Chapter

Space Access for Future Planetary Science Missions

Colin Sydney Coleman

Abstract

Planetary science demands increasingly elaborate experiments, with the result that mission objectives are often limited by space access capability. The orbital skyhook is a momentum transfer device that has been proposed as an alternate launch system. It is an extended orbital structure that rotates to allow access by a low speed suborbital vehicle. After docking, the vehicle gains momentum from the skyhook and is accelerated to orbital velocity, after which the skyhook energy must be replenished. The construction of an orbital skyhook is shown to be feasible with current materials. It is a fully reusable launch system with very high propellant efficiency and could provide the launch capability needed for future planetary science missions.

Keywords: launch systems, orbital skyhook, electric propulsion, momentum transfer, planetary science

1. Introduction

Proposals for a momentum transfer based launch system are not new. Konstantin Tsiolkovsky, credited with the concept of multi-stage rocket vehicles, also proposed the orbital tower. Much later Yuri Artsutanov inverted this idea to suggest a geostationary satellite with a counterweight and a tether extending to the Earth's surface. This so called 'space elevator' was first published in 1960 in Komsomolskaya Pravda and later discovered independently in the US when the term 'skyhook' was coined [1]. The structure was shown to be stable against the effects of lunar tidal forces and payload motions, and functions by extracting energy from Earth rotation [2]. The problem is that no known material has sufficient strength to construct a space elevator in Earth orbit.

Difficulties with the space elevator led to the proposal of the asynchronous orbital skyhook [3]. (The original concept was credited to John McCarthy at Stanford.) This is an extended orbital structure that rotates so that each end periodically comes to a low altitude and velocity, at which instants the system is easy to access. Initial studies advocated configurations that place a low demand on the tether material properties, as this was thought to be the principal challenge. To replace energy lost during launch it was proposed that the skyhook be used to return a similar quantity of material from orbit to Earth.

Detailed studies of the asynchronous skyhook [4, 5] addressed engineering aspects of the tether and docking mechanism. They proposed a set of configurations in which access is provided by a hypersonic vehicle operating at a speed of at least

3.1 km/s (Mach 10). This high speed of the access vehicle reduces the skyhook rotation rate and so places less stress on the tether material.

Hypersonic flight technology is not yet capable of providing routine access to the high Mach number regime. By contrast, several reusable vehicles are available that provide access to suborbital flight trajectories using combinations of air-breathing and rocket propulsion [6, 7]. High strength fiber technology has also made substantial progress with the incorporation of carbon nanotubes into the molecular structure [8]. This suggests a need to review the orbital skyhook concept with a focus on configurations that allow low speed access. It is also necessary to explore different approaches to energy replenishment that do not require access to a repository of orbiting material.

Section 2 reviews the skyhook concept and estimates the parameters of a practical launch system. Expressions for the skyhook mass properties are obtained in Section 3 for the case where centripetal force is the dominant source of tension. The dynamics is modeled in Section 4 assuming the structure remains linear, with the tether mass properties represented by a compact object at the mass centroid. Electric propulsion is proposed as a mechanism for energy replenishment in Section 5, and the feasibility of supplying propellant for the thrusters is explored. Section 6 describes the advantages of a skyhook launch system for future planetary science missions, and Section 7 summarizes the main results.

2. Concept description

An orbital skyhook launch system involves three phases, each exploiting a different physical process. It begins with the delivery of a payload by suborbital vehicle. Docking occurs at one of the skyhook endpoints when it is near minimum altitude and velocity. The suborbital vehicle is required to attain only a small fraction of the energy needed for orbit, and does not need to operate in a hypersonic flight regime. It can therefore employ mature airframe and propulsion technologies, making it easier to design for efficiency and reusability.

The second phase is momentum transfer from the skyhook to the payload [9]. After docking the payload gains energy as the skyhook rotates, reaching a maximum after half a cycle. If the payload is not released energy transfers back to the skyhook in the second half of the cycle as it returns to minimum energy. By selecting when the payload is released, it can be placed into an elliptical orbit or on an escape trajectory. Note that if the payload is released at a subsequent minimum energy point, the skyhook energy and orbit are left unaffected. This means the vehicle is transported around the Earth at orbital velocity, with the only energy cost being that of gaining access to the skyhook.

In the third phase energy drawn from the skyhook during launch must be replenished. If the payload mass is small relative to the total system mass, the orbital perturbation is also small. In this case the structure remains above the atmosphere through subsequent rotations, and energy replenishment may occur over an extended period. Electric propulsion is proposed for this purpose. It provides a small thrust with a large specific impulse, and therefore high propellant efficiency. Propellant can be delivered with the payload to supply thrusters at the skyhook endpoints, but it will be shown that a better approach is to apply thrust at the skyhook mass centroid.

