A rotating, tapered, balanced sling launcher on the Moon made of lunar regolith basalt fiber

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Abstract

Lunar ISRU scenarios tend to focus on extracting trace elements, or on metals refinement from regolith using very high temperature electrolysis. An easier lunar ISRU path seems to lie in plain sight. Space-weathered regolith fines (often thought only a hazard for bases) could be a source of very strong basalt after simple refinement steps that also yield glassy silicates and some oxygen. Basalt fiber's specific strength is close to that of some high-performance industrial fibers. It's been proposed (Baker & Zubrin, Landis, Puig-Suari et al.) to use a tapered rotating sling on the Moon to send cargo on various trajectories. These authors assumed slings made of fiber stock (such as PBO) that would need to be sent to the Moon at high expense. This paper suggests how basalt fiber from a solar furnace could form a sling that can send cargo from the lunar surface to aerobrake passes at Earth. Regolith-derived products (basaltic, glassy) and oxygen out-gassed from the regolith melt could find use near Earth. Among products suggested for satellites integrated in orbit: lunar oxygen combined with hydrogen from Earth for satellite station-keeping and orbit-adjustment propulsion; basaltic parts for parabolic dishes, reaction wheels, solar PV arrays, and satellite frames; and electrical insulation for power systems. What's suggested for economizing on upper-stage return: basaltic thermal protection for aerobraking and atmospheric entry; parachutes made of basalt fiber and fiberglass; landing legs; and oxygen for reentry burns. As a cost-saving measure, a solid rocket with a casing made of refractory metals can serve as a solar-heated regolith melt furnace after it assists in landing on the Moon.

Introduction

Rotating slings have been proposed for launching payloads from the Moon at least as early as 1978,[1] with the concept of a "non-synchronous skyhook" as the favored approach, given both the limits of materials and the desire to facilitate both landings and launches. At that time, Kevlar

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[1] Moravec, 1978, "Non-Synchronous Orbital Skyhooks for the Moon and Mars with Conventional Materials" (unpublished). In Moravec's retrospective "Orbital Bridges" (1986), he credits Stanford's John McCarthy for a rotating (non-synchronous) skyhook "in the 1950s". Rotation was to compensate for the weakness of steel for a synchronous skyhook (now, "space elevator"). McCarthy's thinking might predate Artsutonov's (1959), though Artsutonov was aware of "graphite whiskers" in 1957 and assumed that production of even stronger materials could be scaled up. (See "Space Elevators: A History", ISEC 2017, David Raitt, ed.) Moravec worked out the math with MACSYMA, an early symbolic math system, but he. soon found the work of Jerome Pearson [Pearson75], who had arrived at the same idea of a tensioned, tapered space elevator independently, years earlier. For a full history of related tether concepts, see Raitt, above.

was new and exciting. More recent speculation focuses on other very high-specific-strength materials for the sling material. The speculation has also branched away from non-synchronous skyhooks, with some authors describing slings placed on the lunar surface. Such a sling -- its composition and commercial uses -- is the subject of this paper.

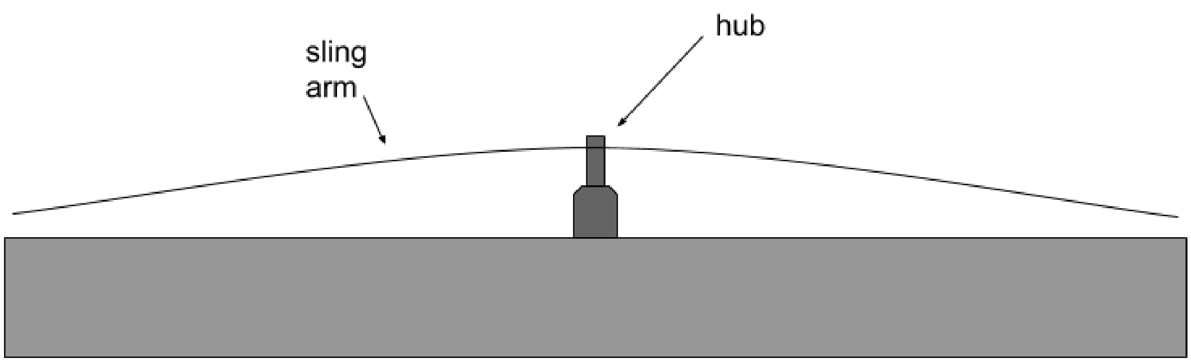

Figure: schematized view (not to scale) of a rotating sling (side view) on the lunar surface

Given the high expense of sending anything to the Moon, ideally, the sling's mass would derive largely from lunar resources processed in facilities whose initial mass to be delivered to the Moon would be a small fraction of the mass of what's produced. Unfortunately for any lunar ISRU bootstrap case, the sling materials proposed so far seem economically inappropriate or flatly impractical. Some are heavily carbon- and nitrogen-based (such as Moravec's Kevlar, and Zylon.) Carbon and nitrogen are very trace on the Moon, detected in potentially economical concentrations only in the volatiles of permanently shadowed areas (PSAs). Other candidates can't yet be made into fiber of the required lengths (iron crystal "whiskers"; graphite "whiskers"; CNTs).

The table below[2] shows various candidate tether materials that can either be produced only from regolith found everywhere on the Moon, with appropriate equipment on the Moon, or by import of carbon and nitrogen from either Earth or the PSAs. Note that we do exclude "iron whiskers" and CNTs because there are still no industrial processes for producing these in the quantity, length and uniformity required.

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[2] Condensed from Wikipedia's article on specific strength, 2018/04/21. Source footnote numbers are those for Wikipedia on that date.

