A Solar-Based Space Elevator Architecture

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Abstract

This paper discusses a climber design that derives a large fraction of its power from direct sunlight conversion. This concept is enabled due to recent advances in photovoltaic technology. While presenting some challenges, this design relaxes the requirement on the power beaming system considerably and offers much increased power levels to the climber, enabling faster motion and increased system throughput.

As explained in "Space Elevator Feasibility Condition", this in turn relaxes the requirements on the ribbon material through a general throughput-lifetime-strength relationship developed there. Finally, since solar-optimized PV panels have great utility at GEO, they can under some situations be counted as payload, further increasing the viability of the system.

1 Motivation

As was argued in [7], the weaker-than-predicted properties of CNTs can be compensated for by a more capable power system. A possible candidate for such a power architecture is the Solar Augmented climber – a hybrid laser/solar climber design capable of achieving 10 times the power levels possible with power beaming. The enabler for this design is the recent development of very low weight thin-film photovoltaic technology, able to provide as much as 5 kWatt/kg.

Figure 1 shows a self-deploying solar panel demo – weighing 32 kg (with deployment hardware – labeled 1) and able to provide 50 kWatt of electric power under A0 illumination. The array size is 20m x 20m, and so operates at slightly under 10%. The power density of the complete panel (foil and booms) is 1.6 kWatt/kg. The superstructure weighs as much as half the complete panel, and the combined mass-area density is 0.08 kg/m^2.

It is reasonable to expect the efficiency level of such panels to increase to around 20%, and to be able to keep at least the same structure-to-foil weight ratio as we go to larger panels. It will be a challenge to keep the same mass ratio for a 1-g structure, but as we'll show below, this is possible.

Figure 1: Space Solar Panel Demo

Moving forward, we'll assume an overall power density of 2.5 kWatt/kg, a mass density of 0.1 kg/m2, and a raw collection efficiency of roughly 20%. With these parameters, a 1-ton panel provides 2.5 MWatt of electricity, though is more than 100 m in diameter. For a mere 8 tons, we can provide the climber with 20 MWatt of climbing power!

Section 2 deals with the interactions of the solar-powered architecture and the 24-hour day-night cycle, which establish a unique set of constraints on the system.

Section 3 deals with the challenges of deploying and controlling very large solar panels in variable gravity. In the panel shown, the deployment hardware weighs more than half of the total mass. Using gravity to help in the deployment, we can do better than that.

2 Night and Day

While a set of several solar panels can give the climber very large amounts of power, they can only do so when illuminated. Regrettably, at the equator in LEO, illumination only occurs 12 hours a day. Since we can get higher power levels during the day, it is advantageous to launch the climber at sunrise, so the large amounts of power are available when needed most. When night falls, our choices are to either wait till the local dawn, or continue moving using power beaming. Hopefully, we'd have traveled far enough by then that power requirements have dropped significantly, and also the length of the night has been reduced.

We therefore know that climbers launch exactly once per day, and the only remaining question is how much payload they carry. This is determined by how heavy the power system is, and how far the climber is after 24 hours, when it is time to launch the next climber.

Figure 2 shows the difference in illumination between the seasons. (The two top views are looking down at the ecliptic plane, and the bottom two views are edge views). At 6 am local time, the elevator (not shown, located directly behind the Earth in the edge views, pointing into the page) hits sunrise, and at 6 pm (shown in orange) the anchor station hits sunset. The climber, located further up the ribbon, sees sunset at a later time as will be explained further below. Midnight is shown in black. The season can thus be characterized by the angle θ of the sun from the vertical at noon, ranging between 0 and 23.5, and only the absolute value of the angle matters.