Of interest here are skyhook configurations that offer low speed access. Ideally the endpoint speed should match the orbital velocity relative to Earth's surface. In addition, acceleration during launch must not be excessive. For a skyhook in a circular equatorial orbit with radius R and orbital frequency Ω the endpoint ground track speed and acceleration are given by:

$$v_M = R\Omega - L\omega - 465 \tag{1}$$

$$a_M = R\Omega^2\left[(1 - L/R)^{-2} - 1\right] + L\omega^2 \tag{2}$$

Here L and ω are the skyhook half-length and rotation frequency, and Eq. 2 includes the acceleration components due to gravity, orbital velocity and skyhook rotation.

Specifying the endpoint velocity and acceleration yields two implicit equations for the skyhook parameters. With a nominal orbital radius of 8000 km the skyhook length is small enough to apply the limit $L \ll R$. Then for a minimum energy state at zero velocity and 40 m/s^2 acceleration, the skyhook parameters are $L = 1090$ km and $\omega = 0.006 s^{-1}$. This system can be accessed at zero velocity by a vehicle capable of ascending to an altitude of 532 km. Moreover, the maximum acceleration experienced during launch is similar to that of a conventional launch vehicle.

One of the skyhook endpoints is at minimum energy when the structure is oriented radially. This state occurs with a period $\tau = \pi/(\omega - \Omega)$ corresponding to a ground track distance of 3176 km around the equator. The orbital parameters could be adjusted so this distance is an exact fraction of the equatorial circumference, in which case the minimum energy states occur above fixed points on the equator. These locations are natural sites at which to establish bases to operate the suborbital access vehicles.

3. Mass properties

The skyhook configurations of interest here have an endpoint speed near orbital velocity to allow access at low energy. The high rotation rate means tension is mainly due to centripetal force, with the field gradient contribution being negligible.

Consider a symmetric skyhook comprising two equal masses m connected by a massive tether of length $2L$ and define the origin at the center. The tether cross-section is $a(r)$ and the tether material has uniform density ρ and ultimate tensile strength T. For a skyhook with rotation frequency ω the tension σ at radius r obeys:

$$\sigma'(r) = -\rho\omega^2 r a(r) \tag{3}$$

Substituting $a(r) = \sigma(r)/T$ and noting that $a(L) = mL\omega^2/T$ this equation can be solved for the tether cross-section:

$$a(r) = \frac{mL\omega^2}{T}\ \exp\left[\chi^2\left\{1 - \left(\frac{r}{L}\right)^2\right\}\right] \tag{4}$$

Here $\chi^2 = \rho\omega^2 L^2/2T$ is a dimensionless parameter characterizing the skyhook. By symmetry the mass centroid is at the origin. This structure may be generalized to describe a set of asymmetric configurations with unequal end masses at different distances from the centroid. The symmetric configuration has the benefit of offering two opportunities to access the skyhook in each rotation cycle, but asymmetric configurations allow access to a greater variety of launch trajectories.

The tether mass M_T and moment of inertia I_T are given by:

$$M_T = 2\rho\int_0^L a(r)dr \tag{5}$$

$$I_T = 2\rho \int_0^L a(r) r^2 dr \tag{6}$$

Evaluating the integrals and simplifying:

$$M_T/m = 2\sqrt{\pi}\ \chi \exp\left[\chi^2\right] \mathrm{erf}(\chi) \tag{7}$$

$$I_T/mL^2 = \sqrt{\pi}\chi^{-1} \exp\left[\chi^2\right] \mathrm{erf}(\chi) - 2 \tag{8}$$

The limit $\chi \to 0$ represents a material of infinite strength, in which case the tether mass and moment of inertia vanish. Adding the contributions of the two end masses leads to expressions for the mass properties of the entire skyhook:

$$M/m = 2\sqrt{\pi}\,\chi \exp\left[\chi^2\right]\ \mathrm{erf}(\chi) + 2 \tag{9}$$

$$I/mL^2 = \sqrt{\pi}\,\chi^{-1} \exp\left[\chi^2\right] \mathrm{erf}(\chi) \tag{10}$$

These expressions for the skyhook mass properties indicate the dependence on tether material properties, and provide key parameters for dynamical modeling.

