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The Lunar Space Elevator, a Near Term Means to Reduce Cost of Lunar Access

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A Lunar Space Elevator [LSE] can be built today from existing commercial polymers; manufactured, launched and deployed for less than $2B. A prototype weighing 48 tons with 100 kg payload can be launched by 3 Falcon-Heavy's, and will pay for itself in 53 sample return cycles within one month. It reduces the cost of soft landing on the Moon at least threefold, and sample return cost at least ninefold. Many benefits would arise. A near side LSE can enable valuable science mission, as well as mine valuable resources and ship to market in cislunar space, LEO and Earth's surface. A far-side LSE can facilitate construction and operation of a super sensitive radio astronomy facility shielded from terrestrial interference by the Moon. The LSE would facilitate substantial acceleration of human expansion beyond LEO.

I. Introduction

The original idea for a Space Elevator was for an elevator from the surface of the Earth up to Geostationary orbit. This idea is attractive since in theory it could greatly reduce the cost of access to space [1,2], however, there are no materials existing or on the horizon which are remotely strong enough to hold their own weight over the distance in the Earth's gravity field. Theoretically Single-Walled Carbon Nanotubes [SWCNTs] would suffice[3], but so far nobody can manufacture them in useful quantities or purity. SWCNTs have only been produced in tiny quantities in laboratories, and there is no prospect of industrial scale production happening in the foreseeable future. However, there is another planetary scale tether concept which is almost as valuable, and can be built with existing industrial materials, and that is a Lunar Space Elevator [LSE].

A LSE is a very long tether, connecting the surface of the Moon to an Earth Moon Lagrange [EML] point, either EML1, between Earth and Moon (nearside), or EML2, behind the Moon as vie wed from the Earth (farside). In order for the LSE system to be stationary with respect to the Moon it is necessary that the center of mass of the LSE be located at an EML point. Therefore, the tether must extend further from the lunar surface than the EML point, and be terminated at a counterweight. The Moon orbits the Earth about once per month, so the LSE is not stationary with respect to the Earth, but it is stationary with respect to the Moon.

The LSE dimensions are larger than any structure in space so far attempted. In a design calculated by T. M. Eubanks the total length of a nearside elevator is 278,544 kilometres [154,747 statute miles], and the total length of the farside elevator is 297,308 kilometres [165,171 statute miles] [5].

On average, EML1 is 326,380 km [203,988 statute miles] away from Earth and 58,019 km [36,263 statute miles] away from the Moon. EML2 is 448,914 km [280,573 statute miles] from Earth and 64,515 km [40,323 statute miles] from the Moon. Hence, in the Eubanks design, the distance from the Lagrange point to the counterweight for the EML1 system is 220,525 km [118,484 statute miles] and for the EML2 system is 232,793 km [124,848 statute miles].

These distances are unprecedented in aerospace engineering, and we can reasonably question whether it is even possible to build structures so large. Yet preliminary analysis indicates it is not only possible, it is relatively inexpensive, and can be done with existing commercial materials[5]. In this paper we will show how the lunar elevator is both feasible and affordable, and indeed profitable. Of course, there will be many technical and engineering challenges, but as far as we know today, there are no obvious showstoppers.

The idea of a lunar elevator is not new, but until recently has been dismissed as fantasy or science fiction. The first known writing, where the concept of a lunar elevator was described, was in 1910 in the unpublished notes of the German-Latvian-Russian scientist Friedrich Zander. These notes were posthumously published in Moscow in 1977[6] and noticed by Dr. Eugene Levin, who has since become one of the leading experts on the concept. Levin

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joined Pearson and his team at Star Technology Inc., where they have jointly studied the LSE concept, notably for NASA Institute of Advanced Concepts in 2005[4].

II. Available Materials

The first key technical challenge of the LSE, is to find a material which is both light enough and strong enough to support its own weight over the entire distance in the cislunar gravity field, and still be strong enough to carry a payload. Until the late 20th century, such materials did not exist, but since the 1990's, revolutionary new polymer materials have become commercially available.

