Asteroid Slingshot Express - Tether-based Sample Return

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Abstract

This paper examines the possibility of returning payloads from a spinning asteroid using a tether system and evaluates the merit of the concept in comparison to a conventional rocket-based return.

1 Concept

This paper examines the feasibility of returning payloads from an asteroid using a long sling powered by the rotation of the asteroid, as illustrated in Figure 1. We define an asteroid as a body with negligible gravity, so its synchronous orbit (SO) is practically on its surface. On an asteroid, there's no minimum length requirement for a rotating tether to stay erect – any outward-pointing tether with a mass at its end will remain taut, and the system will be in stable equilibrium.

Deployment of a tether on an asteroid can therefore be made "bottom-up", starting with a spool on the surface. All we really have to do is get the counterweight beyond the SO (e.g. using a spring-loaded launcher) and simply reel out tether as the counterweight begins to pull outwards.

When we want to launch a mass from the asteroid, we have to get it to the tip of the tether, and then release it at the correct time. The mass will have a velocity of $\omega \cdot r$, and will generally travel in the plane of rotation of the asteroid, perpendicular to the tether. This technique works best for asteroids with an equatorial plane that intersects the Earth.

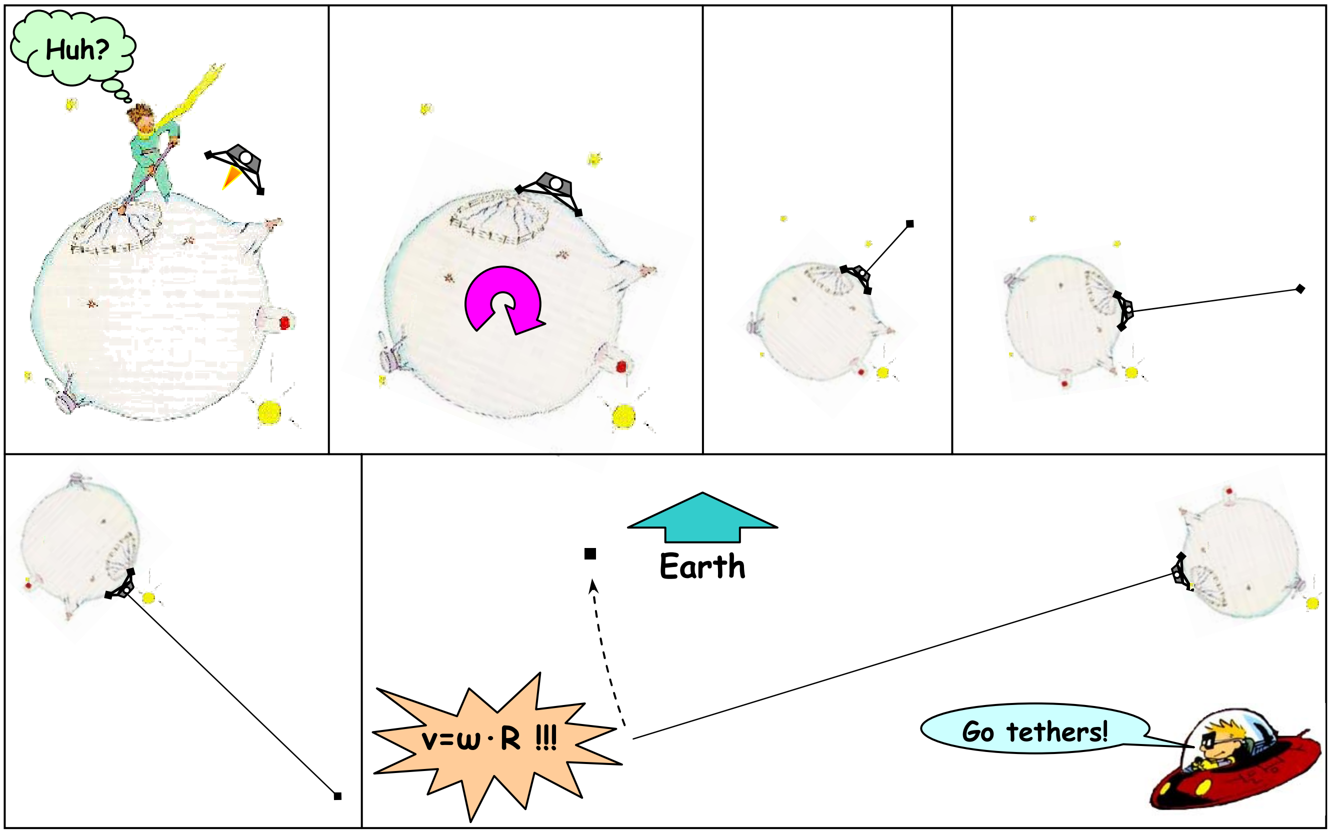

Figure 1: Asteroid Sling

When considering a single sample return, the bottom-up deployment of the cable and the launch of the sample are one and the same – there's no need to climb a pre-deployed tether. For multiple returns, once the tether is deployed, the return samples will passively glide up the cable until they reach the tip. Since all motions happen with the direction of the local effective gravity, no power system of any kind is necessary. The power comes at the expense of the spin of the asteroid.

