Loop Technology for the Space Elevator - Increasing Throughput, Decreasing Radiation

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***Abstract*—This paper proposes four related modifications to the space elevator reference design [1]: (1) An anchor at 8 degrees south latitude in the eastern Pacific, avoiding weather disruption of surface operations. A tether 200 km south of the equatorial plane avoids objects in equatorial orbit, and fratricidal fragments of broken tethers. Forces perpendicular to the tether facilitate orientation and prevent tangling in secondary tethers. (2) An untapered loop pulley moving at 2000 m/s, lifting payloads out of high gravity at 250 m/s. (3) Multiple climber pairs optimized for different altitudes, shuttling up and down, passing payloads between them. (4) Descent energy dissipated as very low frequency RF, coupling with radiation belt particles and precipitating them.**

These modifications can triple space elevator payload rates, reduce time to GEO to 24 hours, and lead to safe passenger service in lightly shielded vehicles.

I. Introduction

Space elevator throughput is seriously constrained by climb power below Medium Earth Orbit. The first 8% (3000 km) of the 35 786 km vertical journey from the Earth's equator to geostationary orbit consumes 41% of total climb energy, while equinoctial solar illumination near the ground is only 53% of the nearly-continuous illumination at GEO, increasing to 76% at 3000 km altitude. Climbers ascending from the ground must tolerate high gravity loads, increasing structural mass and reducing maximum climb speed compared to much higher altitudes. One climber design is not optimum for all altitudes.

High Stage One [2] moves the bottom end of the climb vertically to 50 kilometers. This protects the main tether from winds, weather, and other dangerous conditions. The small altitude increase reduces gravity by 1.6% and taper ratio by 1.8%. Starting above clouds and weather increases solar illumination and reduces weather-related outages.

Imagine a **Stage Two** at 3000 kilometers altitude, and some magic way to get there. The tether taper ratio between 3000 km and the surface is an exponential function of the 20 MJ/kg energy change, a factor of 2.1 for a 27 MY tether. Gravity drops to 46% of surface gravity. If we could somehow bypass the lowest 3000 km journey to GEO, the same climber power could produce twice the speed. Combined with the 2.1x structural advantage and a 43% increase in average equinoctial solar illumination, an optimized climber could move payload more than 3 times faster. Benefits increase as the climber climbs towards increased sunlight and lower gravity.

Space elevator feasibility increases with throughput, the payload lift speed times the number of payloads in process. More heavy payloads require more tether, so only speed increases throughput without increasing tether cost. Speed reduces radiation dose and increases the value of the transportation service. Halfway to GEO at 17 893 km altitude, the vertical gravitational acceleration is 10% of the acceleration at the 3000 km Stage 2 point. Power equals mass times speed times acceleration ($P = m \times v \times a$), so the same power at high altitudes can lift payload 10 times faster. Throughput gain will be maximized by end-to-end movement optimization and multimodal payload transfers, just as cost-effective terrestrial transportation moves packages via a series of optimized vehicles from sender to recipient.

Moving climbers back down the tether faster also increases throughput, but the descent energy is a big problem - the descent rate is limited mostly by power dissipation. The energy of descent from GEO to the surface is 48 MJ/kg, 11.5 kilocalories per gram, enough energy to heat carbon to a plasma. Heat dissipates poorly in vacuum.

Arthur C. Clarke [3] proposed electrically transferring this energy to upbound climbers. However, the electrical system to do so would be massive, suitable only for gigaton tethers with thousands of climbers spaced closely, moving power only short distances through resistive wiring. For early space elevators, with climbers spaced thousands of kilometers apart, the power has too far to go.

Fortunately, there will be good uses for this energy; it can help us eliminate most of the radiation belts.

II. Assumptions

> "There is something fascinating about science. One gets such wholesale returns of conjecture out of such a trifling investment of fact." — Mark Twain [4]

What follows is rank speculation, a placeholder until actual materials are made, measured, and replicated. Much depends on the specific carbon nanotube microstructures designed and manufactured for the space elevator, their electrical and infrared properties, and how they will behave and age under attack by mechanical abrasion, high temperature, high stress, bonding failures, extreme ultraviolet, hypervelocity microparticle bombardment, atomic oxygen, and ionizing radiation. Please do not use any of the numbers that follow if new empirical evidence contradicts them.

The reference space elevator design [1] presumes many capabilities, mostly implicitly. Explicit assumptions about the mechanical properties of carbon nanotube **(CNT)** tethers include a density of 1300 kg/m^3 and a maximum tensile strength of 49.4 GPa. These underlie a tether design with a safety factor of 1.4, a design tensile strength of 35.2 GPa (27 MYuri), a cross section of 1 meter by 62.8 μm at geosynchronous altitude, a 1 meter by 10.5 μm tether at the surface (taper ratio of 6), with a 1900 metric ton apex anchor at 100,000 kilometer altitude on the other end.

The reference design explicitly assumes 7 solar powered climbers spaced a day apart up the tether. These climbers weigh 6 metric tons and lift 14 metric tons of payload, 20 metric tons combined.

The reference design assumes a tether rolled into a circle and somehow centered by electrostatic repulsion inside a circular collar. The forces between uniform-voltage collar to a uniform-voltage tether are unstable; any deviations from perfect centering will magnify until tether and collar collide. This is a consequence of Earnshaw's theorem [5] [6], derived from the positive divergence of electric fields.

Electric fields can be used for centering, if there are multiple (attractive) electrodes controlled by measurement and feedback, and both the collar and the tether are rigidly circular and nondeformable. However, voltages high enough to generate significant mechanical forces for large objects will also cause currents in the ionized plasma of space, and could result in destructive electric arcs, vaporizing tether and collar.

Re-designing tether and collar is beyond the scope of this paper, but there are good reasons to return to the curved-arc tether of the earlier Edwards design [7]. This paper assumes a near-flat ribbon for black body thermal emissivity and pinch-roller traction, distributed through the stack and electronically synchronized for precise spacing and optimum tether tension.

At optimum sun angle, the reference study climbers produce 11.8 MW of power with very lightweight solar cells and structures pointing them at the sun. Other implicit assumptions include lightweight motors, electrical conductors, electronics, and cooling systems, all made possible by so-far-hypothetical electrical properties of carbon nanotubes.

Lightweight climbers will benefit from very stiff but gossamer climber structures with 1 TPa rigidities. All properties are assumed approximately stable over temperature.

Cooling these systems in vacuum will be difficult; waste heat and unwanted energy must be radiated away - somehow. Black body radiation is one approach.

Disordered coatings of carbon black have very high emissivity (>95%), and arrays of CNT tubes standing endwise on a surface have the highest demonstrated albedo of any lab material [9]. However, neither surface is strong or abrasion-resistant, suitable only for non-bearing surfaces such as climber structure and solar cell back sides.

Ordered, semi-metallic systems will be more like mirrors at thermal infrared wavelengths (2 to 20 μm). If they have macroscopic holes larger than those wavelengths, they will be transparent. Both kinds of surface radiate heat poorly.

Assume we can retain these properties up to 600 Kelvin, where black body radiation for a perfectly emissive surface is 7 400 W/m^2. For 3% emissivity, black body radiation is 220 W/m^2 at 600K, the same for a tether rolled into a cylinder, doubled to 440 W/m^2 for a two-sided, nearly flat ribbon.

III. Electrical Assumptions

Carbon nanotubes are unlikely superconductors, especially at non-cryogenic temperatures. Superconductivity is a fragile phenomena in unusual and typically low strength materials. Pairs of electrons (which are fermions) are coupled by lattice distortions into pairs that behave like bosons, forming quantum-mechanical electrical superfluids at low temperatures, at limited current densities, in limited magnetic fields [10]. If any of these limits are exceeded, superconductivity vanishes abruptly, often catastrophically. Many dubious claims of superconductivity emerge from poor measurements, perhaps open or shorted voltage connectors on a Kelvin-sensing measurement, or even cruder measurements of impure bulk material between two thermally mismatched and thermocouple-behaving electrodes. It seems that the most spectacular results occur in the sloppiest labs. The defining characteristic of a superconductor is the Meissner effect, the pinning or exclusion of magnetic fields from the bulk material. This spectacular effect has not been observed with CNT materials; it would manifest as the deflection of a single CNT fiber away from a strong magnetic field, quite visible with good microscopy. **Do not assume superconducting CNT until such experiments produce unmistakable results.**

Let's assume two allotropes of carbon nanotube. We will assume structural CNT is 1 TPa stiff, 27 MYuri strong, and shiny as graphene, with an infrared emissivity around 3% [8].