The first material which was theoretically capable of supporting a lunar elevator was Kevlar ™, but it was only barely strong enough. Fortunately, newer even stronger [by weight] materials have subsequently come on to the market; four in particular are T1000™, Dyneema ™ [7], Magellan-M5 ™ [8] and Zylon ™ [9]. Another theoretical material which would be even stronger would be SWCNTs, however they have only been produced in nano-thin crystal sizes, suffer from extreme susceptibility to nano-defects[10], and are a long way from being commercially viable. Fortunately, the other satisfactory materials are mass-produced in ample quantities and lengths, and we do not need to wait for SWCNTs to begin the construction of LSE. The Magellan M5 material is superior to everything else currently available; however, supplies are very limited on the commercial market. The reasons for this are not entirely clear, but according to anecdotal information, it appears to be twofold. Firstly, M5 is difficult to manufacture, partly because of its extraordinary strength, it tends to destroy the tooling[2]. Secondly, it is in high demand by the US Government, especially for bulletproof vests and helmets, and the US Government buys up nearly all of the available production to date. The three other materials, T1000G, Dyneema and Zylon, are available in large quantities, and are currently the best candidates for LSE construction, at least until M5 eventually becomes available in greater quantity, or until an even better material become widely available.

III. Throughput and Return on Investment

The term "Lunar Elevator" is something of a misnomer when applied to the lunar skylift system. That is because, although the system conceptually bears some similarity to a terrestrial elevator, there is a fundamental difference. That is, a terrestrial elevator typically has a single car, travelling up and down a single shaft. We will show that the optimal configuration for a lunar elevator is significantly different. Specifically, a lunar elevator can and should carry multiple cars to maximize throughput within the strength capabilities of the tether. We will show below that a single LSE can ideally carry six cars simultaneously on the section of tether between the EML and the lunar surface. Furthermore, during a two week period, about 80 car trips could be performed from the surface to EML, resulting in an eighty times increase in payload mass throughput versus a single climber.

A key figure of merit is the speed with which the climber travels up and down the tether. From a business standpoint, we wish to maximize revenue, which means maximizing the payload throughput of the system. Throughput can be expressed in terms of mass of payload [per climber], multiplied by the speed of climber, multiplied by the number of climbers over a given time period.

The Delta Vee required for a conventional chemical rocket to ascend from lunar surface to EML-1 is 2.7 km/s. Goff[3] [among others] showed that the typical payload mass fraction for such a rocket is 34%, ~ 1/3. A rocket which delivers the 49 tonnes LSE to EML-1 would otherwise be capable of soft landing 16 tonnes on to the lunar surface. So for LSE payload of 0.1 tonnes, this is equivalent to 16/0.1 = 160 payload landing cycles [or trips], which is the number of cycles to recoup the LSE launch cost. For sample return missions, another factor of three applies, so 160/3 ~= 53 sample return cycles would recoup the launch cost.

The principal benefit of the LSE is that it reduces the cost of sample return by at least nine times, considering primarily the cost of launch, but without considering the capital cost of manufacture, since that has not yet been studied in detail. In any case, one can reasonably hypothesize that the launch cost will be the dominant cost of the system.

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[22] D-Rmor Gear, Future Developments: M5 Fiber, 21 Aug 2014, https://drmorgear.wordpress.com/2014/08/21/future-developments-m5-fiber/

[3] Goff, The Slings and Arrows of Outrageous Lunar Transportation Schemes: Part 1 Gear Ratios, Selenian Boondocks, 2013. http://selenianboondocks.com/2013/12/the-slings-and-arrows-of-outrageous-lunar-transportationschemes-part-1-gear-ratios/.

In terms of launch cost, we need to make 53 sample return cycles to realize a profit, then we need to complete those 53 cycles as quickly as possible. In 2008 a student team at Asher Space Institute of Technion University [Haifa] postulated that a velocity of 700 metres/sec is feasible, hence the journey from the surface of the Moon to the Lagrange station would take about seven days[4].

Interestingly, it is feasible to have multiple climbers on the tether, without significantly reducing the payload, and this would greatly increase system throughput. At a velocity of 700 metres/sec, it is feasible to have 80 climbers along the tether [see Table-1], and that means that 53 sample return payload cycles can be completed within a month. So the LSE can pay back its launch cost in less than a month, giving a total throughput of ~8 tons per month in each direction, or ~100 tons per year. The incremental operational cost per payload cycle is negligible compared to the corresponding cost of using chemical propulsion; hence it will rapidly reduce the total cost by orders of magnitude.

Of course if the climber could move even faster, then the revenue stream per year would be even greater, which would be very pleasing to investors. Hence, there is a commercial incentive to maximize the climber speed. It might be possible to increase the climber speed even more than 700 metres/sec. This would involve additional technical challenges, which have not been studied to date.

