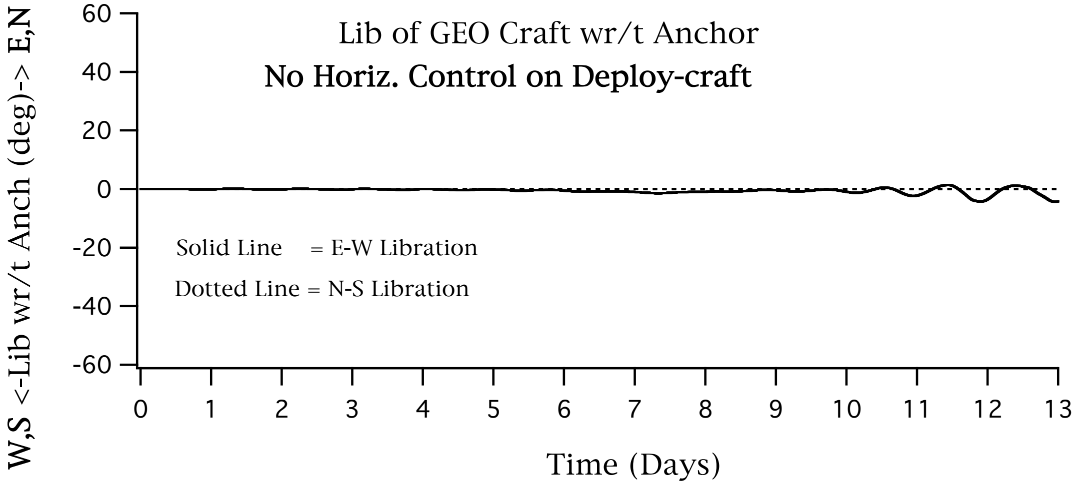
The above correlates well with the Libration of the Deploy-craft relative to the GEO-craft (shown in the following graph below), indicating that the Deploy-craft remains more or less directly below the GEO-craft as it executes major libration excursions. This is highly suggestive that it may be possible to employ minimal, or no, Horizontal control on the Deploy-craft until the final terminal-phase rendezvous with the anchor (so as to enable precise grappling at the ground).



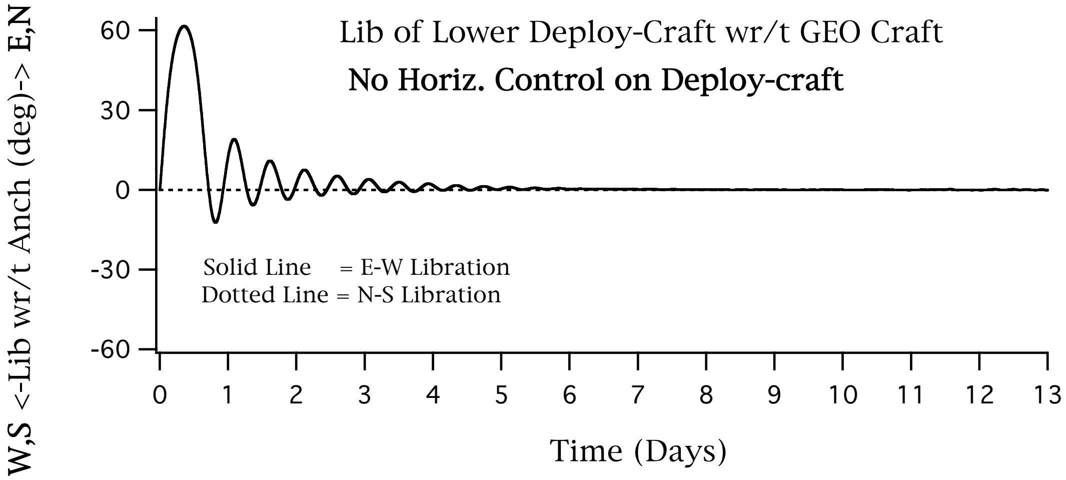
While the graph above indicates that the Deploy-craft is vertically-tracking the GEO-craft during it's uncontrolled deployment, nevertheless, by this same token, the Deploy-craft is realizing large excursions relative to the anchor point (shown in the previous graph above). This also suggests that if the GEO-craft is successfully Horizontally controlled, then the Deploy-craft may simply follow suit.

6.8.2 No Libration Control on Lower Deploy-craft

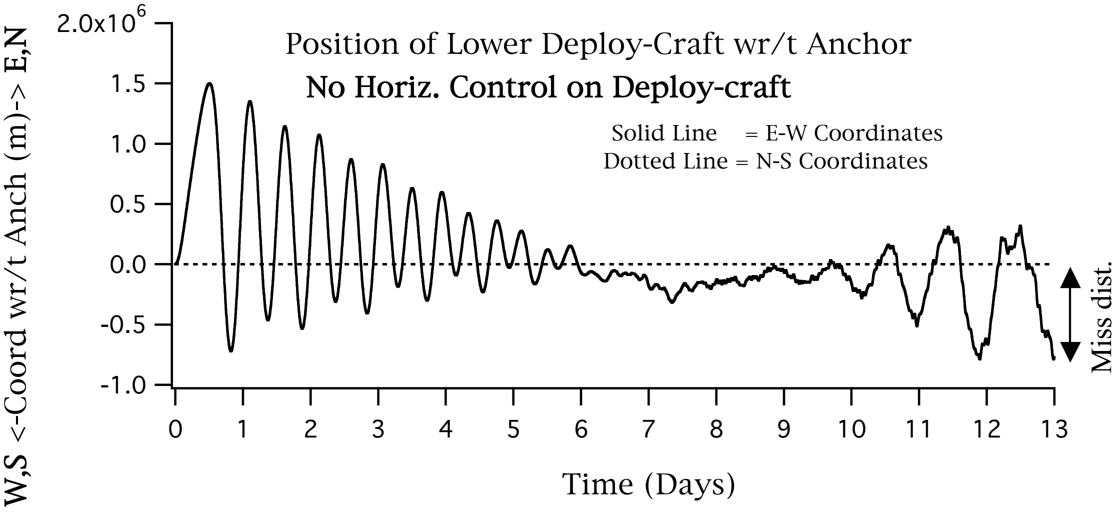
In the example above, it is clear that deploying with no Horizontal control on either end-object would likely be impractical. In the next two runs, the effects are examined of only one or the other of the end-craft having Horizontal control disabled to determine which is the most critical. In this run, the GEO-craft has Horizontal control enabled via classical proportional feedback control, BUT, the (lower) Deploy-craft, had its Horizontal control disabled. It is seen in the graph below, that Horizontal control on the GEO-craft has arrested its large un-compensated Librations (due to Coriolis effects) very nicely.



Consistent with the previous suppositions, now that the GEO-craft is stabilized, the Deploy-craft is behaving quite well, and tracking beneath the GEO-craft. The early initial librations of the Deploy-craft relative to the GEO-craft are simply relative-orbital effects due to the manner in which this deployment is initiated; that is, the Deploy-craft is essentially ejected from the GEO-craft as a free-flying object (under virtually no tension initially), and when the ribbon finally becomes taut (tension manifesting itself), the Deploy-craft "pendulums" beneath the GEO-craft. The progressively decreasing libration of the Deploy-craft relative to the GEO-craft is typical of space tether deployment of this type (that exhibits a stabilizing factor due to the increasing the *equivalent moment of inertia* of the tether relative to the GEO-craft; in short, the "skaters effect"). The apparent ever-increasing stability depicted in the graph below also reflects the fact that as distance increases between the GEO- and Deploy-craft, apparent libration also diminishes; just the opposite will be true when the Deploy-craft is viewed from the anchor point.



The need for precision terminal phase Horizontal control to facilitate grappling at the anchor is shown below. Even though the Libration (angular dispersion) of the Deploy-craft relative to the GEO-craft was ever decreasing, when viewed from the anchor point, even slight GEO-referenced libration angles equate to significant "miss distances".



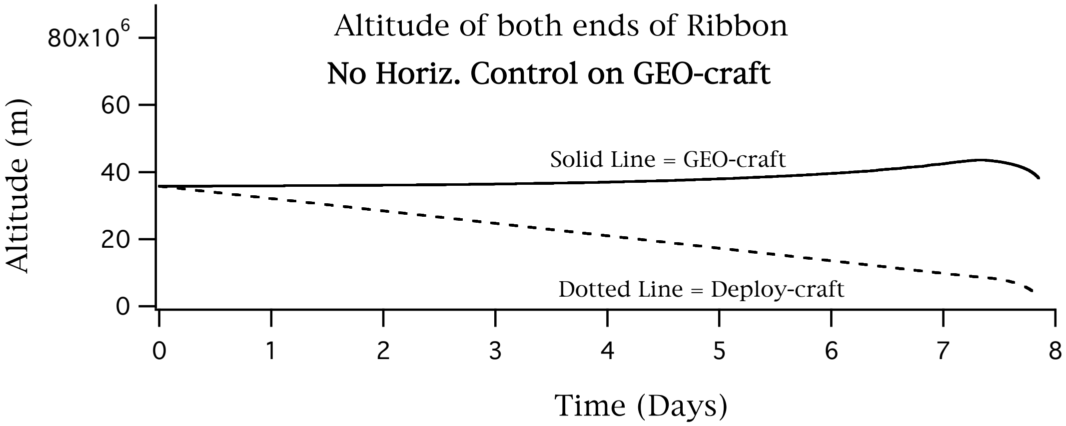
6.8.3 No Libration Control on Upper GEO-craft

From the above examples there is strong suggestion that the primary driver of this deployment as it regards Libration dispersions is likely the GEO-craft; this is probably because it eventually experiences much greater altitude rates than the Deploy-craft. The example above indicated strongly that only very little Horizontal control maybe required for the Deploy-craft.