Early work by Edwards and Westling [7] and a recent paper by Dennis Wright [11] both assume 0.4 ohms per meter of tether for a 62.8 μm^2 structural tether near GEO. The bulk resistivity is 25 $\mu\Omega$-m, a poor conductor.

Without evidence, let's hypothesize a different CNT allotrope, "electrical" CNT, is 500 TPa stiff, 10 MYuri strong, 3% emissive, with bulk resistivity of 16 nΩ-m at room temperature like copper, and with similar temperature behavior. At 600K, copper's bulk resistivity increases to 38 nΩ-m, 135% higher than room temperature [12]. Assume the same bulk resistivities for electrical CNT.

Assume the same percentage increase for the structural CNT of the main tether, changing from 0.4 Ω/m at 300K to 0.94 Ω/m at 600K for our 62.8 μm thick (82 kg/km) main tether. The bulk resistivity becomes 60 $\mu\Omega$-m, the sheet resistivity is 0.94 Ω/square. At 600K a flat tether dissipates 440 W/m, so $I = \sqrt{P/R}$ = 22 A, and I R = 20 V/m . Near the ground, the tether is only 10.5 μm thick, so resistance increases to 5.6 Ω, maximum current drops to 8.8 A, and I R = 50 V/m.

A round version of the same tether radiates half its power internally, so only 220 W/m^2 radiates into space.

A 10 μm thick electrical tether at 600K has a sheet resistivity of 3.8 mΩ/square. It will carry 340 amps per meter of width at 600K, 22 amps in an 6 cm wide ribbon of electrical tether. This masses 800 grams/km, with a resistance of 63 Ω/km and a voltage drop of 1.3 kV/km and power dissipation of 26 kW / km.

Assumed Carbon Nanotube Properties		
NOT empirically validated!		
	Structural	Electrical
density	1300 kg/m^3	1300 kg/m^3
modulus	1 TPa	500 GPa
strength	35 GPa	13 GPa
specific strength	27 MYuri	10 MYuri
temperature	600 K	600 K
emissivity	0.03	0.03
emission	440 W/m^2	440 W/m^2
resistivity	60 $\mu\Omega$-m	38 nΩ-m
use case	main tether	auxiliary tether
width	1.0 m	0.06 m
thickness	62.8 μm	10 μm
mass	82 kg/km	0.8 kg/km
resistance	0.94 Ω/m	63 mΩ/m
current	21 A	21 A
voltage	20 kV/km	1.3 kV/km
power	440 kW/km	26 kW/km

TABLE I
MATERIAL PROPERTIES ASSUMED FOR THIS PAPER

While it would be splendid to have a third allotrope for electrical system, insulating carbon nanotube, carbon in all forms is conductive, similar to the structural form described above. For strong insulating tethers, composites of insulating plastic and short CNT fibers may be adequately strong and adequately insulating. This needs further study.

Assumed CNT mechanical and electrical properties are listed in table I.

These assumptions add risk, but many of these risks are already inherent and unacknowledged in the existing reference design [1]. By facing the new risks squarely, new opportunities emerge, increasing system productivity and lowering overall system risk.

IV. HYPERSPEED ROLLERS AND WHEELS

A high speed roller made of superstrength materials does not need to be heavy or large diameter, merely scaled in pivot strength to the load it bears, and controlled by precision measurement and actuators to minimize wear and drag, slowing or shutting down if failure seems imminent.

Carbon-epoxy flywheels, using composite materials no stronger than one or two MYuri, and optimized for energy storage rather than rim speed, approach 700 m/s rim speeds in deployed energy storage systems [13]. Assume that we can make load-bearing pulleys, rollers, and wheels moving at up to **2000 m/s**, with precision micrometer-accurate sensors and electronically driven actuators adjusting surfaces and tensions to minimize drag and wear. 2000 m/s is two micrometers per nanosecond; at electronic calculation speeds, a high speed mechanical system is effectively stationary, eminently modellable, and accurately characterizable in the lab. These wheels will play a vital role in the systems described here, and find many uses besides space elevators. High speed wheels will justify a large development expense.

2000 m/s and even 1000 m/s may frighten mechanical engineers, accustomed to working with steel, full gravity, full air pressure, and no active electronic control of bearing surfaces. Aircraft and rockets move at these very high speeds. 10,000 RPM disk drive platters move at a leisurely 30 m/s rim speed, but the spacing to the stationary heads is 3 nanometers - crashing the head destroys the drive.

Exquisite precision is possible with electronic control. While the stiffness to density ratio of CNT promises stress propagation speeds of 25 millimeters per microsecond, electronic signals move hundreds of meters in that same time. Laser interferometry can measure spacings to nanometers. Micro Electronic Mechanical Sensors (MEMS) accelerometers can measure tiny accelerations, and piezoelectronic strain gauges can measure stress in structural members. Increasing the force in a 2 mm gap by 10 newtons requires 20 millijoules of energy; a 10 kW power switch can provide this energy in 2 microseconds. If caused by a micrometer of movement a meter away, the equivalent tensile stiffness is thousands of times what even carbon nanotubes can provide.

Imagine a 2 meter diameter, exponentially tapered pinch wheel with an outer rim speed of 2000 meters per second, and an inner 10 centimeter diameter bearing and hub. The wheel turns at 19,000 RPM, as fast as a power storage flywheel. The hub bearings turn at 100 mm * 19 000 rpm = 1 900 000 d_mn (a standard measure for high speed bearings). 2 000 000 d_mn mechanical bearings are available [14].

A CNT based, electronically controlled magnetic bearing should be able to do much better.

If not, the staging ideas described later in this paper will still work, and still increase system throughput spectacularly. The space elevator system can start with lower speed climbers and lower throughput, and be upgraded to higher speed climbers as faster electro-mechanical technologies develop. The purpose of this paper is to stimulate thinking and research, to replace guesses with empirical data, to encourage the construction of prototypes for high speed systems and learn how they work, and how they fail.

All this electronics will not be cheap, and redundancy and radiation hardness will add to the expense. But system throughput and economic value will be proportional to wheel speed, making million dollar wheels very attractive.

V. SOUTHERN ANCHORS AND INCLINED TETHERS

A single space elevator tether anchored at the equator is relatively easy to analyze, and slightly easier to deploy, but the orbital equatorial plane has many uses. A static tether precisely on the equator is incompatible with many of them.

Multiple space elevators raise the risk of fratricide. Broken tethers will fracture many places besides the original break; there is no damping mechanism to remove the enormous stress waves and suddenly released elastic energy propagating upwards from a break. These waves bounce longitudinally and transversely at different speeds on the linearly non-homogeneous tapered tether, sometimes constructively adding to create more breaks. Some material will re-enter, some will remain attached to the anchor (thrusting downwards to balance rotation speed), but a few segments may separate from both, and go into low inclination, highly elliptical orbits near the equatorial plane. If there are other space elevators on the equatorial plane, they will be sliced in half.

If all space elevators are offset from the plane, they will be less likely to be intercepted by tether fragments, which will be dispersed over a wider north/south region. Some other elevator will also be better positioned to disperse interceptors to rendezvous with those fragments, since interceptors can be released into many different shallow orbital planes.

As a space elevator lifts and launches satellites, it will deflect westwards; if launches are interrupted, it may swing like a pendulum between east and west. A GEO orbit with thousands of satellites (the reason we are building a space elevator in the first place!) will be too densely populated for such behavior from an in-plane space elevator. An in-plane space elevator may be a target and a hazard, not an asset.

