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THE SPACE ELEVATOR PAYLOAD JOURNEY BEYOND GEO : CLIMBER CONCEPT AND OPTIONS

Peter Robinson
International Space Elevator Consortium (ISEC), United Kingdom, peter.robinson@isec.org

Abstract

The paper makes use of a spreadsheet-based analysis of the motion of a climber ascending an Earth space elevator tether The basic spreadsheet tool (previously described in paper IAC-22,D4,3,8,x68299 “Space Elevator Climber Dynamics Analysis and Climb Frequency Optimisation”) was extended to cover climber motion between GEO and the Apex Anchor, with the analysis output now including the required climber braking power (braking being necessary as centrifugal force exceeds the gravity force beyond GEO). The analysis assessed the impact of varying maximum climber speeds and maximum braking power on climber velocity and hence journey time to the Apex, the results of this analysis are presented. The effect of these variables on tether tension and consequential actions required at the Apex Anchor was also determined, presented and discussed. Consideration was then given to the climber configuration changes required for the journey beyond GEO, based on the climber configuration described in the 2021-2023 ISEC Study Report “The Climber-Tether Interface of the Space Elevator”. It was concluded that there was little benefit from using the multiple smaller climbers recommended previously for the ascent to GEO : the combination of the smaller climber modules into fewer larger assemblies would have minor detrimental impact and would permit heavier discreet payloads to be carried to the Apex. These larger climbers would each need fewer motors and drive wheels than for the ascent from Earth to GEO, but dissipation of the braking energy might require a new high-temperature heat rejection system. The climber ascent time to the Apex could be well in excess of 14 days, prompting analysis of alternative options for shipping of payload to destinations beyond the Apex : one alternative relies on high specific impulse drives being available for spacecraft departing the GEO node, avoiding the journey to the Apex. Review of existing drives concludes that existing systems (such as ion drives) do not have adequate performance, but a discussion of potential future systems concludes that these systems could be available in the timescale of Space Elevator construction.

Keywords: Space Elevator, Climber, Payload, Dynamics

1. INTRODUCTION

A space elevator is a proposed space transportation system, the primary component being a cable (referred to herein as a tether) anchored to a planet's surface and extending into space. The design permits mechanisms (referred to herein as 'climbers') to travel up the tether directly into space.

The primary function of any Space Elevator (SE) tether is to support the weight of climbers and enable motion of those climbers. A 1960 article by Artsutanov [1] first described how the tether would vary in cross-sectional area ('taper') with altitude : a 1975 paper by Pearson [2] included detailed calculations deriving the taper as a function of planetary and material parameters. Later studies [3] [4] continued this work, highlighting how tether stress could be held constant between the Earth's surface ('Earth Port') to the counterweight ('Apex Anchor') with tether mass also minimised.

The author's 2022 paper [5] described a spreadsheet analysis deriving the tether stress between Earth and GEO with multiple climbers in transit, with automated positioning of the climbers based on multiple variables such as climber mass, power, maximum speed and departure frequency. The analysis led to insights into how climber and operational concepts could be adjusted to maximise the payload raised to GEO for a given tether capacity.

This paper continues the above earlier work by assessing the motion of climbers travelling on from the GEO node to the Apex Anchor. The need for transporting payload to the end of the tether arises from the opportunity to release spacecraft from there on trajectories to the Moon or to other destinations outside the Earth's Hill Sphere, making use of the additional circumferential velocity at the higher radius. Apex release trajectories to interplanetary destinations are discussed in several papers, notably [6] [7] and [8] from ISEC and Arizona State University.

This paper assesses the requirements for a 'climber' ascending from GEO to the Apex assuming technologies similar to those of the climbers ascending from the Earth to GEO during the early years of space elevator operations : this means the climbers would be capable of operation on 'Initial Operating Condition' (IOC) tethers, not on the heavier tethers which could be available in later years. Thus the climbers are assumed to use a clamped-wheel interface with the tether.

Climbers above GEO experience a centrifugal force greater than that of gravity, meaning the effective 'weight' of the climber acts outwards (away from the Earth). The force F_i on a unit mass is calculated using Equation 1 below for a radius r, Earth gravitational constant GM_e and Earth angular velocity w.

$$F_i = GM_e / r^2 - w^2 / r \qquad (1)$$

Figure 1 below shows a plot of this force, shown as the effective 'Gravity' in 'g' units ($g = 9.80665\ m/sec^2$).

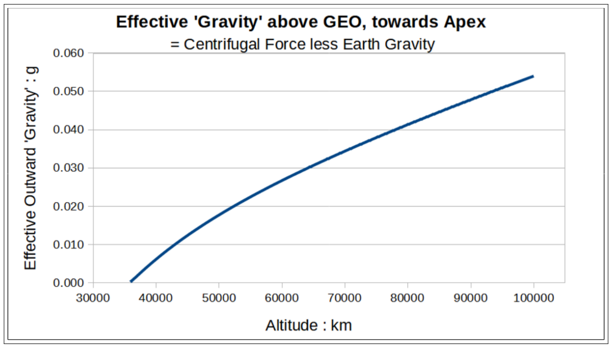


Figure 1 : Net Weight experienced on tether above GEO, subject to Earth gravity and centrifugal forces only

This means that one option would be for the 'climber' to be given some initial velocity from GEO and then travel to the Apex while being accelerated as shown above. Figure 2 below shows the climber velocity in this scenario, assuming no friction or other braking forces.

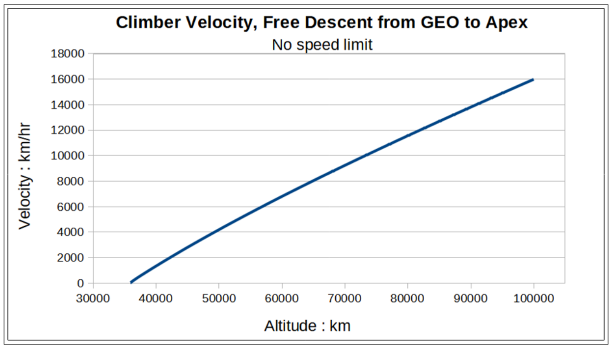


Figure 2 : Climber velocity 'falling' free from GEO with no braking and no speed limit : radial forces only, vertical tether with no Coriolis deflection

The climber velocity shown above is an approximation due to a number of simplifying assumptions : the tether is assumed to be vertical and totally rigid with no deflection by lateral Coriolis forces imposed from climbers. *(With moving climbers the tether would be deflected by an eastward Coriolis force, the resultant deviation from the vertical would then impose a small vertical force, but this force can be shown to be small.)*

Further more-precise analysis is of little value given the magnitude of the calculated velocity, 16000 km/hr being almost two orders of magnitude higher than the target capability of the tether climber interface (wheel or steering systems) required for the ascent from Earth to GEO, discussed in ISEC 2022/23 Study Report [9]. A radically different climber and/or tether design would be required to achieve such high speeds, perhaps a contactless system such as a linear induction motor (LIM) drive : this paper will assume that such a system is not feasible for early SE systems, and that therefore a 'Free Descent' from GEO to Apex is not practical.

