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Analysis of a Lunar Sling Launcher

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Abstract

A method of launching from the lunar surface is analyzed, in which the payload launched is swung on a high-strength cable until it reaches the desired launch speed. For a moderate acceleration limit of 11.5 g, a cable length of 50 km would be sufficient to launch into a lunar escape trajectory. If lower accelerations are desired, the cable length must be proportionately longer. Analysis shows that the concept will be feasible with existing materials, and will be simple to implement using advanced materials.

Keywords: tether, lunar launch, mass-drive

1. Background

Launching payloads from the moon using electrical power but no reaction mass is a concept that was first seriously proposed by Arthur C. Clarke [1]. Clarke proposed using a linear induction accelerator or "mass driver." The concept was then reinvented by Gerard O'Neill [2], whose analysis showed that the use of mass drivers could be a key enabling technology to allow the use of lunar resources for space development.

However, the mass driver is not the only possible method of launching from the moon. A different concept, the "slingatron" [3], where the vehicle is accelerated around a circular racetrack, has been analyzed by Tidman. Tether concepts [4-7] for lunar launch have also been proposed.

This analysis looks at the case of a lunar "sling" launcher. Various forms of lunar sling launchers have been proposed before, most notably by Baker and Zubrin in 1990 [4]. This is an alternate concept for launching from the moon with electrical power. It has a potential advantage over the mass driver in that it does not require a high peak-power on the electrical power system. Since the peak-power requirements are the most difficult challenge of making a mass driver, this can be a great advantage. Instead, the launch energy can be added as slowly as necessary. Furthermore, the system uses simple physics and very little in the way of complicated technology. The simplicity and the low peak-power requirements are enticing enough that it is desirable to analyze an example case and examine the technical issues to determine if the concept is technically feasibile.

The basic concept is to bring a payload to launch velocity using the method of a "sling of David," a technology of accelerating a projectile that dates back as far as written history. A rotating cable (or "tether") is used to swing a payload in a circle. This rotation is accelerated, as the cable is slowly lengthened until the tip velocity reaches the desired velocity, at which point the cable releases the payload.

This launch system can be viewed as a variation of the rotating momentum exchange tether concept proposed to move material from Earth [8] or lunar [5,6,7] orbit, with the change that the tether is fixed to a ground location on the moon.

2. Fundamental Concept

Figure 1 shows the lunar sling launch system in schematic.

The object to be launched is affixed to the end of a high-strength cable, which rotates in a horizontal plane. The launch direction is horizontal. The launch site needs to be selected in such a position that a horizontal launch will put the material on a desirable trajectory.

The launch package is affixed to the end of the cable, which is initially reeled in to a minimum length. The cable is then spun up slowly, paying out the cable while using electrical power to keep the rotation rate high. At the same time, a counterweight is reeled out in the opposite direction for balance. When the tip velocity reaches the launch speed, the cable is cut, allowing the launch package to be tossed away at high velocity.

The constraint on the launch is the maximum acceleration, or "g-loading," that the payload is able to tolerate. The g-loading is inversely proportional to the length of the tether. Thus, the higher the acceptable g-loading, the smaller the system can be, and conversely, the larger the system is, the lower the acceleration can be used to get the same tip velocity.

The fundamental formula relating the tip velocity v to the acceleration a is

$$a=v^2/r \qquad (1)$$

where r is the length of the tether.

This can be conveniently expressed in units of (Earth) gravities, g = 9.8 m/sec. The acceleration as a function of cable length is shown in figure 2 for the three cases, where the tip velocity equals lunar orbital velocity, lunar escape velocity, and the velocity required for direct injection to a trans-Mars orbit.