Shifting the space elevator anchor to 8° south clears the equatorial plane at GEO by 280 km. Clearance increases to 800 km at ISS space station altitudes. Space assets and debris in inclined orbits may still intersect a tether offset from the equator. Fortunately, a diagonal tether in tension can be quickly moved north and south by rapidly adjusting radial tension, propagating up the tether at the 28 km/s longitudinal wave speed, rather than the slow transverse wave speeds associated with lateral moves of the bottom anchor.

For weather, construction ease, and compatibility with other equatorially orbiting assets, we want an elevator to the south.

What would it look like? Fig. 1 shows a space elevator cable to 8°S. The gravity acceleration vector has a tangential component to the north, decreasing approximately as the cube of the radius. At 8°S, the anchor of the cable will be 888 km directly south of the equatorial plane, and 62 km closer to the rotation axis, $6378 \times (1 - \cos(8^\circ))$.

Gassend [15] teaches us that the taper ratio of the tether is proportional to the change in Colomb potential from GEO to anchor, which is uniform across the surface of the earth at sea level; north-south displacement doesn't change taper ratio. However, the angle of the tether relative to the surface does change, and with it the carrying capacity of the tether, reducing climber/payload size by cos(angle). The surface angle is 2 to 3 times the latitude. Beyond 45°S, the tether is horizontal and lift capacity is zero.

The cos() loss is approximately proportional to the square of the latitude, and is 6% at 8°S and 2% at 4.5°S. Choosing the best latitude will be a tradeoff between lift capacity and the logistic costs of surface operations in stormier weather nearer the Inter-Tropical Convergence Zone (ITCZ).

With an anchor at 8° south latitude, the tether leaves the surface at a 20° angle from local vertical. Masses hanging from the tether will swing northwards from the tether by 3.6 meters for for every 10 meters of vertical hang. This allows "sideways" deployment of non-tangling supplemental tethers, and facilitates hoisting transfer of payloads from climber to

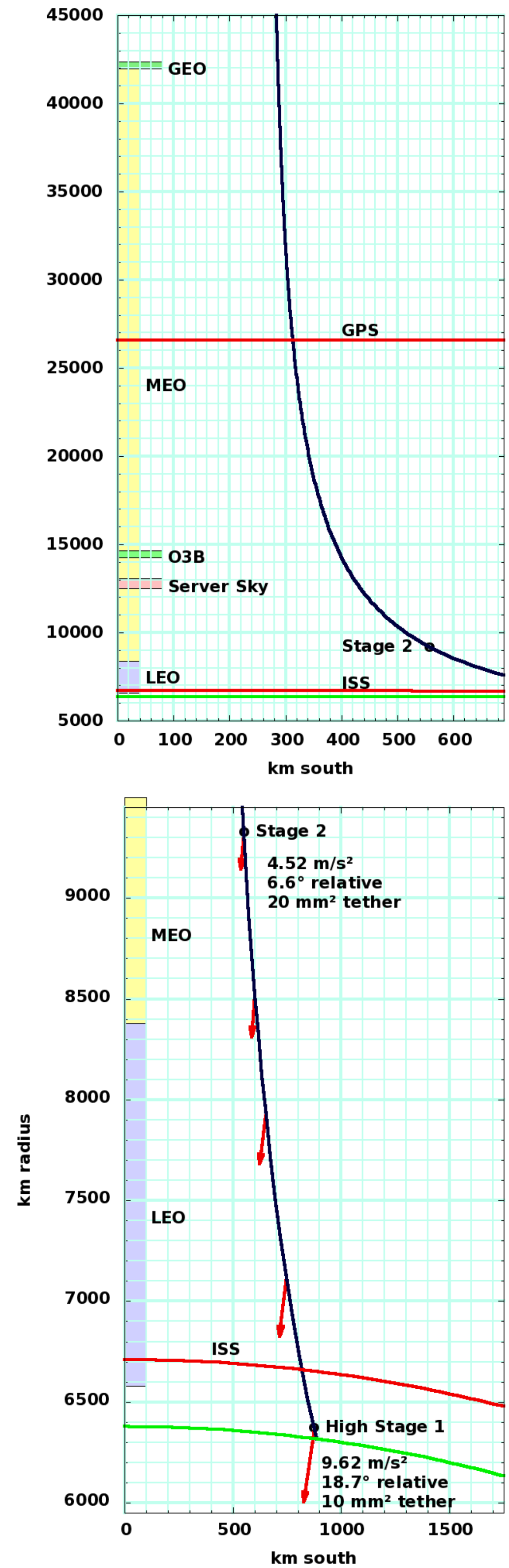

Fig. 1. Offset tether distance from equator versus altitude. Same curve, top graph is not proportionally scaled. Satellites are typically in inclined orbits and cross tether latitudes, but the GEO, O3B, and proposed Server Sky constellations are in equatorial orbits and always stay north of the tether.

climber. That, in turn, allows us to optimize climbers for the different climbing regimes up the tether, from the high gravity low illumination bottom 20% of the tether, to the low gravity, full illumination upper 50% of the cable.

These altitude regions regions are as different as street cars and supersonic transports. Optimized operation demands different vehicles. Four extra payload transfers on the way up will not be difficult, especially if those low gravity transfers involve slowly winching a few hundred newtons of weight a few hundred meters, rather than the 200 kN dead lift required of climbers near the bottom.

The gravity from bottom to top drops by orders of magnitude. Slow and sturdy climbers belong near the bottom, fast and gossamer climbers near the top.

Many varieties of specialized climbers may be stored at GEO station. Should a specialized climber at an intermediate altitude fail, it can be jettisoned from the tether for reentry, with a replacement climber lowered as payload and deployed in hours. This paper suggests splitting climbers into pairs, so a failure slows but does not immobilize vertical transit.

VI. Distance Measured in Energy or Support Mass

Megayuris are not only a convenient unit for tether strength, they are also the same units as energy per kilogram, and can express the potential energy difference between High Stage One and GEO (altitude 35786 km), and the altitudes in between. One megayuri (MY) is one megajoule per kilogram.

We will measure the energy of a position along the tether as the remaining energy cost to finish the climb to GEO. At GEO, the cost is 0 MY. At a 50 km High Stage One (HS1), it is 47.9 MY, decreasing as altitude increases. The job of the space elevator, and the climbers on it, will be to reduce the energy (in MY) to zero.

At 3000 km altitude (a point we will call S2), only 8.4% of the radial distance from HS1 to GEO, the energy to GEO will be only 28.6 MY, 40.3% less. Over that relatively short distance, a solar powered climber will get the least sunlight, face the most mechanical stress, and will be a huge target for space debris. If we can somehow get to 300 km altitude fast, the rest of the climb will be much easier.

There's yet another way to measure the distance to GEO, the **support mass**, the additional kilograms of tether needed to support an additional kilogram of load at a given altitude. This tells us the system cost of a payload plus climber lingering at that point, and how motivated we should be to move mass upwards from there. At the surface, the gravity is high and the tether will be farthest from apex. The support mass will be 222 kg of tether and apex mass per kilogram of loading at the earth's surface. The support mass will be reduced by 3.3% at 50km altitude, High Stage One. and 78% at 3000 kilometers altitude. If adding mass to a climber reduces payload fraction, but moves payload upwards much faster, this will be a win because mass throughput increases.

After optimization, the spacing of climbers and their design will be a complex function of climb energy, tether loading versus altitude, initial construction cost, risk, and the time value of money. There is no one right answer - so let's focus on climb energy.