This means that the climber velocity must be limited, so some form of braking system is required. It would be highly advantageous for the GEO-to-Apex climber to use a similar technology to the Earth-to-GEO climber, meaning an opposed-wheel system with electric motors as described in [9]. These ascent motors should be able to be used as brakes : it can be assumed that the steering and other systems could also be retained, yielding a similar maximum speed.

If the climber speed is constant then the full effective 'weight' of the climber is supported by the tether, leading to a discontinuity in the tether tension. The maximum feasible speed is perhaps 200-300 km/hr [5] [9], leading to a journey time to the Apex of over 10 days, meaning that multiple climbers could be on the journey at any one time.

This paper uses the simple spreadsheet methodology described in the author's earlier paper [5] to determine the impact of these multiple loads on the tether and discusses the consequential effect on the system dynamics. Alternative concepts for delivering payload to the Apex and beyond are then discussed..

Note that this paper considers the operation of early 'Initial Operating Condition' space elevator systems with a lift capacity of perhaps 20 tonnes gross daily from the Earth's surface [4]. Later systems will be more massive and have fewer logistics constraints.

2. METHODOLOGY

The method used a spreadsheet-based finite-element-type analysis with the tether divided into segments of variable length. Full details of this methodology were presented in the 2022 paper [5], and are summarised again here. Revisions to the spreadsheet for the tether region above GEO are also described.

This first calculation derived the element cross-sectional areas and stresses, then applied additional loading representing the weight of climber.

2.1 Tether Element Areas, Masses and Tension

The tether cross-sectional area was defined as before by a 'taper equation' first conceived by Pearson [2] and reformulated in 2013 by Swan et al [4] as Equation 2 below.

$$A_r = A_m * e^{(F*(1.5-(R_g/(r+R_e))-0.5*((r+R_e)/R_g)^2))} \tag{2}$$

where

$$F = D * GM_e / s * R_g$$

Equation 2 : Taper Equation defining tether cross-sectional area at altitude r (A_r) as a function of maximum area at GEO (A_m) , GEO radius R_g, altitude r, Earth radius R_e, tether material density D, Earth Gravitational Constant GM_e and tether stress s .

The spreadsheet used predicted properties for one candidate tether material, graphene super-laminate (GSL, formerly known as single crystal graphene) : chosen values were tether material density D = 2260 kg/m^3 and working stress s = 88 GPa . These values yield a tether sectional area as plotted in Figure 3 below.

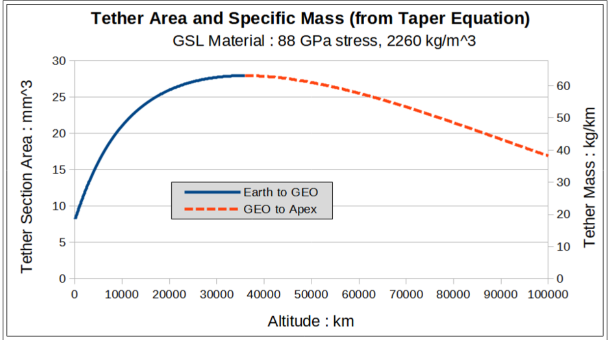


Figure 3 : Tether Section Area. The right-hand scale also shows the tether mass per km : the total mass for a 100000 km tether is 2795.1 metric tonnes.

The net force F_i on each element is the difference between gravity and centrifugal forces on the element, plus the force F_{i-1} from the element below, as shown in Equation 3 below for a mean element radius r, element mass M_r, Earth gravitational constant GM_e and Earth angular velocity w.

$$F_i = F_{i-1} + GM_e * M_r / r^2 - M_r * w^2 / r \tag{3}$$

The tensional stress was then simply derived from F_i and the element cross-sectional area A_i (Equation 4).

$$Stress_i = F_i / A_i \tag{4}$$

For the analysis of the behaviour above GEO the tension at GEO was fixed at the desired operating stress (nominally 88 GPa) by adjusting the tension force in the lowest element (F_1).

2.2 Climber Motion and Braking Power

For climber motion above GEO the spreadsheet used a variant of earlier calculations for the relationship between climber ascent speed and brake power, based on Equations 5 and 6 below.

$$Brake\ Power = Force * Velocity = Weight * Speed \quad (5)$$

or...

$$Speed = Brake\ Power / (Mass * EffectiveGravity) \quad (6)$$

As in the earlier work a logic function was used to derive the climber velocity as the minimum of the speed from the maximum brake power and the specified maximum climber speed, as shown in Equation 7 below.

$$Velocity = MIN\,(Calculated\ Velocity, Limit) \quad (7)$$

This limited the climb speed to the manually input limit value, a design constraint required in the low-weight region close to GEO and theorised to be based on multiple climber design factors.

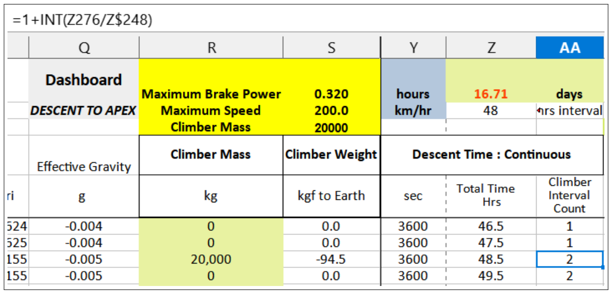
Manual post-processing of data from the spreadsheet was then used to study the relationship between the brake power and climber ascent speed, and on their impact on the time to ascend to the Apex.

2.3 Climber Placement : Continuous Climbing

Using the same methodology as described in the earlier paper for climbers below GEO, for climbers departing GEO in N second time intervals the weight of an additional climber was subtracted from the tether tension in elements where the 'Climber Count' increased in value. This Count was derived from a simple logic formula as shown in Equation 8 below :

$$Climber\ Count = 1 + Integer\,(Time / N) \quad (8)$$

Figure 7 below shows this equation embedded in the spreadsheet : in this snapshot the Count switches from 1 to 2 after 48 hours of climbing (the departure interval defined in the 'Dashboard' section) at an altitude of 39000 km, 3100 km above GEO.