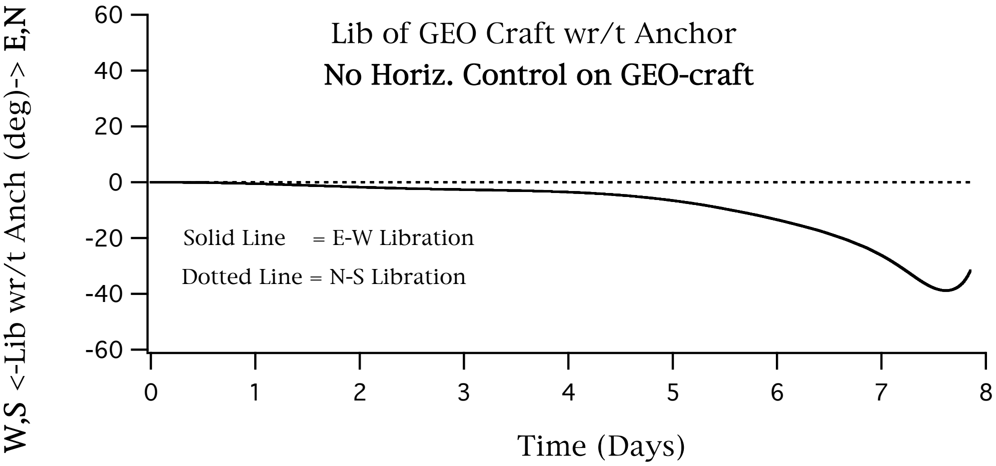
Even as the Deploy-craft is starting to attenuate its altitude rate as it nears earth, nevertheless the gravity-well is picking up intensity as an inverse square function, thus the GEO-craft must be increasing its altitude-rates to ever greater values to compensate for the rising tension. Failure to do so will result in it's getting pulled down; the only means to counter this is through either dynamic equilibrium (that entails large altitude rates) or thrust (impractically expensive due to the long deployment time frames with the corresponding implied total impulse).

The example below confirms that the GEO-craft will need Libration control to effect a successful deployment of the ribbon to the anchor. Note that this example falls to earth in fairly short time, thus the large values of Libration that were accrued in the previous (and much longer duration simulation) due to the greater altitude rates involved are not demonstrated in this example, but would have been had the system not crashed to earth prematurely.

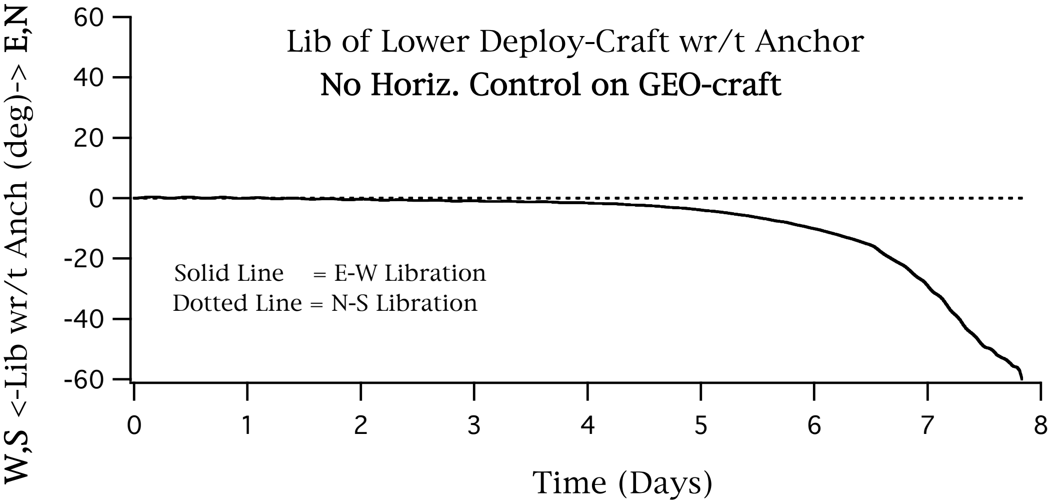
The first graphs shows the altitude of the end-craft for this case, indicating the resulting pull-down.



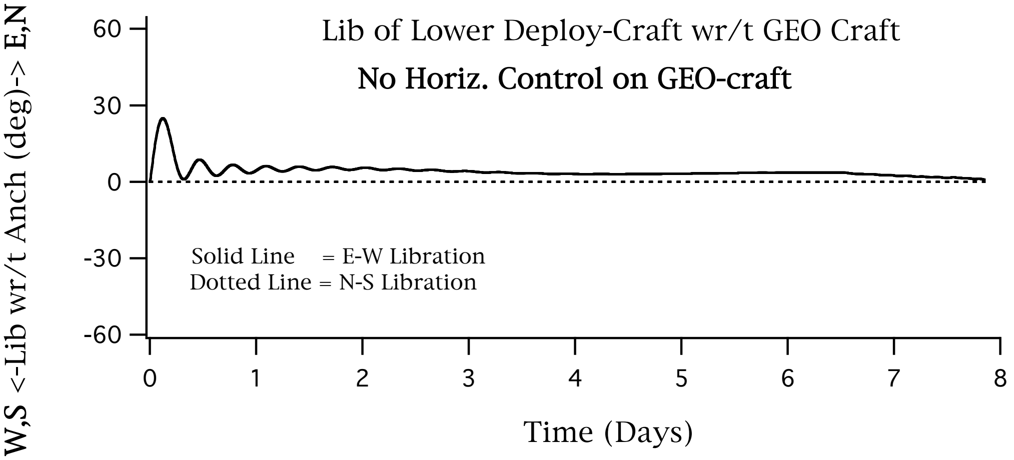
Libration of the GEO-craft relative to the anchor point is shown below.



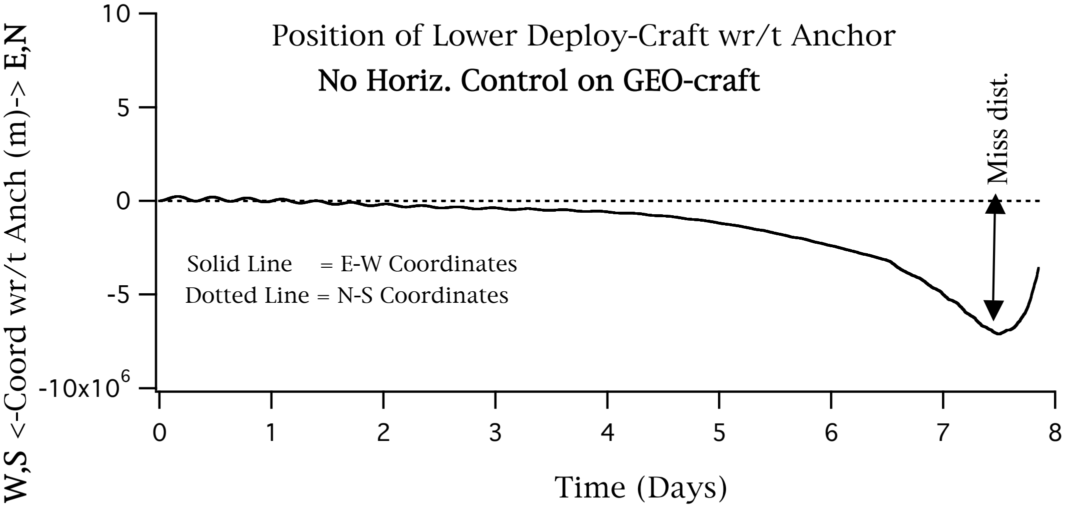
The GEO-craft as it librates, "pulls" the Deploy-craft "in kind" resulting in its being displaced from the anchor point as shown below.



The Deploy-craft (as in previous examples) more or less follows the GEO-craft vertically, as seen below:



However, since the GEO-craft is strongly displaced, it results in the following "anchor point miss" for the Deploy-craft. The main problem with this final dispersion is its high rate of Horizontal change that must be dealt with to effect a successful grappling at the anchor point.



6.9 VERTICAL/HORIZONTAL CONTROL COUPLING

The example below illustrates the phenomenon of coupling between the axes of control on an end-body. In this case it is the GEO-craft controller that is experiencing coupling.