[4] Qedar R. , Grinfeld N. , Bezrodny G. , Reuven O. , Tatievsky A. , Kogan A,. Jacob's Ladder - Lunar Space Elevator http://lunarjacobsladder.webs.com/

Table-1: Number of Ascents/Descents per half lunar solar day [half month], as a Function of Climber Speed

Cruise speed km/sec	Cruise speed km/hr	Time to EML1 [hours] from surface	Time to EML2 [hours] from surface	Time to 5K Km [hours] from surface*	Near side Nr of Ascents [or Descents]	Fars side Nr of Ascents [or Descents]	
1.000	3600.00	17.50	19.31	2.78	122.14	121.49	
0.700	2520.00	25.00	27.58	3.97	83.908	83.258	
0.500	1800.00	35.00	38.61	5.56	58.42	57.77	
0.278	1000.80	62.95	69.44	9.99	30.12832	29.47832	
0.139	500.04	125.99	138.99	20.00	12.40142	11.75142	
0.100	360.00	175.00	193.06	27.78	7.444	6.794	
0.054	194.40	324.07	357.51	51.44	1.58176	0.93176	(takes longer than half lunar day to reach EML2)
0.048	172.80	364.58	402.20	57.87	0.81712	0.16712	(takes longer than half lunar day to reach EML1)

* assuming constant acceleration from 0 at surface to cruise speed at 5,000 km

Moon to EML1 distance is 58,000 km
Moon to EML2 distance is 64,500 km
Lunar solar day period [full Moon to full Moon] lasts 29 days, 12 hours, 44min ~= 29.5 days = 708 hours
354 hours = half lunar solar day

IV. Basic Operational Concept and Performance

LiftPort Group and Marshall Eubanks have calculated the parameters for a 48 ton LSE design which is light enough to be launched on a single SLS launch vehicle using direct injection, or a single Falcon-Heavy class vehicle using electric propulsion to transfer from LEO to EML1 or EML2[5]. This design is probably the smallest that can reasonably be built. The LSE system will be manufactured entirely on Earth, and assembled for launch into a single package. The essential components comprise: the tether, the EML station, the Counterweight [CW], the Surface Attach Fixture [SAF], and the Climbers. Upon arrival at the EML1/2 location the deployment sequence will begin. The CW and the SAF simultaneously detach from the EML, and the respective attached tethers begin to unspool. The two tethers are concurrently unreeled at rates which maintain the center of gravity of the system at the EML location. Once the tether is fully deployed, the SAF will drill into the lunar surface by a meter or two, sufficient to react the small residual tension force, and small lateral disturbance forces.

Once the system is stabilized, and residual deployment transients have damped, the first attempt will be made to drop a climber towards the lunar surface. In order to descend to the lunar surface, no injection of energy is required, instead the climber will accelerate by falling under gravity until it reaches a cruising speed, and thereafter will apply braking to limit the descent speed, and to decelerate for a final soft landing. Hence the descent can be performed during daylight or during darkness. Regenerative braking can be used to convert the kinetic energy to either electrical energy to charge batteries, or heat to melt salt. Blocks of molten salt, similar to those used in terrestrial solar power farms, can be delivered to lunar surface facilities to power them during the lunar night.

Ascent from the lunar surface must be done during lunar daytime since the climbers are solar powered, and will need input of solar power to drive the motors to ascend the tether. An initial run will be made using a single climber to descend and then ascend along the tether. Once the basic function of the system is thus validated, then multiple climbers can be put into action. If the speed of 700 metres/sec can be sustained then it would be possible to have 80 climbers descend and then ascend along the tether during a one month lunar solar cycle, with six climbers simultaneously present on the tether at any one time. This is assuming a single lunar elevator, where the climbers must all move in the same direction at any given time.

There are three types of destinations for lunar raw materials carried by ascending climbers. Firstly, they could either be dispatched towards Earth, to either enter Earth's atmosphere, or to enter a low Earth orbit [LEO]. Or secondly they could be delivered to a cislunar destination, such as another EML [1,2,3,4 or 5], or to the proposed NASA lunar orbiting gateway station. For an Earthwards trajectory, the payload would be accelerated past the EML station and released at a point between the EML and the counterweight [as analyzed by the Technion team]. For a cislunar destination, the payload would be decelerated to reach a stop at or near the EML, then released. A third type of destination would be to boost a payload from Earth on to a hyperbolic Earth escape trajectory, by rendezvousing with a farside LSE then accelerating the payload away from EML2 to interplanetary trajectory, e.g. to Mars or an asteroid; this would save some propellant versus using a chemical rocket for the entire injection..