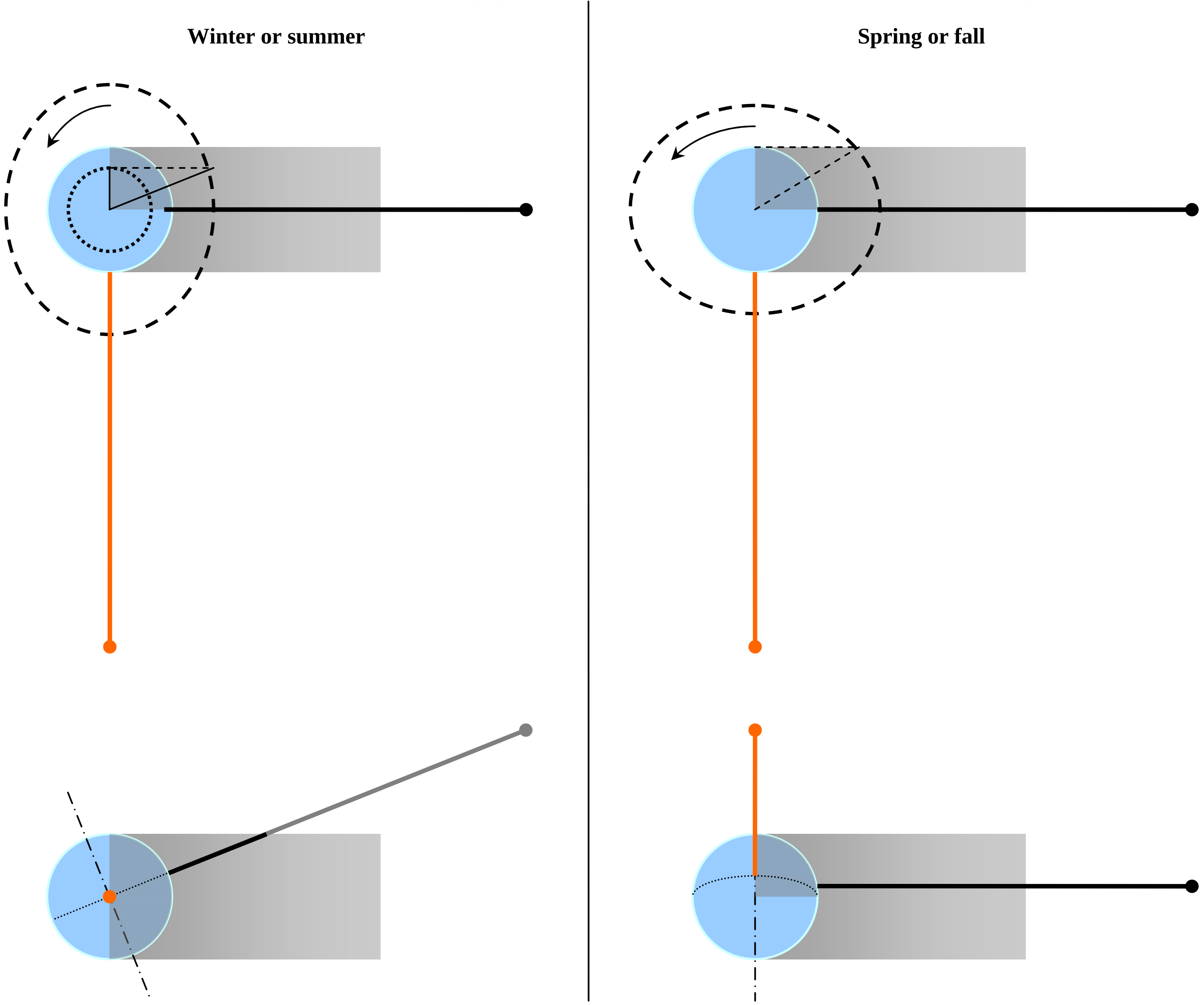

Figure 2: Illumination scenarios (Sun is at left)

In winter or summer, sunrise and sunset are coincident with the ecliptic plane, whereas in fall or winter, midnight and noon are. Sunset for the climber occurs well past 6 pm for two reasons: First, having traveled a certain distance d, the climber is located at radius R = r_e+d, and so it does not have to orbit 180° to clear the night side; Second, as a function of θ, the climber at sunset is located away from the ecliptic and so sees a smaller portion of the Earth's shadow, corresponding to the Earth's radius at that solar latitude.

The earliest sunset time for the climber occurs when it coincides with the ecliptic plane, a situation that occurs 4 times a year and is shown on the left hand side of Figure 3. This is easily shown to take place $t_d = 24\cdot[\arcsin(r_e/R)/2\pi]$ hours before midnight. Note that in this worst-case scenario, even at GEO the climber will experience a brief period of darkness – about 35 minute.