=1+INT(Z276/Z$248)

	Q	R	S	Y	Z	AA
	Dashboard					
		Maximum Brake Power	**0.320**	**hours**	16.71	**days**
	DESCENT TO APEX	**Maximum Speed**	**200.0**	**km/hr**	48	hrs interval
		Climber Mass	**20000**			
	Effective Gravity	**Climber Mass**	**Climber Weight**	**Descent Time : Continuous**		
ri	g	kg	kgf to Earth	sec	Total Time Hrs	Climber Interval Count
524	-0.004	0	0.0	3600	46.5	1
525	-0.004	0	0.0	3600	47.5	1
155	-0.005	20,000	-94.5	3600	48.5	2
155	-0.005	0	0.0	3600	49.5	2

Figure 4 : Dashboard and Weight location logic

The above 'Dashboard' section for the spreadsheet above GEO is simpler than that used below GEO, with no provision for anything other than 24-hour ascent. The brake power and maximum speed values are used to derive the time on each element in the model as described in the earlier paper.

There is no need for the dashboard to show the peak tether stress as the weight of a climber reduces the stress above it, meaning the peak stress is at the GEO node. This GEO stress was set to the assumed working value of 88 GPa by adjustment of parameters below GEO : the details of these adjustments have no impact on the system above GEO.

2.5 Tether and Anchor Adjustment

Analysis of results led to the need to assess alternative tether taper and length options, achieved by making a copies of the main analysis spreadsheet and manually changing cells as required. For example :

- to model a constant-area tether the tether area equation in each element was simply replaced by a fixed number.
- to model a longer tether each element length was increased, this being far simpler than adding additional elements.
- to derive the required anchor mass for any tether length a formula was added on each spreadsheet row (corresponding to each element of the tether) derived from Equation 9 below.

$$Tensile\ Force = Mass * Acceleration \quad (9)$$

where 'Tensile Force' is the tension in the tether element, 'Mass' is the required Anchor Mass at that element location, and 'Acceleration' is the difference between centrifugal and gravity accelerations.

The results of this additional analysis are presented and discussed in section 3.2, 3.4 and 4.4 below.

3. ANALYSIS

Analysis was undertaken using manual inputs into the Dashboard, with outputs then copied to a separate sheet for further processing and interpretation.

3.1 Climber Speed and Braking Power

With a climber mass of 20 tonnes the required brake power for ascent velocities of 200, 250 and 300 kph are shown in Figure 5 below (based on equation 5).

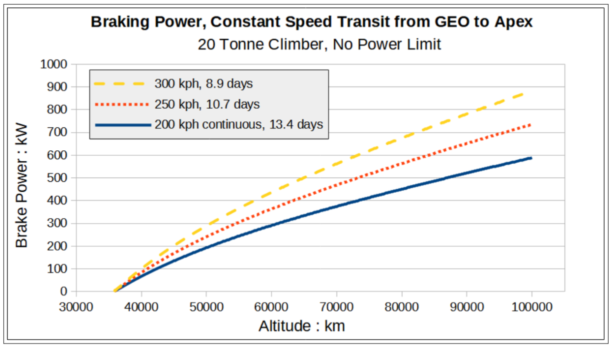


Figure 5 : Effect of Maximum Ascent Speed on required Braking Power and Ascent Time

The Ascent times above do not include the initial acceleration time leaving GEO or any deceleration approaching the Apex, but these will be will be small in comparison to the overall ascent times.

Figure 6 below shows the ascent time from GEO to Apex plotted against maximum brake power for three maximum ascent velocities.

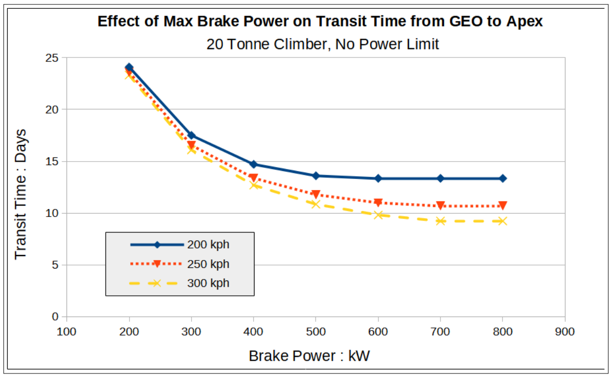


Figure 6 : Ascent Time .v. Maximum Power & Speed

The maximum speed that could be achieved during the ascent to the Apex is likely to be similar to that of the ascent from Earth to GEO, assuming the use of similar tractive technology and steering systems.

Note that even the lowest speed of 200 kph may be challenging, given that the tether will be a flat sheet of material too thin to permit edge loading, but it is a reasonable target value and will be used in further analysis.

Figure 7 shows the climber altitude plotted against time for a 'free descent' limited to 200 kph, now taking into account an initial acceleration assuming a departure from GEO at 10 m/sec.

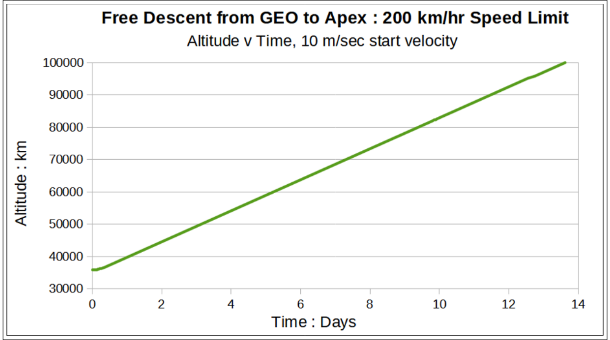


Figure 7 : Free descent from GEO, 200 kph limit

Figure 6 shows that with this maximum speed there is little benefit in brake powers above 400 kW. This highlights that a key design parameter for the GEO-Apex climber will be the heat rejection system required to dissipate the braking energy.

Studies of the Earth-GEO climber [5] [9] have assumed a heat rejection of 4% of the climber drive power : for a 20 tonne climber with 4 MW motors this means a radiator system capable of dissipating 160 kW. Consideration of Figures 5 and 6 leads to the conclusion that the GEO-Apex climber would benefit from additional energy rejection system above 160 kW if an ascent time of less than 3 weeks is required. If it was assumed that only half of the climbers ascending to GEO would continue to the Apex the radiator systems from two climbers could be combined on a single climber for the onward journey, yielding a maximum brake power of 320 kW.

Figure 8 below shows the brake power during the ascent with 160kW and 320 kW power limits : the ascent time from GEO can be seen to increase from 13.4 to 16.7 days with the 320kW limit, and to 29.5 days with a 160kW limit.

Figure 9 shows the ascent velocity with the same brake power limits, highlighting that the speed will reduce to below 110 kph approaching the Apex Anchor with a 320kW limit, and to below 60 kph with a 160kW limit.