Material	Tensile strength (MPa)	Density (g/cm³)	Specific strength (kN·m/kg or kYuri)	Breaking length (km)	Source
Titanium	344	4.51	76	7.75	[6]
CrMo Steel (4130)	560–670	7.85	71–85	7.27–8.70	[7][8]
Aluminium alloy (6061-T6)	310	2.70	115	11.70	[9]
Magnesium alloy	275	1.74	158	16.1	[12]
Aluminium alloy (7075-T6)	572	2.81	204	20.8	[13]
Titanium alloy (Beta C)	1250	4.81	260	26.5	[14]
Glass fiber	3400	2.60	1307	133	[19]
Basalt fiber	4840	2.70	1790	183	[20]
Vectran	2900	1.40	2071	211	[19]
Carbon fiber (AS4)	4300	1.75	2457	250	[19]
Kevlar	3620	1.44	2514	256	[21]
Dyneema (UHMWPE)	3600	0.97	3711	378	[22]
Zylon	5800	1.54	3766	384	[23]

In this paper, it's argued that a highly abundant material on the Moon -- basalt -- suffices for the sling material.[3] This makes such a sling far more conducive to lunar ISRU scenarios. Moravec also considered fiberglass. Of course, silicates are also abundant on the lunar surface, but fiberglass is significantly lower in specific strength (at 1307 kYuri) than basalt fiber (at 1790 kYuri). As suggested below, space-weathered microparticles of basalt could be especially suitable.[4]

[3] Preliminary studies on basalt fiber have been performed with lunar regolith simulants. See "Moon Basalt fiber – preliminary feasibility study", D. Pico, A. Lüking, Á. Blay Sempere, T. Gries, *Basalt Today*.
[4] Lunar basalt is relatively iron-rich, which would seem to make it unsuitable for continuous fiber production. One solution is suggested by U.S. Patent 149866A. In the melt, add carbon as a reducing

There is also arguably a financial incentive to establish this mode of cargo transport from the Moon through cis-lunar space and hence to Earth, and to base initial lunar exports very much on what is produced in producing the sling itself on the Moon. The case made in this paper is that there's much on the Moon that can reduce the cost of long-term maintenance of commercial satellite constellations and that this commercial activity can precede any production of the more usual substances considered in lunar ISRU scenarios.

A lunar sling that can get regolith-derived substances to aerobrake at LEO suggests two major opportunities for cost reduction in the commercial satellite market:

(1) in passive elements of satellites, to reduce the Earth-to-orbit upmass (assuming some satellite assembly is possible in orbit), and

(2) in facilitating economical and intact reentry of the second stages of two-stage-to-orbit satellite launchers, where at present it is practical to return only first stages.

Passive elements for satellites include parts that must now be made very tolerant of fairly high accelerations and rather strong vibrations. These stresses are usually endured only while being launched to their service orbits. Absent such stresses, the mass of these satellites could be significantly lower. Such passive elements include the following:

- **PC boards** (basalt and glass are good insulators; aluminum oxide has long been used in ceramic PCBs[5])
- **reaction wheels** in satellite attitude control systems[6]
- **structural supports** for solar panels and antennae[7]
- **MM/OD shielding** as fabric woven from basalt fiber or fiberglass[8]
- **electrical cable insulation**[9]

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agent, yielding CO and CO_2. The carbon can be recycled as oxygen is extracted. Draw the fibers into an inert or reducing atmosphere, especially if more rapid cooling is desired. However, vacuum itself could suffice. Such processes may be uneconomical on Earth compared to simply feeding fiber production with less ferrous basalt, since it's very abundant. On the Moon, however, to make a high-specific-strength fiber at all, in ISRU fashion, can make all other development more economical compared to exporting a fiber to the Moon, or from Earth to LEO.

[5] See e.g., Fairchild, M., Snyder, R., Berlin, C., and Sarma, D., "Emerging Substrate Technologies for Harsh-Environment Automotive Electronics Applications," SAE Technical Paper 2002-01-1052, 2002.

[6] See e.g., CD Tarrant, M Bailey, "Flywheels for energy storage and methods of manufacture thereof", Patent #WO2015008088A1.

[7] See e.g. "An Architecture for Self-Replicating Lunar Factories", Gregory S. Chirikjian, NIAC Phase I Award, April 26 2004.

[8] See e.g. EL Christensen, DM Lear, "Micrometeoroid and Orbital Debris Environment. &.Hypervelocity Shields", NASA NTRS 2012.

[9] See e.g., "A Short Review on Basalt Fiber", Kunal Singha, International Journal of Textile Science 2012, 1(4): 19-28 DOI: 10.5923/j.textile.20120104.02: p.21 - *"Manufactured basalt fibers have a fineness of 9μ-22μ (chopped fibers 10μ - 17 μ) and 320 tex - 4800 tex for roving. Possibility of the production of basalt and glass fabric for the electrical insulation and construction application has been demonstrated (Figure*

Even integrated circuit packages, if made from lunar regolith, can offer some Earth-to-orbit mass-savings if we assume that chip-bonding can be automated or performed teleoperatively in orbital satellite-integration facilities. As a rough estimate, perhaps up to 75% of a satellite's mass could be sourced from the Moon in various forms of basalt and glass. Only electrical conductors, chips and discrete parts, PV cells and some satellite-propulsion-related items would need to be launched from Earth.

Besides economizing on the amount of mass that needs to be sent from Earth for satellite construction, there is also the prospect of economizing on satellite transportation costs, by facilitating the reuse of upper stages. Among the possibilities:

- **Ablative shielding**: Regolith as the basis for reentry shields has been evaluated, with promising results.[10] Even if fuel tanks prove too delicate for ablatively shielded reentry, liquid-fuel rocket engines -- the higher-valued-added parts -- need not be.
- **Parachutes**: Basalt fiber and fiberglass can be woven into fabric and into cords.[11]
- **Air bags**: With the addition of a small mass fraction of sealant (sent from Earth), fabric woven from basalt fiber or fiberglass could be made into bags, to cushion the landings of upper stage elements, and, in the case of splashdown recovery, for both buoyancy and protection against brine contamination.
- **Oxygen**: The melting of regolith to make basalt and glass throws off oxygen at the higher melt temperatures. A solar furnace that usually only melts regolith to refine basalt and fiberglass silicates can also be used to derive yet more oxygen simply by heating more regolith. This oxygen could find uses initially in cold gas thrusters to help steer payloads from the Moon to the right low Earth orbit, but if delivered in enough quantity, oxygen for liquid-fuel retropropulsion could also facilitate upper stage return.