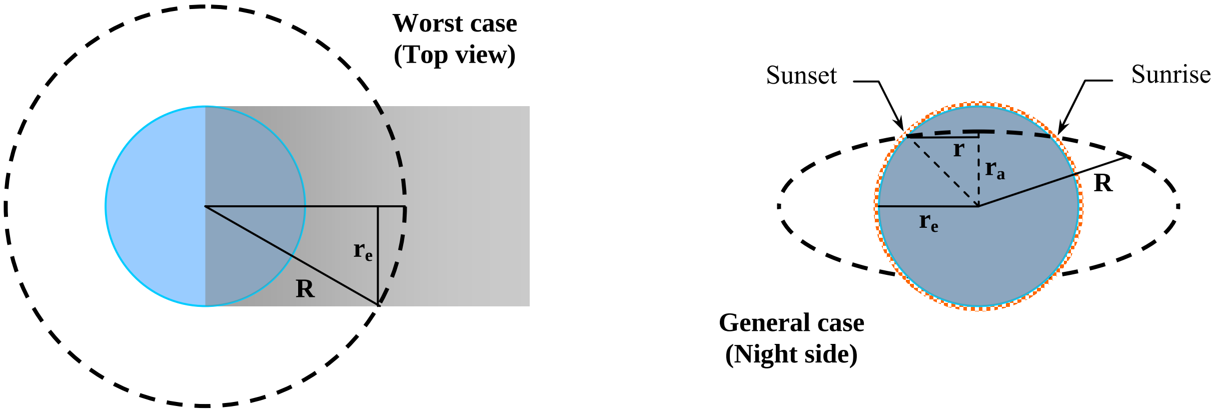

Figure 3: Night Shortening Effects

For example, considering a climber that covers d=4000 km in the first 12 hours (92 m/s), t_d works out to be approximately 2.5 hours.

Of course d and R are functions of t as well (since the climber, having won more sunlight time, is now busy climbing, buying itself yet more time). A climber that starts out at 6 pm at a distance d_6 (and radius R_6) and moves at a steady speed v km/hr is located at time t hours before midnight at $R = R_6+v\cdot(6-t)$. We can also estimate $d_6 = 12\cdot v$

The solution is numerical, and the results are summarized below:

v	m/s	avg. speed	60	70	80	90	100
d6	km	distance at 6 pm	2592	3024	3456	3888	4320
t	hours	sunset before midnight	2.75	2.56	2.39	2.25	2.12
sunset	time	local time of sunset	21:15	21:26	21:36	21:45	21:52
d	km	distance at sunset	3294	3891	4494	5103	5716
R	km	radius at sunset	9672	10269	10872	11481	12094
P	%	% LEO power for laser	43	38	34	30	27
d morning	km	distance at 6 am	5184	6048	6912	7776	8640
R morning	km	radius at 6 am	11562	12426	13290	14154	15018
P morning	%	% weight on ribbon	30	26	22	20	17

Table 1: Sun schedule as function of climber speed

The general case is a bit more complicated, since the climber describes an ellipse that crosses the earth as described in the right hand side of Figure 3, and clearly $r = \mathrm{sqrt}(r^2-r_a^2)$. The precise form for the value of r_a is a bit complicated, but a good approximation (and upper bound) uses $r_a = R\cdot\sin(\theta)$, In this case, for θ=23.5 and d=4000 we get r_a=4138, and r = 4853. To a good approximation we can use the newly calculated r instead of r_e in the in-plane equation, which for the case of v=100, adds another 17 minutes of daylight. Since the effect of θ is relatively small even in the best case, (max θ, max v) we will ignore it.

The seasonal effect can be mitigated by moving the anchor station a significant distance (2000 – 4000) along the East-West direction four times a year, so we're never operating in the worst-case scenario.

The conclusion is that the first night period will last between 4 and 5 hours, and the laser beaming system, in order to keep the same climbing speed, has to supply between 27% and 43% of the climber's LEO power requirement (at full speed). The climber will emerge from the first night at approximately 2 am, and will normally not go into darkness again.

At 6am, when the next climber is ready to go, the ribbon will have between 70% and 83% of its capacity available. Notice that the slower the maximum travel speed is, the more critical the function of night power beaming becomes. At 60 m/s, power beaming more than doubles the distance the climber covers by the time the next climber can be launched.