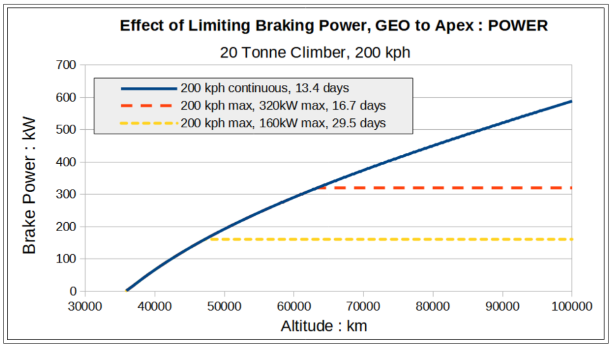


Figure 8 : Brake Power with limits

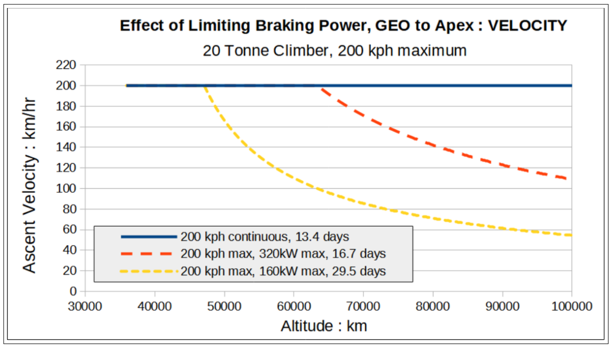


Figure 9 : Velocity with brake power limits

The conclusion of this analysis is that both maximum climber speed and power are key design parameters to minimise the ascent time to the Apex, a key factor given that one of the key benefits of the Apex Release strategy is the reduced transit time to destinations beyond Earth.

3.2 Effect of Ascending Climbers on Tether Tension

The effective weight of a climber above GEO (see Figure 1) will result in an increase in the tether tension between it and the GEO Node, assuming it is static or at constant speed. This means that if the tether is initially at its working stress, which for optimum efficiency will be the maximum stress within specified safety margins, then climbers ascending above GEO will result in a tether stress exceeding those safety margins.

Figure 10 below shows the tether tension with 20 tonne climbers departing GEO at 48 hour intervals : it shows a significantly higher tether stress at GEO if there is no change in the Apex Anchor. Also shown is the effect of reducing the Apex retention force (the Anchor mass 'weight') to restore the tension at GEO to the working stress limit of 88 GPa.

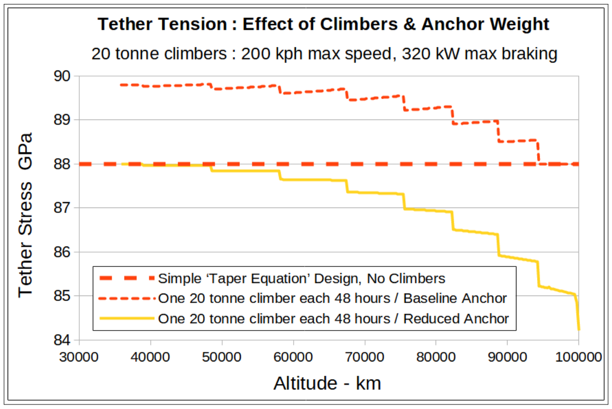


Figure 10 : Tether Tension Reduction resulting from constant-speed 20t climbers

The lower tension at 100,000km is insufficient to support the Apex Anchor mass of c. 2790 tonnes at that altitude, which (by the design of the unladen system) requires the full 88 GPa working stress to counter the weight of 1.48 MN. If the GEO stress is controlled (perhaps by lowering the tension at the Earth Port) the tension at the Apex would also fall, resulting in a force imbalance at the Apex : the Anchor would rise out to a higher altitude until equilibrium was reached at a higher tension : it would not be possible to achieve stable equilibrium with a GEO stress of 88 GPa.

(Note : The reduction in tether stress will also lead to a reduction in the tether strain. Given a Young's Modulus of 1 TGa the strain would be 8.8% at 88 GPa : the strain reduction with 20t climbers departing at 48 hr intervals at 200 kph would be around 50.6 km at the Apex. This reduces the Anchor effective weight by 0.06%, from 151.19 to 151.10 tonne-f : for the purposes of this study this small change can be neglected.)

Three options to maintain stability of the Apex Anchor with 20t/48hr/200kph climbers are as follows :

- **Maintain Anchor position using thrusters**. *The thrust required to maintain Anchor position and keep the GEO stress at 88 GPa would be of the order of 60 kN.*
- **Eject mass from the Anchor**. *An Anchor mass reduction of 113.4 tonnes (4%) is required to counter the weight of the nine 20t climbers distributed along the tether.*
- **Reduce the Anchor altitude**. *The Anchor would need to be lowered by approximately 1200 km, to around 98,800 km altitude.*

Considering **the 60kN thruster option**, comparison can be made, for example, with the BE-7 engine being developed by Blue Origin for their Moon lander. This has a maximum thrust of 44.5kN with a total fuel consumption of 54 kg/s of H_2 and O_2 and a (high) specific impulse of 400 sec : that mass burn rate would exceed the full mass of the Anchor in 14 hours. Future thrusters, perhaps nuclear or advanced ion drives, might yield one or more orders of magnitude better impulses, but even then the vertical thruster option is unlikely to be practical.

Considering the **Mass Eject** option, this would require some degree of certainty that ascending climbers would always be present on the tether. This means that if no further shipments to the Apex were required it would be necessary to despatch climbers with ballast mass to allow cargo already en route to complete their journey. This may be operationally possible, so this option cannot be totally discounted.

Considering the **Altitude Reduction** option, there are likely to be Reel-In-Reel-Out (RIRO) winches at the Apex Anchor for stability control to counter tidal and other vertical perturbations. The winch distance of 1200 km could be an order of magnitude greater than that required to counter tidal forces but appears to be feasible : a timescale of 16 days leads to a mean winch speed of 1200*1000/(16*24*3600) = 0.87 m/sec, which is not excessive.

Given an Anchor Mass of 2795 t and a net effective weight of 0.054g the winch force will be 2795*1000*0.054*9.80665 = 1.48 MN, leading to a winch power of 1.48*0.87 = 1.29 MW. This power is less than half of the daily power required to raise climbers from the Earth's surface and could therefore simply be supplied from a similar power source located at the Apex. If there were a suitable power transmission system the power could be transmitted from the climbers ascending from GEO, but it may well be more cost & mass effective to source the power at the Apex.

In summary, the weight of climbers travelling from GEO to Apex will need to be offset by some action at the Apex to avoid an increase in the peak tether stress, but this could be achieved by a combination of ejecting mass from the Anchor and winching the Anchor to a lower altitude.

The workings above cover the mitigation of 20 tonne climbers with a maximum speed of 200 km/hr and a maximum braking power of 320 kW leaving the GEO node at 48 hour intervals. Any change in any of these parameters would require a different response to stabilise the Apex Anchor : for example, Figure 11 below compares tether stresses with climber departure intervals of 24 and 48 hours.