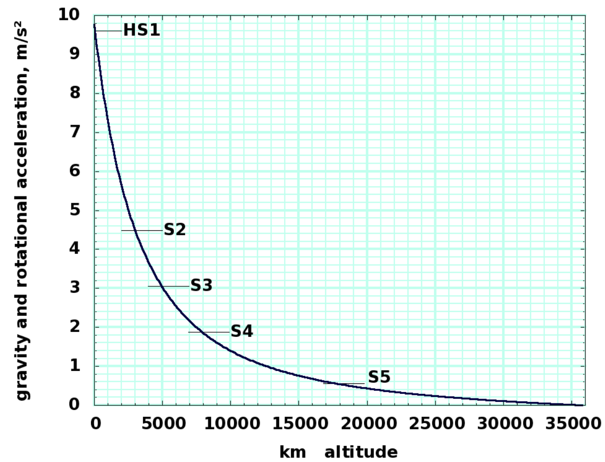

Fig. 2. Gravity versus altitude. The gravity, the lift energy per kilometer, and the structural strength of climbers diminish with altitude, less than half of surface gravity at 3000 kilometers altitude.

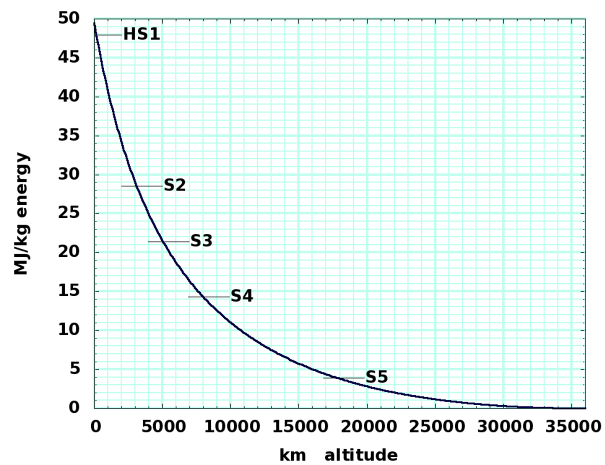

Fig. 3. Remaining climbing energy versus altitude.

Let's pick three more staging points between S2 and GEO, S3, S4, and S5, not spaced by distance in kilometers, but by the amount of energy between them. The four distances between are called legs S2-S3, S3-S4, S4-S5, and S5-GEO .

If all stages are at equal energy intervals, Stage S5 and GEO will be more than 20 000 kilometers apart, requiring speeds greater than 2000 meters per second, or too many hours of travel time for three round trips per day. So S5 will be moved upwards from the equal energy point, shortening the leg up to GEO, lengthening the leg up from Stage S3.

Since the gravity at stage S5 is 5% of surface gravity, and the tether support cost is 1%, another alternative is to park every other payload at stage S5 for a few hours, then lift pairs of payloads from S5 to GEO using a slower and more powerful climber. A way station may be cheaper than a high speed S5-to-GEO climber, However, moving two payloads half as often doubles the angular momentum jolt that sways the space

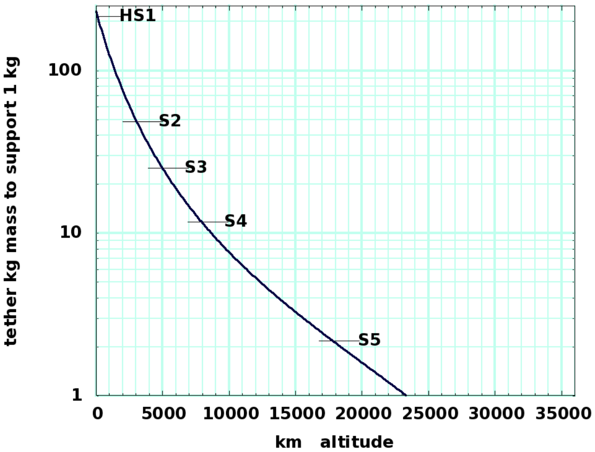

Fig. 4. Tether and apex mass to support one kilogram. Adding a kilogram of mass at higher altitudes requires less additional mass of main tether and apex counterweight to support it. Climber weights and spacings should be chosen to "top load" the main tether, maximizing end-to-end throughput.

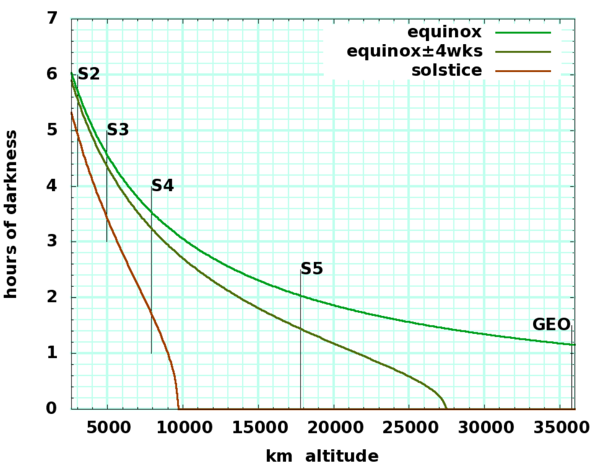

Fig. 5. Hours of darkness versus altitude. The orbital tilt relative to sun angle changes over the year, with the night side of the orbit blocked for more hours at the fall and spring equinoxes than at the winter and summer solstices.

elevator during climber transit.

Another alterative adds one more stage, S6, between S5 and GEO. This maintains throughput with slower climbers, but increases complexity and end-to-end travel time.

First estimates of stage height are shown in table II.

Table II is interesting. We can double the mass of the climber PLUS payload at every stage S2, S3, S4, and S5 for the same increment of total space elevator mass, if it produces better throughput and return on investment. It makes no economic sense to use the same climbing system all the way up. A one-stage-to-GEO system also implies bringing groups of climbers all the way down for another load, delaying a sizable fraction of annual throughput during the weeks required to clear GEO of accumulated climbers. The alternative, discarding climbers at GEO after one operation, will be extremely expensive, and reduces the investment we can make in climber performance. A downwards return tether cuts system performance in half, and coriolis forces will swing it in the opposite direction of climbing tethers, increasing the risk of collisions.

One Possibility for Staging Altitudes				
Stage	Energy	Altitude	Gravity	Mass Cost
	MY	km	m/s^2	kg/kg
Ground	48.42	0.00	9.76	37.18
HS1	47.94	50.00	9.61	36.60
S2	28.56	3000.00	4.48	16.94
S3	21.42	4927.11	3.06	11.49
S4	14.28	7900.12	1.88	6.94
S5	3.87	17786.03	0.55	1.90
GEO	0.00	35786.03	0.00	0.00

TABLE II
STAGING ALTITUDES

Imagine five climbing legs, shuttling between staging points: HS1 to S2 and back, S2 to S3 and back, and so forth. The first leg must function in full gravity - the next section describes a trick for that, enabled by the inclined tether and powered mechanically from the ground. The second leg from S2 to S3 will be a solar powered climber operating in 47% gravity, climbing 1900 km, a shorter distance. The third leg operates in 32% gravity, climbing 3000 km. That climber can weigh more and go faster. The top leg, S5 to GEO, will be limited by maximum pinch wheel speed, climbing and descending.

We will attempt to cycle each leg in less than seven hours, allocating approximately 4 hours for payload-laden powered ascent, 3 hours for empty climber descent, with 30 minutes for payload transfer at each staging point, plus 30 minutes for contingencies. We will time the descents to occur during eclipse. HS1 to S2 ascent will be fast, 250 m/s, and take about 3.5 hours.

If we can average 4.5 hours per leg between S2 and GEO, we can complete the trip from HS1 (the last place with shielding and living quarters) to GEO (with shielded habitat) in less than 24 hours.

We will cheat a bit on the regularity of the bottom legs, because eclipse lasts longer at low altitudes. One of the lower descent legs will be stretched to cover it. That will be a good time for main tether inspection and patching; we can make the last upward payload before nightfall a little light, and add a high-speed camera assembly to the payload. The camera will descend with the empty climber, capturing multispectral micrometer-scale pixel images to memory for a swath of main tether on the way down. We can send up a spool of patching material before the next night, use descending climber weight to stretch it, and descent energy to bond it.

VII. Pulley Tether to Stage Two

The bottom leg, from HS1 to S2 has too high a gravity field, requires way too much power, and darkness is far too long to use a photovoltaic climber. For this relatively short but very high energy consuming leg, we will power the climber with a pulley cable, not photons.