The upshot is that for slow climbing speeds, using power beaming to gain ground during the first night period is advantageous. If the climber can keep high average climbing speeds (>80 m/s) then the benefit of power beaming is much lower.

3 Climber design

The main challenge is designing a solar climber is the very large and flimsy nature of the panels. Typical in-space structure benefits from the lack of an atmosphere and the lack of gravity. In our case, we do not have the latter advantage, and must design the structure to withstand 0 – 1 g, and be tiltable as well.

Figure 4 shows the basic concept. Each panel's shape and position are completely determined by a large number of marionette-style pull-strings that suspend it against gravity. Except for the top panel, the panels are simply supported by the strings.

The top panel has to withstand compression forces. The longer the distance between the climber and the first panel, the smaller these force become. Inflatable or foam filled tubes can act as stiffeners without breaking the mass budget.

The distance between the panels is 3-4 times their diameter, corresponding to a shading angle of 14-18 degrees. This distance can be reduced at the expense of not getting optimal sun tracking around local noon time. Since the panels can only tilt 90 degrees, they need to convert light received on either side.

Since the system has to function in zero g as well, a trailing "caboose" car keeps a minimal tension in the strings as necessary.

3.1 Gliders

Each panel is assembled around a ribbon glider (Figure 5) that prevents contact with the fast moving ribbon. The glider is connected to the panel by a number of radial tension wires that can only transmit transverse loads. The glider does not carry the panel nor is carried by it, and does not control the tilt angle of panel.

Since the panels are so much heavier than the ribbon, and since the ribbon cannot exert sideways tension-related forces, the gliders force the ribbon to conform to any transverse motion the panels may exhibit. (Rather than move the panels to conform to the position of the ribbon.)

Each glider consists of a round cavity whose circumference is slightly larger than the width of the ribbon. For a 1 m wide ribbon, the cavity is about 33 cm in diameter.

To assure separation, we make sure that the ribbon is electro-statically charged before it gets to the first glider. This may already be the case due to solar wind or radiation, but if it isn't, it is easy to achieve artificially. The glider ring is then charged too, so it repels the ribbon. A back-up gas cushion system can keep the ribbon from touching the glider if the primary system fails.