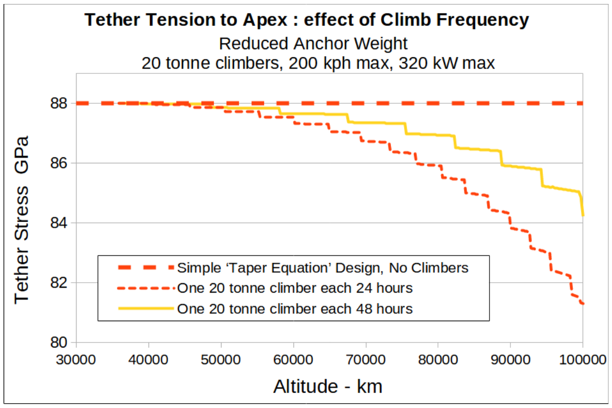


Figure 11 : Tether Tension with change in GEO departure interval

It is clear that more frequent departures would result in even more disturbance to the Apex Anchor stability and require additional mitigation action.

3.3 Climber Configuration Options

3.3.1 Design Overview

This paper concentrates on early operational Earth elevator systems. At this stage it must be assumed that the overall lift capacity to GEO is limited to approximately 20 tonnes gross per day per elevator tether, with the payload capacity fully dedicated to a range of key projects. This in turn means that the climbers that continue from GEO to the Apex should ideally have maximum commonality with the climbers that ascend from the Earth to GEO.

Earlier papers, notably [9] and [10], have described the Earth-to-GEO climber as a friction-drive machine with multiple opposing wheel pairs clamped on the tether and driven by electric motors. The climber is usually described as a 20-tonne machine with daily Earth departures with a power source often described as solar, but [5] has highlighted the payload benefits from multiple smaller climbers each day using some continuous power source. Section 3.1 above concluded that these aspects of the below-GEO climber are not directly relevant to the climbers above GEO : the smaller climbers could be combined into fewer larger climbers with no impact on tether loading or payload, and the input power source is of little importance.

The different design requirements for the climbers above GEO are the **brakes** and **heat rejection** systems. Other systems such as the chassis, steering and communications will be little changed from the below-GEO climbers, but safety and reliability are perhaps more important as a braking failure would lead to unchecked acceleration of the climber. (Below GEO a power failure results in the climber coasting to a halt.)

This paper assumes that **braking** can be achieved by using the electric motors that powered the ascent to GEO.

The required **heat rejection** function can be achieved by using the radiators installed on the below-GEO climbers to reject the heat losses from the lift motors and other systems. For a 20 tonne climber with 4 MW drive motors the losses have been assumed to be 4% [10], requiring a radiator system able to dissipate 160kW to space : even if multiple smaller climbers were launched from Earth each day the cumulative daily radiator capacity would be similar.

As also discussed in sections 3.1 above and 3.3.3 below, some higher brake power is ideally required to avoid a large increase in the transit time from GEO to Apex : departures from GEO every two days (on average) would mean sufficient radiator systems would be freely available at GEO, given daily climber arrivals from Earth. More frequent departures would require additional radiator systems, but whether such departures would be needed is a future operational decision that is outside the scope of this paper.

3.3.2 Motors / Generators

If the climbers ascending from GEO to the Apex are to use the same motors as used in the ascent from Earth to GEO then those motors must also be able to operate as generators, thereby acting as brakes to limit the ascent velocity. Most DC motors will have this functionality, so this is not seen as an issue.

If the total climb power of the climber(s) departing Earth each day was 4 MW then the total rated power of the motors arriving at GEO would be this figure or higher. The analysis in Section 2 shows that the generator power required for the climbers departing GEO for the Apex could be less than 400 kW for each 20 tonne climber : if each motor rating when operating as a generator was similar to the rating when acting as a motor then fewer than 10% of the motors arriving at GEO would be needed on the climbers above GEO.

The optimum number of motors on the climbers continuing the ascent from GEO may well not be as low as this 10% figure, but this depends on the ascending climber configuration. For example, if the 4MW ascent power is delivered by just eight 1MW motors driving four opposed wheel pairs then two motors may be kept.

Another consideration is safety : on the ascent to GEO a drive system failure would result in the climber coasting to a halt (followed by application of some ‘parking brake’), but on the ascent from GEO to Apex a braking system failure could lead to indefinite climber acceleration leading to wheel or steering failure.

Surplus motors could be removed at GEO for storage or for return to Earth to be used again. Alternatively they could remain on the climber as cargo to the Apex and onward to an interplanetary destination to support some other application.

3.3.3 Power Systems

The substantial power source on the climbers ascending from Earth would not be required above GEO, though a small power source would be needed to operate climber systems close to GEO (where braking power generation is very low) and if the climber needs to stop before reaching the Apex.

This report will not make assumptions regarding what climber power source would be selected. If the power source were solar panels then these could be removed and retained for use in the GEO orbit, or alternatively stowed and shipped as cargo to the Apex for onward transportation. Other power source types might also be retained at GEO or shipped off-world.

3.3.4 Heat/Energy Management

The simplest heat management system for the climbers **below GEO** would be a fluid radiator to reject the low-temperature waste heat from motors and other systems, operating at perhaps 400K [10]. : other power dissipation systems are feasible, but may not be selected for early climbers due to the cost, simplicity and technology readiness of radiator systems.

Above GEO the braking energy could be dissipated by electrically-heated high-temperature radiators, much smaller than the fluid radiators used below GEO. For example, if their working temperature was 1000K their size would be reduced by a factor of (1000/400)^4 = 39.06 (assuming the Stefan–Boltzmann law applies) : using the workings in ref [10] this yields a radiator area of 4.5 m^2 for 160kW heat rejection. Such smaller radiators appear to be a superior design solution, but suffer the penalty of additional cost and mass required only for the second stage of the journey to the Apex.

Whatever radiator system is chosen the maximum power rejection has a very significant impact on the transit time from GEO to Apex. Figure 12 below shows the travel time in days for three maximum ascent speeds plotted against maximum braking power.

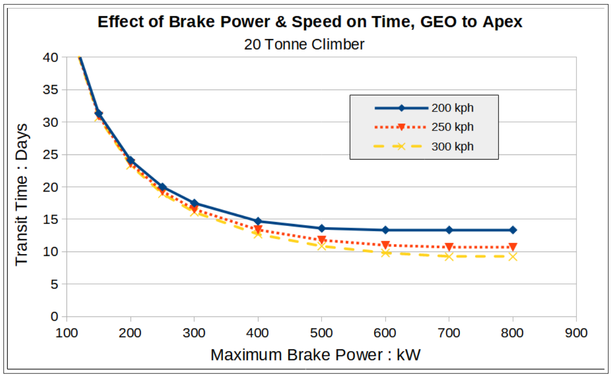


Figure 12 : Effect of Maximum Braking Power and maximum Speed on Transit Time to Apex

It can be seen that higher maximum ascent speeds lead to little reduction in ascent times unless high values of braking power (and hence heat rejection) can be achieved. The 160kW radiators alone, as used on the ascent to GEO, would clearly lead to a major increase in transit time : doubling this value to 320kW by combining the radiators from two sub-GEO climbers would be very beneficial and would not incur the cost or mass penalty of launching high-temperature systems.

