Space Elevator Initial Construction Mission Overview

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Abstract: This paper presents an overview of a proposed GEO-originating deployment mission flight scenario currently under consideration to accomplish the initial construction of a space elevator. Much as a suspension bridge's initial strand of cable must be established, so must the elevator's first strand of vertical ribbon and ballast mass be erected. Results of dynamic simulations of initial deployment accomplished using the Generalized Tethered Object Simulation System (GTOSS) software tool are presented via discussions and summary graphs. A brief overview of dynamic models that constitute GTOSS is presented, and the physical configuration of the elevator as it manifests itself within GTOSS is characterized. A general discussion of orbital dynamics challenges facing this initial deployment process is presented, with emphasis on dynamic control issues and implications on the two space craft delegated to performing the deployment. Finally, a proposed control strategy is presented and simulated to demonstrate the possibility of a GEO originating deployment.

1. Introduction

Currently two different approaches to deploying the initial elevator ribbon are identified. Both start with a space craft containing (either initially or via build-up by multiple courier-missions) the Ribbon, Ballast mass, Ballast-end controller (GEO craft), ribbon Anchor-end controller (Deploy craft), and propulsion-control systems. While they differ in starting point and maneuver strategy, they both must face the dynamics challenges of extreme tether extension. The two scenarios are:

(a) Start with a space-craft at **GEO**, thus deploying Ribbon downward from there, in conjunction with a coordinated *upward* maneuvering of the GEO craft). See Reference 1.

(b) Start with a space-craft in **LEO**, deploying the Ribbon and Ballast mass upward, creating a *system* with ever-longer orbiting period, until the configuration grows to include GEO altitude and beyond, and manifests an "orbital period" corresponding to earth rotation rate. See Reference 6.

This paper specifically explores the dynamics of the GEO deployment mission. A proposed deployment control strategy is presented that serves to expose the nature of the dynamics challenges inherent in this mission, and explores some of the intrinsic ingredients that might constitute a successful deployment mission design.

2. GTOSS Overview

The **G**eneralized **T**ethered **O**bject **S**imulation **S**ystem is a time-domain dynamics simulation code, conceived by the author in 1982 to provide NASA with a tool to simulate dynamics of combinations of space objects and tethers for flight safety certification of the Shuttle Tethered Satellite System missions. Since then, GTOSS has undergone continuous evolution and validation, being applied at some stage in the formulation of virtually every US tethered space experiment flown or proposed to date. Below is an overview of GTOSS features.

- Multiple bodies, with 3 or 6 degrees of freedom, connected in arbitrary fashion by multiple tethers, subject to natural planetary environments, including standard earth models as well as more rudimentary models for the other planets.

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

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

- Tethers can possess length-dependent non-uniform attributes describing elastic cross section, aerodynamic cross section, and lineal mass density.

- Tethers are subject to distributed forces from: Subsonic and hypersonic aerodynamics; Electrodynamics of current interaction with magnetic fields using current-flow models incorporating effects of insulated or bare-wire conductors interacting with a plasma environment model. With a ribbon-to-plasma contact model, grounding-current in a conducting elevator may possibly be assessed.

- Tethers experience thermal response, gaining heat under the influence of solar radiation, earth albedo, earth infrared radiation, aerodynamics, and electrical currents; heat loss occurs through radiative dissipation.

- Tethers can be severed at multiple locations during simulation.

- Objects and tethers can be initialized in many ways, including creating stabilized extremely long tether chains, attached to and rotating with a planet (a space elevator) with due consideration for variation in longitudinally non-uniform tether properties.

- GTOSS creates a database containing results of response to the user-defined material configuration, initialization specifications, and environmental options; this permanent data base can then be *post processed* to produce a wide variety of result displays, from tabular data, to graph plots, to animations.

3. Deployment Configuration Model and Mechanics

For the GEO deployment mission, the topology consists of a Deploy craft, (as the ribbon's lower body) that proceeds earth-ward during deployment and a GEO craft (as the ribbon's upper body) that proceeds ballast-ward; it is the GEO craft that contains the ribbon characterized by a dual tapered design. Deployment occurs initially by downward ejection of the Deploy craft attached to the earth-end of the tapered ribbon (emerging first along with the Deploy craft), leaving the ballast-end and upper portions of the tapered ribbon stowed within the GEO craft (as the GEO craft rises toward the ballast altitude). Figure 1 below depicts schematic snapshots of the system at various stages of deployment.

