LEO Based Space Elevator Ribbon Deployment

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Abstract

This proposal examines the possibility of deploying the elevator ribbon from LEO. Unlike the procedures described in [1] that work at a fixed geosynchronous orbital period, LEO deployment slows the orbit down towards that condition as the deployed structure evolves, keeping the lower end of the deploying ribbon at a constant altitude.

LEO deployment significantly reduces Earth-to-LEO launch costs compared to GEO-based deployment, and works particularly well with the segment-based ribbon architecture described in [3].

Numbers we present are based on a numerical tool written by us for this purpose.

1. Motivation

The space elevator is often described using the analogy of swinging a rock at the end of a string.

Our deployment plan is analogous to starting with a very short (and fast spinning) system, and slowly feeding out more string, so that the rock makes larger and larger circles, taking longer and longer to complete each revolution.

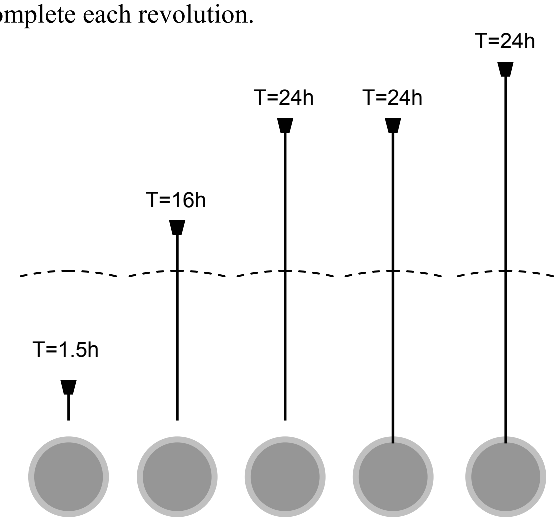

Figure 1: LEO deployment sequence

As you feed out the string, you need to "help the rock along" by making small circular motions with your hand, to compensate for the drop in the speed of the rock.

The situation in space is a little bit different (since gravity is not quite like a string) but the same principle still applies — as we feed out the ribbon, we have to continuously boost the system in order to keep it in a stable orbital state and keep the lower end at the same altitude.

We can achieve this using beamed power and some variation of an electro-dynamic drive system, in much the same way as boosting the deployer to GEO is described in [1].

2. Ribbon calculator

The discussion presented below is mostly qualitative. In order to support it with numerical results, we wrote a numerical tool to calculate the relevant quantities. The calculator is basically a fancy version of the spreadsheet described in [1]. We only consider stable, circular-orbit states of the ribbon, and use a very coarse fixed step size when integrating.

In having an interactive graphic front-end, however, the calculator proved invaluable as a tool to gain insight into the qualitative factors that contribute to the numeric end results.

The ribbon calculator is available for use over the web at [4].

3. LEO vs. baseline

In this section we compare LEO deployment of a ribbon to the baseline (GEO) deployment of the same ribbon.

Both proposals launch the ribbon, counterweight, thruster and propellant to LEO, then use a separate high ISP propulsion system for the rest of the deployment procedure.

The baseline proposal first transfers the entire payload to GEO. This requires a first quantity of propellant. The ribbon is then fed downwards until it anchors, with propulsion happening at the top end of the ribbon. This step requires a second quantity of propellant. After anchoring, no more propellant is required.

The LEO proposal deploys the ribbon from where it is, so there is no initial transfer to GEO. The ribbon is fed upwards, with more propellant being used to boost it during the reel-out.

There are two variables that we can control for this deployment:

1. Propulsion unit location: The propulsion unit can be placed at the tip of the ribbon (same as in the baseline design) or it can be placed at the root and kept in LEO. Conceptually, this variable has a number of competing effects:
   a. If placed at the tip, the fuel store has to be pushed out to higher altitudes.
   b. In addition, while boosting, the fuel store has to achieve faster orbital velocity.
   c. At the tip, a fixed amount of impulse buys us much more angular momentum.

Arguments a and b, being essentially "rocket-equation" arguments, lose much of their steam when considering high ISP propulsion. To get a sense of the numbers, a chemical rocket takes about 150% of the payload mass in added fuel to go from LEO to GEO, while a 5000 sec ISP drive takes only 10% of the payload mass.

Argument c, on the other hand, can yield a several-fold advantage, since GEO is almost 6 times as high as LEO.

2. Ribbon reel location: The ribbon reel can also be placed at either the tip or the root of the growing ribbon.
   a. Without considering the propulsion unit, the delta angular momentum between the stored state and the deployed state of the ribbon are the same, so the reel location does not matter to the amount of propellant mass needed.
   b. If the propellant store is placed at the top and the reel is at the bottom, the reel mass has the effect of making the propellant store significantly super-orbital early in its life time, when it is still heavy, thus wasting impulse on needlessly accelerating stored propellant.