For some cargos an increased transit time may not be critical, but it must be remembered that one reason for the Apex journey is to make use of the high release velocity and so reduce interplanetary transit times.

Other means of rejecting the braking energy may not have the limitations of a radiator system, for example power transmission along the tether itself. Such systems would only be of value if they were also used on the ascent to GEO, otherwise they would again suffer the cost and mass penalty of being raised from Earth.

3.3.5 Structure and Other Systems

The chassis, steering and emergency eject systems above GEO would need little change from those used in the ascent from Earth. Control and power management systems would need to be reconfigured to operate the motors as generators and feed power to whatever heat rejection system is being used : the capability for this reconfiguration should be included as a key design specification for the climber.

Another structural requirement is the ability to combine climbers into larger units, especially if multiple climbers depart Earth each day as recommended in [5]. This is likely to be a requirement before the departure from Earth to enable large indivisible payloads to be raised : even longer climber 'trains' might need to be assembled at GEO for the onward journey to the Apex to carry larger and more massive assemblies such as fully laden interplanetary transport spacecraft.

3.4 Effect of Anchor Release on Anchor Position

Some payloads despatched from GEO to the Apex Anchor will be carrying material for the Anchor itself, such as fuel for positioning thrusters or material for maintenance, but the majority of payloads are likely to be for release to beyond the Earth making use of the high relative Apex velocity as described in [6] [7] & [8].

Section 3.2 describes the result of an increase in mass at or near the end of the tether : payload release from the Apex will have the opposite effect, resulting in the Anchor being accelerated towards the Earth by what has suddenly become an excess tether tension force.

The released mass may be less than the gross mass of the ascending climber as material could be retained at the Anchor for many reasons, such as for ballast or as fuel for Anchor station-keeping. Whatever the step change in Anchor mass some mitigating action will be required for dynamic stabilisation, the opposite of that discussed in section 3.2 . The use of vertical thrusters would again be impractical, as would be sudden addition of some compensating mass, meaning that winching would again be required to maintain Anchor altitude stability.

A step change in the Anchor mass is also likely to result in oscillation of the tether system, which may include some variation in the tether stress at GEO. This means that the mean operating stress at GEO may need to be reduced to prevent oscillation peaks exceeding the operational tether stress limits, thus reducing the daily climber mass capacity for launches from the Earth.

4. DISCUSSION

4.1 Limitations of Analysis Methodology

The spreadsheet used for much of the analysis in this paper represents the tether as 'elements' in which parameters are constant, similar to a finite element analysis. Thus the accuracy is determined by the chosen element length, and by the rate at which variables are changing from one element to the next. This rate of change is lower above GEO for all parameters other than those related to a 'free fall' acceleration close to GEO, but all key conclusions are based on climbers travelling at constant speed.

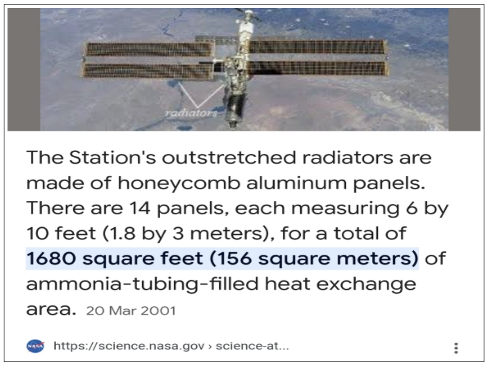
For a more detailed discussion on the methodology limitations see the author's earlier paper [5].

4.2 Climber Design

The analysis in sections 3.1 and 3.3 highlights the importance of adequate braking power capability at higher altitudes to minimise the Apex transit time, and hence the need for an adequate energy rejection system.

If 50% or fewer climbers arriving at GEO from the Earth continue to the Apex then one solution is to transfer surplus radiator systems to the climbers that are ascending further, this would minimise the need for some other radiator system to be raised from Earth as payload : all that would be needed would be some heating element to heat the radiator fluid using the generated braking power.

A problem with this approach might be the physical scale of the fluid-based radiator system : the 2022 ISEC paper [10] suggested that a 20-tonne climber might well require 160 m^2 of radiator system, this exceeds the total radiator area at present installed on the International Space Station (ISS) as shown in Figure 13 below.



The Station's outstretched radiators are made of honeycomb aluminum panels. There are 14 panels, each measuring 6 by 10 feet (1.8 by 3 meters), for a total of 1680 square feet (156 square meters) of ammonia-tubing-filled heat exchange area. 20 Mar 2001

https://science.nasa.gov › science-at...

Figure 13 : NASA summary of ISS radiator system

The radiators designed for a space elevator climber would be quite different from those on the ISS, given that they do not need to withstand launch loads but would need to operate continuously at 1g at the start of the ascent from Earth, but the size would be similar. Installation of a second set of such radiators on a 20 tonne climber while at GEO could be difficult from a simple space-claim perspective and time-consuming in a weightless environment.

It may be that the installation of even 160kW-scale radiators on climbers ascending from Earth to GEO might prove technically challenging or have unwanted compromises. One new technology that might result in a smaller radiator solution would be superconducting drive motors with an efficiency much higher than the assumed 96%. The feasibility of such motors is outside the scope of this paper, but they would result in there being no suitable fluid radiators available at GEO for the journey to the Apex.

An alternative to a low temperature fluid radiator system could be a high temperature radiator with direct electric heating. Such a radiator might only be a few square metres in area, depending on the possible working temperature.

Other heat rejection systems are possible, but all would need to be shipped from Earth to GEO as cargo. The system with minimum potential mass would be power transmission along the tether itself to either GEO or Apex nodes, but this would require a tether with at least two insulated conducting pathways.

Apart from the radiator systems there would be few major changes needed for climbers above GEO, assuming the motors were capable of operating as generators. The braking systems would need adequate redundancy for safety reasons, but it may be possible to remove surplus motors and wheels to minimise mass.

4.3 Apex Anchor Dynamic Control

Sections 3.2 and 3.4 presented an analysis of the impact of the weight of climbers on the tether between GEO and Apex, and on the effect of a sudden release on mass from the Apex. The conclusion was that a 'Reel-In-Reel-Out' (RIRO) winch system is needed at the Apex Anchor to compensate for the tether/node system imbalances that such transient operations will cause.