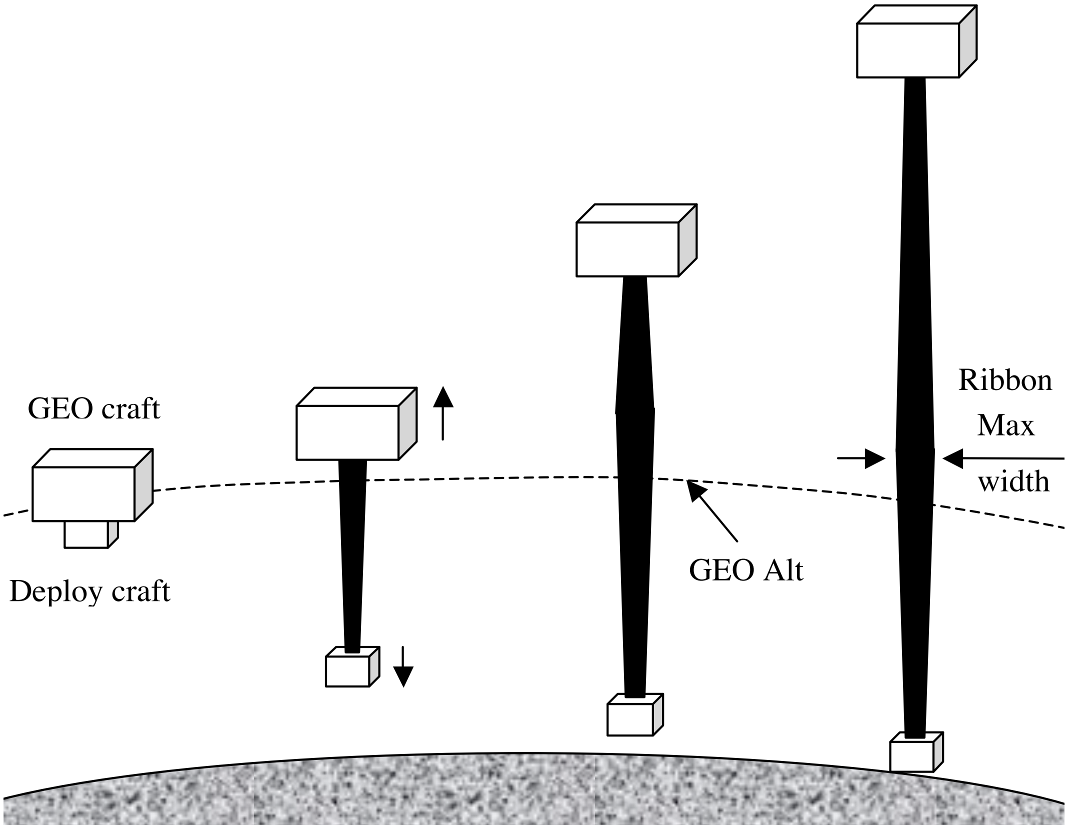


Figure 1. Snap Shots of Deployment Topology

4. Physical Properties of Initial Deployment Ribbon

GTOSS characterizes the elevator ribbon with length-varying attributes of density, elastic-area, modulus, aerodynamic-area, and damping that correspond to baseline ribbon design (described in References 1, 2, 3, and 4), but, appropriately modified to reflect a proposed initial deployment configuration. This initial deployment envisions two 20 metric ton reels of ribbon being deployed from a GEO craft (deployed simultaneously as one ribbon, 10 cm wide in the GTOSS simulation). By assuming that this initial ribbon would have a longitudinal taper design identical to the mature elevator, then, corresponding ribbon properties for the initial deployment mission can be derived as a scaled version of the mature ribbon. Baseline mass of the mature elevator ribbon is 825 tons, so the ratio between the initial 40 tons of ribbon and the mature ribbon yields the *lineal density ratio* of the initial ribbon in comparison to the mature ribbon. This is:

$$\frac{\rho_{i}}{\rho_{m}} = \frac{M_{i}}{Mm} = \frac{40}{825} = 0.0485$$

The ribbon elastic area is also scaled per this ratio. Based on the *scaled* elastic cross sectional area profile and a nominal value of the ribbon material's bulk density of 1.3 gm/cm^3 (CNT), the lineal density profile was derived for use in GTOSS. Figure 2 depicts these resulting properties.

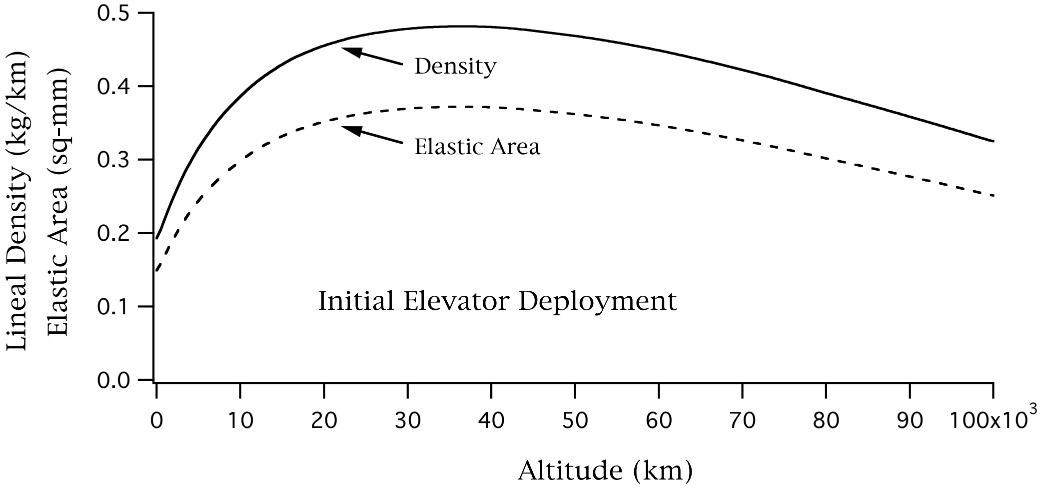


Figure 2. Ribbon Elastic Cross Sectional Area and Lineal Density vs Altitude

This above data combined with a nominal Young's modulus of 1,300 GPa (assumed for the CNT ribbon material) fully defined the ribbon's *static* elastic properties. Dynamic attributes were characterized by a material-intrinsic, strain-proportional damping factor, $\beta = 0.02$, where:

$$\sigma = E(\varepsilon + \beta \frac{d\varepsilon}{dt})$$

and, σ = stress
ε = strain
E = Young's Modulus

5. Physical Properties of GEO Craft and Deploy Craft

Both the GEO craft and Deploy craft were simulated as 3 degree of freedom objects, thus no attitude control considerations were involved; this was deemed appropriate considering the study was only focused on the overall orbital behavior of the deploying *distributed mass* system, and the fact that the attitude dynamics of the end-bodies would essentially be uncoupled from the gross orbital dynamics. Both of these craft can loose mass due to propellant expenditure. Only the GEO craft will loose mass due to ribbon deployment. In these preliminary studies, mass loss specifically due to propulsion was inhibited because of many factors; for instance the non-optimal nature of these initial controllers *plus* the lack of propulsion technology definition that would be employed (with attendant specific impulse uncertainty) would likely produce misleading propellant usage estimates.

The initial total mass of the (upper) **GEO craft** was 69,000 kg, of which 40,000 kg is ribbon mass and 29,000 kg is ribbon deployment mechanisms, control systems, thrusters, and propellant. The initial total mass of the (lower) **Deploy craft** was 1,500 kg. This entire mass is delegated to anchor-station grappling hardware and fixtures, control systems, thrusters, and propellant.

6. Uncontrolled Natural Deployment Tendencies

It is naïve to assume that a ribbon can simply be dropped straight down from a geo-synchronous station to the earth's surface, thus effecting the initial construction of the elevator. This part of the paper addresses the natural dynamic tendencies exhibited by a GEO-positioned craft attempting a totally uncontrolled vertical deployment of ribbon. While this behavior simply reflects the response of a *greatly-extending system of connected particles* in an inverse square central force field, it nevertheless manifests tendencies indicative of what must be dealt with to successfully deploy an elevator ribbon. The GEO craft is positioned in a geo-synchronous orbit. The Deploy craft is ejected vertically down at 200 km/hr, attended by a constant ribbon deploy rate slightly in *excess* of 200 km/hr, intentionally creating a transient slack ribbon condition. No attempt is made to exercise control of either *end body*. Prior to the ribbon going taut, the Deploy craft is simply in a free Keplerian orbit moving posigrade relative to the GEO craft (that essentially remains at GEO). At about ½ day, gravity has accelerated the Deploy craft away from the GEO craft removing ribbon slack and resulting in a minor impact loading event. Following this, *range rate* between the Deploy craft and GEO craft tracks *deploy rate* until near the end of deployment, when high tension comes into play. This is shown in Figure 3 which compares the constant deploy rate to the range-rate between the GEO- and Deploy crafts.