The existing market for satellite launch could benefit by reduced costs from lunar basalt reentry devices, or lunar oxygen, or both, simply by making upper stages economically returnable. Would this benefit precede or follow the development of a satellite-parts market in Earth orbit? Would the two developments proceed in parallel? This paper does not suggest any particular order of development, but only the possibilities.[12]

Calculations

4b). The magnitude of specific volume electrical resistance was found one order higher than that of the glass cloth[4, 7, 9-10].”

[10] MD Hogue, et al., “Regolith Derived Heat Shield for Planetary Body Entry and Descent System with In Situ Fabrication”, NIAC 2012.

[11] See, e.g., https://www.albarrie.com/industrial-fabrics/products/rolled-goods/basalt/

[12] There is little question that work on fabrication of space-grade parts and structures in space will continue. See, for example, the recent Made in Space SBIR award. (“Made in Space Eyes Glass Alloy Production & Modular Science Platforms in Orbit”, June 5, 2018 Doug Messier)

Michel Lamontagne, at the instigation of the author, performed initial calculations on a rotating sling made of various materials, including basalt presumed to be sourced on the Moon. He reported these results on the World Space Forum FB group in 2014 or 2015. Lamontagne recalculated based on Geoffrey Landis' work that had assumed Zylon in a worked example,[13] substituting typical specific strength values for basalt. Lamontagne first tried assuming a constant-width basalt sling and found that it could just barely send a payload to low lunar orbit. But this result was encouraging: A tapered sling would undoubtedly do much better.

Subsequent calculations were based on the derivation by Puig-Suari, et al.[14] These results were checked against the results for Zylon in both the Puig-Suari and Landis papers, and agreement was seen. Then a few different values for basalt fiber specific strength were tried. The results confirmed that basalt was a reasonable candidate material for a sling that could send payloads beyond low lunar orbit, with a sling mass only about four times that for Zylon in the case of stronger basalts, and without the cost of sending sling mass to the Moon.

What kind of basalt?

The specific strength of terrestrial basalt strength varies, depending on composition. Tensile strength of terrestrial basalt has been correlated with SiO_2 and Al_2O_3 content.[15] The strength properties of the basalt available at the immediate surface of the Moon is an important question, both for quantifying the ease of excavation and for deriving ultimate sling mass. In this, there seems to be cause for optimism.

The "finer fines" in the uppermost layers of lunar soil in basalt-rich mares would be the product of repeated fracturing by eons of meteoroid bombardment. The repeated fracturing would have tended to eliminate weakness along the most probable lines of cleavage, including at the boundaries with crystals that could otherwise compromise the strength of a fiber.

These same "gardening " impact processes would have tended to churn the finer fines, to keep re-exposing them to the higher levels of GCR and solar proton flux on the immediate surface. Such space weathering would yield basalt fines whose surface "soft spots" have been significantly milled out.

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[13] "Analysis of a Lunar Sling Launcher", Geoffrey Landis, *Journal of the British Interplanetary Society*, Vol. 58, No. 9/10, pp. 294-297 (2005)

[14] "A tether sling for lunar and interplanetary exploration", J Puig-Suari, JM Longuski, SG Tragesser. *Acta Astronautica*, v. 36, no. 6, pp. 291-295, 1995.

[15] T Deák, T Czigány, "Chemical Composition and Mechanical Properties of Basalt and Glass Fibers: A Comparison", Textile Research Journal, Vol 79, Issue 7, 2009.

Analyses of some lunar samples suggest that “finer = stronger” is a safe assumption, if in fact higher alumina and silica content are reliable indicators.[16] We accordingly adopt the upper range of terrestrial basalt specific strength as appropriate for analysis of a sling made of “the finest fines” of lunar basalt. It is no small advantage of extracting these candidate particles that they are otherwise problematic for a lunar base, both for machinery and in human lungs and other tissues. Better to turn them to some good use.

How to extract the better basalt?

Even the basalt-rich mares do not consist entirely of basalt, however, and this poses the question of refinement. And the finest-of-the-fines still need to be sorted from coarser ones. Filtering regolith to create a production stream of “finest fine” particles could be mostly a matter of sifting (a gravity-driven process that can work even in low gravity). If some density differentiation is required to increase the concentration of basalt, perhaps further sorting could be done with electrostatic levitation of particles, which has already been observed as a natural process on the Moon.[17]

Molten glass is slightly less dense than molten basalt, suggesting another simple gravity-driven process for removal of glass as a contaminant of molten basalt.

Byproducts of basalt production: glass and oxygen

Production of high-strength basalt on the Moon for use near Earth may be enough in itself for financially sustainable operation. But having invested heavily in that production, the marginal return to further investment in exploiting the system’s “waste products” should be explored.