A full dynamic analysis is required to confirm the requirements, but it appears that the Apex Anchor cannot be the simple counterweight as is often portrayed. The RIRO system may well need to include winch motors with powers of many hundred kW, with associated power source and heat management systems. It must be noted that these systems would be less powerful than those of a single climber departing the Earth : the component that is unique to the Apex RIRO would be the winch wheel on which many hundred km of tether would need to wound.

There would be some similarities between the Apex RIRO and the Earth Port RIRO systems, but the latter would not have the mass and other design constraints of a system operating in the vacuum of space.

Without climbers ascending from GEO the Apex RIRO must only compensate for tidal disturbances, but these would be an order of magnitude less and may not even require a RIRO system at all : a full dynamic analysis is required.

4.4 Alternatives to Wheeled Climbers Above GEO

Sections 4.2 and 4.3 above highlighted the additional complexities associated with climbers travelling along the tether from GEO to Apex. Two alternative concepts address one or both of these issues, as follows.

4.4.1 No Tether Taper – Conveyor Ascent

The Pearson taper equation described in section 2.1 yields the cross-sectional area for constant stress in the tether under gravity loading alone. This taper is essential close to the Earth to prevent gravity loading leading to excessive stresses at higher altitudes, but above GEO it merely ensures a constant stress between GEO and the Apex. A tether without taper above GEO (i.e. with constant cross-section) would experience reducing stress as altitude increases and require a less massive counterweight for the same tension force at GEO.

With or without a taper, the length of the tether (the altitude of the Apex Anchor) and the mass of the Anchor are linked : a longer tether would require a lower anchor mass for the same tension force at GEO. Figure 14 below shows a plot of the Anchor mass, total Tether Mass and total system mass (Tether + Anchor) for varying Anchor altitudes with a constant-area tether above GEO and the same stress at GEO.

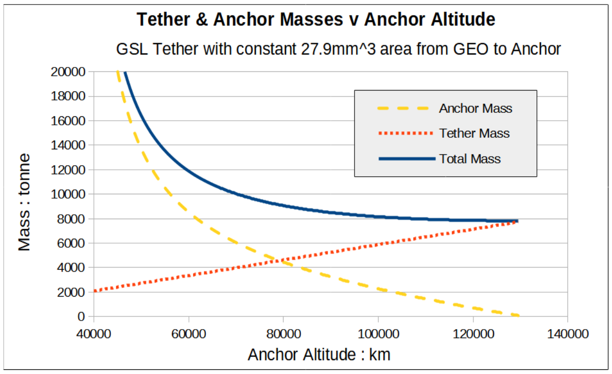


Figure 14 : Anchor and Tether Masses with constant area GSL tether

The calculated altitude for zero Anchor mass is 130,655km, but this is highly dependent on the assumed tether material properties and the chosen stress at GEO. It is perhaps more relevant to compare the constant-area masses with those for a taper with the 'standard' taper, as shown in Figure 15 below.

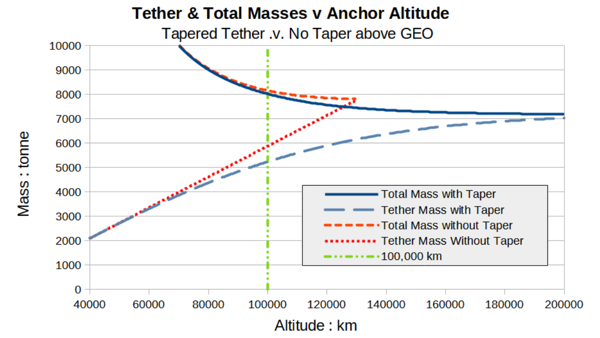


Figure 15 : Total and Tether Masses with tapered and constant area GSL tether

The transition to a tapered tether can be seen to raise the potential length of the tether to above 200,000km, (which potentially would further increase the release velocity from the Apex), although at extreme altitudes the Anchor mass (the difference between the Total and Tether masses) becomes small and could result in stability issues. Of greater interest is perhaps the small difference in Total Mass in the 100,000km region.

The purpose of this discussion is that the feasibility of a constant-area tether above GEO allows for an alternative to a climber ascent, avoiding the need to shed the energy of the ascent using radiators or other systems. If the single fixed tether were replaced by twin tethers, or rather a single continuous tether of twice the length wrapped around pulleys, it could operate as a conveyor belt or 'cable car' and carry the payload to the Apex without the need for a wheeled climber.

This solution would eliminate the difficulties associated with a climber ascending from GEO to Apex, with no need for an energy rejection system and no other concerns such as wheel fatigue life, steering safety or braking system reliability. However, there would be many other technical requirements that require careful consideration, such as pulley drive systems and payload retention. The effect of Coriolis force acting on the entire length of the tether might be significant, and the need for an Apex RIRO system means the top pulley would need to be some distance below the Apex. Systems would also be required to load and unload payloads from the rapidly-moving tether.

Much more work is required to study the technical feasibility of this 'conveyor' approach : it may well prove to be a more demanding and costly concept than wheeled climbers.

4.4.2 GEO Release

The above sections have highlighted the technical challenges of transporting payloads along the Space Elevator tether from GEO to the Apex Anchor. It is likely that a feasible solution can be developed, but the cost of that solution may not be insignificant.

A means of avoiding this onward shipping cost would be to despatch spacecraft direct from GEO, also saving at least 2-3 weeks of travel time on the tether. This means the spacecraft release velocity would be significantly less, the circumferential velocity being 7.76 km/s at the Apex and 3.07 km/s at GEO. The required additional velocity for a spacecraft released from GEO is not simply the difference between these velocities (4.69 km/s), but must be higher to achieve the same Specific Orbital Energy.

Specific Orbital Energy is the difference between an object's gravitational potential energy relative to a planetary body and the kinetic energy in the reference frame of that body, defined by Equation 9 below.

$$E=\left(v^2/2\right)-G*M/r \qquad (9)$$

where E = specific orbital energy, v = velocity, G = gravitational constant, M = planetary mass and r = distance of object from planet centre. For the Earth, $G*M_E$ *=* $3.986E+14\ m^3/sec^2$ *. Source : Wikipedia [11]*

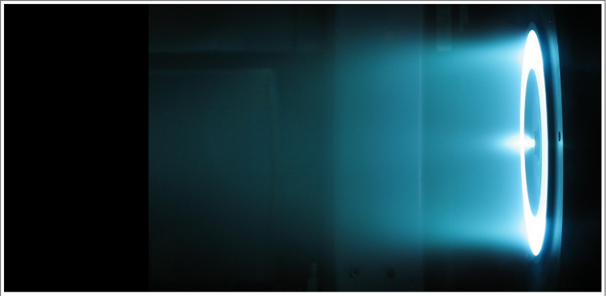
At an Apex altitude of 100,000 km, v_{apex} = 7760 m/s and r_{APEX} = 106378000 m, yielding a specific orbital energy of 26340105 J/kg. At a GEO altitude of 35782 km the value of r_{GEO} is 42160000m : a simple calculation then yields a velocity v of 8461 m/s for the same orbital energy, 5387 m/s higher than v_{GEO}.