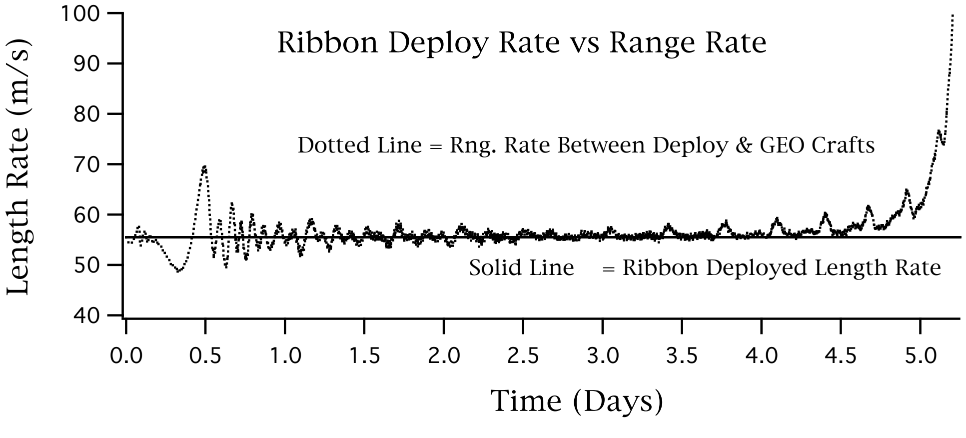


Figure 3. Ribbon Deploy Rate vs Range Rate

The steady increase in tension at both ends of the ribbon is seen in Figure 4 below. The higher tension at the GEO craft is responsible for pulling the GEO craft earthward and a resulting significant posigrade motion of the GEO craft with respect to its initial geosynchronous position. 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. This case clearly illustrates the potential for a deployment to end disastrously in a crash to earth!

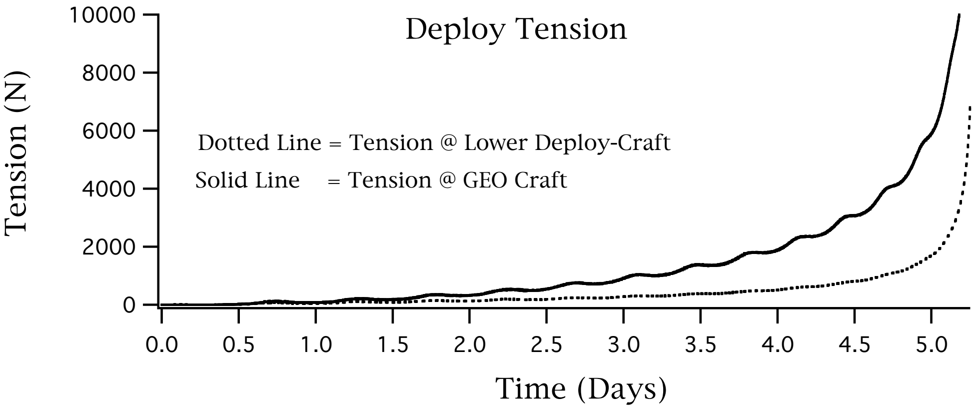
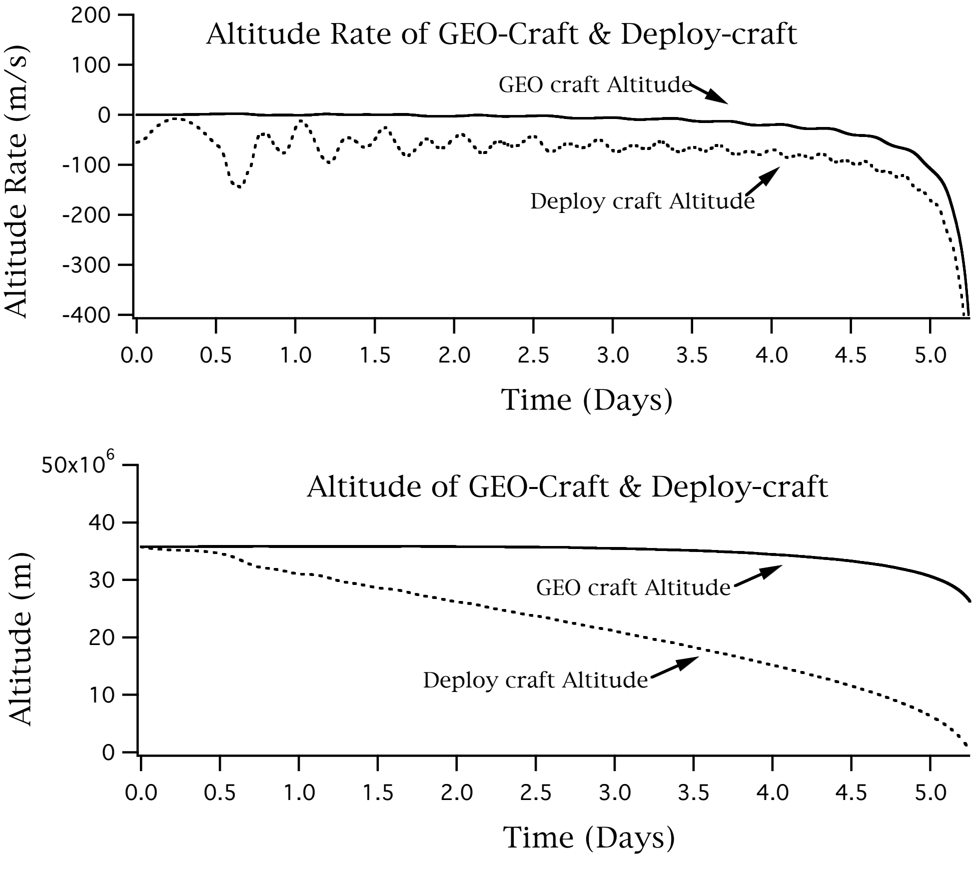


Figure 4. Tension at Upper and Lower Ends of Ribbon

The altitude state of both end-objects, shown in Figures 5 and 6, exposes the sharp increase (at 4.5 days) in the Deploy craft's accelerating encounter with gravity, *dragging everything down with it*. Consequently, the GEO craft vacates its geo-synchronous condition (loosing altitude as ribbon tension increases, pulling it earthward), and simultaneously moves through about 180 degrees of posigrade earth longitude prior to the system's eventual plunge to earth.



Figures 5 and 6. End Object Altitude Response

The Deploy craft dips deeply into the *gravity well* at 4.5 days, shown in Figure 7.

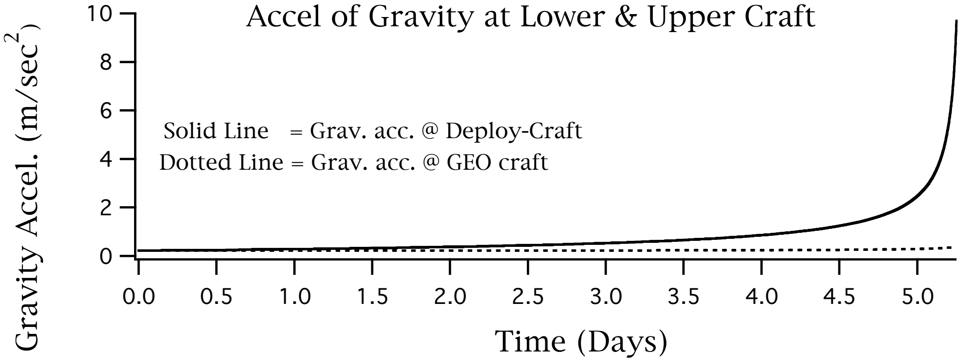


Figure 7. End Object Acceleration of Gravity

Figure 8 shows the earth longitude traversed by the GEO craft.