An important quantity to observe during a deployment process is the maximum stress along the ribbon, since the ribbon is not under the same orbital conditions it is designed for.

One cause for high tensions is having large lumped masses at different ends of the ribbon, which by definition causes them to become sub- or super-orbital.

This argues strongly against having the propellant store and the ribbon reel on opposite ends of the ribbon. (Very strongly — in some scenarios we have seen the stress numbers exceed the design limit by more than a factor of 20!)

We have thus come full circle and ended up very close to the baseline proposal — we follow the exact same procedure, except we start deploying the ribbon as the deployer leaves LEO towards GEO.

We did not uncover major improvements to the deployment process, but we have explored several directions and gained some insight into the parameters that influence the mechanics of the deployment process.

4. JIT

JIT (Just-In-Time) is a variation on the LEO strategy in which resources (ribbon, propellant) are only launched to the bottom of the ribbon as they are needed.

Resources that are launched in JIT fashion require that their respective consumers (deployer, thruster) be located at the bottom of the ribbon.

JIT offers two main advantages:

1. Reduced launch costs: As the bottom of the ribbon slows down and becomes suborbital, launching the resources to it requires less boost.
2. Reduced ribbon stress: Not having the store of unused resources hanging at the bottom does wonders to our stress numbers.

We have looked at both propellant and segment JIT.

4.1 Propellant JIT

As in the previous discussion, if we rely on a high-ISP design, the mass of the propellant is small compared to that of the ribbon, and the increase in the amount of propellant needed because of the low thruster position more than offsets the potential reduction in launch cost per ton propellant.

4.2 Ribbon JIT

The reader may have already noticed that we are assuming that the ribbon can be launched up in piecemeal fashion, and the individual units hooked up in orbit. Indeed, this option relies on some sort of connection mechanism, and we describe two such designs in [3].

In the scenario of a tip-mounted thruster, in comparison to a non-JIT implementation, ribbon JIT also eliminates the added problem of super-orbiting the thruster unit.

In other words, ribbon JIT is good.

In the simulation, LEO with ribbon JIT looks very similar to LEO with tip-mounted deployer and thruster, except that instead of being “laid out” the ribbon is “pulled up” with new ribbon pieces attached at the bottom as we proceed.

Launch costs, as calculated, are significantly improved. The top-heavy ribbon reaches an orbital period of 10 hours after only 7 segment launches, and so subsequent launches are very suborbital.

We are therefore able to trade expensive launch boost for efficient high-ISP propulsion (the MPD drive has to make up for the suborbital launch by carry a higher portion of the total impulse required to get the mass to its destined orbit).

As an aside, the ability to lift payloads from a suborbital trajectory to a super-orbital one, without the orbital acrobatics of rotating momentum-exchange tethers (as described in [2]) is interesting in itself.

We will, however, stay focused on the elevator.

5. LEO Assembly

We have so far concentrated on conserving the classical resources — launch costs and high-ISP propellant mass. The main benefit of the LEO-JIT method may actually lie in practical considerations.

We assume that the seed ribbon idea, while clever and resource-friendly, will not be pursued, since it leaves the ribbon vulnerable and unusable for a long period of time. Given the capabilities of the elevator, once the design becomes feasible, the launch costs of a larger elevator will be allocated. We further assume that earth-to-LEO launch capabilities will remain in the 20–100 ton range.

Under these assumptions, if we try to pursue full-out elevator deployment, we realize that a significant amount of in-orbit assembly is required. The biggest advantage of LEO-JIT is that it keeps all the interesting stuff happening in LEO.

6. Segment based ribbon

In [3], we advocate the use of a segment based ribbon, and include a description of unattended segment connect and disconnect procedures that are required to work at any altitude. Still, we would like to see the assembly in the initial deployment phase done at LEO, where people can fix it when it breaks.

Lessons learned during the deployment process can then be incorporated into the ribbon maintenance structure that will become operational once the ribbon is in place. This “training period” greatly increases our confidence in the ability of the segment-based architecture to avoid a very expensive or fatal glitch in a high orbit later on during the operational life time of the elevator.

7. References

[1] B. Edwards, E. Westling, “The Space Elevator” *BC Edwards*, 2003

[2] Hoyt, R.P., “Design and Simulation of a Tether Boost Facility for LEO->GTO Payload Transport", AIAA Paper 2000-3866, *36th Joint Propulsion Conference*, July 2000.

[3] Ben Shelef, “Segment Based Space Elevator Ribbon Architecture”, *Proceedings of the 3rd Space Elevator Conference*, June 2004

[4] Ben Shelef, “The Ribbon Calculator”, http://www.gizmonicsInc.com/elevator/ribbonCalculator.html