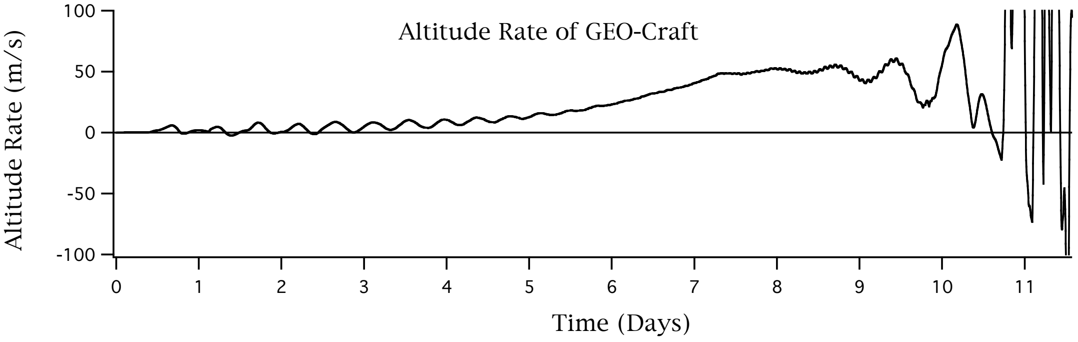
Definition of System Experiencing Coupling

The vertical control mode consists of altitude management to equilibrate the rising tension due to deployment. This results a (more or less) continuously increasing altitude and is achieved by way of a classical, closed-loop, error/error-rate feedback, proportional thrust controller. Gains are chosen to provide a stable/and reasonably tight control.

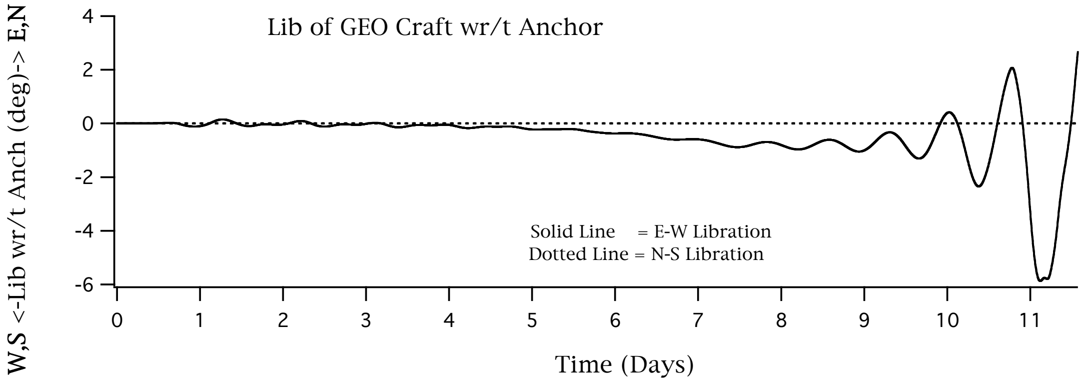
The horizontal control consists of a simple earth referenced latitude/longitude controller. This control is achieved (as above) via a classical closed-loop error/error-rate feedback proportional thrust controller acting in the horizontal plane. This mode while explicitly managing latitude/longitude is also, in fact, indirectly managing Coriolis effects arising due to altitude-rate along the local vertical.

Origin of the Coupling

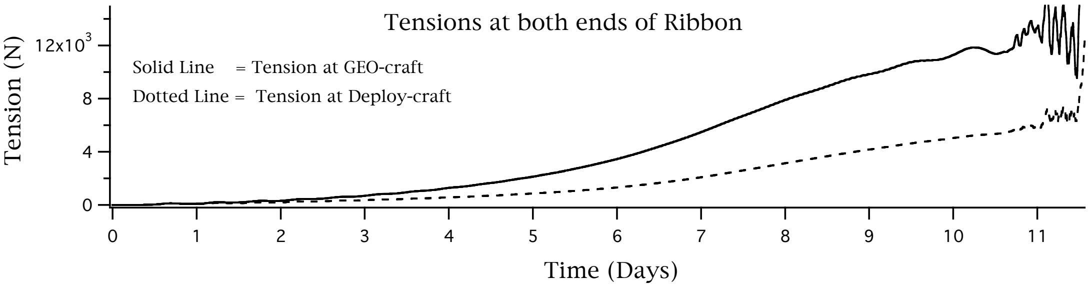
As the deployment progresses towards completion, the ribbon and Deploy-craft are encountering ever-intensifying gravity near the earth, with an associated rise in net ribbon tension at the GEO-craft. This in turn, demands that the vertical controller must correspondingly accelerate altitude rate. But this precipitates a greater Coriolis acceleration resulting in libration (the extent of which reflects itself in a net libration oscillation consistent with the gains/effectors in the horizontal plane controller). Now, this libration has a characteristic tension profile associated with it (at the GEO-craft, much like that experienced when one swings on a playground swing). This tension disturbance can be *seen* by the vertical control tension sensors, and will be reacted-to in the fashion for which the vertical controller is designed; thus is seen the mechanism that allows control coupling. In this example, the coupling effect occurs late in the deployment as shown below. The altitude rate divergence starting to appear in the graph below,



is seen to be in phase with the corresponding libration angle shown below:



The corresponding tensions in the ribbon are shown below:



The oscillation in tension is not as evident as the manifestations in libration and altitude rate due to the scale of the tension plot, and the fact that small tensions variations have a large gain with respect to the altitude commanded as a result of incremental tensions.

Resolution of the Problem

The solution to this problem can take many avenues. For example,

1. One classic solution is to filter the sensor signals (tension in this case) to remove frequencies that are coalescing to cause the resonance. But, there is a limited amount of filtering that can be done because the period of the offending oscillations (about 17 hrs) is so great that tension can build up appreciably over this time, and if the GEO-craft altitude controller is denied information of changes in tension over this length of time, the system as a whole can be become out-of-equilibrium, thus defeating the purpose of the equilibration maneuver in the first place. Furthermore, near the end of deployment, tension is changing rapidly, which exacerbates the problem, and forces the GEO-craft to expend propellant to do thrusting equilibration, a likely impractical solution.

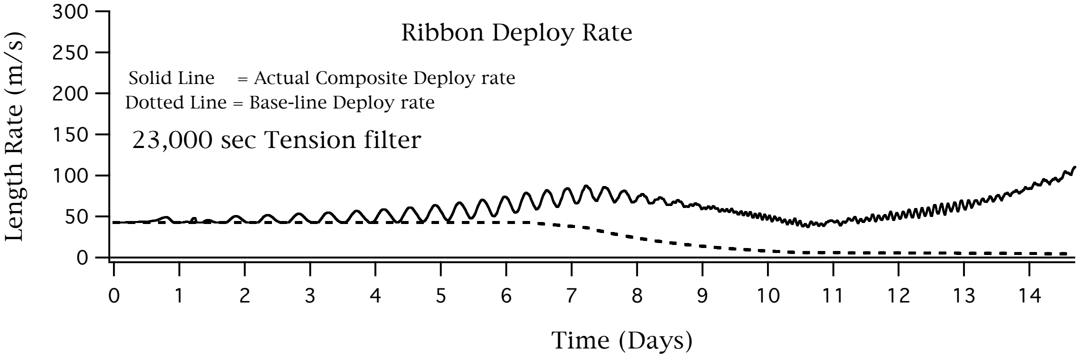
2. Lengthen the deployment time (ie slow down the approach into the gravity-well) so that changes in tension are minimal over a period of 17 hours, thus allowing filtering of the tension sensor signal. The problem with this solution is that the total

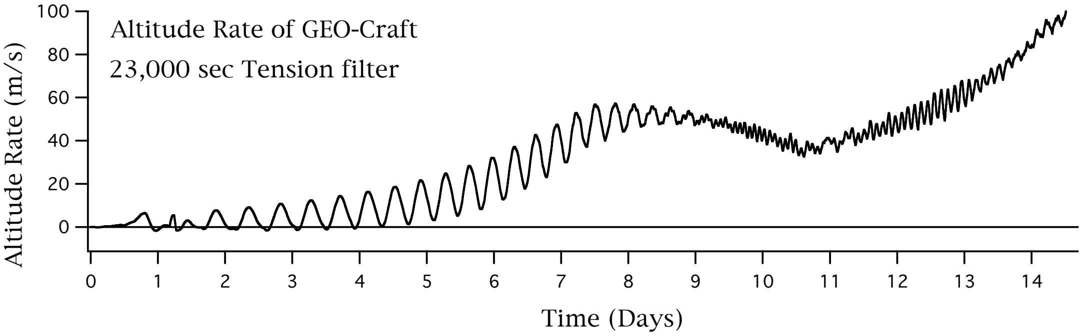
deployment mission becomes so lengthy that other factors come into play; for instance as total mission time lengthens considerably, so will the propulsion *total impulse* expended just due to, say, the controller's being active to manage GEO-craft attitude increase.

3. Adjust gains on the vertical and horizontal controllers. This is a potentially efficacious solution. For the simulations being conducted in this case, the gains were chosen to produce appropriate control for both the vertical and horizontal axes, and it was those gains which produced the ultimate coupling instability. To decouple the axes gain-wise may well yield controllers with other artifacts the appear during the course of the deployment. Note that frequencies are changing significantly during the course of this deployment. Tension has already been filter for instance to eliminate an undesirable oscillatory phenomenon with a 4000 sec period.

4. The scheme used in this simulation to decouple the axes was a change in the control algorithm. Due to the very specific task that the vertical controller must accomplish, it was not a good candidate for change, but there were many ways that the horizontal controller algorithm could be changed. Basically the solution was to abandon the classical proportional-thrust feedback scheme on latitude/longitude, and replace it with a scheme that provided a Coriolis-countering thrust bias, in conjunction with a classical on-off dead-band controller to maintain latitude /longitude.