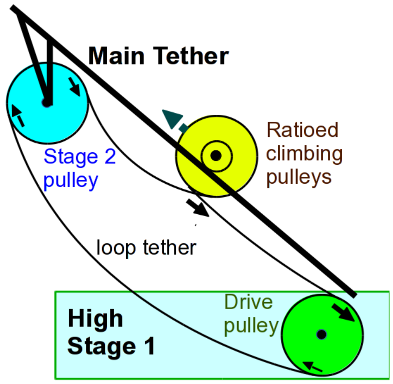

Fig. 6. Climbing with pulleys; a CNT loop driven power system.

Tethers are poor electrical conductors, but great mechanical energy conductors. An 800 g/km CNT tether moving at 2000 meters per second under full 27 MYuri tension can transmit 43 megawatts (!), far exceeding the power that an 800 g/km superconducting wire could move. Ideally, 43 MW can lift a 15 ton payload and pulley assembly straight up in a 9.6 m/s^2 gravity field at 300 m/s, and traverse 3000 vertical kilometers from HS1 to S2, an energy difference of 19.38 MY, in 2 hours, accelerating up to 650 m/s as gravity decreases to 4.48 m/s^2. We cannot achieve that ideal, but can manage 250 m/s. Gentle payload starts and stops will bring total HS1 to S2 link time to 3.5 hours.

Why run the loop tether so fast? The tether itself can certainly go very fast, it will not lift off the pulleys until the velocity exceeds the square root of the tensile loading in Yuris. For 27 MYuri loading at the Stage 2 pulley (Fig. 6), that is more than 5 km/s. Some lift on the top pulley is **exactly what we want** - this dynamic structure lift reduces the loading on the main tether. It would be even better if we could run the top pulley at 4 or 5 km/s, making the loop tether effectively almost weightless - but most mechanical engineer readers are cursing at this point. The clever ones might figure out a way to do it.

This system will still work with a loop tether moving at 1000 m/s, but the loop tether will carry twice the load, and mass will quadruple.

The payload, and the cable that supports it, hangs from the axle of the ratioed climbing pulleys, the yellow pulleys in Fig.6. The ratio of the diameter of the pulleys is 9 to 1. One rotation of the inner pulley moves the assembly up the main tether by one small circumference, while the loop tether moves downwards by the difference of the large and small circumferences, 8 small circumferences. If the loop tether is moving downwards at 2000 m/s, the tandem climbing pulleys move upwards at 250 m/s. The mechanical advantage between upward pulley motion and downward loop tether motion is 9 to 1. This reduces the force on the downleg of the loop tether by a factor of 8 over the force needed to push the climbing pulley and payload up. The main tether loading is sum of the downleg force plus the vehicle gravitational force, 9/8 of the weight of the climber on the 20° diagonal tether. $9/8 \times 15000kg \times 9.5m/s^2 \times cos(20°)$ The total 150.6 kN, about 78% of the 192.2 kN force that a 20 tonne climber and payload would put on the tether if lifted vertically from High Stage 1.

The loop tether will not be straight, and the modified catenary shape it will take in the nonlinear gravity field between High Stage 1 and the Stage 2 pulley will be complicated, not computed for this paper. At the start of the climb, the downleg tether below the yellow pulleys will have 1/9th of the main tether force - 16.73 kN - so it would weigh more than 16.73 kN / 27 MY, or 620 grams per kilometer.

If we assume the shape and the diagonal and a safety factor adds 60% to the mass of a 6000 km circumference vertical loop, the mass of the loop will be around 6 tonnes, and the weight per meter increases to about 800 grams per kilometer.

The average gravity on the loop tether is the energy difference divided by the vertical distance, 19 MY / 2900 km, 6.6 m/s^2 on 6000 km of 0.8 kg/km tether, 32 kN load at Stage 2.

Assume the stage 2 pulley and anchoring structure masses 3 tonnes, adding 13.4 kN to the attach point at High Stage 2.

The dynamic structure lift of the loop tether moving around the drum is -2 x 8E-4 kg/m x (2000 m/s)^2, or -6.4 kN at speed, nothing at rest. This will help when the payload is moving up fast up the main tether, but not at the start. Since the worst case load is when the climbing pulleys, payload, and loop tether are accelerating from a full stop at the bottom, dynamic force doesn't help us.

Accelerating the loop tether and payload will add inertial forces to the static support force of a lifting climber. The 4.8 tonne loop tether mass accelerates 8 times faster than the 15 tonne climber. Accelerating the pulley climber at 0.5 m/s^2 adds a 9.6 kN acceleration force on the main tether at HS1 (9/8 x 8.5 kN) and 19.2 kN at the S2 pulley.

The force supplied by the drive pulley is the acceleration force on the tether system plus 1/8th of the acceleration and gravitation on the pulley climber, 38.2 kN. The drive power is this force times the increasing loop tether speed, approaching 76 MW at 2000 m/s loop tether speed. After that, the sustaining power lifting the pulley climber is 250 m/s times the gravitational force, decreasing from 36 MW to 17 MW as the pulley climber ascends from HS1 to S2.

Reducing HS1 to S2 transit time is important, but an 80 MW power plant and wiring system, needed only a few minutes a day, is wasteful. Limiting power to 40MW slows the acceleration approaching full loop tether speed, but delays arrival at S2 by only one minute.

VIII. Paired Climbers

The reference design [1] shows a climber with huge hexagonal solar panels suspended by cables from a small climber. At low altitudes with high gravity, large panels will require considerable mechanical stiffness (and considerable structural mass!) to avoid collapse. At high altitudes near GEO, gravity is near zero. There are no forces to keep the cables stretched and the panels spread apart.

This paper's design separates the climbers and the payloads, and requires payloads to be winched from the climbers of one

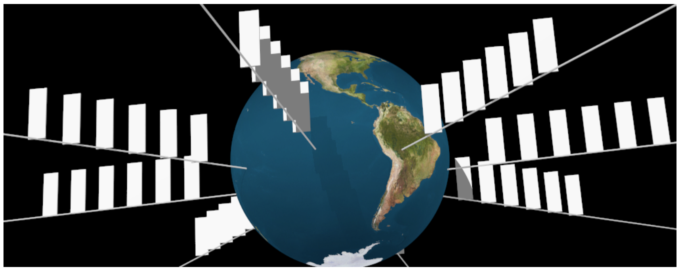

Fig. 7. Shading of photovoltaic panels near zenith. NOT TO SCALE. An idealized view of solar panels, north of a south-offset tether and oriented to the sun. Note that panels must turn 360 degrees to follow the sun throughout the day, and will shade each other when the sun is near zenith. Equinoctial shading at noon will be nearly total, unless the array is curved by coriolis or gravitational forces.

stage to the climbers of the next. Large panels would pose a challenging barrier to this transfer.

This paper suggests dividing the climber into two traction systems, with an upper tractor supporting the solar panels, and a lower tractor supporting the payload, with the solar panels in between, as shown in figure 8. Power is distributed to both tractors from the solar panels. More power to the upper tractor increases the vertical tensile force on the solar array in between, allowing electronic regulation of the tension.

The space elevator system has strength, and a lot of it, in the vertical direction. Holding a climber taut by stretching it towards the upper and lower ends, compressing the main tether a little bit, reduces strain in the main tether.

Using the main tether as the stiff central spar of a paired climber system, we can reduce cantilever stress with a long strip of many more and smaller solar panels connected in series, producing lower currents and higher voltages. A 12MW climber may have 25 hectares (60 acres) of solar panel. That is a PV strip one meter wide and and 25 kilometers high. We should segment the strip and tilt sections (with full 360° sun tracking rotation) to minimize solar angle cosine losses. To reduce shading at solar zenith, we can space the one meter panels 4 meters apart, making the whole array 100 kilometers high. The vertical array collects full sun power when the sun angle is within 15° of tether zenith, and 25% power within 3.6° of zenith, assuming the array is collinear with the tether, see figure 7.