Thus a spacecraft released from GEO would require an additional velocity (ΔV) of 5.39 km/s (19,392 km/hr) at that altitude to achieve the equivalent orbital energy for an Apex release. To establish the feasibility of achieving such a ΔV the standard rocket equation must be considered : Equation 10 below gives the mass of ejected propellant (m_0-m_f) as a function of final rocket mass m_f, propellant velocity v_e and required ΔV.

$$m_0-m_f=m_f*\left(e^{\left(\Delta V/v_e\right)}-1\right) \qquad 10$$

The propellant velocity v_e is simply the rocket specific impulse I_{sp} (sec) multiplied by g (9.80665 m/s^2), enabling the fuel mass to found for the required ΔV.

For example, for a 20 tonne final spacecraft mass and an I_{sp} value of 500 sec (better than almost all chemical rockets) a fuel mass of 40 tonnes is found. This is excessive for a GEO launch option, so a more efficient propulsion system is required. In practice this means a form of electric propulsion system such as an ion thruster such as that shown below in Figure 15.



6 kW Hall thruster in operation at the NASA Jet Propulsion Laboratory

Figure 15 : Ion Thruster Example (Public Domain)

Advanced electric propulsion systems are discussed in detail in reference [12] (Genovese & Maraqten, 2022), describing ion drive systems with I_{sp} values from 3000 to 20,000 seconds. The paper highlights how ion drive powers increase in a near-linear way with I_{sp}.

If a climber power source were to be transferred at GEO to the spacecraft there could be ample available power, permitting a high-I_{sp} drive to be used to minimise the fuel requirement : the trade-off might be complex, with a key parameter being the thruster mass.

The most powerful ion drive for which data is readily available in 2023 is the 'Variable Specific Impulse Magnetoplasma Rocket' ('VASIMR') being developed by Ad Astra Rocket Company, described in [13]. This has a target power of 200kW, with the VX-200SS variant claimed to be at TRL5 at 100kW. At 200kW input power it would generate a thrust of 5 N, with an I_{sp} of 5000 sec (v_e = 49,033 m/s) and a mass of 52kg. The thrust and velocity can be used to derive a fuel flow rate of 0.000102 kg/s (=5/49033).

From the above data the rocket equation (10) yields a total fuel mass of 2322 kg for a 20 tonne spacecraft. This is a considerable mass to be raised to GEO for each interplanetary launch, but must be compared with the mass to convert a climber for operation above GEO.

There should be an ample supply of solar arrays (or other form of beamed power receivers) at GEO from climbers arriving from Earth, perhaps as much as 4MW each day. If it is assumed that only a power of 2 MW was available for the spacecraft then ten VASIMR 200kW thrusters could be powered, with a total fuel flow rate of 0.00102 kg/sec. Thus the required ΔV of 5.39 km/s could be achieved in 2.28E+06 seconds

(=2322/.00102), or 26.3 days. This is slightly more than the transit times from GEO to the Apex in Figure 6, but at the end of the thrust period the spacecraft would be at a greater distance from Earth than the Apex.

The above analysis has flaws that make it merely an order-of-magnitude estimate, not least being the assumption that all the ΔV is applied at the GEO altitude, but one key observation is that the specific thrust of the VASIMR thrusters is c 0.1 N/kg, far higher than that of ion drives in operation in space in 2023.

VASIMR is merely an example, it can be expected that thruster technology will advance further in the timescale of Space Elevator deployment, reducing the thruster and fuel requirement masses for the target ΔV. Work on nuclear-powered interplanetary spacecraft will accelerate the design of high-power electric thrusters.

High-thrust ion drive systems could be developed and used on interplanetary craft before the deployment of the Space Elevator, either integral with spacecraft or operating on near-Earth ‘tugs’. Further exploration of the GEO-launched ion drive option is well outside the scope of this paper and could be the subject of a separate study.

5. CONCLUSIONS

5.1 Climbers ascending from Earth to GEO will require some modification before continuing to the Apex Anchor. An uncontrolled ‘free’ ascent would result in a speed on the tether in excess of 15,000 km/hr, which could not be achieved by present climber concepts.

5.2 The above means that continuous braking will be essential above GEO, generating energy that must be dissipated. The low-temperature radiator systems sized for Earth-to-GEO wheeled climbers using conventional motors would limit the maximum speed and result in a transit time to the Apex perhaps in excess of 4 weeks. Climber modification options to increase heat rejection and allow higher speeds include additional low-temperature radiators or bespoke electrically-heated high temperature radiators.

5.3 Climbers ascending to the Apex will disturb the Tether/Anchor equilibrium, resulting in either additional tether stress at GEO or requiring a reduction in the effective ‘weight’ of the Apex Anchor on the tether. Allowing further stress at GEO would reduce the overall system payload-to-GEO capacity: the Anchor weight reduction is best achieved by winching to a lower altitude.

5.4 Release of spacecraft from the Apex Anchor would have a similar but opposite effect to that of climbers ascending to the Apex, but would impose a step stress reduction rather than a steady increase. Full dynamic analysis is required to optimise winching strategies and to assess the amplitude of any system oscillations : significant stress changes at GEO could enforce a reduction of the lift capacity of the tether to maintain operational stress safety margins.

5.5 Tether stress analysis has concluded that a constant-area tether should be possible above GEO with only a minor reduction in the feasible maximum anchor altitude. This would allow a ‘conveyor belt’ or ‘cable-car’ system to be used to transport payload above GEO, eliminating the need for climbers in some or all of the region but introducing several other complex technical challenges.

5.6 The challenges outlined above could be avoided by launching payloads direct from the GEO Node instead of via the tether to the Apex Anchor. An equivalent velocity to that of an Apex release could be achieved using future high-power electric ion drives in conjunction with whatever power source is used for the Earth-GEO climber, or by using future solar arrays under development for Space-Based Solar Power systems.

6. RECOMMENDATIONS

6.1 A design study should be undertaken for a high temperature radiator system capable of dissipating over 300kW of electrical energy, with design objectives including both low cost and minimum mass. Other energy dissipation options should also be assessed.

6.2 System simulation should be undertaken to assess the dynamic response of the tether system to climbers ascending between GEO and Apex, and to sudden Anchor mass loss due to the release of a spacecraft. This study should include transient stress changes along the entire tether and options for mitigating action at the Anchor Apex and elsewhere.

6.3 A detailed study should investigate the feasibility of lunar and interplanetary launches from the GEO Node, in particular assessing the technical requirements for electric (ion) drives assuming the availability of MW-level power from solar arrays or beamed power receivers. This study should compare trajectories and travel times with those associated with the Apex-release option.

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