It would be feasible to have two lunar elevators, one for downwards descending payloads, and another for ascending payloads. Coriolis force on each tether would act in opposite directions. The easterly tether would be used for downwards traffic, and the westerly tether for upwards traffic. The respective Coriolis forces would act in opposite directions and cause the two tethers to be pulled apart so they would not interfere with each other. In such a dual tether system, the downwards tether could be in continuous operation, day and night. The upwards tether would only be able to operate during the lunar daytime, unless power beaming becomes available. With such a bi-directional dual tether system, the number of climbers could be reduced to twelve, since each ascending climber could be unloaded, reloaded and transferred to the descent tether and thus be reused. Each of the twelve climbers would perform six or seven round trip journeys each month.

V. Technical challenges

There are several technical challenges involved in building a lunar elevator, but so far we do not believe there are any showstoppers, and that all the technical problems can be solved within a reasonable cost.

A key figure of merit is the speed with which the climber travels up and down the tether. From a business standpoint, we wish to maximize revenue, which means maximizing the payload throughput of the system. This means maximizing the velocity of climbing up and down. The Technion University team in 2008 suggested that 700 metres/sec is a reasonable velocity, since it is below the speed of sound in the tether material, which would otherwise result in a destructive shock wave developing. Pearson et al in 2005[4] suggested that 15 metres/sec would be a more conservative velocity, and question whether 700 metres/sec is realistic[5]. Challenges in achieving such

[5] Personal correspondence, Pearson to Radley, 2017

high speeds include high gear ratios, friction, lubrication and wear of all the respective moving parts, and abrasion of the tether material.

Another overall challenge of LSE is to maintain the center of mass of the system at or close to the EML location at all times. The EML is an equilibrium point between the Earth and the Moon, but it is not stable. Objects which are offset from the EML will tend to move away from the EML. Hence, some method of active station-keeping will be required. Geosynchronous satellite around Earth suffer from a similar challenge, and they typically use chemical rockets or Hall thrusters to maintain station. In similar fashion, we anticipate that electric propulsion or Hall thrusters could be used to maintain the EML station on to station. There are several disturbance forces which will need to be dealt with, for example, the lunar orbit around Earth is not circular, it is elliptical and as a result the location of the EML point itself is not stationary and will tend to move in a cyclical manner. It has been proposed that a Lissajious orbit be used around the EML, which has a greater time constant than the EML itself[11]. Furthermore, although the Moon is tidally locked to the Earth, it experiences periodic rocking motions back and forth, about two axes, known as "Libration". In order to compensate for these various orbital and libration disturbance forces, it has been proposed that an active control system could actively vary the length of the tether to the lunar surface and/or to the CW, and achieve some degree of station-keeping control[12].

Another issue to address is the Coriolis Effect. A climber which travels up and down the tether will experience Coriolis force due to the difference in lateral velocity between the EML location versus the lunar surface. According to my calculations below, it is feasible to use electric propulsion [Hall thruster] to compensate for the Coriolis force, with a modest loss of payload capacity, taken up by the weight of the thruster. Most of the electric power of the solar arrays is needed only in the first 5,000 km of the climb from the lunar surface[6], above that, most of the power can be used instead to supply an electric thruster for Coriolis compensation, and a small amount of power used to maintain cruise speed of the climber up the tether.

A first order analysis of electric thruster requirements is summarized in Table-2.

The Moon's sidereal rotation period (the sidereal month) is ~27.3 days = 655.2 hours
Moon to EML1 distance is 58,000 km
Moon radius is : 1,079 mi = 1726.4 km
Moon circumference = 6,786 mi = 10857.6 km => Speed of lunar surface = 16.57 km/hour
Circumference of EML1 orbit = 364424.75 km => Speed of EML1 = 556.2 km/hour
Hence, Coriolis Delta-vee needed for reaching EML1 from lunar surface = 539.6 km/hour
= 149.9 m/s

[6] Eubanks, T. M., A Space Elevator for the Far Side of the Moon, 2013, https://www.researchgate.net/publication/260989829_A_Space_Elevator_for_the_Far_Side_of_the_Moon