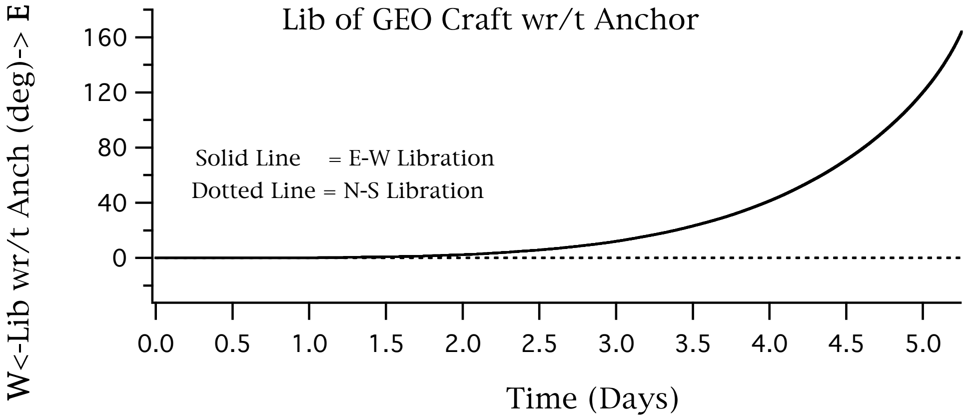


Figure 8. Earth Longitude Traversed by GEO Craft

As soon as tension manifests itself (at about ½ day) Figure 9 shows that the Deploy craft starts to librate with respect to the GEO craft, typical of tether deployment behavior. But this libration naturally tends toward zero amplitude, a feature that can be used to advantage in the mission design.

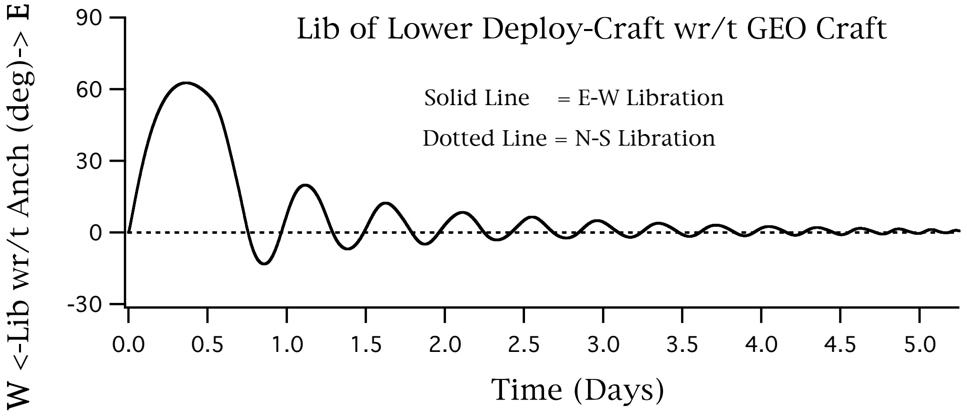


Figure 9. Libration of **Deploy** craft with-respect-to the **GEO** Craft

7. A Controlled Fly-Away From Earth

This is an example of a system under the action of a deployment controller, that while intended to equilibrate the rising vertical tension by maneuvering the GEO craft to higher altitudes, in fact over-compensates as a result of oscillatory coupling between control modes and amongst natural frequencies inherent in the elevator elastic system. The final cause of the fly-away is due to an inadequate amount of elevator mass engaging the *gravity-well* due to the instability and a subsequent ever increasing altitude rate for the elevator. These control instabilities were caused by improper gain selections and inadequate sensor filtering to insure overall stability. Figure 10 shows that the deploy rate is modulated in an attempt to control the deploy craft altitude rate as it approaches earth.

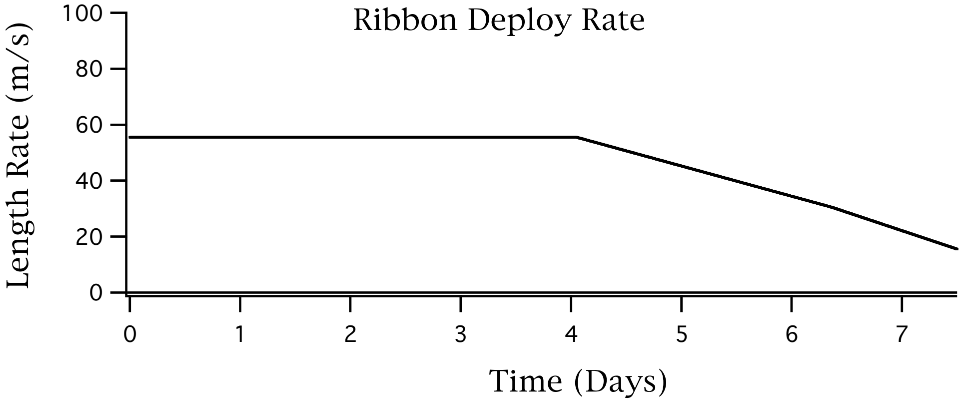


Figure 10. Deploy Rate

The ultimate failure of this deployment is clearly seen in the GEO and Deploy craft altitude histories shown in Figure 11. The GEO craft is rising, attempting to equilibrate tension, but at about 6 days into the mission, a vertical instability starts manifesting itself, after a few cycles of which, the system instability overwhelms the control effectors, and the system irretrievably departs controlled flight!

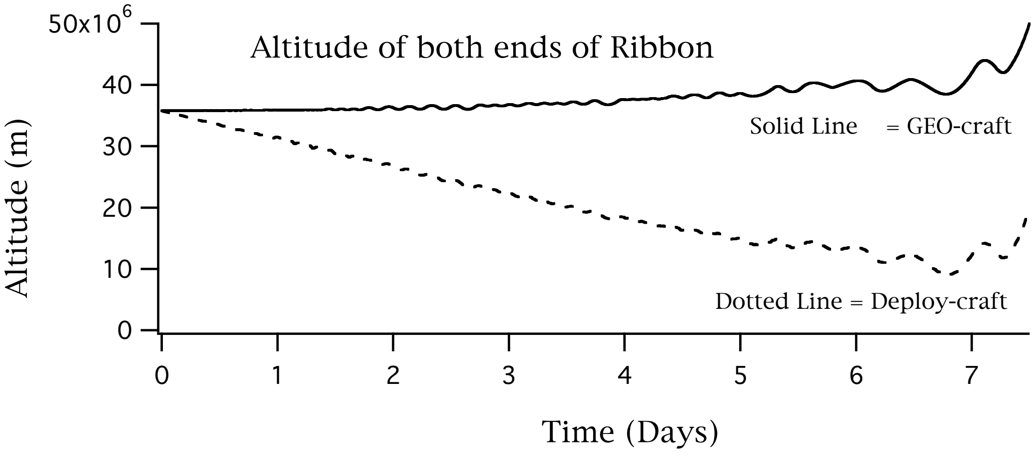


Figure 11. Altitude of GEO craft and Deploy craft

In Figure 12, it is seen that the system as a whole has failed to "bite into the gravity well" sufficiently to prevent a centrifugal departure.

