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 its merit 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**. In this paper we approximate an asteroid as a body with negligible gravity, so its synchronous orbit is practically on its surface. Real asteroids have a small measure of gravity, but for practical purposes, this approximation is good enough as long as the asteroid's escape velocity is much smaller than the return delta-V.

On such an asteroid, there is 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 the tether can therefore be done "bottom-up", starting with a spool on the surface and simply shooting the deploying mass out using a spring.

To launch a mass from the asteroid, we have to get it to the tip of the tether, and release it at the correct time. The mass will have a velocity of $\omega \cdot r$ (see definitions below), and will initially travel in the plane of rotation of the asteroid, perpendicular to the tether. This technique therefore works best for asteroids with an equatorial plane that intersects the Earth.

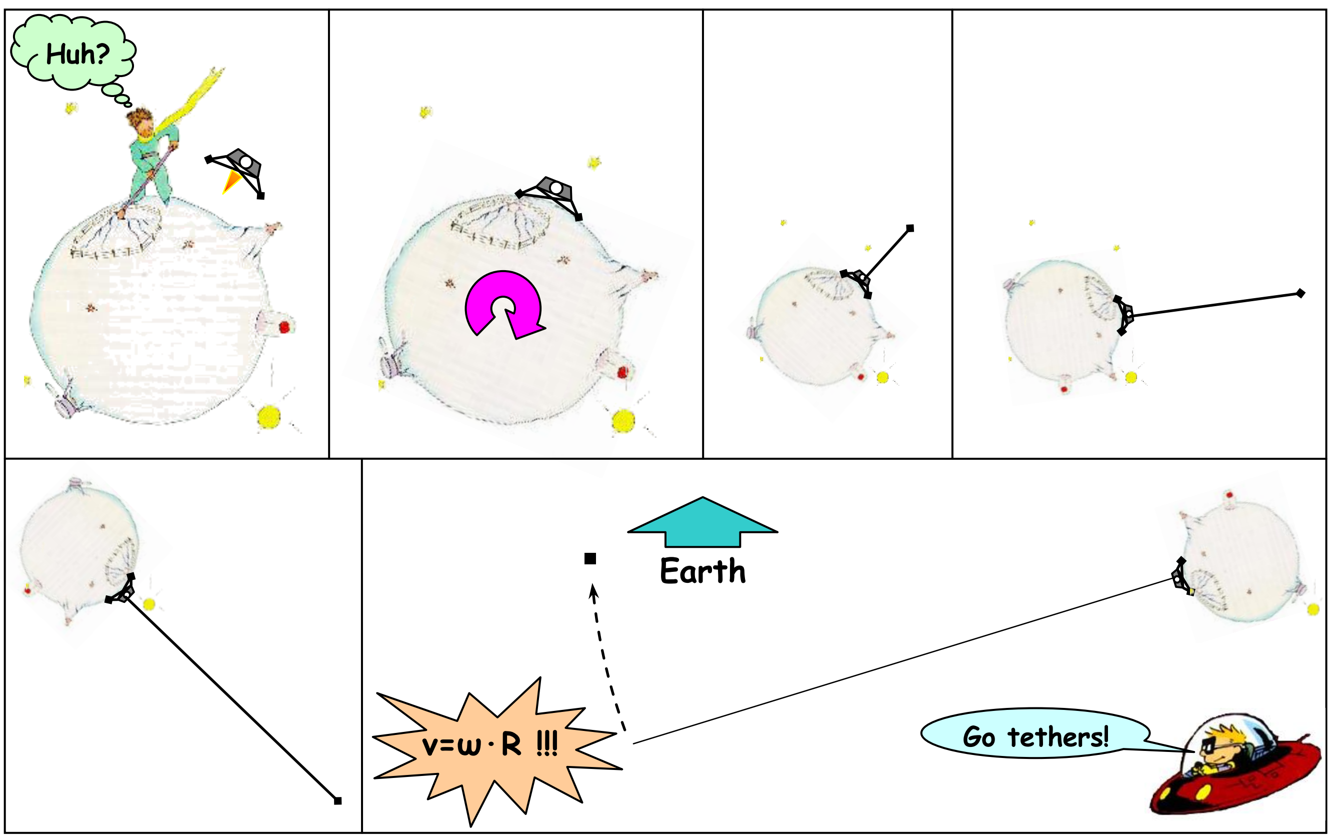

Figure 1: Asteroid Sling

When considering a single sample return, the bottom-up deployment of the tether 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 masses will climb "down" 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.

This analysis is valid only for quasi-static systems. Care must be taken during motion not to deviate too far from equilibrium, or we may risk wrapping the line around the asteroid. This is particularly true during the first deployment phase.

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 [rad/s]
r: Asteroid surface radius [m]
g: Asteroid surface gravity [m/s^2]

(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 diminished 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. (Determined by the desired tip velocity rather than the lifting capacity at the base) 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 ratio" ψ_T of the tether system as

(5) $\psi = \omega R / \sqrt{2\tau}$ (Velocity characterization of a tether)

And rewrite:

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

And using the initial condition:

(7) $\beta(R) = 2\psi^2 \cdot m / R$, $k_1 = 2\psi^2 \cdot (m/R) \cdot e^{\psi^2}$ (Linear Density at x - specific)

The area taper ratio is:

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

And the total line mass is

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

(9)
$$... = 2\psi^2 \cdot (m/R) \cdot e^{\psi^2} \cdot (R/\psi) \cdot \tfrac{1}{2}\sqrt{\pi} \cdot erf(\psi \cdot x/R)\Big|_r^R =$$

$$... = \psi \cdot m \cdot e^{\psi^2} \cdot \sqrt{\pi} \cdot erf(\psi \cdot x/R)\Big|_r^R$$

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 equation)

Note that for a given delta-v, we can equally choose a fast rotating asteroid and s 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

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.

The merit of a tether system is in saving mass in comparison to a rocket-based system. A good figure of merit is the "equivalent ISP" – the ISP of a hypothetical rocket system that would weigh the same as the tether system. I assume that the rocket system has zero empty weight, which is of course conservative. Chemical rockets have ISPs between 2.5 and 3.5 km/s.

Table 1 shows several examples of tether systems using existing (green, columns A-E) and futuristic (blue, columns F-H) tethers, and their equivalent ISP. For multiple samples, the weight of the tether is divided by the number of samples.

		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		Equivalent ISP of tether system [km/sec]							
1		**6.1**	3.2	1.8	0.92	0.54	**10**	**5.3**	2.5
2		**12**	**5.8**	2.8	1.0	0.56	**20**	**10**	3.6
5		**29**	**14**	**5.7**	1.3	0.59	**49**	**23**	**6.2**
10		**59**	**27**	**10**	1.6	0.61	**97**	**45**	**10**
100		**584**	**269**	**95**	**4.2**	0.71	**968**	**438**	**84**

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

Bold numbers represent cases in which a tether-based system can be advantageous.

4 Conclusion

With NEOs and main asteroid belt objects requiring 3500-7000 m/s in delta-v, especially for multiple return masses (as in the case of asteroid mining), tether systems can quickly become more mass efficient than rocket based system. 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).

Additionally, even before Space Elevators become feasible, a tethered asteroid sample return system will be an interesting proof of concept mission.