The array will actually form a bow shape between tractors, pulled westward from the main tether by coriolis acceleration, a distance proportional to vertical climber speed and inversely proportional to tension on the PV array. A climber moving at 300 m/s at 3000 km altitude has 4.5 m/s^2 of vertical gravity force and 0.04 m/s^2 of coriolis force. This force is small, but will pull the solar panel strip hundreds of meters west of the main tether. The main inclined tether itself is tilted 6.5° degrees relative to gravity at this altitude, which will pull the cell strip many kilometers north.

Farther up, main tether inclination and gravity almost disappear, and climbers move upwards much faster. This increases coriolis forces and bows the array farther west.

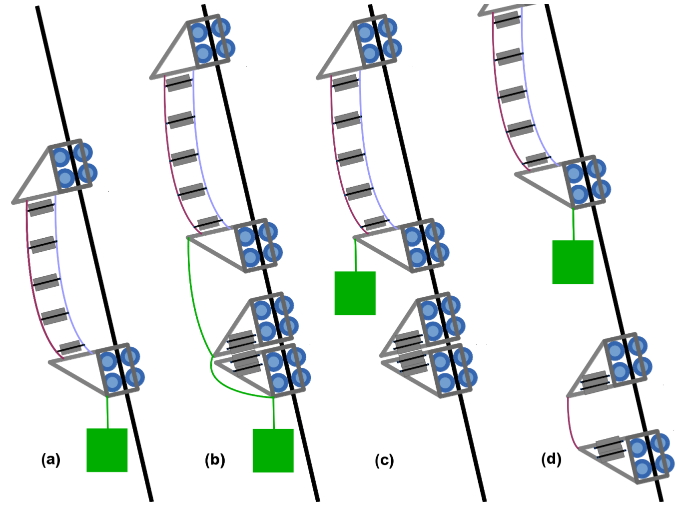

Fig. 8. (a) Climber pair with a solar array stretching from the upper to lower climber tractor. The climber's top tractor lifts the array and keeps it straight, also providing some lift on the bottom tractor, which lifts the payload. (b) Delivering payload to the next climber above. After stopping, the top tractor of the lower climber descends, and the descent energy is used to reel up the solar array, shortening the stack, while the upper climber descends to rendezvous. It lowers a cable to be attached to the payload cable. (c) The payload is gently hauled up to the upper climber pair. More cables on the lower climber pair (not shown) guide the payload. (d) The upper climber takes off upward - slowly, acceleration is limited. The lower climber descends more rapidly, accelerating under gravity, perhaps assisted by the temporary redeployment of some of the solar panels near GEO where gravity is near zero. It will then refurl the solar panels, extend the conductive descent tether, and start broadcasting radio energy, as described below.

IX. Optimizing Climbers For the Upper Legs

With many stages, and many legs between them, there are many ways to optimize the climbers for each leg. The upper climbers do not descend into full gravity, and if they are assembled and deployed from GEO, they can be ultralight, perhaps collapsing in full gravity. Upper climbers can have much larger components, such as solar arrays and wheels, since much less tether mass is required to support these enhanced high altitude climbers.

This design exercise was optimized for moving payload from High Stage One in less than 24 hours. This puts minimum speed limits on the climbers - there is a lot of vertical distance to cover. Gravity halfway to GEO is less than 6% of earth surface gravity, and the tether support mass is 2.15 kg/kg, less than 1% of the of surface tether support mass of 222 kg/kg.

This design assumes that pinch rollers can be massive and optimized for very high speed, 2000 m/s (!) for this exercise. This is not essential to the idea; if we can tolerate 40 hours (still much less than 168 hours) to GEO, we can add stages, and reduce maximum speed below 1000 m/s.

Climbers are assumed to have a minimum basic mass for core structure, electronics, winches, communication, cooling, etc. Increasing power (motor plus photovoltaics), speed (pinch wheel size and taper), or forces due to gravity and acceleration presumably increase climber mass.

The actual mass needed for each of these parameters can only be determined by detailed, clever design and empirical

Assumed climber mass coefficents	
More climber capability adds mass	
Crude and **NOT empirically validated!**	
Payload mass	14 000 kg
Minimum basic mass	1 600 kg
Mass per maximum acceleration	100 kg per m/s^2
Mass per maximum velocity	3 kg per m/s
Mass per generated power	250 kg per MW

TABLE III
CLIMBER MASS COEFFICIENTS

experience. The numbers chosen for this design are crude and preliminary, see table III.

Given these mass parameters, the stage spacings from above, some plausible guesses for the characteristics for each stage climber, we can calculate some values for cycle times, shown in table IV. One way of arranging these cycle times is shown in figure 9; schedules are optimized for HS1 to GEO transits of less than a day.

Many different combinations are possible. If longer transit times are acceptable, climbers at higher stages can move more slowly and carry more than one payload at a time; above stage 4, payloads weigh a fifth of what they weigh further down. We can choose more stages, shuttling up and down more than 3 times a day. The stages will not be not fixed points in space, so the staging altitude can be adjusted up and down, compensating for unforseen delays.

The less-than-24-hour scheduling shown is suboptimal for throughput; ideally, we want to schedule all climber downward transits at night, and make maximum use of the daylight hours for climbing. To minimize load on the main tether, idle climbers should wait at the highest altitude possible, descending only for scheduled pickups at lower altitudes. We will not need solar power for descent from stages 5 and below; we can do so during darkness. There is zero downwards acceleration at GEO, where gravity and centrifugal acceleration balance; that climber will need solar power to accelerate to full descent speed.

Highest revenue results from keeping the pipeline full. There should always be a manifest of lower value payloads waiting at High Stage One. If nothing else is scheduled, haul tanks of water up to GEO. Someday water may be useful for shielding, reaction mass, circulating coolant, or rocket fuel.

legs	S2-S3	S3-S4	S4-S5	S5-GEO
Stage and Gravitational Characteristics of climbers, semi-optimized for each Leg				
lower altitude (km)	3000	4927	7900	17786
upper altitude (km)	4927	7900	17786	35786
lower gravity (m/s^2)	4.48	3.06	1.88	0.55
upper gravity (m/s^2)	3.06	1.88	0.55	0.00
lower energy (MY)	28.6	21.4	14.3	3.9
upper energy (MY)	21.4	14.3	3.9	0.0
delta energy (MY)	7.1	7.1	10.4	3.9
tether cost (kg/kg)	48.56	25.26	11.74	2.18
lower tether angle (°)	6.48	4.12	2.50	0.98
Assumed Climber Characteristics				
climber mass (tonnes)	6.0	7.8	13.6	13.8
max. velocity (m/s)	300	600	1400	2000
max. acceleration (m/s^2)	5.00	4.00	3.00	2.00
solar power (MW)	12.00	16.00	30.00	24.00
Climber Behavior				
coriolis accel. (m/s^2)	0.04	0.09	0.20	0.29
lower coriolis angle (°)	0.56	1.64	6.20	27.76
upper coriolis angle (°)	0.82	2.67	20.23	90.00
electrical tether length (km)	2231	3268	5290	15968
lower descent power (MW)	8.07	14.31	35.78	15.29
upper descent power (MW)	5.51	8.80	10.55	0.00
max. descent power (MW)	7.92	13.83	31.52	13.11
ascent time (hours)	3.35	2.75	3.07	3.18
descent time (hours)	1.86	1.48	2.17	2.84
cycle time (hours)	5.21	4.23	5.23	6.03

TABLE IV
THE LEGS BETWEEN STAGES

X. RADIATION BELT REMEDIATION

High energy in the van Allen belts are deadly, but surprisingly scarce. The particles in the belts are moving at relativistic speeds and pack an enormous amount of energy, but if you stopped the protons and electrons and combined them into hydrogen atoms, they would barely fill a child's balloon. The particles move so fast that they fill a volume of space 200 times the planet with a withering bombardment of particles, each capable of ionizing or displacing thousands of atoms in ordinary material.