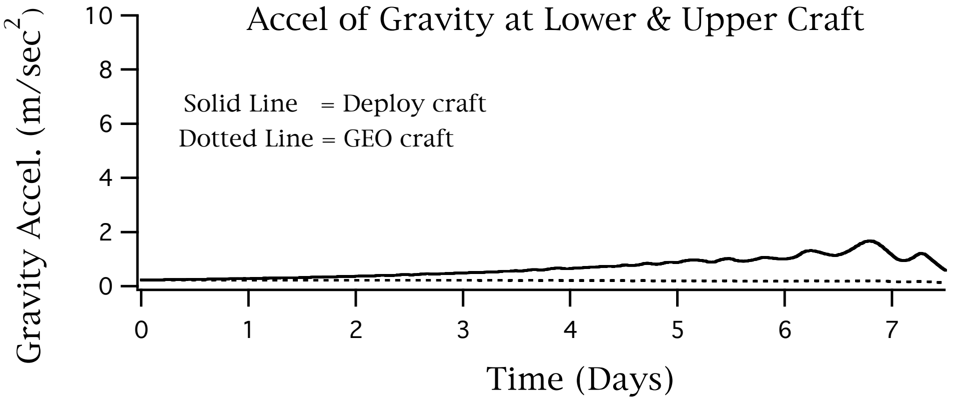


Figure 12. Acceleration of Gravity at GEO craft and Deploy craft

Tension shown in Figure 13 illustrates inappropriate control system design that is exciting longitudinal ribbon dynamics and the system. These variations are indicative of the need for an elevator ribbon deployment control system design to be able to reject undesirable frequencies in the tension signal so as to deduce *intrinsic tension level*, against which the GEO craft must fly a compensating equilibrium-altitude maneuver.

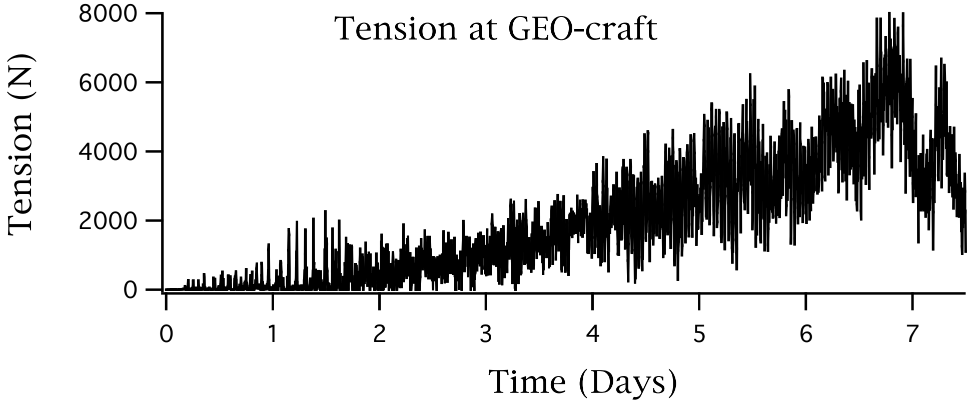


Figure 13. Tension at GEO craft

8. The Deployment Venue

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

- Regardless of whether deployment starts at LEO or at GEO, the final *configuration* must be a vertical ribbon extending from near earth up to *centrifugally effective altitudes* at which net ribbon tension can be maintained to produce at least a condition of *neutral buoyancy*. Such a configuration (until actually attached to the earth) is neutrally stable; a perturbation that moves the (neutrally) stable-state *upward* results in a net downward force reduction that encourages the tendency. This is because every particle of mass becomes attracted less toward the earth by virtue of the *inverse radius-squared* gravity field, thus a net reduction in gravity force ensues. Countering this gravity reduction, the corresponding particles are subject to less *centrifugal effect*, however this varies as the *inverse radius*, thus restoration due to gravity is decreasing faster than the centrifugal effects are decreasing, *all of which contributes to the initial upward perturbation combining to move the system higher*. Conversely, if the ribbon moves closer to earth, just the opposite of all the above ensues, and the net effect is to pull the system lower. Small incipient departures from neutral stability may be problematic to detect directly, that is, incipient departure may have to be deduced from position or velocity dispersions alone.

- Note that the balance point depends upon the mass distribution of the system, that in turn, depends upon the ribbon's density and taper, the amount of ribbon deployed, and the fuel remaining in the end-craft. The ribbon must be maintained *delicately poised* between the conflicting tendencies of centrifugal and gravitational effects with no control effectors other than (a) position state of the end-masses, (b) distributed mass within the ribbon, and (c) onboard propulsion.

- Insuring stability (for anchor grappling) will require active-propulsion since *ribbon deployment,* per se, may prove ineffective for overcoming departure from the balance point. Such imbalance can result from factors ranging from uncertainty in state-recognition (obscuring detection of an insipient departure at deploy termination), to the transport delays inherent in control inputs propagating the length of the ribbon, thus attenuating the effects of control inputs related to deploy rate modulation; note, time for tension gradients to traverse the ribbon are about 20 minutes from earth to GEO, and 45 minutes from earth to Ballast.

- In order to *minimize* the need for onboard propellant, the progression of intermediate states comprising the deployment must all be delicately balanced between gravitational attraction and centrifugal effects; this becomes increasing problematic as the Deploy craft approaches increasingly non-linear *lower* regions of the inverse square gravity field.

- As the ribbon is extended up, a tangential velocity *make-up* is required to maintain effective angular rate consistent with the earth angular velocity; failure to do this will compromise the necessary centrifugal counter-balance effect. At Ballast altitude the required tangential velocity is 7292 m/s (23,900 ft/s) relative to the anchor point (note, this is on the order of LEO insertion velocity).

- *Orders of magnitude* change in ribbon *effective end-to-end spring rate, length, and tension* are experienced over the course of this deployment. Initially end-to-end spring-rate and related natural frequencies can be quite high, but, near terminal phase (when vertical control near earth becomes critical), the ribbon will exhibit a spring rate on the order of .004 N/m. End-mass bobbing mode frequencies, and longitudinal and transverse string mode frequencies of the ribbon system change drastically over the deployment. This means that control systems must adapt to a vast range of frequencies potentially compromising control precision.

9. Deployment Phase Definitions and a Control Scenario

This is a summarization of a strategy and control scenario that has proved useful for envisioning deployment of the elevator from an initial GEO position.