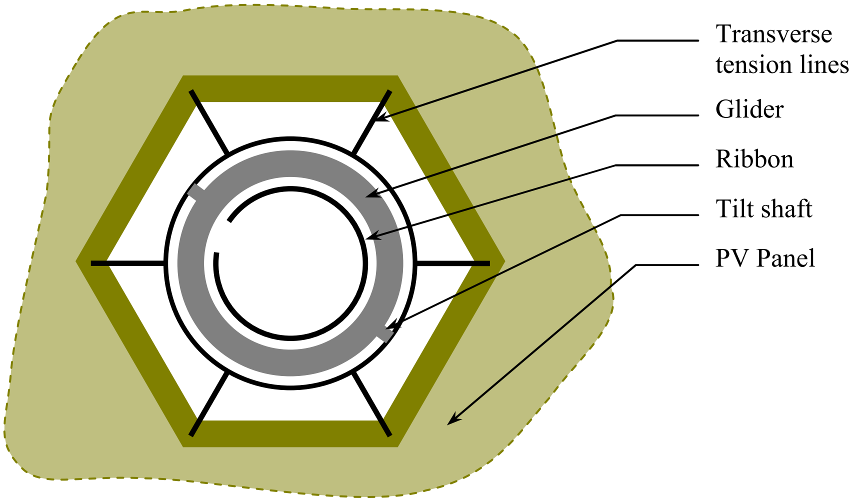

Figure 5: Glider structure

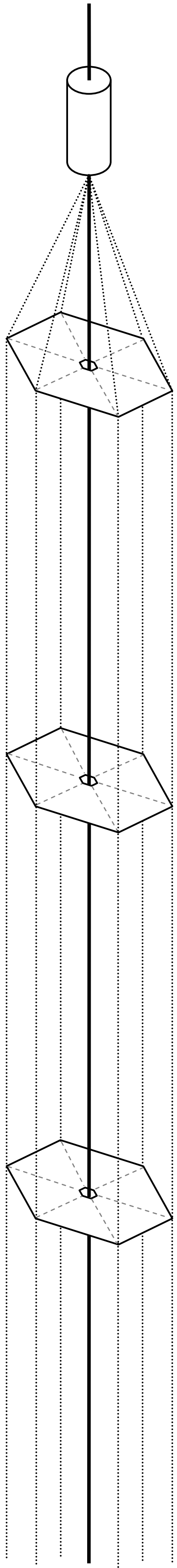

Figure 4: Solar Climber Structure

3.2 Deployment

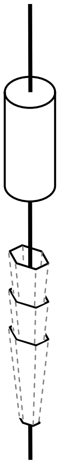

Figure 6: Stowed Panels

The foil panels obviously cannot function inside the atmosphere. During launch, the panels are folded upwards like upside-down umbrellas (Figure 6). The six radial diagonals are folded up until almost vertical, and then the extra material, in the form of six doubled-up triangles, is wrapped around the newly formed core.

The core is left as a narrow cone rather than a straight cylinder, so that multiple panels can be nested like ice cream cones. Deployment consists simply of releasing the lines in a controlled manner against gravity.

Deployment occurs once the climber clears the atmosphere, at an altitude of 50-100 km. Travel to the deployment point can be done using stored on-board energy, or by "church-bell" ascent – pulling the main tether down 50 km, attaching the climber, and releasing the tether in a controlled manner.

These activities are performed in the pre-dawn hours, so when the sun rises, the climber is deployed and ready to go.

3.3 Threading

The climbers, as described, encircle the ribbon completely, which raises the question of how we get them "threaded" on the ribbon.

A first option is to build all components with side slots, and build the climbers, (one per day) around the ribbon before they are launched. This requires a very complex just-in-time assembly operation at the anchor.

A second option is to have the ribbon anchored at one of two decks at the anchor station. While the ribbon is held at the upper deck, the climber is placed on the lower deck and the bottom of the ribbon is threaded through it. The ribbon is then held at the bottom deck below the climber, tension is transferred, and the top deck hold point is released so that the climber can ascend.

4 Odds and Ends

4.1 Power Beaming

Power beaming comes into play during the first night, since keeping the climber moving allows us to launch a heavier climber on the following morning.

In this context, the requirements for the power beaming system are relaxed considerably when compared to the original beam-power based design:

- Range is decreased from 40,000 km to about 7000 km, when the climber re-emerges into sunlight.
- The required target spot size is increased from 10 m to 100 m.
- Power density is decreased from 10 suns to 1 sun.
- Power requirements at nightfall are about 33% of what they were at launch.
- Power beaming only needs to support a single climber.

The full angle beam divergence required to cover a 100 m diameter panel at 7000 km is roughly 15 μRad, which can be easily achieved with a 1 meter aperture and 1 μm wavelength light. In this case it will make sense to split the power among several beam sources.

4.2 Initial Ascent

Since the foil structures will never survive even the slightest wind, a method must be devised to get to an initial height of 50-100 km. Multiple methods are possible, including "church-bell ascent" in which the tether is reeled in 50 km and then allowed to "float" back up, stored power, and even a very long pulley based system.

4.3 Space Solar Power

While the jury's still out on the viability of Space Solar Power, using sun-optimized light weight foil as a power source is very lucrative for such a venture. With a 20-ton Space Elevator, the climbers will lift at least 10-15 MWatt of electricity generation to GEO every day. That's up to 3.5 GWatt per year. For free. So if the facilities are there in orbit to attach the hexagonal foils to each other, very large flat foils can be easily constructed.

5 Conclusion

Solar powered climbers are a very different beast than their beam-powered cousins. They are a lot more gossamer-like, and “float up” mostly under their own power. From a power engineering perspective, they simplify the system considerably, and definitely lower cost. From a mechanical engineering perspective, they are very challenging.

A solar-based system can launch climbers weighing up to 85% of the ribbon lift capacity once every 24 hours, with a total trip time to GEO of 4 days. Since the larger mass throughput allows us to maintain a heavier ribbon, this improvement enables us to construct the Space Elevator from weaker materials.

Unless another technology comes along that can operate at multiple kWatt/kg, however, Space Elevator system designer had better get used to this technology.

6 References

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