Removal of silica by allowing it to float to the top of a basalt-melt crucible, to be drawn off by tap, suggests a useful byproduct: fiberglass, at least some lower grade.[18] Previous work on extraction of useful materials from regolith has assumed glass used for its optical properties, but the process design for deriving glasses in this way labors under the constraint that the ISRU system should produce highly transparent glass.[19] This optical constraint complicates matters. Natural glass on the Moon is dark, largely because of its high iron content. The process outlined by Landis can also produce relatively pure silicon, iron, and other metals, and at lower temperatures than what is required to melt basalt, but it is quite complex and may require very high voltages for effective electrolysis throughput. If the purpose of glass is only structural,

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[16] **“**Oxygen, silicon and aluminium in Apollo 11 rocks and fines by 14 MeV neutron activation”. Ehmann, W. D. & Morgan, J. W., *Geochimica et Cosmochimica Acta Supplement, Volume 1. Proceedings of the Apollo 11 Lunar Science Conference*. A. A. Levinson, ed.. New York: Pergamon Press, 1970. p.1071.
[17] “Simulations of the photoelectron sheath and dust levitation on the lunar surface”, A Poppe, M Horányi, *Journal of Geophysical Research*, 26 August 2010.
[18] Magnetic separation of silicates should also be possible considering that they are Fe^0-rich. See “The Lunar Dust Problem: From Liability to Asset” , L Taylor, H Schmitt, WD Carrier, M Nakagawa, 1st Space Exploration Conference: Continuing the Voyage of Discovery Orlando, Florida. AIAA.
[19] G Landis, “Materials refining on the Moon”, *Acta Astronautica* 60 (2007) pp. 906 – 915

however -- for fibers and fabric -- the complexity of optical glass production (and the importation of needed substances from Earth, such as potassium fluoride) can be avoided.

Oxygen evolution from heating lunar basalt has been demonstrated at temperatures lower than those required to melt basalt.[20] Heating was done in a hydrogen atmosphere at standard pressure, yielding water vapor for 10 minutes, with yields (on a mass basis) between about 3% and 4.5%. However, it may not be necessary to import hydrogen to the Moon. Vacuum pyrolysis, which would require no chemical inputs, but only further heating of molten regolith, can produce oxygen with temperatures that are possible with concentrated sunlight.[21] The resulting oxygen could be useful in cold gas thrusters to adjust the trajectories of payloads flung from the Moon to Earth aerobrake. In large enough quantities, lunar oxygen could re-supply fuel depots visited by the upper stages of satellite launchers, to serve as an oxidizer for the retropulsion required for eventual intact recovery of the upper stages on Earth.[22]

The following section discuss various objections to the idea of such a sling

Typical "show-stopper" (and "show-slower") objections

On the face of it, as a near-future lunar ISRU opportunity, there doesn't seem to be much to which anyone would reasonably object in the idea of tapered rotating lunar slings made of basalt. The potential advantages of any such sling have been made clear by a number of authors (Parker & Zubrin, Landis, Puig-Suari et. al, etc.) As they point out, these advantages are as follows:

- *No energy storage required*: the rotational momentum of the rotating sling can be maintained by continuous rotation after spin-up.

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[20] MA Gibson, et al. "Reduction of lunar basalt 70035: Oxygen yield and reaction product analysis", Journal of Geophysical Research, vol. 99, no. E5, May 1994, pp. 10887-10897

[21] See J Matchett, "Production of Lunar Oxygen Through Vacuum Pyrolysis", DTIC #ADA443950, Jan 2006. Fiber optic technology has been proposed for generating the required heat - see Takashi Nakamura, Benjamin K. Smith, "Solar Power System for Lunar ISRU Applications", 48th AIAA Aerospace Sciences Meeting Including the New Horizons Forum and Aerospace Exposition, Aerospace Sciences Meetings, 2010 - but may be unnecessary with a "smart materials" approach to parabolic concentrators. For added comparison, consider that Constance Senior, in her "Lunar oxygen production by pyrolysis" (Princeton/AIAA/SSI Conference; 10th; May 15-18, 1991) notes oxygen evolution starting at temperatures as low as 1400 K, only about 200 degrees higher than the temperatures required to melt the most heat-resistant basalt.

[22] Tom Myers estimates that the return of Falcon 9 upper stage would entail 1650 kg added thermal protection, 450 kg for adding "Landing Legs, RCS & grid fins", but 2,230 kg for added fuel -- most of which would be oxygen. He cites Elon Musk, explaining why SpaceX was abandoning this goal. Musk said, in an interview at MIT in 2014, *"I don't expect SpaceX's Falcon line to have a reusable upper stage. With a kerosene based system, the specific impulse isn't really high enough to do that, and a lot of the missions we do for commercial satellite deployment are geostationary missions. So we're really going very far out – these are high delta-velocity missions, so to try and get something back from that is really difficult."*

- *Low power requirement*: the initial spin-up can be done slowly; after slinging a payload, power can be supplied at relatively low levels to restore the sling's previous kinetic energy.
- *Launch to any inclination*: although the sling is constrained to launch only horizontally, the direction taken can be determined by timing alone, with no refitting or redeployment required.
- *Lunar-night energy storage*: with sufficiently low friction at the hub, or at worst with slight power input to prevent the tether tips from deflecting under lunar gravity to graze the landscape, a rotating tether system can store energy as kinetic energy through the long lunar night. Before lunar "dusk", with no payloads scheduled until "dawn", the sling could even be sped up in anticipation of friction losses, and (if massive enough) used as a power supply for any processes requiring power through the lunar night.
- *Relative simplicity*: in contrast to lunar ISRU architectures that rely on supporting rocket propulsion or electromagnetic propulsion for reaching orbit, rotating tethers on the surface of the Moon require only a tether material, a hub, a motor, and a source of torque.

The idea of using basalt has nevertheless met with a number of objections (as has the sling idea itself.) To begin with, since the literature (such as there is) on tapered rotating lunar-surface tethers seems to stretch over two decades, one perfectly natural objection arises: somebody must have thought of basalt already, and dispensed with it easily.

"Surely, if lunar basalt was so good for ISRU-bootstrapping of a lunar sling, other authors would have noticed."