Initial Phase:

This could be accomplished by ejection of the Deploy craft with a ribbon deploy-rate slightly greater than Deploy craft ejection rate. As the Deploy craft recedes into the gravity field, it slowly accelerates, removing ribbon slack; Prior to realizing tension, 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, tension will cause the Deploy craft will begin a harmless libration relative to the GEO craft. This libration is naturally damped, becoming inconsequential to the overall deployment. This maneuver requires virtually no control intervention by the Deploy craft (except minimal attitude control to avoid ribbon entanglement). This Initial Phase is not a critical mission phase from a dynamics standpoint. The design criteria would be to simply get some ribbon deployed and the Deploy craft sufficiently removed from the GEO craft to enable continuing gravity gradient driven separation. Tension would be kept to a minimum to facilitate the growing departure between the craft. Ideally this phase would be accomplished with minimal propulsion by both craft.

Mid Phase:

This phase will be a long duration maneuver during which the majority of the ribbon will be deployed. As deployment progresses towards consequential tension buildup, the GEO craft must take action to counter this. To avoid being pulled down, either direct equilibrating vertical thrust must be provided (with significant fuel budget consequences), or, *dynamic equilibration* of this mounting tension achieved. A method to achieve dynamic equilibration is outlined below:

- a desired Deploy craft Altitude-rate -vs- Altitude profile is <u>*indirectly*</u> commanded as an expression of (compensated) <u>*ribbon deploy rate,*</u>

in conjunction with the above deployment, the GEO craft is controlled such that,

- the GEO craft Vertical translational control algorithm attempts to achieve an altitude at which centrifugal effects *fully equilibrate* the tension and gravitational acceleration being realized at the GEO craft.
- the GEO craft Horizontal translational control algorithm provides tangential velocity make-up to ensure centrifugal equilibration effectiveness and limit libration oscillations that might adversely couple with vertical dynamic modes.

Note that for Mid Phase deployment, vertical and horizontal control may not be necessary for the **Deploy craft**. Mid Phase terminates at the atmospheric interface. 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:

Atmospheric traversal may entail (a) Delaying atmospheric encounter until that time when minimum wind conditions prevail, (b) Propulsive control *closing the loop* on earth position sensing. This phase was not simulated in this paper.

Terminal Phase:

Terminal phase consists of the combined actions of *fine control* of earth position, altitude, and altitude-rate. Altitude rate control would likely be accomplished by propulsion in conjunction with vernier ribbon deployment. This phase was not simulated in this paper.

10. Dynamics of a Possible Control Algorithm for Deployment

The above described deployment mission scenario demonstrates the possibility of dynamically balancing the vertical ribbon during the course of deployment and suppressing un-desirable dynamic ribbon responses, all by means of control effectors of *significantly less force* than the *steady tensions* being managed during the deployment. This technique is an interplay of a Vertical and Horizontal controller for the GEO craft *combined with* a ribbon deployment scenario that modulates the ribbon deployment-rate as a function of the Deploy craft altitude, while paying due regard to a supplementary deployment rate component required to compensate for the rising altitude of the GEO craft itself. Ideally, the GEO craft Vertical control is of such precision as to require virtually no static propulsive-makeup against tension; in which case, a minimum propulsive impulse would roughly correspond to the sum of the *work* that must be done to vertically control the GEO craft through the gravity field from GEO to Ballast altitude (a quantity highly sensitive to optimal design) plus tangential velocity make-up (an essentially fixed quantity). This controller uses logic to minimize modal interaction with the combined ribbon/end-body system, while counteracting the intrinsic tension and gravity state; problematically, the vertical controller can induce spurious tension transients into the ribbon system in the act of maneuvering, then in turn, react to these very transients. For this reason the vertical controller uses *filtered tension sensor* data to plan maneuvers (along with other schemes to counteract instabilities). Details of the control algorithms and deployment scenario follows.

GEO craft control:

For the Horizontal axis, conventional on/off control logic was employed to maintain the GEO craft to within a specified dead-band of a specified fixed earth longitude and latitude. This control logic is combined with a Coriolis bias that commands a horizontal thrust-level proportional to the altitude rate and earth rotation rate. The maximum horizontal thrust allowed for this mode was 2200 N.

For the Vertical axis, a conventional error/error-rate feedback proportional controller commanding a maximum of 6500 N of thrust was used. This controller commanded an altitude that would be consistent with equilibrating the ribbon tension with due regard for local gravitational acceleration; this equilibration assumes a tangential velocity corresponding to the GEO craft's position *as though it were on a vertical radial rotating with the earth.*

Deploy craft control:

It was determined that due to the inherent *relative libration stability* of space tether deployment, no active translational control was needed on the Deploy craft for the *Initial-phase* and *Mid-phase* of this deployment.

The Ribbon Deployment:

Ribbon deployment rate is the sum of two contributions: (a) the baseline rate profile from a table of *Deploy-rate* -vs- *Deploy craft Altitude* representing a desired rate of descent for the Deploy craft, and (b) the *altitude rate* of the GEO craft (as it rises to equilibrate the ever-building tension). This algorithm is configured to inhibit negative deployment rate so as to attenuate deployer participation in longitudinal dynamic modes and GEO craft controller-induced vertical dynamics. A strain-bias of 0.075 (based on a reference tension of 22,000 N) accounts for the fact that the deployer algorithm dispenses *un-elongated* tether, which, upon being emitted into the domain of the tether, is destined to acquire a strain consistent with the level of stress extant in the tether.

Figure 14 below shows the *base-line* deploy rate for this example, and derived from an idealization of a possible *Altitude-rate* -versus- *Altitude* profile that might be appropriate for a Deploy craft to experience. The ribbon deploy rate is commanded as *this baseline value*, plus, the *Altitude rate of the GEO craft.*

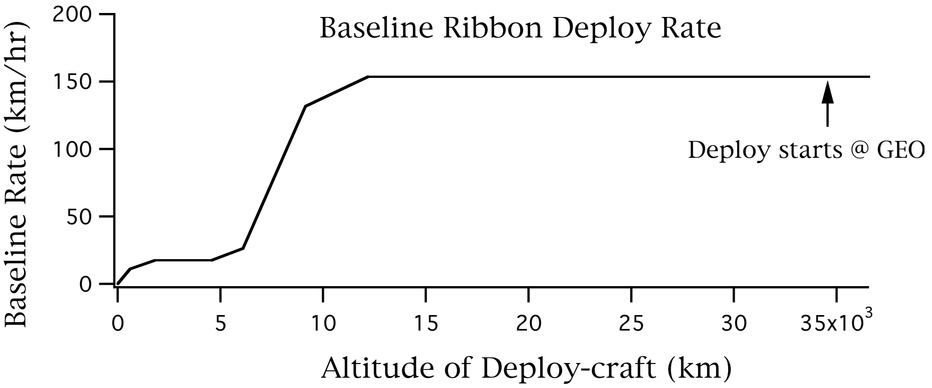


Figure 14. Baseline Deploy Rate Component -vs- Altitude of Deploy craft

Figure 15 shows the composite ribbon deploy rate experienced by this mission.