Table 2: Rocket Thrust needed to compensate for LSE Coriolis Forces

Time to EML1 [hours] from surface	time to EML1 [seconds] from surface	Coriolis acceleration m/s^2	Coriolis acceleration [g]	Coriolis force [N] on 100 kg	Coriolis force on 100 kg in mN	Number of Busek BIT-3 thrusters	KW for Busek *	Weight of Busek kg
17.50	63000	0.002380952	0.000243	0.238095	238.0952	170.068	10.2381	34.01361
25.00	90000	0.001666667	0.00017	0.166667	166.6667	119.0476	7.166667	23.80952
35.00	126000	0.001190476	0.000121	0.119048	119.0476	85.03401	5.119048	17.0068
62.95	226620	0.000661901	6.75E-05	0.06619	66.1901	47.27864	2.846174	9.455728
125.99	453564	0.000330714	3.37E-05	0.033071	33.07141	23.62243	1.422071	4.724487
175.00	630000	0.000238095	2.43E-05	0.02381	23.80952	17.0068	1.02381	3.401361
324.07	1166652	0.000128573	1.31E-05	0.012857	12.8573	9.183789	0.552864	1.836758
364.58	1312488	0.000114287	1.17E-05	0.011429	11.42868	8.16334	0.491433	1.632668

Busek BIT-3 thruster consumes 42.86 W/mN, weighs 142.86 grams / mN thrust

* The power consumption of Busek [Iodine] thrusters for compensation of the Coriolis Effect is well within the solar array capacity of the climber

Alternative Aerojet BPT-4000 thruster consumes 15.51724138W/mN, weighs 42.41 grams / mN thrust

A single BPT-4000 hall thruster exerts 290 mN, ample to compensate for Coriolis Effect, it weighs 12.3 kg. This type of thruster has been flown in space commercially several times on communications satellites, it is well proven and reliable.

Total impulse of burn needed, regardless of climber velocity, is 15 KNs = 15,000 kg m / s

For chemical rocket, propellant mass needed= total impulse / specific impulse [Isp]

Assume Isp of 300 seconds, then propellant mass needed would be: 50 kg

Therefore, the weight of the BPT-4000 electric propulsion system would be much less than the weight of chemical propellant needed for the same burn impulse.

Other technical challenges include:

- Control of tether deployment process
- Dynamic analysis including handling of Coriolis forces
- Dynamic analysis of changes in center of mass
- Maximize payload throughput
- Trajectories for delivering payloads to Earth
- More detailed design of surface attach fixture interfaces
- Static charging by solar wind
- Electric power supply to robotic climber
- Methods of station-keeping
- Micrometeoroid impacts. Note, initial estimates by Eubanks suggests that the LSE strands will be impacted and severed twice per year by micro-meteoroid impacts. It will be necessary for the tether to be damage tolerant and reparable, such as using a multi-strand Hoytether design[13]

We propose that these issues should be addressed in the next steps of the concept development.

VI. **Safety Reliability and Failure Modes**

Relatively little work has been done to address the effects of failure modes in the LSEI , and possible methods for mitigation or recovery from failures, and abort modes. Consequently, the effects of failures are not well understood. Hence, it would be too risky to carry human cargos in the early phases of the LSE operation, until a high level of confidence in the safety and reliability of the system has been achieved. . Initially the LSE will be used to transport unmanned cargo, such as equipment from Earth and raw materials from the Moon. In order to perform a proper Failure Modes and Effects Analysis [FMEA] we will need to consider what are the potential targets or victims of a failure, i.e. what elements within the system could be adversely affected, as well as what items outside of the system. Our initial assessment of items which might be adversely affected include the following:

- Human population centers on Earth
- Terrestrial infrastructure and property
- Terrestrial environment
- Spacecraft in Earth orbit, LEO, MEO, HEO
- Payloads of the LSE
- LSE tether
- EML station of LSE
- Lunar surface installations
- Lunar orbiting spacecraft
- Spacecraft in Cislunar trajectories

A preliminary qualitative assessment of the failure effects is attempted as follows:

- Human population centers on Earth

There is no credible scenario where human population centers could be threatened by major debris from the failure of an LSE. The total mass of the LSE is about 48 tons[5], but there is no failure scenario where this entire mass would reach Earth. Various scenarios are considered. If the LSE is severed between the EML station and the lunar surface, then a section of tether attached to the EML station and the counterweight could drift away from the Moon. The section would weigh perhaps 40 tons, but its orbit would not intersect with the Earth, having a perigee probably higher than geosynchronous orbit, where even the counterweight extending towards Earth would be unlikely to encounter the Earth's atmosphere. It is possible that if the tether failed near to the counterweight, then the counterweight and a small piece of attached tether could enter the Earth's atmosphere. The counterweight might weigh a few tons, and some of it might survive entry into Earth's atmosphere and reach the Earth's surface. Fortunately, the time and place of an impact on to the Earth's surface could be predicted with some precision about three days in advance, so evacuation of any nearby population centers could be accomplished, although this will probably be unnecessary.