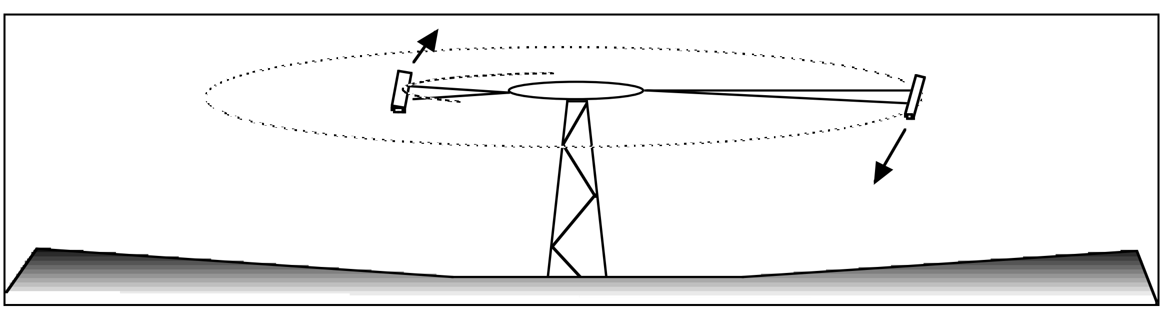

Figure 1: schematic of a lunar sling launcher, showing the launch mass on the right (longer cable), and the counter weight on the left (shorter cable).

Example cases of radius of 10, 50, and 115 km are examined.

To reach lunar orbital velocity requires a tip velocity of 1.68 km/sec. (For a lunar orbit to be achieved, the payload will require an apogee kick motor to circularize the orbit, to avoid the launch trajectory from returning to the surface of the moon.) The acceleration required is 28.6 g for a 10 km cable length. This reduces to 5.7g if the cable is increased to a length of 50 km. For a human launch, a maximum acceleration limit of perhaps 2.5 gravities would be imposed. This would require a tether length of 115 km.

To reach the launch velocity of v = 2.4 km/sec (slightly above lunar escape velocity of 2369 m/sec), the 10 km cable will subject the launch package to an acceleration of 57 gravities. Raising the length up to 50 kilometers will drop the acceleration to a reasonable 11.5 gravities. For the 115 km "human launch" cable, an acceleration of 5 gravities would be required for the lunar-escape launch. (Twice this length would be needed if an acceleration not to exceed 2.5 g is required.).

Finally, if it is desired to launch to 3.84 km/sec, which will yield a hyperbolic excess velocity of 3 km/sec, sufficient for a trans-Mars orbital injection, the acceleration (for the 50 km cable) increases to 16.5 g.