As far as this author can determine from a literature search, however, the possibility was simply overlooked. Here, we must apologize for dwelling on what may amount to a social psychology theory about the space development milieu. It is the hope of this author that these are not wasted words, and that the present paper leads not only to further analysis of some of the technological developments proposed, but also to a softening of some limiting paradigms.

The oversight on basalt may owe to a combination of several factors:

(1) **Unfamiliarity**. Basalt's excellent natural sling properties were not obvious. Basalt -- mere brittle rock in the view of many aerospace engineers -- doesn't suggest itself immediately as a tether or fiber source to those unacquainted with the applications in which it is important not only for its low cost, but also for its specific strength (or even just its tensile strength.) Nor did basalt suggest itself (even as a source of structural stiffness) as a very useful material in the commercial satellite market. Basalt had aerospace vehicle applications, and basaltic rock-wool does get mentioned as a source of fabric in some MM/OD shielding designs. But use of basalt by the USSR as thermal protection for ICBM nose cones was a Cold War secret. Much of the scene-setting literature for a lunar sling (on skyhooks, space elevators and the like) predates the end of the Cold War, or coincides with the early years of its aftermath.

(2) **Too much "commonsensical" familiarity**. Basalt is very ordinary. Even lunar basalt is pretty ordinary. Extraordinary problems seem to cry out for extraordinary solutions. Among those who seriously entertain the more speculative ideas in space development, there is often a bias toward the highest technology available, when faced with very severe engineering constraints. For Moravec, in assessing skyhooks, Kevlar was the supermaterial of the time. Later, Zylon emerged. Many in the community still pine for carbon nanotubes of the required length and purity. In any case, surely, doing better was a matter of better technology, not of simply finding some mineral already abundant on the Moon and getting it to Earth orbit?

(3) **Early assumptions gained momentum**. Although the strength properties of basalt fiber have been known since the 1920s, there was no precedent for discussing basalt in the literature on skyhooks and the like. These papers mostly repeated the same tether material candidates over and over. It was safe for authors who followed such protean conceptualizers as Hans Moravec and Robert L. Forward to assume that these "space thought leaders" hadn't overlooked any other likely candidates -- materials which, in any case, would presumably come from future technological developments in materials science, rather than being "hidden in plain site",[23] in the lunar mares.

(4) **Earth-to-orbit problem focus**. It is a truth universally acknowledged among aerospace engineers that cheap access to Earth orbit *from Earth* is *the* engineering problem to be solved for the creation of a "true" space economy. This half-truth may contribute to a kind of conceptualization myopia. That is, it becomes more difficult to notice bulk substances on the Moon as a potential source of solutions to the Earth-to-orbit (and back) *engineering* problem, or as having any bridging role in the parallel *economic* problem of generating (or serving) sufficiently increased demand for products in space. If you are focused strongly on how to get to the Moon (or Mars) cheaply, then -- even as a lunar ISRU partisan -- you may overlook how the Moon's resources can help reduce Earth-to-orbit space transportation costs.

(5) **De facto standardization of space development narratives**. There are three "narrative theme-clusters" that are relevant here: (a) humans to the Moon and/or Mars, (b) the satellite industry stock-analyst view, and (c) space mining.

(a) In "humans to Moon and/or Mars", the "public-private" discourse has assumed that massive government investment should appear, by and by, while the debate on how to spend the money is of course trapped in the "shuttle diplomacy" of trying to reconcile the Moon and Mars as complementary public spending targets. Lunar basalt purification and its uses would be a rounding error in this debate's calculations, no matter which side one takes.[24]

(b) In the "satellite industry stock-analyst view", the profitable incumbents will tend to stick close to Earth (literally and in market focus) wherever they are already making money.

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[23] Pun intended.

[24] The author's "side" is to ignore this "theme-plex" and focus on what could have relatively near term commercial value in the space economy we have, not the space economy that many would like to have.

They are answerable to relatively staid stockholders, and are understandably risk-averse. They have their story, they are sticking to it, and until somebody brings them low-risk innovations, they will continue to stick to it. That story does not include lunar basalt, and it probably shouldn't at this point: it would only unnerve investors.

(c) Then there's space mining, which of course doesn't really exist yet. It's a small R&D startup complex whose dreams may not come to fruition for decades, if ever. The NewSpace mining startup scene emphasizes relatively trace substances, such as platinum-group metals, for their obvious terrestrial market value.

In the "public-private" discussions of how both large and small firms could help enable large-scale interplanetary crewed missions, the emphasis falls primarily on lunar PSA H_2O (secondarily on other volatiles) for the presumed fuel source for these enormously expensive missions.

(4) **The unforeseen scale of the coming satellite constellations**. This is a compelling story on both the demand side and the supply side, the full import of which is still unknown. In the mass market for electronics, Moore's Law seems to be breaking down but the remaining momentum means satellites are still becoming ever more functional on a mass basis.[25] Use of COTS electronic parts, redundantly, is steadily eclipsing the market for "rad-hard" parts. Another big change on the cost-performance side is the trend to lower power and longer battery life. Space apps are generally power-constrained, so this is a virtuous convergence of mass market demand and space market demand -- with both markets meeting supply.[26] On the ground, phased-array antennas have improved dramatically, which reduces the cost and increases the bandwidth of satellite broadband. Coincident with both of these developments is the ubiquity of mobile access to social media and other internet resources. This creates user demand for continuous mobile internet communications, including for passengers and staff aboard ocean-going cruise ships and on overseas flights, where only satellite communications can reach. The constellations now being launched will feature hundreds, even thousands, of satellites to serve the wealthier nations of the world (which, from an orbital mechanics point of view, are inconveniently concentrated above northern subtropical regions, which only multiplies the number of satellites needed.) The constellations will also require replacement within a decade as orbital decay sets in. This new market will create large passive-component needs in space that can currently be met only by integration of satellites here on Earth. This market is still very new, however. This makes it unlikely that many space development advocates have looked to the Moon -- much less to lunar basalt -- as a way to make satellite replacement cheaper. Nevertheless, as on-orbit servicing, fabrication and assembly improves, it's no longer

[25] As an example: the crowd-funded (and now NASA-funded) KickSat project carries hundreds of secondary payloads in the form of Sprites, a "chipsat" which, at tens of grams, is comparable in functionality to the almost-30-kg AMSAT-OSCAR-7 launched in 1974.