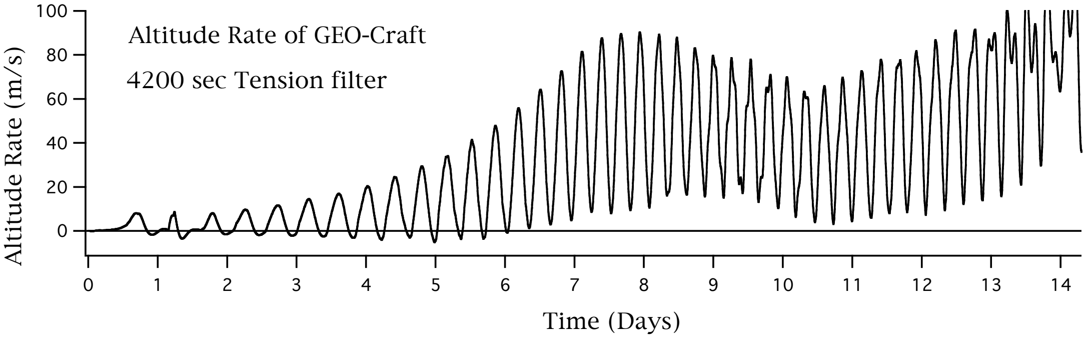
The new horizontal control algorithm resulted in the following response for the previous case. Not that the vertical-horizontal coupling is now eliminated.



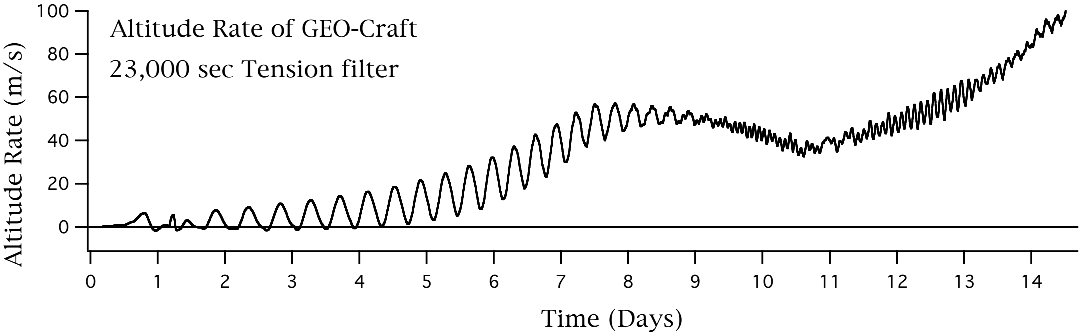


6.10 EFFECTS OF TENSION SENSOR FILTERING

This is an example of using a time-averaging filter to remove an undesirable oscillation from the dynamic response of elevator ribbon deployment. The vertical and horizontal controllers on the GEO-craft are combining with the ribbon deployment algorithm to produce a incessant oscillation that results in "rough deployment". The altitude time history of the deploy craft *before* and *after* insertion of the filter is compared in the two graphs below.

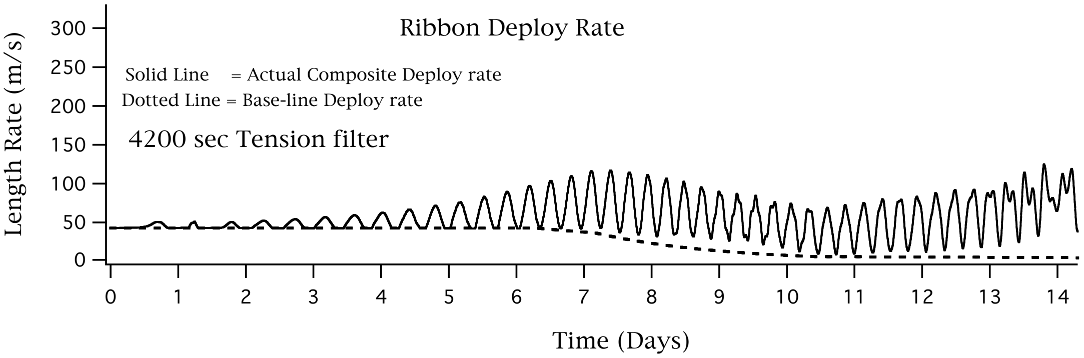


Note that the characteristic oscillation seen above has a period of about 23,000 sec. By applying a 23,000 sec averaging filter to the tension values *seen* by the vertical controller on the GEO-craft, the above response was transformed into that shown below.

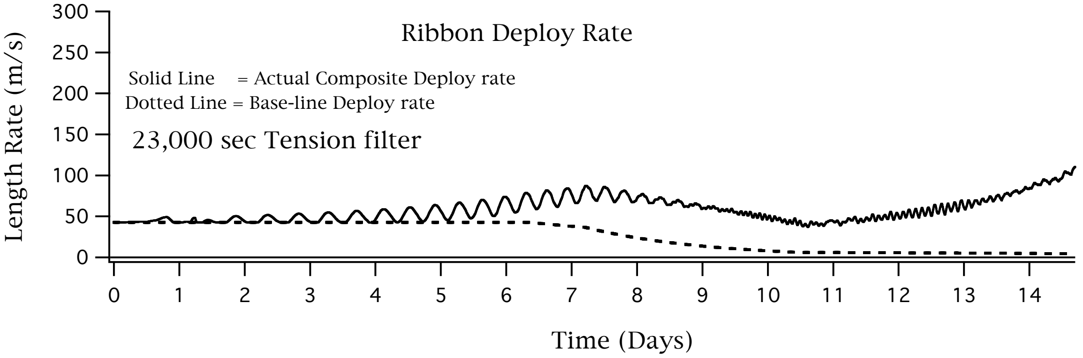


In the definition of the ribbon deployment algorithm, the altitude rate of the GEO-craft plays a direct an critical control, so by eliminating the oscillations, the ribbon deploy rate also becomes much better behaved. The comparison between the ribbon deploy-rate *before* and *after* filtering is shown below:

Deploy rate before filtering:



Deploy rate after filtering:



6.11 SUCCESSFUL BALANCED DEPLOYMENT

The example behaviors above have illustrated the natural unruly tendencies and potential difficulties of controlling this system during deployment. The example below now counters the above by showing how system stability might be approached in a controlled fashion to effect a successful deployment of the elevator ribbon.

This particular example demonstrates the possibility of dynamically balancing the vertical ribbon during the course of a deployment, and is the culmination of an investigation that employed multiple combinations of conventional and unsophisticated control in an attempt to render a more or less stable deployment. This study eventuated in a system approaching a level of vertical balance so as to achieve an almost successful deployment in terms of vertical equilibrium and suppressing un-desirable dynamic ribbon responses.

While this run in no way exhibits the fine terminal-behavior required of an actual deployment mission, it does demonstrate the possibility of dynamically balancing such a system by means of control effectors of significantly less force than the steady tensions being managed during the deployment. Given unlimited propulsive control thrust and fuel, this task could of course been accomplished quite nicely, albeit, such a “brute-force” approach would be impractical from many standpoints.

> Point of Interest: While this example in no way exhibits the fine terminal-behavior required of an actual deployment mission, it <u>does</u> demonstrate the possibility of dynamically balancing such a system by means of control effectors of significantly less force than the steady tensions being managed during the deployment. Given unlimited control thrust and propellant, this task could of course been accomplished quite nicely, albeit, such a “brute-force” approach would be impractical from many standpoints.

The crux of this technique revolves around the interplay of a “vertical and horizontal controller” for the GEO-craft *combined with* a “ribbon deployment controller” that recognizes the need to modulate the ribbon deployment rate as a function of the altitude, while paying due regard to ribbon deployment rate required to compensate for the rising altitude of the GEO-craft. The essence of the GEO-craft vertical controller is its algorithm designed to achieve an altitude that will continuously equilibrate the ribbon tension using the centrifugal effect, said equilibration *ideally* occurring with a precision that requires virtually no propulsive-makeup; ideally then, the minimum propulsive force needed would correspond to the “work” that must be done to “lift” the GEO-craft against the gravity field from GEO altitude to Ballast altitude (along with tangential velocity make-up). This vertical controller incorporates logic to minimize modal interaction with the combined elastic ribbon and end-body system, and to respond effectively to tension transients; a particularly insidious problem involves vertical control activity’s inducing spurious tensions into the ribbon system in the act of maneuvering, then in turn reacting to these very transients. For this reason the vertical controller uses “filtered tension” to plan maneuvers, and can also be adjusted to enter into quiescent periods in which it does nothing other than maintain existing commanded altitude. All of these facets are employed to achieve a fairly stable deployment.