The particles are created by cosmic rays hitting the upper atmosphere, and by particles trapped from the sun. The outer belt is active and variable, the inner belt is long lived. The charged particles, mostly protons and electrons, are trapped in helical orbits by the Earth's magnetic field. Most of their motion is circular (see Fig. 10), circling at rates determined by the particle mass and the strength of the earth's magnetic field. Electrons can have high relativistic masses, but protons have more rest mass, and have much lower cyclotron frequencies.

The earth's magnetic field drops off with the cube of the equatorial radius, so the cyclotron frequencies of the particles drops off proportionally. Cyclotron frequencies for a 1 MeV electron at 3000 km altitude (9 378 km radius) is about 90 KHz, for a 10 MeV proton it is about 140 Hz. At GEO (42 164 km radius), the magnetic field is 90 times weaker, so the electron frequency is 1 KHz and the proton frequency is 1.57 Hz. More examples and explanation in this document [16].

The electrons do not just circle around the field lines in one place; they have some north/south velocity, too, so they travel helically along the magnetic field lines towards one of the magnetic poles.

The magnetic field increases as it descends towards the poles. As particles get closer to the surface, they reach a mirror point, where their trajectory bounces back along the field lines towards the other pole. Particles bounce back and forth, north to south to north again, about 1 to 10 times per second. Particles also drift east or west, circling the planet 5 to 100 times per hour. The protons drift westward, the electrons eastward, making an electrical current of a few kiloamps circling the globe. This **ring current** connects solar coronal

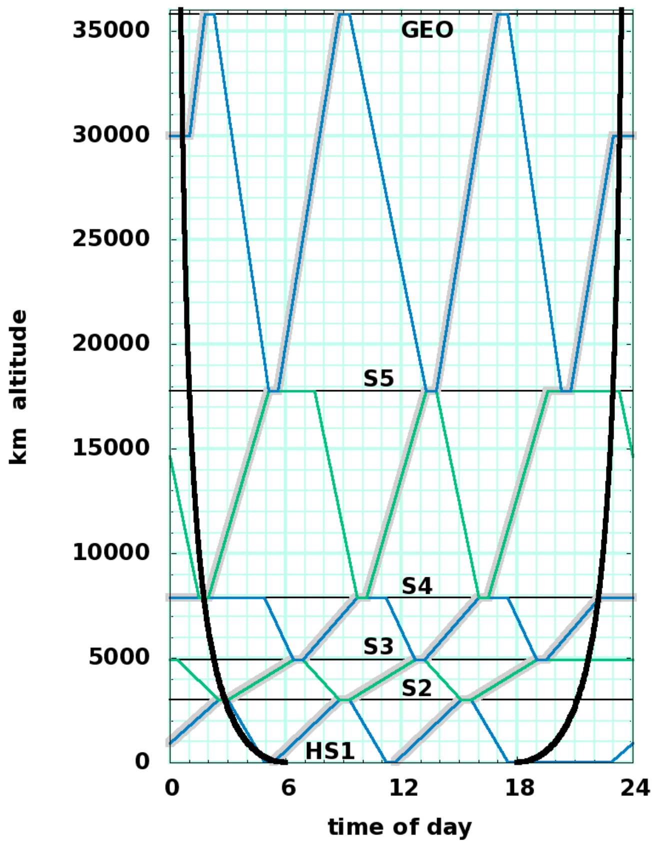

Fig. 9. Climbers cycling between stages, and transferring payloads between lower and upper stages. Black lines represent equinoctial dawn and dusk; more sunlight will available most of the year. Climbers stop climbing during darkness, adding to trip time. Three different payloads shown, with climb times of 18.1, 20.4, and 21.1 hours including overnight stops.

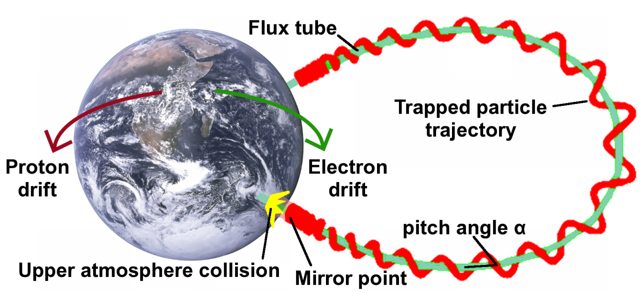

Fig. 10. Proton trapped in the Van Allen belt. Charged particles move in kilometer-scale helices around the Earth's magnetic field. The field grows stronger near the poles, bouncing particles in the other direction. If the pitch angle is decreased crossing the equator, the particle may collide with the atmosphere before bouncing.

mass ejections to the changes in the Earth's magnetic fields. Those changes induce the large DC currents that can damage terrestrial power grids during solar storms.

It is the magnetic field itself that protects the earth's surface from cosmic rays - the particles in the van Allen belt only weaken the protection somewhat. Eliminating those particles will protect space assets and astronauts, strengthen the magnetic field, and reduce the production of stratospheric nitrous

Cyclotron Frequencies and Wavelengths				
	1 MeV electrons		10 MeV protons	
eff. mass	2.69e-30 kg		1.69e-27 kg	
	2.69e-30	kg	1.69e-27	kg
	Frequency	Wavelength	Frequency	Wavelength
Stage	Hz	km	Hz	km
HS1	277 759	1.1	442.6	677
S2	89 449	3.4	142.5	2 103
S3	51 060	5.9	81.4	3 685
S4	30 182	9.7	49.1	6 106
S5	5 229	57.3	8.3	35 983
GEO	984	304.6	1.6	191 165

TABLE V
CYCLOTRON FREQUENCIES IN THE VAN ALLEN BELT

oxides. This will protect high stratosphere ozone, increase stratospheric heat radiation into space, reduce earth-surface UV flux, and cool the earth by a small fraction of a degree.

It is hard to imagine a downside of eliminating the radiation belts. However, if we attempt this, we must carefully observe what happens, stopping VLF broadcast and letting the belts regenerate if unforeseen consequences emerge.

Driving the particles with radio frequency energy just below their cyclotron energy causes them to increase their north-south velocity. That moves their mirror point below the top of the polar atmosphere, where they hit atoms, make a brief flash of aurora, and neutralize. It takes surprisingly little energy to do this. Although the ionosphere at about 300 kilometers altitude is an almost perfect reflector for low frequency energy, such as radiating losses from the 60 Hz power grid, or from lightning strokes, enough of this energy leaks through to create changes in the particle belts, effects observed by satellites. Although many mysteries remain in the radiation belts, we know we can change them a lot, because we have changed them a little already.

Space tether remediation systems have been proposed, such as the HiVOLT [17] system, based on long linear high voltage antennas made with tidally-aligned electromagnetic tethers. Unfortunately, high voltages attract charged particles in space plasma, creating a conductive plasma sheath that reduces the electric displacement field and coupling capacitance. A center-fed dipole may also produce high voltage arc discharges at the feed points.

Rather than transmit voltage, it is also possible to transmit magnetic fields with kiloamp currents in hundred-meter-scale loops [18]. The radiation resistance of such loops will be small, on the order of $R_{rad} = 10\ \mu\Omega$, coupling on the order of 100 W of VLF energy into space. Even this small amount of power can significantly deplete the radiation belts in time.

So, what does this have to do with the space elevator?

Descending climbers must shed 28 megajoules per kilogram between GEO and Stage 2 at 3000 km altitude. Instead of wasting this energy as heat, generator-connected climb motors on the climber pairs can drive a connecting tether with kilovolts and kiloamps of low frequency AC power. Descending at high speed, the connecting tether will pushed far to the east by Coriolis acceleration. If a conducting tether connects the pairs, this will create a large loop that can broadcast some of the AC power as very low frequency radio waves.