An important feature of a tether is the taper factor, the ratio of maximum to minimum cross-section area. A tether constructed from low strength material has a large taper factor, indicating its impracticality. The nominal skyhook described above with a carbon fiber tether has a taper factor of 237, in which case the diameter at the centroid is about 15 times that the end points. If the tether had the properties of carbon nanotubes the taper factor reduces to 3.3. The properties of any future tether material are likely to fall within these bounds.

Table 1 indicates the mass properties of the nominal skyhook for several tether materials. Notionally high strength materials like steel and diamond are excluded by the very large taper factor. Aramid fibers like Kevlar are possible but the total mass is large. The strongest carbon fiber offers a solution with a skyhook mass about 4600 times the endpoint mass. If materials with still greater tensile strength become available, such as by incorporating carbon nanotubes or colossal carbon tubes into the tether material, the taper factor and skyhook mass can be much smaller.

For the skyhook configuration described here the endpoint mass is regarded as the maximum payload capability. This assumes the endpoint mass may be replaced by a docking mechanism of negligible mass to capture the payload. Engineering margins have not been included in this analysis, but the nominal configuration is a

Material	Density (kg/m^3)	Strength (MPa)	χ^2	Taper Factor	Mass (M_T/m)	Moment (I_T/mL^2)
Steel 2800	8000	2693	67.7	1.2×10^{25}	2.9×10^{27}	3.1×10^{23}
Diamond	3500	2800	26.7	4.1×10^{11}	3.9×10^{13}	2.7×10^{10}
Aramid fiber	1440	3757	8.2	3629	1.05×10^5	783.4
Zylon (PBO)	1560	5800	5.75	315	6421	96.1
Carbon fiber (T1100S)	1790	7000	5.47	237	4596	75.8
Carbon nanotube	1340	63,000	0.45	1.58	5.46	5.06
Colossal carbon tube	116	7000	0.35	1.43	1.70	5.93

Table 1.
Tether mass properties for various materials (from Eqs. (4), (7) and (8)).

'worst case' in the sense that skyhook rotation is specified to allow access at zero velocity relative to the Earth. If the access vehicle provides a horizontal velocity component the rotation rate is smaller, in which case the taper factor and skyhook mass are also decreased.

4. Equations of motion

Skyhook length is a significant factor in the dynamics because field strength is not uniform across the structure. This differs from most problems in astrodynamics where the object of interest is small compared to the field gradient length scale, or the system can be simplified by assuming spherical symmetry.

Here the skyhook is assumed to behave as a rigid body, kept in tension by the rotation and experiencing no stretching or bending. The validity of these assumptions depends on the tether material properties, but they are sufficient for the present purpose. The structure is expected to remain linear due to the large centripetal restoring force that counters any bending.

The equations of motion of a rigid body are typically obtained by a Lagrangian method using the mass properties. This formulation ignores the field gradient effect, which is important for skyhook dynamics. To see this note that the skyhook structure experiences a moment due to the two arms being subject to different field strengths according to their proximity to Earth. If the skyhook were treated as a single compact object this behavior would not be represented.

The skyhook system is modeled here as three objects connected by tethers of fixed length L as illustrated in **Figure 1**. The central object has the mass properties of the tethers as calculated above. This formulation represents the physical extent of the skyhook in a non-uniform field. It is also a good approximation for the mass distribution of the tether if it has a significant taper factor, in which case much of the mass is concentrated near the centroid. Based on these considerations a Newtonian formulation is used for the analysis.

The system state is described by a six element vector comprising the skyhook centroid location $\boldsymbol{r} = (r, \theta)$ and orientation angle φ and their derivatives. The endpoint locations are specified by the vectors $\boldsymbol{r_1}$ and $\boldsymbol{r_2}$ which are functions of the state