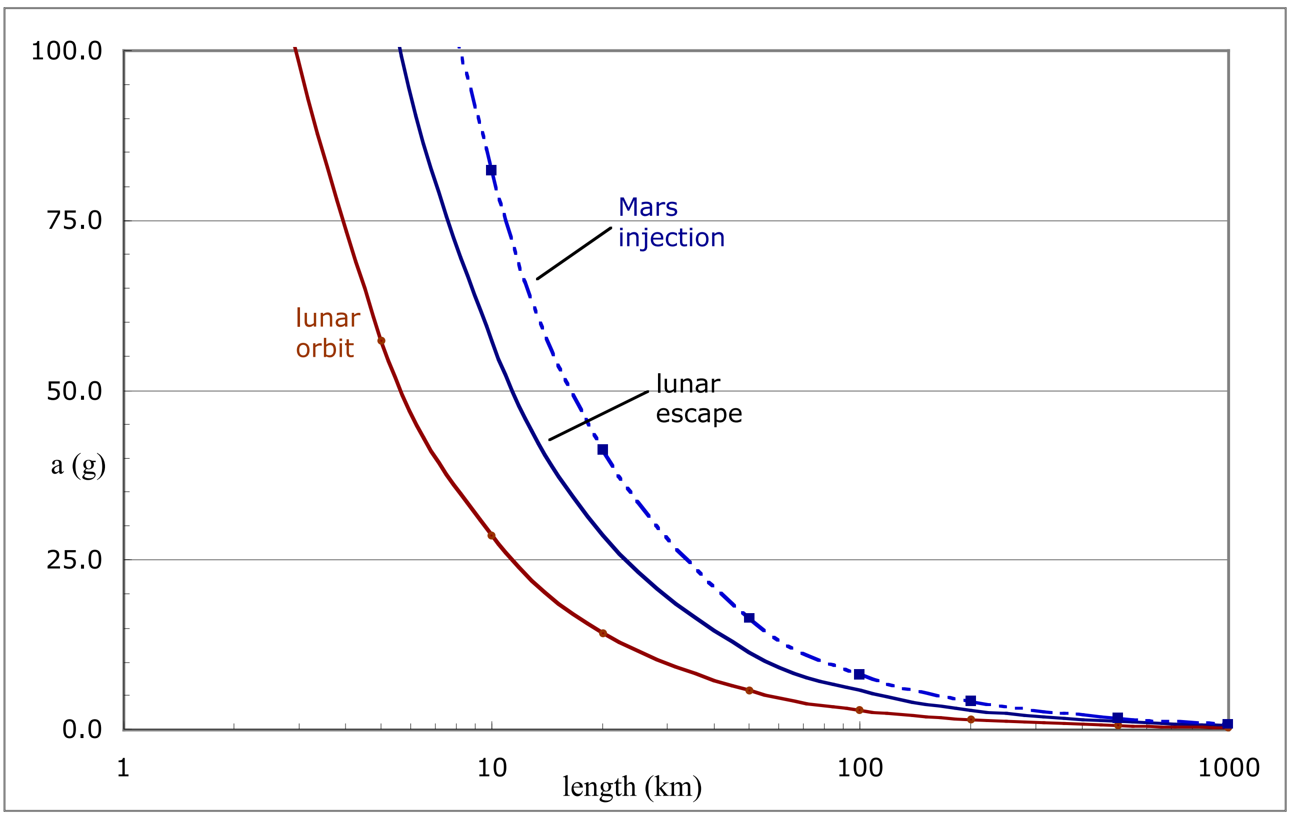

Figure 2. Acceleration in multiples of earth gravity as a function of cable length for a sling launcher with tip velocity sufficient to achieve lunar orbit, lunar escape, and direct injection into a trans-Mars orbit.

Another possibility is that the sling launcher may be used to launch payloads to velocities less than lunar orbital velocity. For example, a payload may be launched to rendezvous with a tether transportation system, such as that proposed by Forward [5] and Hoyt [6, 7]. In this case, the required acceleration will be less than the lunar orbit minimum, and, depending on the architecture, could be arbitrarily low. Likewise, payloads may be launched into a trans-Earth injection orbit to rendezvous with a tether transportation system in Earth orbit. This would require a launch velocity intermediate between the lunar escape and the trans-Mars injection values.

3. Lunar Escape Launch with 50 km Cable

For the analysis, the intermediate case of a 50 km cable is assumed unless otherwise noted, with a launch velocity of lunar escape; in the baseline case, the launcher is not designed to accommodate humans. For the 50 km cable, the launch velocity of 2.4 km/sec is achieved when the spin rate reaches 131 seconds per revolution, or 0.46 RPM. The basic parameters for the 50 km cable launcher are shown in table 1.

To avoid excess stress on the hub, the launch cable will require a counterweight for balance. The counterweight will be released simultaneously with the launch package, and will fly off in the opposite direction. The mass of counterweight required is equal to the mass of the object being launched, times the ratio of the launch cable length divided by the counterweight cable length. For convenience, the counterweight is assumed to be twice times the mass of the launch object, and hence is on a tether of half the length. For the case of a 50 km launch tether the counterweight is on a 25 km tether. The acceleration on the counterweight is thus half the acceleration on the launcher, or 5.7 g.

A simple way to implement the counterweight would be to have it be a bucket filled with lunar regolith.

To start the rotation of the cable system and keep it off the ground while the tether is getting up to speed, a 10-meter cantilever arms holds the launch package, while a 5-meter arm holds the counterweight. A motor is used to accelerate the rotation until the acceleration at the tip reaches half of the final value of 11.5 gravities, which occurs when the rotational speed reaches approximately 32 RPM. At this point the centrifugal force is sufficient to keep the payload from dropping to the ground, and the tethers on the launch and counterweight are allowed to reel out. The motor is used to add angular momentum to the system to keep this centripetal acceleration constant as the cable length increases.