The question we want to answer is whether this concept is mass efficient – will the tether spool weigh less than a rocket that can launch the same sample back to Earth? Are there Asteroids that are more suitable for a tether slingshot mission?

2 Tether system analysis

We will assume a small asteroid with very low gravity relative to its rate of spin such that with:

ω: Asteroid rotation rate
r: Asteroid surface radius
g: Asteroid surface gravity

(1) $\omega^2 r \approx g$ “geo” is near the surface

In which case the behavior of a tether attached to the asteroid is governed predominantly by the centrifugal acceleration, so the analysis becomes a special case of the general Space Elevator tether equation, with a diminishing gravitational field.

Further denoting:

m: payload mass [kg]
τ: Tether specific strength [µN/Tex, pa-m^3/kg, or (m/s)^2]
R: Tether tip distance from center of asteroid [m]
x: Distance from center of asteroid [m]
T(x): tension of tether at x [N]
β(x): tether linear mass density at x [kg/m]
m_T: total mass of the tether [kg]

We have the following constraints:

(2) $T(x) = \tau \cdot \beta(x)$ (Constant loading)

(3) $dT(x) = -(\omega^2 x) \cdot \beta(x) \cdot dx$ (Tether tension continuity)

(4) $T(R) = (\omega^2 R) \cdot m$ (Initial condition)

Note that unlike the Space Elevator, the initial condition in this system is at the tip, where the tip velocity is predetermined. And so:

$$\tau \cdot d\beta(x) = -(\omega^2 x) \cdot \beta(x) \cdot dx$$

$$\beta'(x) = -(\omega^2 / \tau) \cdot x \cdot \beta(x)$$

$$\beta(x) = k_1 e^{-(\omega^2 / 2\tau) x^2} = k_1 e^{-(\omega x / \sqrt{2\tau})^2}$$

For convenience, we’ll define the “aspect ratios” ψ_T of the tether system as

(5) $\psi = \omega R / \sqrt{2\tau}$

And rewrite:

(6) $\beta(x) = k_1 e^{-(\psi \cdot x / R)^2}$ (Linear density at x - general)

And using the initial condition:

(7) $$\begin{aligned} \beta(R) &= 2\psi^2 \cdot m / R \\ k_1 &= 2\psi^2 \cdot (m/R) \cdot e^{\psi^2} \end{aligned}$$ (Linear density at x - specific)

The area taper ratio is:

(8) $TR = \beta(r) / \beta(R) = e^{\psi^2 \left(1 - \left(\frac{r}{R}\right)^2\right)} \approx e^{\psi^2}$ (The tether profile)