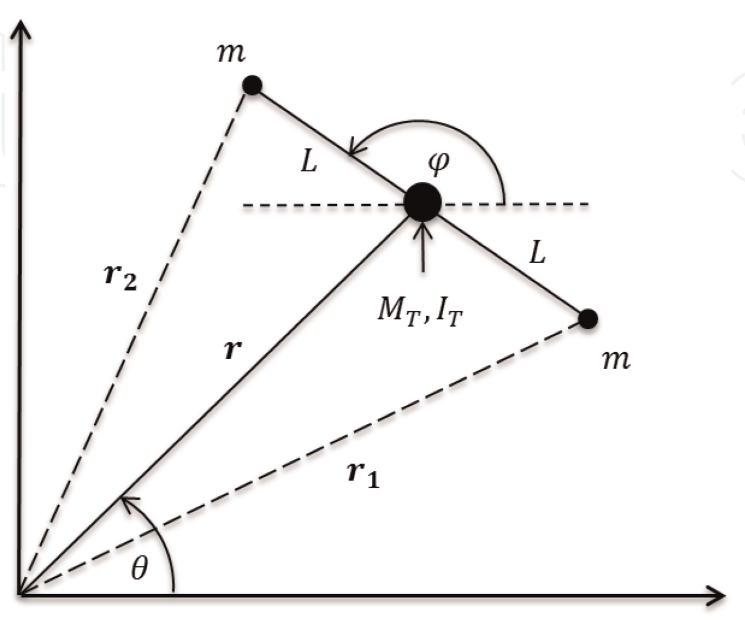

Figure 1.
Skyhook geometry with the tether mass and moment of inertia represented by a compact object at the mass centroid.

vector and may be written as follows where $\hat{\boldsymbol{t}} = (\cos \varphi, \sin \varphi)$ is the skyhook orientation unit vector:

$$\boldsymbol{r}_{1,2} = \boldsymbol{r} \mp L\hat{\boldsymbol{t}} \tag{11}$$

The gravitational force on each mass is projected through the centroid to obtain the net radial and azimuthal forces, and onto the normal for the torque:

$$F_r = -\left(\frac{GM_E}{r_1^2}m\right)\hat{\boldsymbol{r}}_1.\hat{\boldsymbol{r}} - \left(\frac{GM_E}{r_2^2}m\right)\hat{\boldsymbol{r}}_2.\hat{\boldsymbol{r}} - \left(\frac{GM_E}{r^2}M_T\right) \tag{12}$$

$$F_\theta = -\left(\frac{GM_E}{r_1^2}m\right)\hat{\boldsymbol{r}}_1.\hat{\boldsymbol{\theta}} - \left(\frac{GM_E}{r_2^2}m\right)\hat{\boldsymbol{r}}_2.\hat{\boldsymbol{\theta}} \tag{13}$$

$$\tau = -\left(\frac{GM_E}{r_1^2}m\right)L\,\hat{\boldsymbol{r}}_1.\hat{\boldsymbol{t}}' + \left(\frac{GM_E}{r_2^2}m\right)L\hat{\boldsymbol{r}}_2.\hat{\boldsymbol{t}}' \tag{14}$$

Here $\hat{\boldsymbol{t}}' = (\sin \varphi, -\cos \varphi)$ is a unit vector normal to the skyhook. In circular polar co-ordinates the acceleration is:

$$\ddot{\boldsymbol{r}} = \left(\ddot{r} - r\dot{\theta}^2\right)\hat{r} + \left(r\ddot{\theta} + 2\dot{r}\dot{\theta}\right)\hat{\theta} \tag{15}$$

The skyhook equations of motion are then:

$$\ddot{r} - r\dot{\theta}^2 = F_r/(2m + M_T) \tag{16}$$

$$r\ddot{\theta} + 2\dot{r}\dot{\theta} = F_\theta/(2m + M_T) \tag{17}$$

$$\ddot{\varphi} = \tau/I = \tau/mL^2\left\{\sqrt{\pi}\,\chi^{-1}\exp\left[\chi^2\right]\mathrm{erf}(\chi)\right]\right\} \tag{18}$$

Evaluating the vector dot products and re-arranging:

$$\ddot{r} = r\dot{\theta}^2 - \frac{GM_E m}{2m + M_T}\frac{1}{2r}\left\{\left(\frac{1}{r_1} + \frac{1}{r_2}\right) + \left(\frac{r_1^3 + r_2^3}{r_1^2 r_2^2}\right)\cos\left(\theta_1 - \theta_2\right) + \frac{2}{r}\frac{M_T}{m}\right\} \tag{19}$$

$$\ddot{\theta} = -\frac{2\dot{r}\dot{\theta}}{r} + \frac{GM_E m}{2m + M_T}\frac{1}{2r^2}\left(\frac{r_1^3 - r_2^3}{r_1^2 r_2^2}\right)\sin\left(\theta_1 - \theta_2\right) \tag{20}$$

$$\ddot{\varphi} = -\frac{GM_E m}{2I}\left(\frac{r_1^3 - r_2^3}{r_1^2 r_2^2}\right)\sin\left(\theta_1 - \theta_2\right) \tag{21}$$

The skyhook trajectory was obtained by numerical solution of these equations of motion for the nominal parameters. The endpoint altitude and ground track speed are shown in **Figure 2**. Note that the minimum energy point occurs at zero ground track speed at an altitude of 532 km. The specific energy of a stationary object at this altitude is about 5% of one in orbit. The configuration could be altered to allow access at a lower altitude, but it may then incur an unacceptable risk of collision with satellites in low Earth orbit.