Mission:	*Lunar orbit*	*Lunar escape*	*Mars injection*
Tip speed (km/sec)	1.68	2.4	3.84
Acceleration (m/s^2)	56.1	112.2	161.3
Acceleration (g)	5.7	11.5	16.5
Cable stress at tip (kN)	56	112	161
Rotation speed (RPM)	0.32	0.46	0.73

Table 1: parameters for a lunar sling launcher with a 50 km cable length launching a 1000 km payload

If the release can be done with an accuracy of 1/10 second, the resulting inaccuracy in the orbital plane of the resulting trajectory will be 0.28 degrees. This inaccuracy can be corrected with a small trajectory-correction rocket, requiring less than 1 m/sec of delta-V.

4. Cable mass and construction

For high velocities, the strength (and strength to weight ratio) of the cable material is an issue. Fullerene nanotubes have sufficiently high enough tensile strength that, if the materials can be made in macroscopic lengths, it is not difficult to achieve 2.4 km/sec.

The ultimate tensile strength of fullerene nanotubes is predicted by theory to be well over 100 GPa [9], with measured values on individual tubes approaching this value. Allowing an engineering factor of 5 (including the added strands for cross-connections, discussed below), the material should allow a working stress of 20 GPa. A mass of one thousand kg at 11.5 gravities (110 m/sec^2) results in a force on the cable of 112,000 N, as shown in table 1, so the required cross-section of the cable is 0.00389 cm^2 (0.389 square millimeters) per ton of end-mass. (More likely, this will be in the form of a number of separate cables which sum to a total cross-sectional area .389 mm^2).

The density of fullerene nanotubes is 1.3 gr/cm^3. The mass of the 50 km cable itself is then about 25 kg, and it is clear that neglecting the mass of the cable itself in the calculation was justifiable. The counterweight cable carries half the mass, but at half the acceleration, and half the length, so the counterweight cable has a total mass of about 13kg.

An ultimate strength of 20 GPa may be optimistic for a realistic material. If the working stress is reduced to 10 GPa, the cable cross-section is doubled, and the mass increases to 51 kg and 15 kg for the launch cable and the counterweight respectively.

It would be inviting catastrophic failure to make the cable in the form of a single rope. The cable should be a web with a large number of small fibers, well separated so no single failure would take out the whole cable. Most likely, these cables will be crosslinked in the "Hoytether" multi-stranded configuration [10, 11]. The Hoytether configuration has the feature that failure of a single strand will not result in catastrophic failure, and moreover, that a strand failure will not change the length of the cable when it is under tension.

If fullerene materials are not available, the concept could be implemented with existing materials. This increases the tether mass, and the sling launch becomes more difficult, but not impossible. The highest strength-to-weight ration for a currently available tether material are obtained with Poly(p-phenylene-2,6-benzobisoxazole), or "PBO" fibers, or with gel-spun polyethylene fibers. PBO (sold under the trade name "Zylon®") has a with tensile strength of 5.8 GPA, and density of 1.54 g/cm^3 [12, 13]. High-strength polyethylene fiber (sold under the trade name Spectra-2000) has an ultimate strength of 4.0 GPa and a density of 0.97 g/cm^3 [11]. Assuming an engineering factor of 2.5, the allowable load strength for the Spectra-2000 fiber is 1.6 GPa.

For the example case of a launch to lunar orbit, 1.68 km/second, the required acceleration is 5.7 g (56 m/sec^2). To carry a thousand kilogram payload, the force will be 56000 N. This will require a cable cross-section of 0.35 square centimeters at the tip. Since the cable must have additional cross-section to carry its own weight as well as the end mass, the cable must now be made to increase in cross-section from the tip to a wider cross-section toward the hub. This taper increases the cable mass. The cable mass is now about 2500 kg, no longer less than the mass of the launched object, but still a value which is feasible for an engineering system.

As a final note, when the launch mass is released, the elastic energy stored in the cable will be released. Since fullerene nanotubes stretch considerably under load, this energy can be considerable. If it is desired that the cable be re-used after each launch, then it would be desired that the release should be done in such a way that the energy release is not abrupt.