Coriolis acceleration can be used to deploy a loop of wire eastward from high stage descending climber pairs, and gravity forces on the inclined tether can deploy a loop downwards from low stage descending climber pairs. A vertical loop 500 kilometers high (much less than the support length in low gravity) and tens of kilometers wide near the bottom has far higher radiation resistance and radiative efficiency than sub-kilometer high current loops. Many megawatts of descent energy can feed the loop, and even though most of the power will be wasted on ohmic heating, many kilowatts can be converted to radiated energy, at whatever frequency we decide to make with our motors and power converters.

How big a loop can we make with the tether? At lower altitudes, the inclination of the tether makes the gravitational vector tilt north by more than 2.5°. At higher altitudes, with faster descent and less gravity, coriolis acceleration tilts the gravitational vector eastward by more than 2.5°. The vector sum of the tilts rotates by 90 degrees from west to north as the climber descends, 90° at GEO, to a minimum of 3.6° at stage 4, to 6.5° at 3000 km altitude (Stage S2).

Assume the lowest climber will descend toward stage 2 ° down the main tether angled 6.5° from gravitational vertical. The tangent is 0.11; over a 500 kilometer vertical distance, the tangential "droop" will be 57 kilometers. Gravity is approximately constant over this vertical distance. A minimum-force half-catenary tether shape minimizes stress but reduces the spreading to 25 km, as shown in Fig. 11.

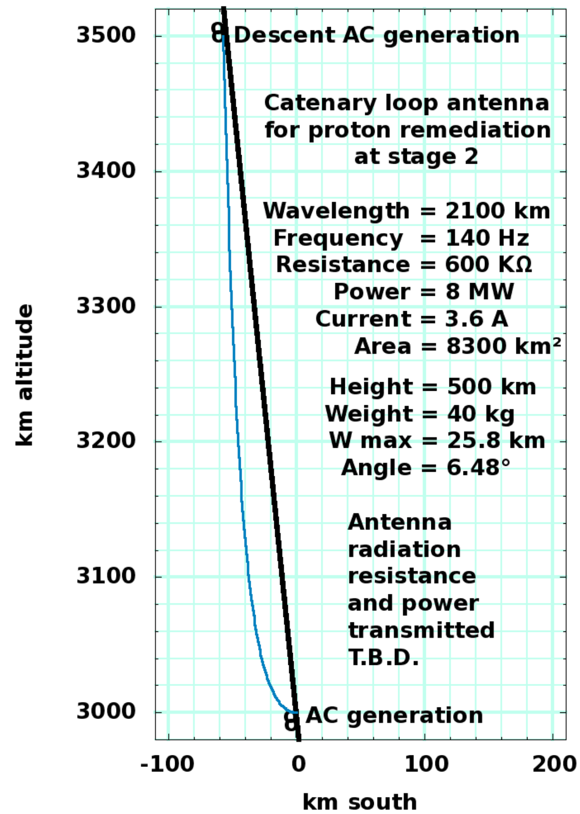

Fig. 11. Half-catenary loop antenna using climber descent energy for radiation belt remediation.

This loop will have an area of 8300 km^2, 50 000 times the area of the 220 meter radius round loop described by [18]. The enormous space elevator tether and loop will couple energy far better than the smaller loop; radiation resistance (and efficiency) is roughly proportional to the square of the area. Even though the currents will be 200 times smaller, the larger loop will radiate far more energy to remediate protons near their resonant frequency of 140 Hz (see table V). Electrons, resonating at 90Khz, will couple efficiently with a much smaller loop. The spacing and currents in the loop can be adjusted to different values for different descent profiles.

The actual calculation of the radiation efficiency, and the speed with which it removes particles at different altitudes and frequencies, is beyond the scope of this paper.

XI. Wasting Lots of Descent Energy: Option 2

But what if the pair-connecting tether, or the solar panel string, breaks? We can drop high stage climbers from above, and pull the broken climber tractors up to GEO for repair. That will be slow, as these high climbers will be working in higher gravity environments they are not designed for.

The broken climber tractors can go back down; there will be plenty of gravitational energy for that. In fact, there will be way too much, and the climbers, with limited heat radiation capability, must move down very slowly or they will overheat.

The launch loop has a similar problem on the pulley loop elevator from the surface to the 50 km altitude launch platform [19]. The pulley loop will run continously at 500 m/s. 5 tonne payload capsules must accelerate quickly to match speeds. Capsules ride on racks (like simple climbers), racks ride on pinch wheels on the elevator tether, and pinch wheels drive generators. The velocity mismatch (initially 500 m/s) times the acceleration (3 gees, 30m/s^2 times 5000 kilograms, 150 000 newtons) creates 75 megawatts of drag power, decreasing to 0 MW over 25 seconds, 940 MJ or 260 kW-hr.

What to do with that energy? The electrical power will load-matched to eight long tungsten ribbons, each 30 centimeters wide and 5 meters long, with a highly reflective mirror between the ribbons and the rest of the system. The tungsten ribbons will heat up to 3000 K, like the filaments of a huge incandescent light bulb. Assuming a black body emissivity of 0.8, the ribbons will emit 3.6 MW/m^2 on both sides, producing 75 MW of heat and light, 1.2 billion lumens, as bright at 20 kilometers distance as the full moon. Intensity drops to zero as capsules reach full speed at 6km altitude. That will be one heck of an aircraft beacon!

The same technique can be used, in an emergency, on a slowly descending climber tractor. Descent motor/generators will drive 10 MW into a redundant array of mirror-shielded tungsten filaments, broadcasting heat and light away from the climber and tether Dissipating up to 100 MW-hr will take many more hours than a normal power-broadcasting descent. The connections to the heater ribbons will pass a lot of heat; descent-powered refrigerators will be required to dispose of it, adding more weight to this backup descent system.

XII. Conclusion

Some problems with the existing space elevator reference design have been identified here - unacknowledged material and bearing assumptions, electrostatic bearings that may not work, huge cantilever photovoltaic panels, and climber descent energy with nowhere to go. The vast range of environments encountered by a climber from near the surface to GEO severely compromises the "one-climber-fits-all-altitudes" design. High gravity and low solar illumination during the first two days of ascent slows a photovoltaic climber to a crawl. Gravity puts way too much stress on the bottom of the main tether, and on the climbers themselves. Low speed raises travel time to a week, and lowers payload throughput to 14 tonnes per day. Throughput is further reduced by service interruptions to return climbers to the surface for re-use. Tethers running vertically from the equator encounter too much surface weather, make climber orientation difficult, and block useful orbits.

A main tether offset to the south avoids weather and equatorial orbits, while providing useful lateral forces for orientation, auxiliary tethers, paired climbers, and long strings of meter-scale solar cell panels, instead of hectare-scale platforms.

The diagonal allows the deployment of hanging tethers separated by tens of kilometers from the main tether, which can be deployed without tangles. That permits a "second stage" pulley power system, which can rapidly raise payloads to 3000 kilometers above the surface, reducing gravity and climb energy more than half, support tether mass for the lowest photovoltaic climbers by a factor of five.

A four stage solar-powered climber system, handing off payloads between altitude-optimized climbers three times per day, triples throughput, eliminates the need to return every climber to the surface, and permits ultralight climbers optimized for faster climb speed in low gravity environments. This leads to travel times from High Stage One to GEO of less than a day.

Splitting climbers into tractor pairs, with solar cells and auxiliary tethers strung between them, will use the main tether as a free compression member in tall, skinny structures. This will save mass and preserve orientation in low gravity near the geosynchronous upper terminal.

During descent, increasing the vertical spacing between tractor pairs will permit the deployment of very long broadcast antennas, emitting very low frequency radio waves that will eliminate the particle radiation belts surrounding the earth, improving both the space and terrestrial environments. Reduced climb times and greatly reduced radiation will permit human passenger operations without heavy shielding.

This paper is not a precise description, but a door to new possibilities and a stimulus to the imagination of others. With more inventions, and optimization by logistics professionals, it may be possible to squeeze ten times more throughput out of the same 8200 ton main tether and apex mass, leading to far faster exponential growth of space launch capability.

The C programs, spreadsheets, and plot formatting software that went into this paper, as well as copies of the openly available documents that informed it, will be available at the launchloop.com website [20].

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