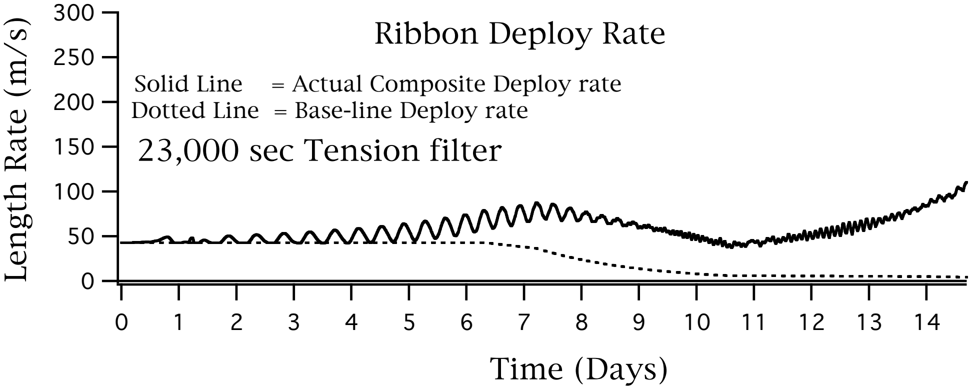


Figure 15. Final Composite Deploy Rate Reflecting GEO craft Altitude Rate

Shown in Figures 16 and 17 are the actual altitude rates achieved by the Deploy craft and GEO craft, and clearly show rate modulation starting at about 8 days.

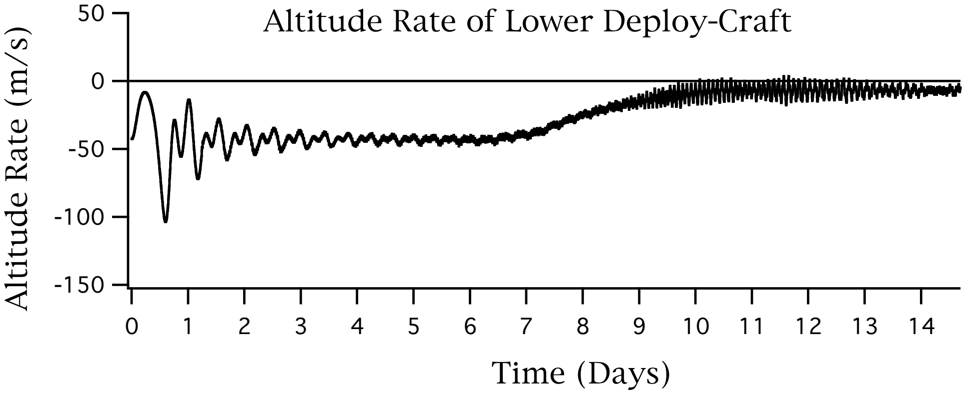


Figure 16. Altitude Rate of Deploy craft

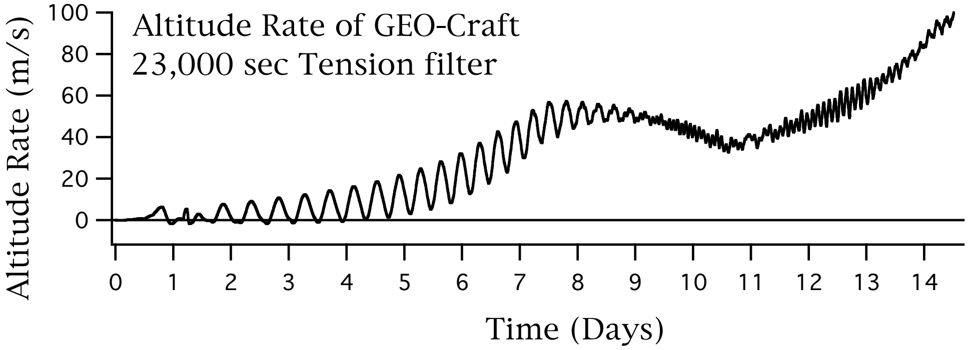


Figure 17. Altitude Rate of GEO craft

The resulting altitude profiles of the GEO and Deploy craft are seen in Figure 18.

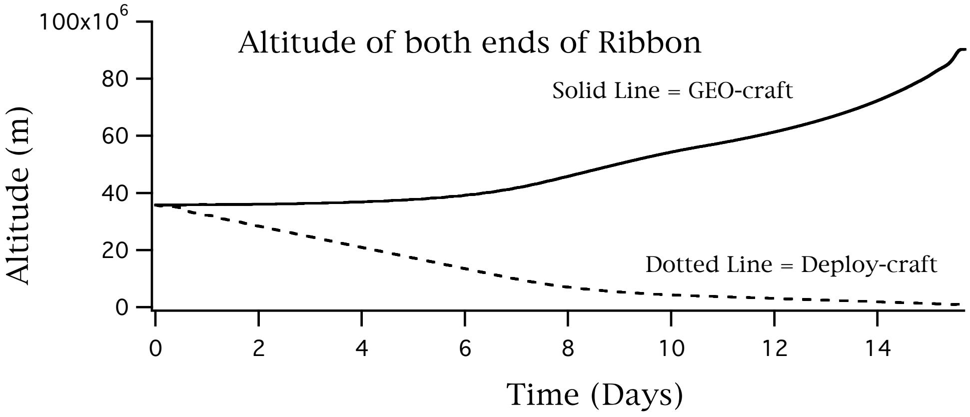


Figure 18. Altitude of GEO craft and Deploy craft

The ribbon tension is shown in Figure 19.

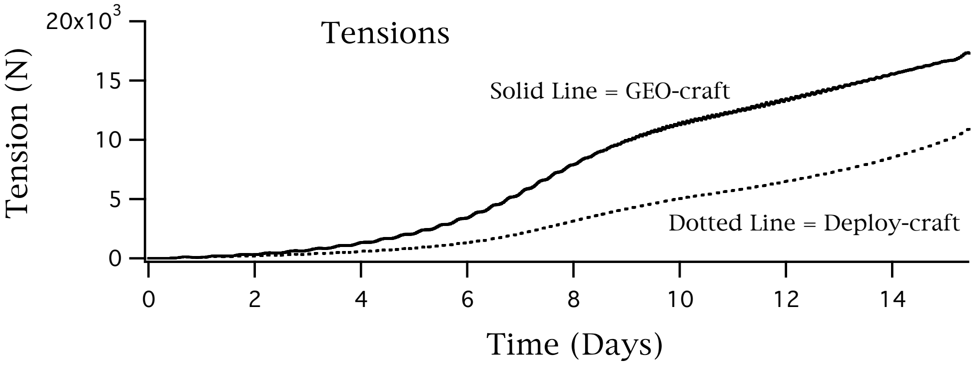


Figure 19. Tension

Libration experienced by the GEO craft is shown in Figure 20. Notice that the horizontal dead-band controller bounds the libration at about the +1 degree dead band indicating that the tangential velocity makeup control was slightly biased.