An alternate launch technique would be to release the payload from the hub, instead of the tip of the rotating tether and allow it to slide down along the tether. This would allow the payload to acquire an outward (centrifugal) velocity, which in the best (zero friction) case will equal the tangential velocity. The total velocity imparted would thus increase by a factor of the square-root of two. It would require, however, that the rotating arm be stiff enough to accelerate the payload in the circumferential direction as it slides along the cable. For a small launcher, this could possibly be done using structural stiffness, using a truss instead of a cable to provide bending stiffness. For the multi-kilometer system sizes discussed here, the stiffness would be produced by using a tensioning weight at the tip of the cable of sufficient mass to keep the cable in tension. The mechanism would have to be designed such that the moving payload would not impact the end mass as it slides along the cable and is released (for example, the payload being launched could slide down a radial tube).

The dynamics of this alternate launching technique would be complex, and it is not clear that the advantages of somewhat higher launch velocity would be worth the added complexity.

5. Central tower

The centripetal acceleration is 56 m/sec^2, while the downward acceleration due to lunar gravity is 1.62 m/sec^2 so the cable will deviate from the horizontal by an angle ϕ of

$$\phi = \tan^{-1}(a_{grav}/ a_{cent}) \qquad (2)$$

$\tan^{-1}(.029)$ is 1.66 degrees. Over the 50 km cable, the drop is 1.45 km.

A 50 km long cable is long enough that the moon can not be considered a flat plane. The horizon will have dropped 720 m over the 50 km radius from the hub to the circumference. Placing the hub on a tower or a hilltop will be needed to keep the launch cable above the ground.

The counterweight, at a lower acceleration, has a proportionately higher deviation angle from the horizontal, about 3.3 degrees, with the same total drop of 1.45 km meters over half the distance. Over the 25 km radius, the horizon drops only 180 m. The counterweight cable is closest to the ground at the tip, where it is 1.27 km below the hub.

To account for this, the hub will be located at least 1280 m above the ground. This could be atop a tower, on a mountain, or most likely a combination of both, with a tower built on a lunar hill. The counterweight cable will then skim 10 meters above the ground, while the launch system will be half a km above the ground. Many lunar mountains exceed this height. It will be required that nothing in the rotation plane is high enough to clip the counterweight cable, and nothing in the direction of launch high enough that the released object hits it on the outward launch.

The requirement for a 1.27 km elevation of the hub is a result of the fact that the counterweight is more massive than the launched weight. This is a trade-off; the mass and cable length was chosen so that the counterweight is not launched into orbit. However, if the hub elevation is a major problem, the counterweight could be chosen to be equal to the launch weight, and a different technique (for example, a convenient mountain in the direction of the counterweight release) could be used to avoid orbiting the counterweight. In this case,a 730-meter tower (or mountain) could be used.

6. Power

One of the advantages of the sling launch is that it does not require high peak power output. The energy required is the sum of the kinetic energy in the launched payload plus the energy of the counterweight, or 4.3 GJ. Allowing for 86% mechanical and electrical efficiency, the energy needed to launch a thousand-kilogram payload to lunar escape is 5 GJ, independent of the cable length. A 100-kW solar array supply would provide this energy in 50,000 seconds, just under 14 hours. Since most lunar base scenarios assume power levels at or above 100 kW, the power level required for the launch is not expected to be a limiting resource. If a dedicated solar array is used, at an assumed conversion efficiency of 20% the array area required would be approximately forty square meters. The system would be able to launch about 20 payloads in a lunar day. Higher power levels would allow correspondingly higher launch rates.

7. Conclusion

A "sling" style launcher [4] to accelerate a payload to escape velocity from the lunar surface appears to be feasible with existing materials, and easy to implement using advanced (nanotube) materials. A cable length of 50 km would suffice to launch a payload to lunar escape with a peak acceleration of 11.5g. If lower accelerations are desired, the cable length must be proportionately longer.

Applications for such a launch system include providing liquid oxygen derived from reduction of lunar regolith [4], as well as hydrogen or water derived from lunar ice, to markets in Earth orbit, where they can be used for rocket fuel or as life-support consumables. Other applications include launching of construction supplies for habitats, as proposed by O'Neill [2], and sending resupply consumables to Mars or to other destinations. In the longer term, such a launch system may even be part of a human transportation infrastructure.

Assuming that the cable can be reused, the system would be capable of just under two launches per (terrestrial) day at a power level of 100 kW.

8. Acknowledgement:

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