And the total line mass is:

(9)
$$\begin{aligned} m_T &= \int_r^R \beta(x) dx = \int_r^R k_1 e^{-(\psi \cdot x / R)^2} dx = k_1 (R/\psi) \cdot \tfrac{1}{2} \sqrt{\pi} \cdot erf(\psi \cdot x / R) \Big|_r^R = \\ \ldots &= 2\psi^2 \cdot (m/R) \cdot e^{\psi^2} \cdot (R/\psi) \cdot \tfrac{1}{2} \sqrt{\pi} \cdot erf(\psi \cdot x / R) \Big|_r^R = \\ \ldots &= \psi \cdot m \cdot e^{\psi^2} \cdot \sqrt{\pi} \cdot erf(\psi \cdot x / R) \Big|_r^R \end{aligned}$$

And the mass ratio (ignoring the r term)

(10) $m_T / m \approx \sqrt{\pi} \cdot e^{\psi^2} \cdot \psi \cdot erf(\psi)$ (The tether mass equation)

Note that for a given delta-v, we can equally choose a fast rotating asteroid and a short tether, or a slow rotating asteroid and a long tether – the mass fraction is a function only of the required delta-V and the specific strength of the tether.

3 Results

Table 1 shows several examples of hypothetical tether systems using existing (green, columns A-E) and futuristic (blue, columns F-H) tethers, and their "equivalent ISP", which is the ISP of a rocket whose propellant weighs as much as the tether and that supplies the same delta-v. For multiple samples, the weight of the tether is divided by the number of samples.

This assumes the empty weight of the rocket is zero, which is optimistic – high ISP rockets have heavy power systems that need to be factored in. Low ISP (solid) rockets, however, have low dead weights, and can provide ISPs of roughly 2500 m/s – comparable to the green tether at a delta-v of 1500 m/s and the blue tether at 5000 m/s.

		A	B	C	D	E	F	G	H
delta-v	m/s	500	1000	2000	5000	10000	1000	2000	5000
τ	$(m/s)^2$	3E6	3E6	3E6	3E6	3E6	10E6	10E6	10E6
ψ		0.20	0.41	0.82	2.04	4.08	0.22	0.45	1.12
TR		1.04	1.2	1.9	64.5	17E6	1.1	1.2	3.5
m_T/m		0.09	0.4	2.1	232.5	125E6	0.1	0.5	6.1
# of samples									
	1	6082	3155	1758	917	536	10163	5306	2546
	2	11919	5848	2768	1050	557	19838	9702	3566
	5	29425	13900	5660	1295	587	48854	22826	6249
	10	58601	27309	10406	1568	612	97210	44674	10459
	100	583768	268624	95376	4162	712	967609	437819	84051

Table 1: The merit of the Asteroid Sling as a Function of Delta-V and Specific Strength

As an example, for an asteroid that is spinning once every 2 hours (ω=8.7E-4 rad/sec), and for a 1000 m/s tether system, the length of the tether is approximately 1100 km, and the tip centrifugal acceleration is 0.87 m/sec^2. A payload capsule weighing 100 kg will require a 40 kg tether, and will pull on the tip of the tether with a force of 87 Newtons (18.8 pounds). The tether cross section at the tip is therefore approximately 0.029 mm^2, or 0.2 mm in diameter.

4 Conclusion

Compared with the rocket equation, the dependence of system mass on the strength is steeper, so for large delta-V, the tether system performs poorly when compared with rockets. For all other regions, however, the tether system is very attractive in comparison to a rocket based return. Even for the case of a single sample high delta-V return, it is still advantageous to use the sling system for the first 0.5 km/sec (in the green case) or 2 km/sec (in the blue case).

With the development of strong CNT tethers, even before Space Elevators become feasible, a tethered asteroid sample return mission will be an interesting proof of concept mission.

5 References

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