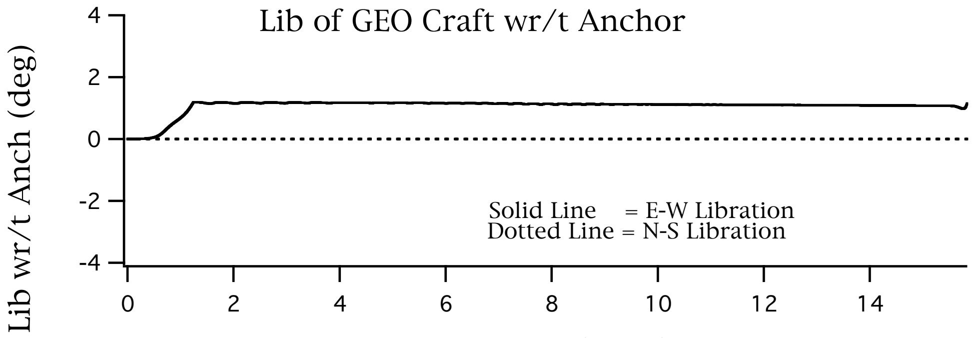


Figure 20. GEO craft Libration relative to Anchor Point

Libration experienced by the Deploy craft is shown in Figures 21. Even though the Deploy craft has no active control, its initial libration perturbation (associated with tension onset) attenuates over time, a behavior typical of tether deployment.

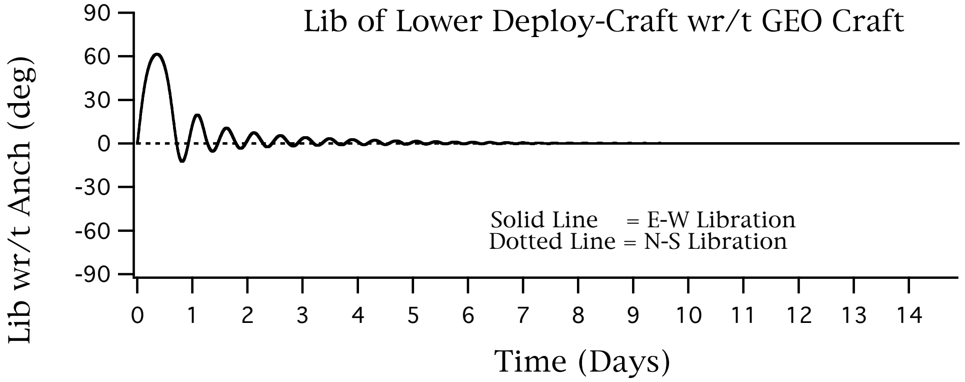


Figure 21. GEO craft Libration relative to Anchor Point

Deploy craft position relative to the anchor is shown in Figure 22. Note, if the GEO craft were initially positioned 1.5 deg. west of the anchor, the resulting eastward dead-band bias would position the Deploy craft directly over the anchor.

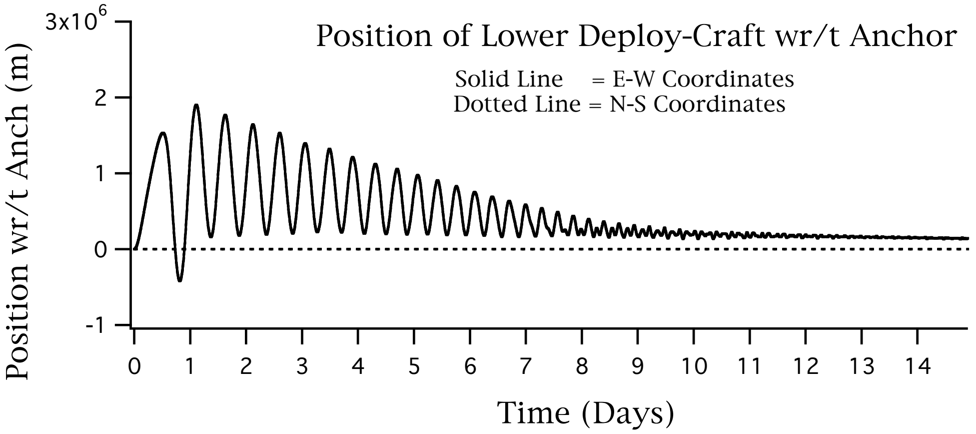


Figure 22. Deploy craft Position Error Relative to Anchor Point

11. Importance of Horizontal Control

Examination of cases in which horizontal control was not active on the GEO craft clearly indicates the critical need for tangential velocity *compensation* related to Coriolis acceleration effects. For instance, in the example above of a successful deployment, by simply disabling horizontal control on the GEO craft (but with the *successful* vertical control modes *still* enabled), the system crashes to earth. This is because the centrifugal effect is the paramount mechanism in the physics of the elevator, and as the GEO craft rises, failure to introduce tangential velocity make-up allows the GEO craft to drift into a higher "orbit" with a corresponding longer orbital period, hence, a lesser effective *angular velocity*. Thus the intrinsic centrifugal effect on which the elevator relies is removed; under these conditions the ribbon tension can easily pull-down the GEO craft.

12. Conclusions

Due to the inherently unstable attributes of a tethered system whose length spans a significant portion of the gravity field, as in the case of the space elevator, it appears that active control effectors will be necessary to perform this mission. Failure to accomplish such control was found to easily result in total loss of the initial elevator system since un-attenuated vertical imbalances result in either the entire system collapsing to earth, or flying off into an irretrievable trajectory.

While such control can be doubtlessly accomplished given sufficient propellant budget, the engineering challenge facing an actual deployment is to achieve control and stability within practical levels of total propulsive impulse expenditure. The ideal lower-bound on mission impulse could be thought of as the sum of the impulse required to achieve tangential velocities consistent with earth rotation, plus the impulse required to lift the ballast (and ribbon) against the gravity potential. Since expenditure of total impulse has mission-lapsed-time implications (analogous to gravity losses for classical rocketry), short mission durations are desirable; however, stability and safety of deployment speaks for long slow deployments, thus, the mission design will likely entail compromises related to this area of performance.

Only *insignificant* *transverse ribbon oscillation modes* were excited during the process of deployment. While, this was not true during the engineering development process for the various control modes and deployment strategies, it was found that as deployment scenarios started to meet mission objectives successfully, then simultaneously, transverse string mode deflections became inconsequential. This was probably because *successful* deployment schemes (almost axiomatically) manifested themselves as *smooth* deployment processes.

A proposed control law and deployment scenario has been simulated and found to demonstrate the possibility of effectively managing the space elevator ribbon deployment down to the atmospheric phase interface.

13. Future Work

Many areas of new investigation regarding initial ribbon deployment invite further exploration. The optimization of control algorithms will be critical to accomplishing the mission, yet expending an affordable total impulse. Transit though the atmosphere was not addressed in this study; the effective use of propellant in this phase of the mission may be critical. Finally the terminal phase of the mission in which contact is made with the anchor station will require sensitive control of altitude rate of the Deploy craft, as well as the development of innovative grappling schemes and maneuvers.

The potential benefits of a LEO originating deployment were not addressed in this study. The dynamic responses of such an approach should be addressed next in order to determine which mission scenario might be optimal for the initial space elevator deployment.

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