During launch momentum transfers from the skyhook to the payload, perturbing the skyhook orbit into an ellipse. This perturbation is small if the skyhook mass is much greater than the payload mass, as is true for most tether materials. If the tether material is sufficiently strong the skyhook mass can be small enough for the orbital perturbation to be significant. This can be overcome by placing ballast mass at the centroid.

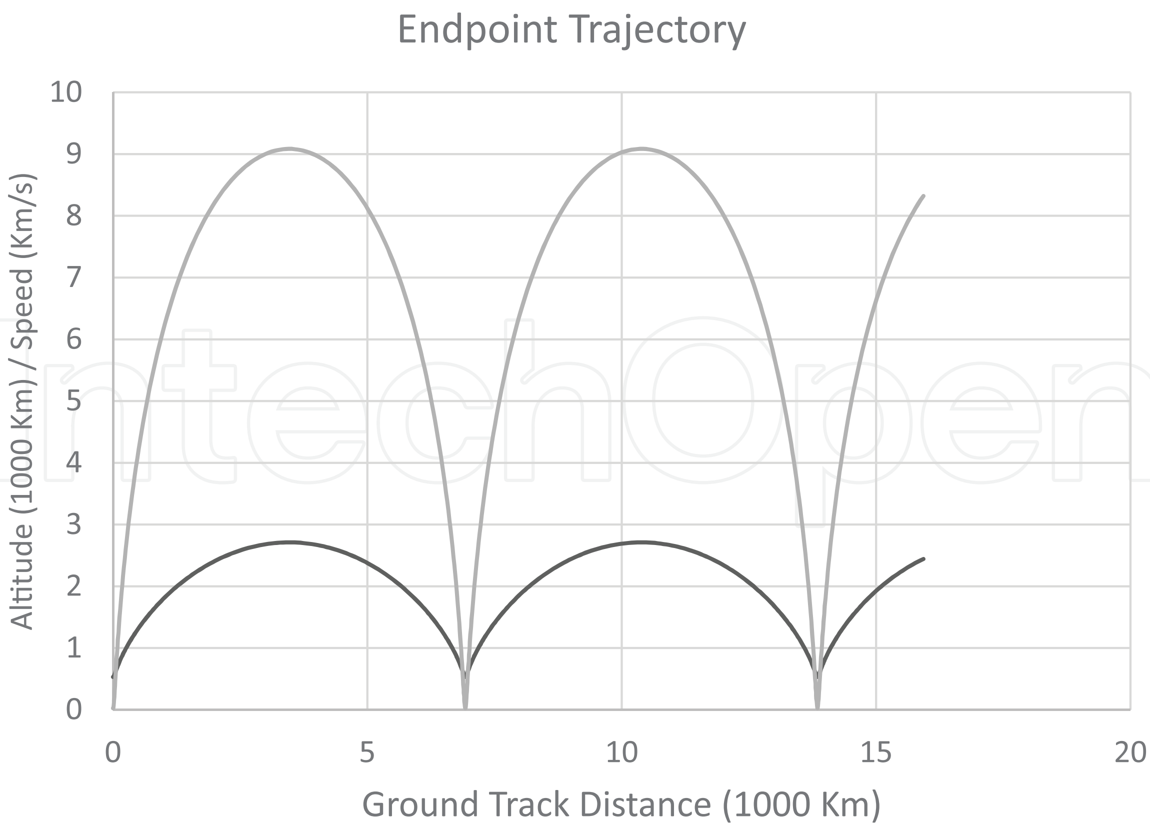

Figure 2.
Altitude (dark) and ground track speed (light) of a skyhook endpoint.

5. Energy replenishment

After launch it is necessary to replenish the skyhook energy and circularize the orbit. If the orbital eccentricity is small there is no interaction between the skyhook and the atmosphere, so this may occur over many orbits. Electric thrusters are proposed as a suitable technology for maintaining the skyhook orbit. They produce thrust with a high specific impulse, and therefore utilize propellant very efficiently.

The preferred location to apply thrust is the skyhook centroid. A force at this point maximizes energy transfer, the rate of work being the product of the thrust and orbital velocity V_0. The skyhook is also very robust at the centroid, and with a local acceleration near zero it is the optimal location for solar arrays to power the thrusters. Note that mass at the centroid does not affect the skyhook structure or energy transfer rate. This means the propulsion system mass and efficiency is of no concern. The key thruster performance characteristics are the efflux velocity and mass flow rate, which together determine the propellant quantity and time needed to achieve energy replenishment.