[26] There has even been a PhoneSat project, using a smartphone for most of a cubesat's electronics, with some spin-off projects like KickSat 1 ending up based on the PhoneSat bus.

unthinkable to assemble satellites in orbit using parts based on lunar materials.[27] With an earlier view of passive structural components as the basis for an initial Earth-Moon economy centered on supporting the commercial satellite market, basalt might have been evaluated much earlier as a lunar sling material.[28]

It was left to Dani Eder to point out lunar basalt finally, but this was still in a wikibook chapter that was more about making lunar skyhooks, in which he proposed a lunar "catapult" (getting no more specific than that, about propulsion means) to put lunar basalt into lunar orbit.[29]

The author apologizes again here for the length of exposition on these possible factors behind ignoring basalt as a lunar-surface sling material until now. It is hoped that the reader's reflection on these biases will inspire some introspection. The space development scene needs a renewable supply of Moravecs and Forwards. There is no shortage of intelligence and education on the scene. What's needed is to break with old (sometimes unconscious) assumptions.

To resume the litany of common objections:

"The masses of such slings are exponential according to the inverse of specific strength; basalt must surely be too weak to be a realistic material."

In the estimates of mass developed in the appendix, it appears that the difference in sling mass between high-strength basalt and Zylon (one of the more popular materials in such sling studies) is a factor of about 4:1. For very-low-strength basalt, we see a factor of about 60:1.

A Zylon sling sent to the Moon from Earth could perhaps compete head-to-head with weaker basalt, especially if the Zylon sling were a skyhook in orbit around the Moon, as this would save on the cost to put the sling on the lunar surface. It's hard to believe that this skyhook could be more economical against stronger varieties of lunar basalt, however, when one considers the export value of purified basalt in our space-economy sketch. Basalt production for export to orbital markets nearer to Earth is already assumed here, so the marginal cost of adding more basalt to a rotating sling on the Moon is probably negligible in comparison. See also the

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[27] In some cases, in-space proofs of concept have run 20 years ahead of the operational capability. See for example, "Space Experiment of Advanced Robotic Hand System on ETS-VIII", Kazuo Machida, et. al., Proceedings of the Space Sciences and Technology Conference v.42, pp. 101-106 (1998). And "Antenna Assembling Experiment on ETS-VII. 2: Results of Basic Experiments", Shin'ichi Kimura, et al., op. cit., pp. 107-112(1998). These papers document the assembly and disassembly of a dish antenna, dozens of times, with a robotic hand in orbit, teleoperated from a lab in Tokyo.

[28] If so, it would hardly be the first time that prognostication about space development has failed for lack of an appreciation of advances in electronics technology. Arthur C. Clarke proposed his GEO satellite network as a kind of "killer app" for human spaceflight, since (he confidently predicted) you'd need workers up there to replace the vacuum tubes as fast as they burned out.

[29] *Space Transport and Engineering Methods: An Introduction to Space Systems Engineering*. A wikibook by Dani Eder. Mention of basalt for skyhook sling material appears in an edit made in 2012.

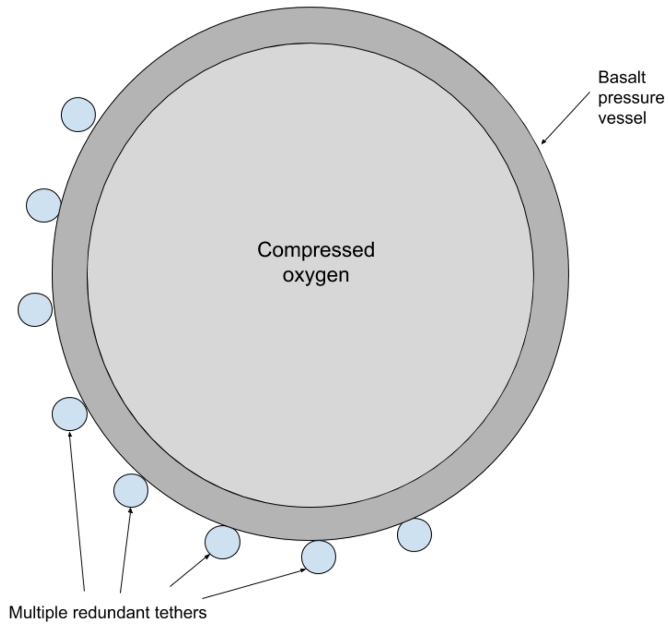
discussion above of lunar basalt fines for a plausibly optimistic view of relative strength. But theorizing about lunar “super-basalts” aside, even a 60:1 ratio may be *economically* more feasible, depending on *in situ* fabrication and construction cost versus Earth-to-lunar-orbit cost.

"The stresses induced on the structure by sudden changes in weight distribution when payloads are released could be intolerable."

Analyses of non-synchronous skyhook structures, which must release payloads in a similar fashion, suggest that the tension-wave propagation issues are negligible. This leaves the added stresses on a hub structure caused by a sudden reduction in tension at the tip. As other authors have pointed out (Landis, Parker & Zubrin) this should not be a serious design issue if the sling is double-armed: in the same instant, one of the arms would sling payload, the other would release a balancing mass. This arrangement should cause the tension waves excited by sudden release at the two tips to arrive at the hub almost at the same instant, largely canceling any horizontal stresses on the hub. The amplitude of the tip-to-hub waves will also attenuate as a function of the sling taper, as they move from thinner tip to thicker base. The questions then become: (1) how serious of a structural issue are these tension waves, for the sling arms themselves? and, if they are a serious problem (if only a problem of more rapid degradation of the sling’s strength), (2) how might the problem be solved?