In terms of the GTOSS simulation, the above described control effectors were invoked for each of the craft as follows:

GEO-craft as:

- Vertical control option 6 (altitude equilibration based on tension)
  - Error gain = 0.00035
  - Rate gain = 1.0
  - Max Thrust Avail = 1500 lbf
  - Quiescent Time Interval = 500 sec
  - Duration of Tension Filter = 23,000 sec
  - No. of Filter Samples =50

- Horizontal control option 8 (Coriolis thrust-bias w/on-off DB logic)
  - Dead-band = +/- 1.0 deg
  - Max Thrust Avail = 500 lbf

Deploy-craft:

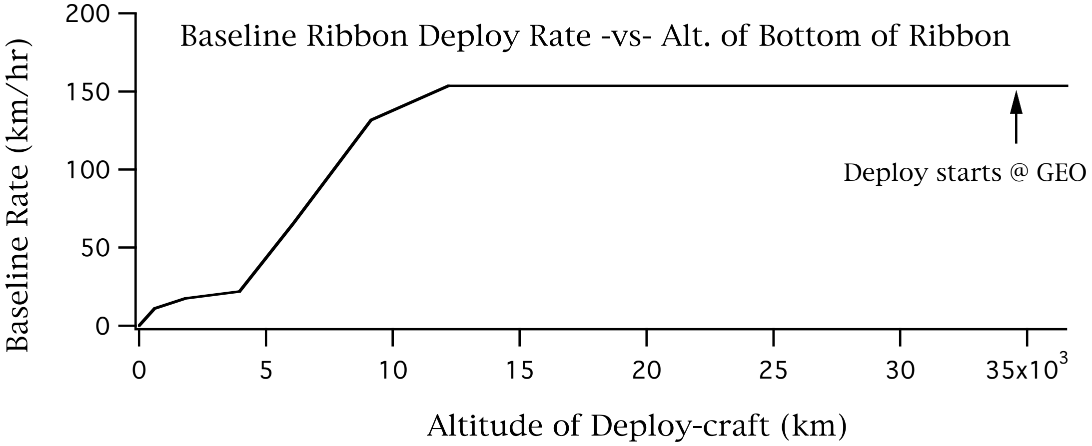
- Vertical control ~ **None Used**
- Horizontal control ~ **None Used**

The Ribbon Deployment:

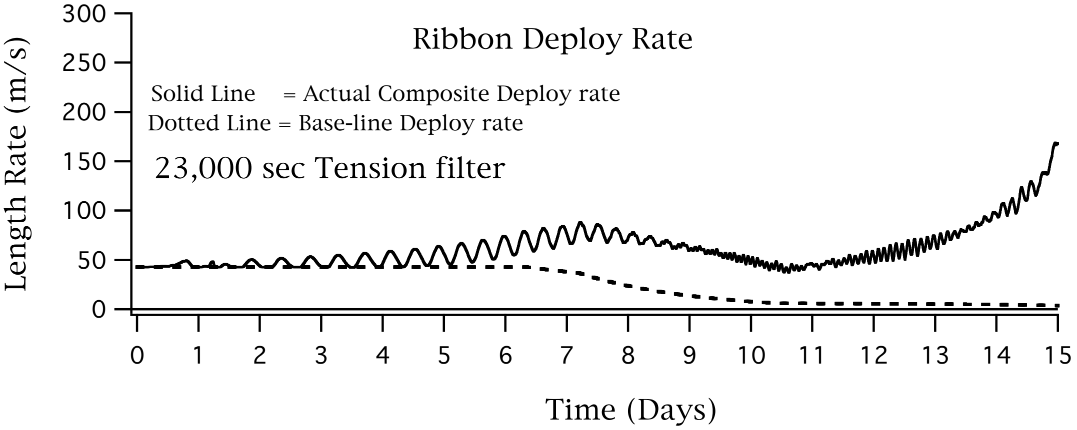
This was accomplished with a type 12 deployment controller. This controller determines a basic deployment rate profile from a table of "Deploy-rate -vs- Altitude" that represents a simplified ideal rate of descent of the Deploy-craft, then *adds to that* the altitude rate of the GEO-craft (as it rises to equilibrate the ever-building tension). This algorithm is configured for this example (as a user input option) to also inhibit "negative deployment" rate so to limit (to some degree) the deployer's participation in both system longitudinal dynamic modes and GEO-craft controller-induced vertical dynamics.

Under the chosen type 12 deployment, a strain-biased deployment was specified with a reference strain of 0.075 based on a reference tension of 5000 lbf. This allowed for the fact the deployment scenario deploys "un-elongated" tether, which, upon being emitted into the domain of the tether, is destined to undergo strain at the level of tension extant in the tether at the GEO-craft at the moment of deployment. Thus the deployment components associated with both the *Baseline profile* and the *GEO-craft altitude-rate* were reconciled with the real strain conditions extant in the ribbon.

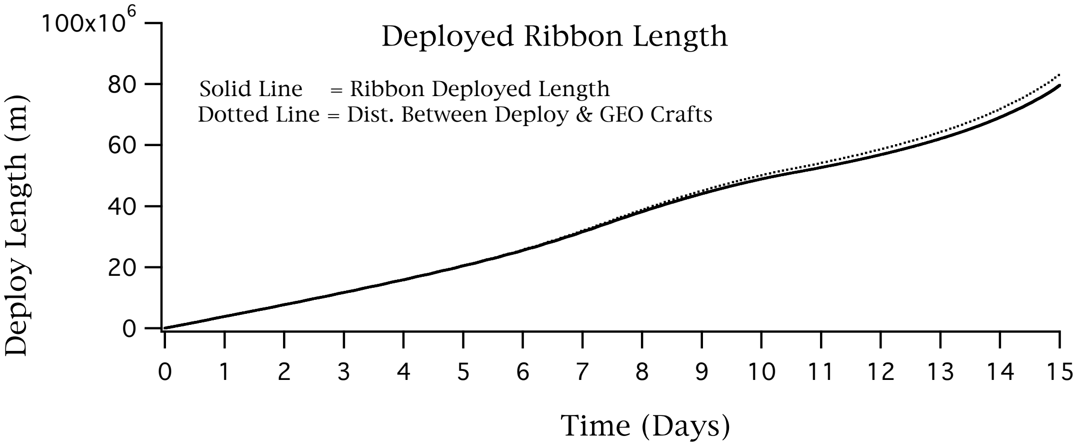
Below is the *base-line* deploy rate that was used for this particular example. This represents a idealization of a possible "altitude-rate -versus- altitude" profile that might be appropriate for a Deploy-craft to experience.



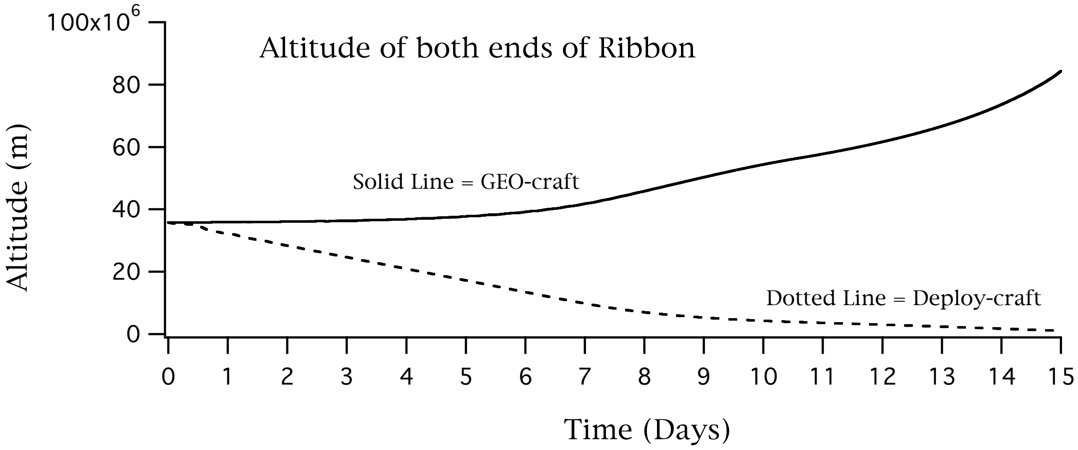
This resulted in the following deploy length and length-rate time history from the deployment scenario algorithm:



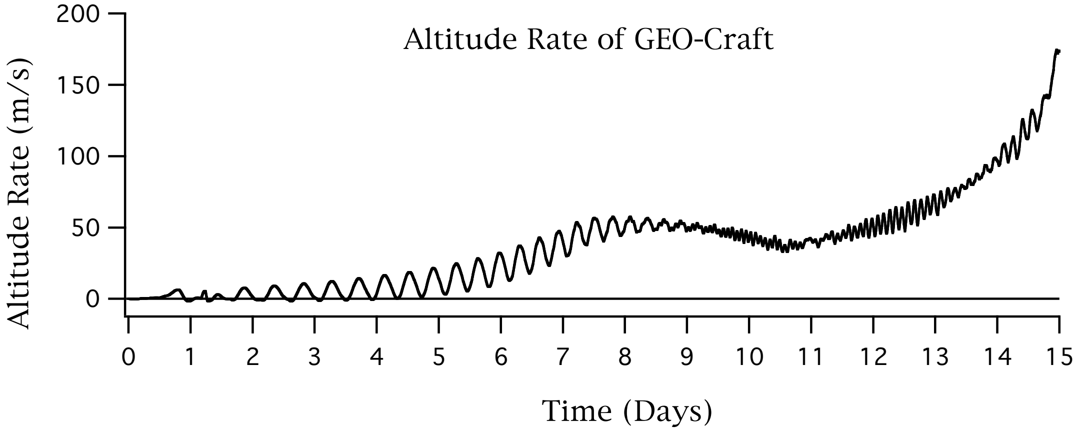
The deviation between the two curves below is representative of the strain within the ribbon as it deploys, and is the quantitative source of the strain-factor definition for the deployment algorithm of this example.