Electric propulsion has been developed for tasks that require a small thrust with high specific impulse. Examples include orbital transfer and deep space missions, for which ion thrusters are the preferred technology. Energy replenishment requires a high specific impulse and sufficient thrust to limit the replenishment time. A magnetoplasmadynamic (MPD) motor is best suited for this purpose. MPD thruster technology is developmental, but their performance can be inferred from experimental demonstrators.

An MPD thruster creates an electric current in plasma in the presence of a magnetic field. The field may be generated externally by coils or intrinsically by the current itself. In either case Lorentz force acts on the plasma and expels it at high velocity. Laboratory MPD thrusters have demonstrated 5 N of thrust with a mass

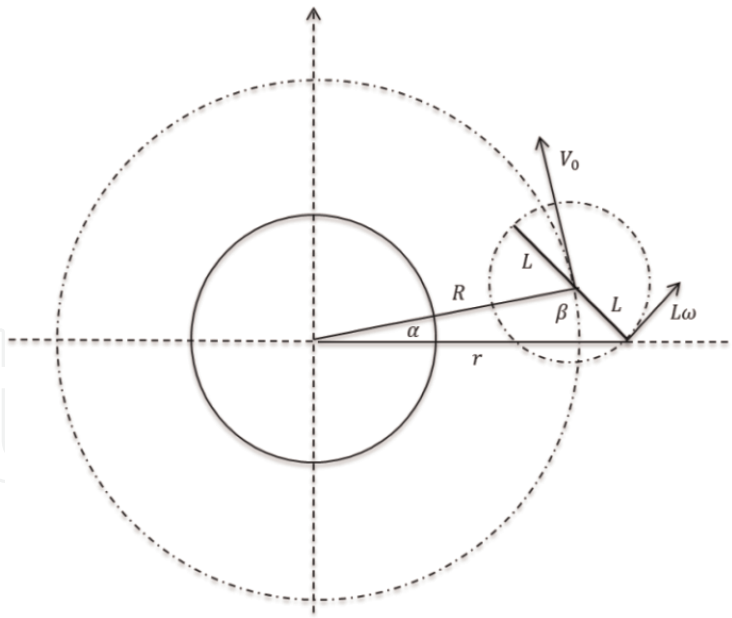

Figure 3.
Skyhook orbital geometry and payload velocity at detachment.

flow rate of 60 mg/s [10]. The MPD thruster is a compact and robust device, but it operates most efficiently at high power levels in the order of 1 MW. It is estimated that a practical MPD thruster could achieve a thrust of 2.5–25 N with an efflux velocity of 15–60 km/s [11].

A thruster with efflux velocity V_E and mass flow rate $\dot{m}$ acting at the centroid can replenish the launch energy $E_L = m_0 V_0^2/2$ for a payload m_0 in a period T_R given by:

$$T_R = E_L/\dot{E} = m_o V_0/2V_E\dot{m} = m_P/\dot{m} \tag{22}$$

The ratio $m_P/m_o = V_0/2V_E$ is the fraction of payload mass that must be reserved for propellant to replenish launch energy. For an efflux velocity of 50 km/s this ratio is 0.07. This means the amount of propellant needed to replenish launch energy is only 7% of the payload mass. With a realistic mass flow rate of 0.4 g/s the time needed to replenish the energy used to launch a 1000 kg payload is about 2 days. This can obviously be reduced by operating several such thrusters in parallel.

The quantity of propellant needed for energy replenishment is much smaller than the payload mass, but it must be delivered to the skyhook centroid. This can be achieved by having the skyhook launch a transport vehicle into an elliptical orbit, after which it uses conventional propulsion systems to perform an orbital transfer maneuver and rendezvous with the centroid. The analysis concludes by demonstrating that it is possible to deliver propellant efficiently to the skyhook centroid.

Skyhook endpoint kinematics is characterized by near uniform circular motion for both the orbit and the rotation. The velocity may be determined by adding the two rotational velocities as illustrated in **Figure 3**.

$$v_r = -V_0 \sin(\alpha) + L\omega \sin(\alpha + \beta) \tag{23}$$

$$v_\theta = V_0 \cos(\alpha) - L\omega \cos(\alpha + \beta) \tag{24}$$

The triangle in the figure is fully specified, so all angles can be expressed in terms of the skyhook parameters and endpoint radial coordinate. If the payload detaches at a speed less than escape velocity it enters an elliptical orbit with a periapsis, apoapsis and eccentricity given by:

$$r_P = \left(\frac{2}{r} - \frac{v^2}{GM_E}\right)^{-1}(1-e) \tag{25}$$

$$r_A = \left(\frac{2}{r} - \frac{v^2}{GM_E}\right)^{-1}(1+e) \tag{26}$$

$$e^2 = 1 - \frac{r^2 v_\theta^2}{GM_E}\left(\frac{2}{r} - \frac{v^2}{GM_E}\right) \tag{27}$$