Another approach to reducing stresses on the hub caused by sudden cargo release would be to simply avoid sudden release -- in the sense of “suddenly reduced tension” -- almost entirely.[30] A monolithic cargo container with a circular cross section (as seen through the plane of rotation) could be sent to roll freely down the length of the sling arm. The figure below suggests one embodiment, a cross section of a candidate payload (oxygen and basalt doubling as cargo vessel) as it nears the far end of a sling arm.

[30] Landis proposes a sliding payload, and a permanent tensioning weight at the tip in order to confer stiffness out to the tip. To avoid impact with the tension weight, he proposes a “radial tube”, which would imply a cylindrical or toroidal weight at the tip. In the frictionless case, he writes, the exit velocity would be higher by a factor of the square root of 2 than for the static-suspension-and-release case.



Cross-section of hypothetical sling arm arrangement with spherical cargo vessel

This mode of travel on the arm is not without its own issues, admittedly. It would undoubtedly generate horizontal displacement waves along the length of the arm, in contrast to tension waves, which could be more like shock waves internal to the arm. To suggest a possible solution:

The problematic stresses in the rolling-container case are more toward the tip (or tips) than at the hub. Since the sling is tapered, the closer to the tip the container gets, the lower will be the mass of the arm-section spanned by the container. The acceleration imparted at the point of contact between the cargo vehicle and the sling arm is made possible only by kinetic energy of the sling being converted to an increasingly horizontal force - implying an equal and opposite force backward, against the sling. It becomes a question of the stiffness of the sling material at that point, and of how resistant it is to breakdown under such forces. Basalt fiber has a relatively high elastic modulus. In bulk form, basalt is, of course, rocklike, which suggests that any such waves, provided they weren't violent enough to fracture the sling arm, would be rapidly damped, perhaps even negligible by the time they reached the hub. Given a supply of basalt and a way to grow a sufficiently massive sling, this problem can be solved with "brute force": make the sling arm thick enough at the tapered end that the forces involved in accelerating a rolling container are negligible. (Admittedly, a rolling cargo container may be much more subject to inaccuracies in trajectory compared to a vehicle that's held until release at a precisely computed instant.)

"Wouldn't it almost double the expense of the whole system to have two balancing sling arms? You need to double your cost estimates. Maybe a Zylon sling sent from Earth is still economically superior."

Not necessarily. This ISRU strategy for sling fabrication implies the ability to make at least one sling arm on the Moon already and fling payloads from the Moon -- payloads that may be mostly basaltic themselves, which leverages the potential of continuous production facilities for basalt after the arm is built and deployed.[31] A second arm can be fabricated with the cost of the first arm already capitalized. The economic case may even depend in part on how well the equipment sent to the Moon can reproduce the entire sling apparatus after the loss of one sling arm or both, a loss caused by eventual strength degradation after many shipments. The added expense of fabricating and deploying two sling arms may even be small compared to designing a stronger hub that supports the rotation of only one sling arm.

"Both releases [of payload and balancing mass] are exactly simultaneous, a technical feat in itself."

Decoupling the stages of multi-stage spacecraft with simultaneous electronic detonation of explosive bolts was worked out long ago, and under more onerous mass constraints than this apparatus would suffer. Would the timing need to be even tighter than that? The technology exists. As Robert Oppenheimer pointed out in testimony about the leak of atomic secrets to the USSR, the *theoretical* physics of nuclear explosions had been worked out before the Manhattan project even started. The harder engineering for the A-bomb was the near-perfect timing of multiple lens-like implosive charges.

“You’re limited to sites at the lunar poles, because otherwise the rotation of the moon itself will cause precession of the sling. And there is relatively little in situ basalt in polar areas of the Moon.”

A number of authors have worked out the issues of rotating sling sites elsewhere than the poles of a moon or asteroid. It’s true that frequent adjustment of the plane of rotation means more power consumption. However, over a lunar day (around a month of Earth days), this power requirement does not appear to be unmanageable. Baars and Tragesser conclude that their “results demonstrate the dynamic feasibility of locating a tether sling facility at any location of a rotating moon or asteroid.”[32]

“This may be a good idea but only after a big public-private partnership establishes major physical plant, as part of a big base on the Moon. You’ll obviously need a major construction

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[31] The two approaches -- imported fiber vs. ISRU -- aren’t entirely mutually exclusive. A commenter who prefers to remain anonymous suggested that the system could initially deploy the tether sling arms as much thinner “pilot tethers” of Zylon or the like; basalt fiber could then be layered over and sintered onto the arms to bulk them out for greater payload capacity. Dani Eder made a similar suggestion a few years ago, but for the concept of lunar space elevator.

[32] Luis Baars and Steven Tragesser. "Dynamics and Control of a Tether Sling on a Rotating Body", AIAA SPACE 2010 Conference & Exposition, AIAA SPACE Forum. More recently, see also "Optimal Oscillation Suppression Control for Tether Sling-Shot System", Shohei ISHIKAWA, Hirohisa KOJIMA, Transactions of the Japan Society for Aeronautical and space Sciences, Aerospace Technology Japan (2017)

project on the Moon. Look at the heights of the towers proposed in these papers. And siting will still be a problem because of how low a long sling arm will droop even under lunar gravity and high tension -- you'll need a very wide flat area. Landis works out an example for which the radius is 50 kilometers. His hub tower is 1280 meters tall!"