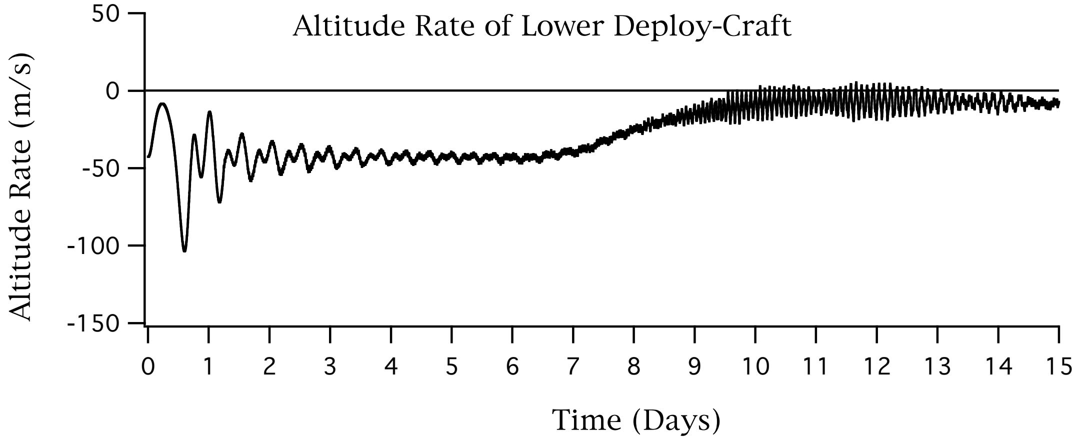


This ribbon deploy profile drove the entire mission in conjunction with the vertical controller on the GEO-craft , resulting in the following altitude histories for the GEO-craft and Deploy-craft:

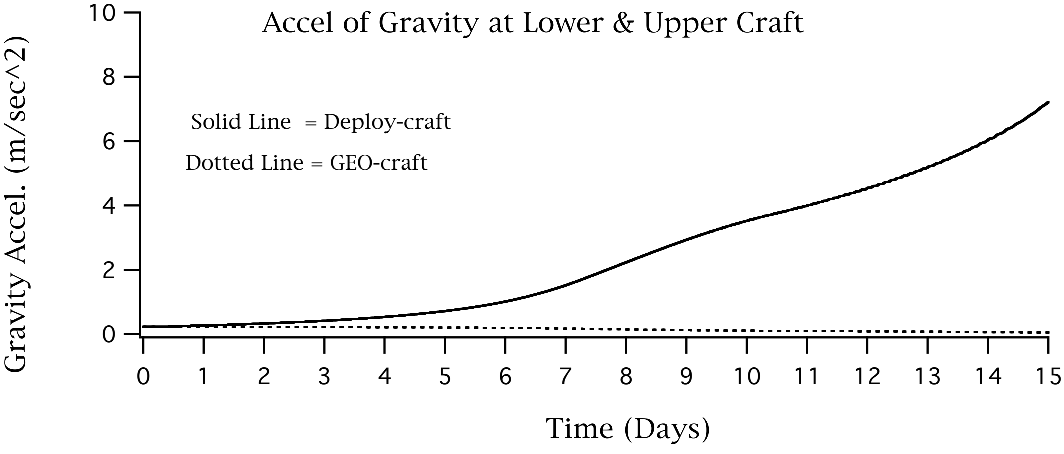


and corresponding to these altitude histories the dynamic response of the deploying system experienced these altitude rates for the ribbon end-objects:

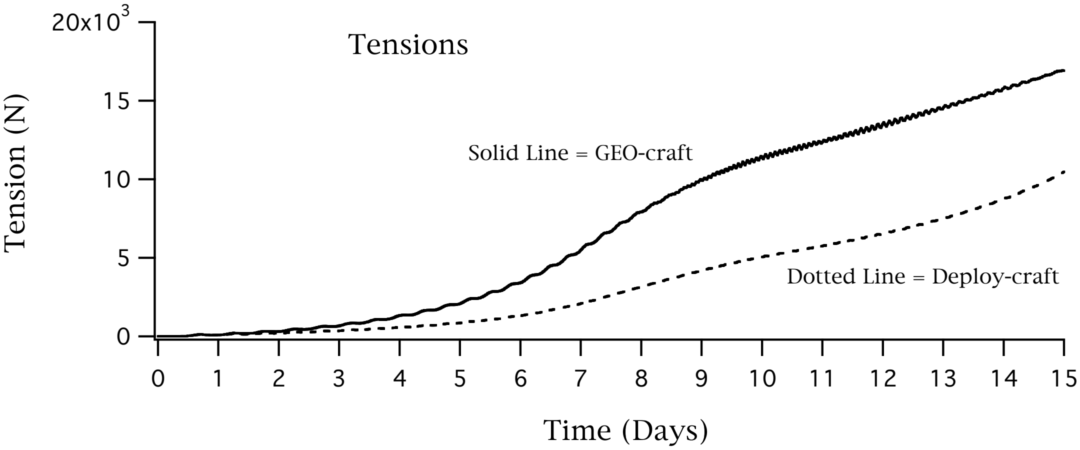




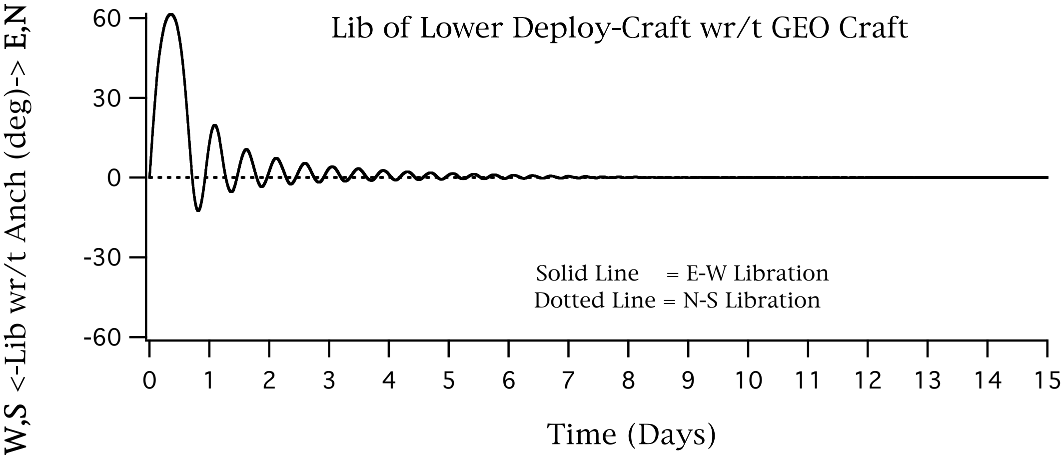
At these altitude profiles, the acceleration of gravity being seen by the end-objects (and ribbon in between), as they traversed the gravity-well is shown below:



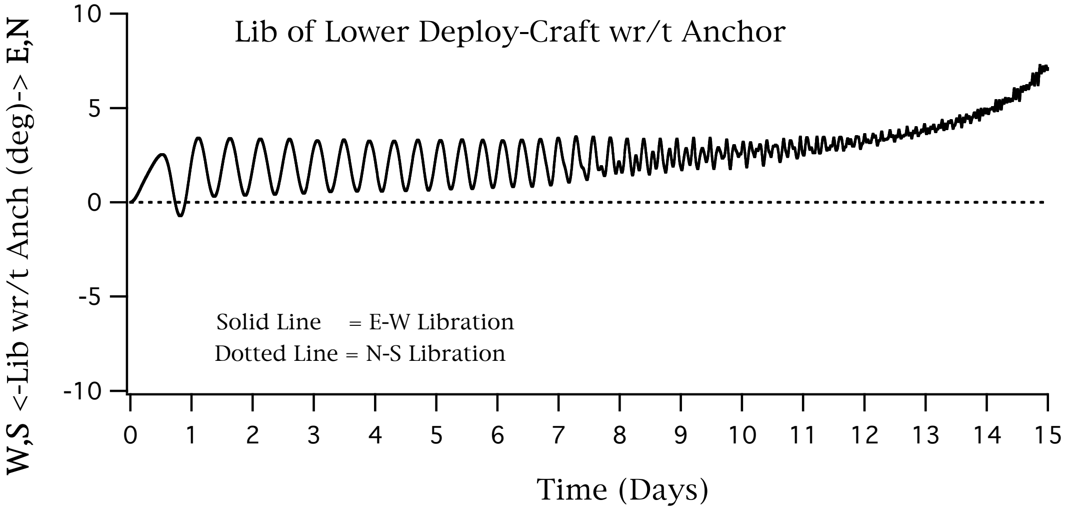
This in turn created the following tension histories at both ends of the ribbon:



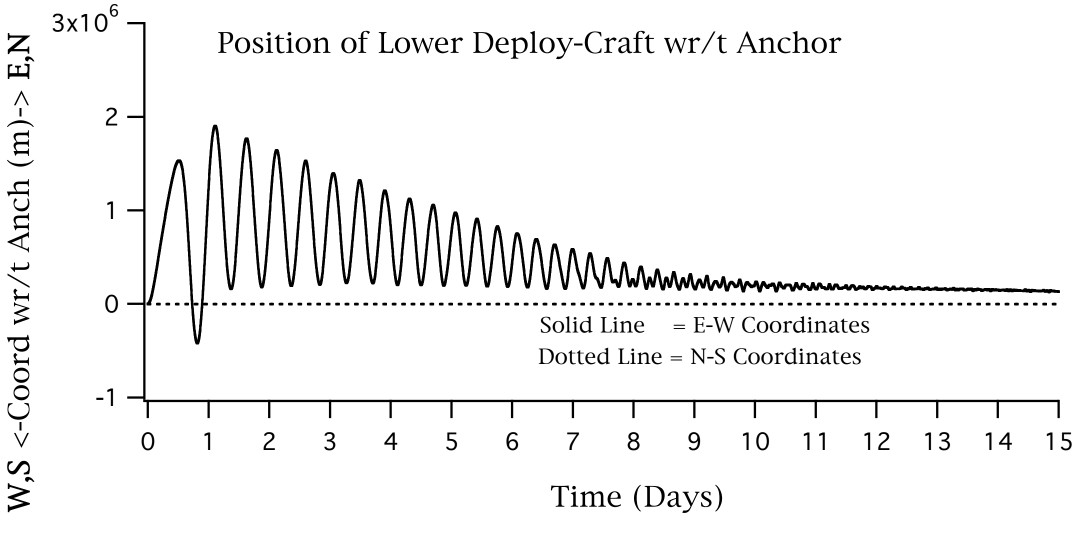
The horizontal state of the Deploy-craft (lower object) reflects NO horizontal control activity and is shown below:



The libration response at the beginning represents the Initial-Phase of the deployment, and quickly damps out (due to natural tendencies of tether deployment dynamics).
The libration of the Deploy-craft as seen by the anchor point is shown below. Note that this is a somewhat different picture than that seen from way above by the GEO-craft. This represents the challenge remaining for Terminal-Phase mission design in effecting a rendezvous with the anchor station. Note also that since libration is defined as a subtended angle, *libration relative to the anchor* will tend to grow as the range between the Deploy-craft and the anchor diminishes (as witnessed below).

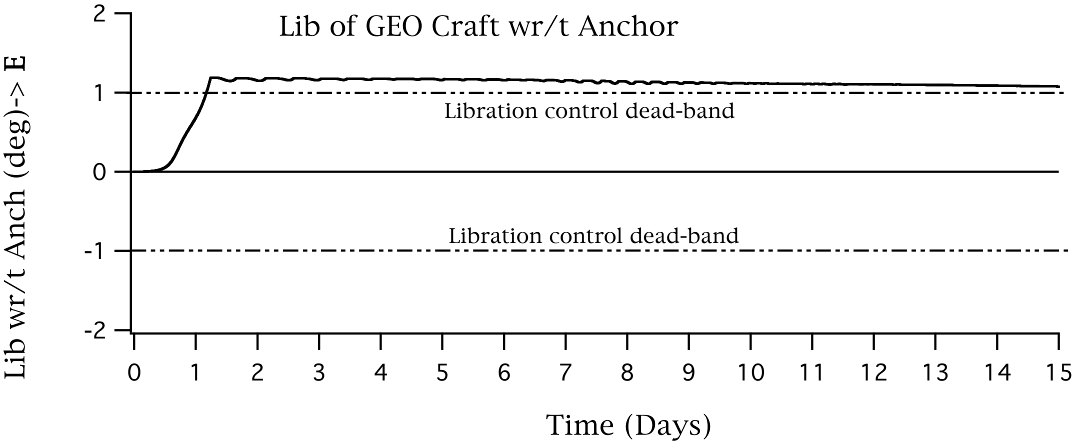


In terms of Terminal-Phase rendezvous with the anchor, a more meaningful expression of the information in the graph above would be the "miss distance" as the ribbon approaches earth. This is shown below:



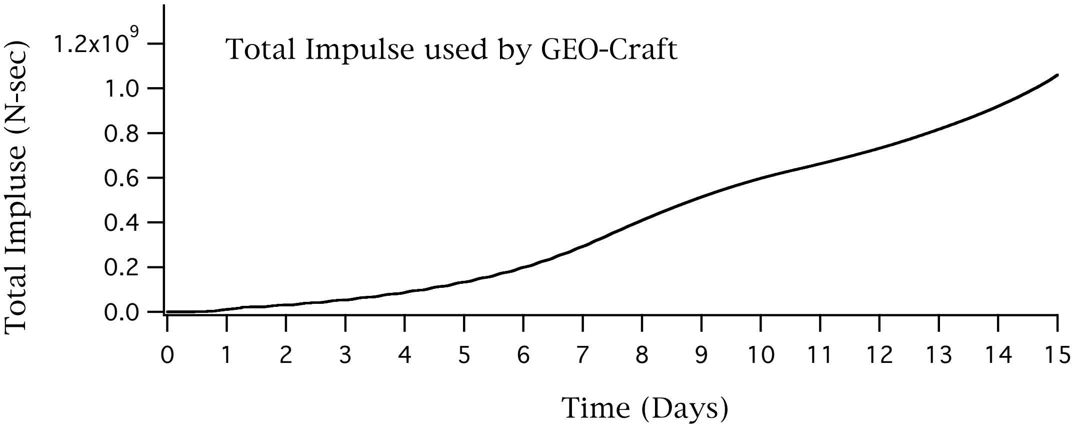
Note that this miss-distance settles out at a steady 14km; this is not an insurmountable distance to manage during terminal phase, and well within designable Deploy-craft control abilities; the management of altitude-rate will likely be a much more challenging task.

As the deployment unfolds, the GEO-craft is itself librating under the action of the dead-band controller. This libration history is shown below:



The libration of the GEO-craft relative to the anchor points shows the GEO-craft firmly up against on side of the +/- 1 deg dead-band used in this example; this indicates that the Coriolis management logic is biased, as ideally, this libration angle would be wandering back and forth between its limits (for minimum impulse control).

To understand the propulsion implication of this deploy mission design the, one can examine the total thrusting impulse used by the GEO-craft to accomplish the required control activity. This is shown below:



Total Impulse Assessment

The amount of total impulse shown above is a significant value. Converting this to an equivalent propellant budget via a specific impulse of, say, 500 sec (high end of conventional bi-propellant technology) would correspond to a fuel budget of 200,000 kg. However, before jumping to conclusions about this value, one must consider the following:

This total impulse can be thought of as consisting of:

1. Impulse to make-up *tangential* velocity requirement between (the initial) GEO altitude and the Ballast altitude,

2. Impulse expended in overcoming the vertical gravity to raise the GEO-craft from GEO to Ballast altitude, and,

3. Control activity to provide dead-band latitude/longitude control and damp altitude fluctuations, and indirectly provide vertical gravity make-up support that might arise due to imperfect equilibration of the gravity/centrifugal balance against ribbon tension.

Consider now, each of these three contributions:

A total impulse contribution corresponding to **Item 1** is fairly straightforward to assess, since the tangential velocity make-up has associated with it simply a momentum-change. This can be directly equated to an impulse; this corresponds to about 4.8×10^7 Newton-seconds.

A total impulse that might be assigned to **Item 2** is not so straightforward. Here, it becomes evident that the time expended by propulsion against a GEO-craft that, due to imperfection of equilibration maneuver, is tending to “fall” (either up or down), becomes a very significant factor; this is analogous to the classical “gravity-loss” aspect of propulsion performance related to conventional rocket-performance analysis. The amount of work that must be done to lift a GEO-craft from GEO to Ballast-altitude is approximately 4.6×10^{11} Joules. Assuming an average GEO-craft mass of about 43,000 kg, this work equates to an equivalent momentum of about 2×10^8 kg-m/s, thus an equivalent impulse of the same value. This value represents the minimum that must be expended to elevate the GEO-craft to Ballast altitude. It by no means represents what is actually expended, which, is a value that would be very sensitive to the perfection of the vertical equilibration-controller, and mission total lapsed time.

A total impulse that might be assigned to **Item 3** is difficult to assess, but is likely small compared to the first two items.

In summary, the total impulse of 1×10^9 is quite a large value (about 10 times in excess of that identified above as an inescapable minimum requirement), and if it were the last word on propulsion requirements could represent an almost prohibitive obstacle. The caveat below is of paramount importance concerning this investigation:

Important Note: Due to scope limitations, these studies in NO WAY addressed optimizations of the various controllers. Nor did these studies address actual propellant usage and its commensurate impact on mission and vehicle design. *Any conjecture based on implied fuel usage or propellant budgets derived from this data stands to be in gross error since all of these related factors are closely allied and must he addressed as a whole, rather than in disjoint fashion.*

6.12 DISCUSSION AND CONCLUSIONS

A Possible Methodology for Deployment

This is a summarization of a strategy and control scenario that might be a useful way to envision deployment of the elevator from an initial GEO position.

Initial Phase:

This phase could be accomplished with a simple ejection of an initially minimal Deploy-craft and the ribbon such that the deploy-rate is slightly greater than the Deploy-craft ejection rate. As the Deploy-craft recedes into the gravity field, it will eventually be accelerated to "catch-up" with the ribbon; Prior to this point the Deploy-craft will simply progress below and forward of the GEO-craft in accordance with relative orbital motion (per Clohessy-Wiltshire equations). When the ribbon finally goes taut, then the Deploy-craft will start a harmless libration relative to the GEO-craft. This libration is naturally damped and will eventually become inconsequential to the overall deployment. Of significance here is the fact that this maneuver requires virtually no control intervention by the Deploy-craft (except maybe minimal attitude control to avoid ribbon entanglement) with a corresponding minimal propellant budget.