The transition to a circular orbit can be achieved with a bi-elliptical transfer maneuver [12]. This involves a prograde impulse at apoapsis to increase the periapsis, followed by a retrograde impulse at periapsis to circularize the orbit. The maneuver can be implemented with a series of small impulses over several orbits, but the single orbit procedure serves to illustrate the process. The velocity changes at apoapsis and periapsis are given by:

$$\Delta V_A = \sqrt{\frac{2GM_E}{r_A} - \frac{2GM_E}{R + r_A}} - \sqrt{\frac{(1-e)GM_E}{r_A}} \tag{28}$$

$$\Delta V_P = \sqrt{\frac{2GM_E}{R} - \frac{2GM_E}{R + r_A}} - \sqrt{\frac{GM_E}{R}} \tag{29}$$

The initial orbit depends on the skyhook configuration and its orientation when the payload is released. For the nominal skyhook most orbits have a periapsis smaller than Earth radius, necessitating an impulse during the first orbit to increase the periapsis to avoid reentry into the atmosphere. Only a small impulse is needed for this purpose, which can be provided by a conventional rocket. The rest of the orbital transfer maneuver can be achieved efficiently by employing low thrust electric propulsion over multiple orbits.

To illustrate the process consider a vehicle that is released from the skyhook at an orientation angle $\beta = 1.6$ radians. It enters an elliptical orbit with periapsis 5550 km and apoapsis 71,400 km. A velocity change of 68 m/s at apoapsis increases the periapsis to 6500 km, sufficient to avoid reentry. This can be provided by a chemical rocket with a propellant mass fraction of 0.03. Subsequent circularization of the orbit at the centroid radius requires a velocity change of about 2.8 km/s which can be provided by electric thrusters with a propellant mass fraction of 0.06. This means a reusable vehicle can be used to transport propellant to the skyhook centroid, with only 10% of the initial mass expended as propellant during the journey.

6. Planetary science

Planetary science and space-based astronomy demand increasingly complex infrastructure, and the high cost of launch limits the scope of experiments. A more efficient launch process would allow larger vehicles to be constructed and more ambitious experiments to be undertaken. The orbital skyhook is a fully reusable launch system with high propellant efficiency, and which can be constructed using current materials technology. It can deliver payloads directly to Earth orbit, or to a trajectory for transfer to lunar orbit.

Access to orbit is the first stage of any planetary science mission. Typically a launch vehicle places the spacecraft and its propulsion system into orbit to await the appropriate time to commence interplanetary transfer. Because of the high launch cost a low energy trajectory is usually employed. This restricts the available launch window and increases the transit time. With a more efficient launch process it would be possible to use a larger and more capable propulsion system, and thus to allow a less efficient trajectory. This flexibility could be used to deliver a larger experimental payload, conduct more frequent missions, or achieve a reduced transit time.

An emerging ambition of national space programs is a return to the moon, often extending to the establishment of permanent bases on the moon and in lunar orbit. Planetary science is unlikely to be a primary driver of this initiative, but it stands to be a significant beneficiary. For astronomy the moon offers a low gravity environment free of atmospheric and ionospheric effects, Earth based radio emissions, and interference due to the large number of satellites in low Earth orbit. A skyhook launch system that provides efficient transport to the moon would allow astronomical experiments with far greater sensitivity than is possible with terrestrial instruments.

Lunar orbit is also a favorable location from which to launch planetary science missions. It is close enough for easy access but at a significantly higher energy than low Earth orbit. Complex modules constructed on Earth can be delivered efficiently by the skyhook, while fuel and water can be supplied from the moon at a much lower energy cost. Vehicles returning from the moon could dock with the skyhook as it approaches a minimum energy state, using it to decelerate in preparation for a low speed re-entry while also returning energy to the system. The use of an orbital skyhook for efficient transport to and from the moon is therefore a key enabler of future planetary science missions.

7. Conclusions

The orbital skyhook derives its advantage principally from using different propulsion technologies in the various physical regimes experienced during a launch. The payload gains energy by momentum transfer from the skyhook, with this energy being later repaid over an extended period. This overcomes the large energy threshold associated with a launch by drawing from a repository and replenishing it efficiently by electric propulsion.