In Landis' main worked example, he assumes a radius and tip speed that yielded only moderate accelerations (5.7 g for lunar orbit, 11.5 for lunar escape) at the tip. It's not stated in the paper (where Landis puts an upper limit of 2.5 g on human launch), but with this choice, Landis appears to keep open the option of launching, and perhaps even catching, spacecraft with human beings inside.[33]

The existing space economy of commercial satellites (with its expected burgeoning of satellite constellations) does not impose much of a limit on the accelerations of payloads. If the means existed today to launch satellite parts more economically from Earth at thousands of g's, the commercial space launch industry would be taking advantage of it. What effect does relaxing Landis' tacit human-rating acceleration constraint have on the calculations for sling size and mass?

An interesting property of the expression for the mass of the sling as derived by Puig-Suari, et al., is that, for a given combination of specific strength, payload mass and target velocity, the mass of the sling is *constant*. For any much shorter radius, acceleration will naturally be higher, but this is not an issue for the economic scenario in question. Cargo shipments from the Moon could be engineered to endure a hundred times more acceleration than a human being could survive, with corresponding reductions in sling arm length.

A much shorter sling arm also largely eliminates the issue of tower height. Over the length of a sling arm perhaps a few kilometers in length, at great tension because of the high rate of rotation, the drooping caused by lunar gravity should be negligible.[34]

Perhaps the main issue of scale is in the rate of production of fine-enough basalt, and in the construction and deployment of tether arms. Further limits might be seen in the problems of deployment of cargo containers on the tether arms: what forces can they withstand? If, for example, it's desired that the payloads consist mainly of basalt spheres containing highly compressed oxygen, what are the implications for the sizes, respective mass fractions of basalt versus oxygen, pressure vessel thickness, etc.?

Future Work

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[33] If so, he could have gone further: human test subjects have taken up to 32 g for 25-second runs. See "The G Machine", Air & Space magazine, May 2007.

[34] "For the [lunar] orbital case a 7,000 m tether has a droop of 58.5 meters and the payload experiences 42 g." AIAA 90-2109 Lunar and Mars Mission Architecture Utilizing Tether-Launched LLOX, D. Baker and R. Zubrin. Baker and Zubrin assume Kevlar braid, with segments joined by end fittings. Kevlar has somewhat higher specific strength than basalt, but is still roughly comparable.

The reader will have noticed that there is very little technical detail in the paper. It is certainly not a mechanical engineering treatise covering all possible problems and their solutions. The agenda for any future work on this concept should include:

Sling arm deployment strategies: Can the sling be deployed by threading it through the hub, in continuous production of the sling? Need it be fabricated first, then attached and spun up? Baker and Zubrin envision a tether that can be spooled and unspooled, which not only helps solve the sling arm deployment problem, but also the problem of payload deployment on the tether tip. Basalt is a stiffer material than Kevlar, so this approach may be impractical for basalt.

Sling arm fabrication details: specifically, whether basalt fiber can be woven in a manner that doesn't significantly compromise the advantages of tapering. Deployment might be incremental, using additive manufacturing, with successive layers applied by a “climber” that moves inward and outward from the hub, along the sling.

Hub design: for low friction, and power extraction through the lunar night. Basalt may feature enough compressive strength that ball bearings made of basalt would suffice. (The sling may be massive, but, under lunar gravity, not necessarily so heavy as to destroy ball bearings, except very gradually, through rolling friction.)

Furnace design: it is suggested in the abstract that a solid rocket casing used for most of the retropropulsion for putting equipment on the Moon, to produce the sling and its products, could be repurposed after landing -- as a crucible. Solid rocket casings are often made of refractory alloys that could easily tolerate the temperatures required to melt regolith on the Moon. The fact that they are tall and thin is a feature, since under lunar gravity, achieving the hydrostatic pressure needed for extrusion of fibers will require more depth in the melt. Work remains to be done on how this repurposing could be managed; if it's possible, this vehicle-as-payload concept could substantially reduce the cost of putting the needed equipment on the Moon.

Moon-to-Earth-aerobrake trajectory adjustment: The proposed packaging of payloads includes the idea of spheres of basalt containing compressed oxygen. To fling such payloads off the tip of a rotating sling without trajectory adjustment Moon-to-Earth would be to leave the initial aerobrake dynamics to chance -- to say the least. In any case, aerobraking on multiple passes and then thrusting to establish a reasonably stable low Earth orbit is a problem that probably can't be solved except in flight, because so many unpredictable and/or chaotic factors enter in. What is the minimum of equipment (per payload) required to use a fraction of the oxygen payload for cold-gas thrusting at various poorly-predictable points in time? The control systems will need to be heat- and radiation-tolerant. Fabrication of optimal valves and nozzles from basalt and glass, on the Moon, may be impractical. Although reaction wheels made of regolith are a plausible export opportunity, sending to the Moon everything required to make cast basalt wheels useful for thrustless in-flight attitude control seems a tall order. And we certainly do not propose electronics fabrication starting from lunar silicon in this scenario. That should only come later, when profitability is established. What is the minimum that needs to be sent to the Moon in order to get payloads back?

Conclusions

It has been proposed here that a continuously rotating, tapered, double-armed sling made of lunar basalt can propel to Earth aerobrake the constituents of satellite parts and products for intact return of upper stages of satellite launchers. The sling can be made mostly of lunar basalt, and so can these proposed exports. With (probable) favorable marginal return on the added investment, oxygen and glass are likely byproducts of producing both the basalt sling and the basalt to be sent to Earth orbit. The promise of such a supply of basalt, glass and oxygen could spur the development of orbital satellite integration facilities, lunar oxygen depots, and the reengineering of existing upper stages to take advantage of lunar-derived products that facilitate upper stage return. The key conclusion is that basalt is a very plausible material both for the propulsion requirements of lunar export to existing commercial space markets (given the integration of satellites in orbit) *and* a plausible main ingredient of a number of spacecraft elements.

Acknowledgements

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