In general this Initial Phase could be accomplished in any number of ways as it is not a critical phase of the mission from a dynamics standpoint. The design criteria for this phase would be to simply get some ribbon deployed and Deploy-craft removed sufficiently from the GEO-craft to enable a natural gravity gradient driven separation of the two craft culminating in a continuous progression of range between the craft. This would be done so as to preclude any possible entanglement by either craft with ribbon being deployed. Tension would want to be kept to a minimum to facilitate the growing departure between the craft. Ideally this phase would be accomplished with minimal propulsion by either craft.

Mid Phase:

This phase will be a long duration maneuver during which most of the ribbon will be deployed. As the deploy progresses toward the regime in which gravity on the Deploy-craft starts to create consequential tension at the GEO-craft, the GEO-craft must take action to counter this. To avoid being pulled down to earth, the GEO-craft must either provide vertical thrust (with significant, and likely prohibitive fuel budget consequences), or attempt a *dynamic equilibration* of this mounting tension. The best method determined for this relatively crude attempt (described in this handbook) is obtained when:

- a pre-planned altitude-rate -vs- altitude profile for the Deploy-craft is indirectly attempted to be achieved via ribbon deployment alone (ie. using a type 12 *GTOSS Deployment scenario*),

in conjunction with the vertical controller described below,

- an altitude control algorithm for the GEO-craft that attempts to achieve an altitude consistent with *fully equilibrating* the tension being realized at the GEO-craft upper end of ribbon (*GTOSS Object vertical control sub-option 6*).

Horizontal control of the GEO-craft is adopted to provide tangential velocity make-up, and limit libration oscillations that can couple adversely with the vertical control mode; this horizontal control is accomplished via a scheme that will be devoid of resonances or coupling with the vertical axis controller. An example of this is a *Coriolis-makeup* thrust (horizontal thrust proportional to altitude-rate) combined with a classical on-off dead-band latitude/longitude controller. The explicit Coriolis counter-thrust relieves the dead-band controller of the role of indirectly providing this make-up thrust.

Note that for this Mid Phase of deployment, no vertical nor horizontal control was required for the **Deploy-craft**. Mid Phase terminates when the atmosphere is approached. By Mid Phase termination, Deploy-craft altitude rate will have been stabilized and controllable via a combination of ribbon fine-deployment, and propulsive control.

Atmospheric Phase:

Atmospherics can be dealt with via dual actions (1). Delaying atmospheric encounter until that time when minimum wind conditions prevail, (2) Propulsive control *closing the loop* on (say GPS) earth position. Actual simulation of this phase was not within scope of the current effort for the Elevator Dynamics Handbook.

Terminal Phase:

This phase consists of the combined efforts of *fine control* of earth position and altitude/altitude-rate. The altitude control would be accomplished by active propulsion in conjunction with vernier ribbon deployment (as a possibility). Actual simulation of the terminal phase of the rendezvous with the anchor station was not simulated in this study.

The above constituted a reasonably successful Initial-Phase and Mid-Phase deployment in that it showed that it was at least possible, using reasonable thrust levels to keep the system in balance, and effect a potentially successful rendezvous with the anchor station.

Thus, the Deploy-craft experienced essentially “open-loop, passive” control while the GEO-craft used an essentially adaptive control scheme. This becomes evident when it is realized that the actual primary control effector driving the *mission profile* was simply a deploy-rate modulation of the ribbon; this deploy rate was constituted of; the altitude rate that was actually being realized by the GEO-craft (as it attempted to equilibrate ribbon tension), summed with a “canned” deploy-rate that was a function of altitude. These two components of the deploy rate worked together to attempt to achieve a Deploy-craft progression toward earth that followed the “canned rate-vs-altitude profile” by compensating properly for the rising altitude of the GEO-craft, which could only be done by virtue of the total deploy rate directly reflecting the GEO-craft altitude rate.

The GEO-craft used a horizontal control mode that provided a *tangential velocity bias* designed to exactly counteract Coriolis acceleration. This mode was augmented by on-off dead-band thruster logic that tracked earth-referenced latitude/longitude.

Due to the inherent libration-stability of deploying the ribbon downward (with the GEO-craft libration maintained under control) it was possible to perform an uncontrolled Deploy-craft mission right up to the Atmospheric-Phase interface.

Conclusions

This section of the Dynamics Handbook is a work-in-Progress, and **did not address**:

1. Interaction of the ribbon and Deploy-craft with atmospheric disturbances.
2. Final (terminal) rendezvous with the anchor station that would require precision altitude-rate management and latitude/longitude control of the Deploy-craft.
3. Propellant utilization (although total propulsion control impulse was determined for both craft).

As a result of the dynamics behaviors that have been exposed during the course of this attempt to perform a stable space elevator deployment, they following conclusions have been assembled:

1. As deployed ribbon increases in length, the system becomes increasing unstable and problematic to manage; overall system balance (vertical equilibration) becomes an increasing delicate proposition.

2. To achieve a deployment mission with a practical and achievable fuel budget, the GEO craft will be required to raise its altitude consistent with *equilibrating* the building tension in the ribbon during deployment. As the Deploy-craft proceeds deeper into the gravity–well, his entails GEO-craft ever-raising altitude rates eventually mounting to many times greater than the Deploy-craft's descending altitude rate. For this reason, the deploy mission may become a long term affair (weeks) in order to limit deployment mechanism rates to realistic values.

3. Altitude rate control related to terminal rendezvous with the anchor station may be problematic. This is because (the GEO-craft originated) ribbon deployment rate becomes virtually a second-order control effector due to the great distance of the GEO-craft from ground at terminal rendezvous. Furthermore, ribbon deployment originating at the Deploy-craft will likely also be ineffective due to the very low spring-rate of the fully deployed ribbon; this leaves only propulsive control at the Deploy-craft as the alternative, which implies that an appropriate fuel budget must be provided for the Deploy-craft to accomplish this phase of the mission.

4. As ribbon length increases, deliberations driving vertical control inputs for tension and altitude management, by either thrusting or deploy rate modulation, becomes increasingly complex due to the ever greater tension gradient transmission times along the ribbon as well as the attendant excitation of richly varying vertical-modes of oscillation that can serve to obscure intrinsic conditions attempting to be controlled.

5. Failure to maintain system stability will lead to loss of the entire mission (ie the system will crash towards earth or hurtle off into a useless high altitude trajectory).

6. Due to the extreme delicacy of the system, the entire deployment will likely take a significant duration of time (on the order of *weeks*). Smooth, slow deployment is desirable from the standpoint of its minimizing perturbations, but undesirable from the standpoint of propulsive total impulse. Control thrust levels will have to be minimized to limit the total impulse expended for control.

7. The "natural control effectors" that might be used to advantage are ribbon deploy profile, and gravity gradient; both have a limited venue of applicability (compared to the benefits of overt thrusting control), and both become essentially useless to remedy incipient instability, once it has started.

8. The one control effector that commands priority attention is, of course, <u>thrust</u>, but that comes at a big price, namely all propulsion (in the GEO scheme being studied) must be launched to GEO initially. High Isp's (above 500) are obtainable only for electrical-based thrusting, which has notoriously *low thrust*, and high-energy price tags (which implies beamed energy for the deployment). Conversely high thrust will be available with, at best, maximum Isp's of about 500, thus may carry a big penalty in GEO-craft weight (to meet propellant needs).

9. As the ribbon nears the more intense gravity-well gradients (at low altitude, where system response becomes problematic), a GEO-craft ribbon-tension (deployment) control input takes 20 minutes to reach the bottom end of the ribbon (an hour for a fully deployed ribbon), a fact that exacerbates controllability.

10. The LEO-up deployment concept may have benefits over the GEO-down scheme, but likely not for the reason usually touted (ie. ostensibly lower total fuel needs), but rather because the lower end of the ribbon starts *firmly ensconced at a stable, and low altitude in the gravity well.*

11. <u>Both</u> LEO and GEO deployment schemes must deal with the large tangential velocity gradient along the length of the ribbon sooner or later, in their own way. Both schemes must deal with the work required to elevate the Ballast mass to its altitude.

12. <u>Both</u> LEO and GEO deployment schemes must deal with the neutral stability of the system at long ribbon lengths.

14. Likely, Non-Linear optimal control theory will be mandatory to exercise practical control over this deployment, or, possibly artificial Neural Network control theory may be efficacious to exercise practical control over this deployment.

15. Of paramount importance in this system design will be *precise state-recognition* to provide lead-time in heading off any tendencies toward system departure while existing control authority is still sufficient to arrest divergence; error in this regard could easily lead to mission loss.

16. As a corollary to the previous item, a system controller design, robust in the face of *state indeterminacy*, will also be of prime importance.

17. Only insignificant *transverse ribbon oscillation modes* were excited during the process of deployment. While, this was not true during the development of the various control modes and deployment strategies, it was found that as soon as a deployment scenario met even the most elemental of successful mission objectives, then simultaneously, transverse mode deflections became inconsequential. This was probably because *successful* deployment schemes (almost) axiomatically manifested themselves as *smooth* deployment processes.

7.0 ELEVATOR FAILURE MODE DYNAMICS

………………Work in Progress …………..

7.1 GENERAL FAILURE RESPONSES

- *Categorize response by Break-Altitude*
- *Define possible "worst-case" breaks*