The focus here is on skyhook configurations that allow access at a low speed relative to the Earth. These can be accessed much more easily, but necessarily rotate rapidly to counter the orbital velocity. This means centripetal force dominates the tension, making it is possible to obtain simple expressions for the skyhook mass properties. With a carbon fiber tether the skyhook mass is about 4600 times greater than the endpoint mass, which represents the maximum launch payload. The skyhook mass can be greatly reduced if a stronger tether material were to become available.

Because the skyhook is an extended structure in a non-uniform field, it is subject to forces and torques that vary with orientation. To represent this behavior the skyhook was modeled as a linear structure comprising two masses connected by an inelastic massive tether. The tether mass properties were represented as a compact object at the mass centroid, and a Newtonian formulation used to obtain the equations of motion. These equations were solved numerically to confirm their validity and investigate the dynamics.

Skyhook energy lost during a launch can be replenished by an electric thruster acting at the centroid. The MPD motor is a suitable propulsion technology for this purpose, and was shown to be capable of achieving energy replenishment in a reasonable time with high propellant efficiency. This result holds regardless of the size and efficiency of the propulsion system because the energy transfer process depends only on the efflux velocity and mass flow rate.

Applying thrust at the centroid is beneficial because the structure is most robust at this point and the local acceleration is near zero. It is necessary, however, to transport propellant to the centroid and a mechanism is proposed to achieve this. A transport vehicle is launched by the skyhook into an elliptical orbit, after which it executes an orbital transfer maneuver to rendezvous with the centroid. This process can be accomplished with a high propellant efficiency using available propulsion systems.

The endpoint mass represents the maximum skyhook payload capacity. This envisages the endpoint carrying a docking mechanism of negligible mass that can accept the payload. The skyhook mass scales linearly with the endpoint mass, and so also with the maximum payload. When an initial system has been established it can be used to launch material to add to the structure to increase the payload capacity. This process is likely to be limited by the access vehicle payload capacity, at which point there is no benefit in further increasing the skyhook mass.

Planetary science requires increasingly elaborate experiments. Improved launch efficiency allows more ambitious missions to be undertaken, with larger propulsion systems to deliver more massive experiments to the planet of interest with sufficient propellant for soft landing on the planet surface. The renewed enthusiasm of national space programs for a return to the moon could provide the incentive for construction of an orbital skyhook to provide efficient transport to and from the moon. This would make it possible to conduct astronomical observations from the moon with a sensitivity far greater than is possible from Earth, and to exploit lunar orbit as a base for launching future planetary science missions.

Author details

Colin Sydney Coleman
Defence Science and Technology Group, Edinburgh, Australia

*Address all correspondence to: colin.coleman@dst.defence.gov.au

References

[1] Isaacs J, Vine A, Bradner H, Bachus G. Satellite elongation into a true "sky-hook". Science. 1966;**151**(3711): 682-683

[2] Pearson J. The orbital tower: A spacecraft launcher using the Earth's rotational energy. Acta Astronautica. 1975;**2**(9–10):785-799

[3] Moravec H. A non-synchronous orbital skyhook. Journal of the Astronautical Sciences. 1977;**25**(4): 307-322

[4] Bogar T, Bangham M, Forward R, Lewis M. Hypersonic airplane space tether orbital launch (HASTOL) system: Interim study results. In: 9th International Space Planes and Hypersonic Systems and Technologies Conference; Norfolk VA; 1999

[5] Bogar T et al. Hypersonic airplane space tether orbital launch system. NASA Institute for Advanced Concepts. Research Grant No 07600-018, Phase 1 Final Report; 2000

[6] Branson's virgin galactic reaches edge of space. BBC News. 13 December 2018

[7] Amos J. New Shepard: Bezos claims success on second spaceship flight. BBC News. 24 November 2015

[8] Coleman J et al. Small but strong: A review of the mechanical properties of carbon nanotube-polymer composites. Carbon. 2006;**44**:1624-1652

[9] Coleman C. The orbital skyhook: Launch dynamics and energy replenishment. In: International Astronautical Conference; Adelaide; 2017

[10] Albertoni R et al. Experimental study of a 100-KW Class applied-field MPD thruster. In: IEPC-2011-110, 32nd International Electric Propulsion Conference; Wiesbaden, Germany; 2011

[11] Choueiri E. New dawn of electric rocket. Scientific American. 2009;**300**: 58-65

[12] Hoelker R, Sibler R. The bi-elliptical transfer between co-planar circular orbits. Planetary and Space Science. 1961;**7**:164-175