- Terrestrial environment

Following from the previous discussion, the portion with the LSE counterweight might weigh a few tons at most, probably much less, and this does not represent a significant threat to Earth's environment. The configuration and composition of the counterweight comprises primarily expended rocket upper stages used as ballast, and these would be of low density. Hence the counterweight would be significantly decelerated by the atmosphere, and much of it would be vaporized or broken into tiny pieces. The final impact velocity will probably be little more than the atmospheric terminal velocity, with most of the ballistic orbital velocity eliminated. Any impact of the object on to the Earth's surface would have less effect than a meteorite of comparable size. If it lands in the ocean there would be no Tsunami; if its impacts on land, any debris cloud would be localized and short lived. The potential for human injury or property damage appear comparable to the current risk of decay of large LEO satellites, which is generally regarded as very low.

- Spacecraft in Earth orbit, LEO, MEO, HEO

It is possible that the LSE counterweight and some portion of the attached tether, perhaps including the EML station, could end up in orbit around the Earth. Either a high orbit [HEO], or MEO [Medium Earth Orbit] or LEO [Low Earth Orbit]. This might represent a collision hazard for any spacecraft in these orbits. The large length of the tether means that its cross sectional sweep area would be significantly greater than for most satellites launched to date, so the probability of collision would be quite high. This could represent a space situational awareness challenge. The present methods used for tracking space debris would probably suffice for tracking larger pieces of the LSE. There is a high probability that the LSE orbiting fragment will experience multiple impacts with man-made orbital debris [MMOD], especially in lower orbits. These MMOD collisions will most likely sever the tether into smaller fragments which will drift apart from each other. There is a risk that the multiple LSE fragmentations could cause a modest increase in the total count of MMOD objects orbiting the Earth. It would be desirable for the counterweight to contain some propulsion capability to try to keep it to a higher orbit, further away from Earth if possible, where the population of MMOD and spacecraft is relatively low. . It would be desirable to recover the LSE fragment, and restore it to service back at its proper location, there is a high likelihood that the fragment would stay in orbit long enough that recovery could be achieved.

- Payloads of the LSE

The fate of each payload depends on where each climber is along the tether, and where exactly the break in the tether occurs. The tether can be considered to be in two parts, an upper part, which is detached and free flying, and a lower part which remains attached to the lunar surface. There could be payloads in transit attached to either, or both, parts of the tether. It is possible that many of the payloads attached to the lower part will be lost since they will fall to the Moon and impact with destructive velocity. It might be beneficial to include some braking rockets on to the payloads to reduce the effect of impact on the lunar surface, this will need to be analyzed. For payloads attached to the upper tether, it will be undesirable to lose the payloads by having them burn up in Earth's atmosphere. Hence, it might be beneficial to separate those payloads from the tether, and include some propulsive capability in the payload to raise the perigee so that it will not enter Earth's atmosphere. Whether that would be cost effective is a question which needs to be analyzed.

Having multiple climbers on the tether would help considerably to mitigate failure and afford additional abort/recovery scenarios. As shown earlier, it is attractive and feasible for there to be multiple climbers on the tether at any one time. In such a scenario, the climbers would be about 10,000 km apart, which means there would be no more than six on the section between the Moon and EML at any given instant. A novel approach is suggested here, that is, these climbers could be tethered to each other by a thin secondary tether, thinner and lighter than the main LSE tether. In the event of the main LSE tether failure, the backup tether could be used to hold one or two, perhaps up to three climbers from the lunar attached portion of the LSE. Those payloads would detach from the lunar attached LSE section, and remain attached to the lowest climber on the free flying portion of the LSE. This would have the significant benefit that it would reduce the amount of abort propellant needed for an emergency soft landing on to the lunar surface. Only the lowest one or two of the climbers along the portion attached to the Moon would not be able to stay with the free flying portion, and in order to survive, they would need to perform rocket powered soft landings, from an altitude of no more than 15,000 kilometres, i.e. 5,000 km + the 10,000 km separation. This would potentially allow survivable abort modes for future astronauts being carried along the LSE.

- LSE tether

If the LSE tether breaks into two sections, one remains attached to the Moon, the other becomes free-flying. The portion attached to the Moon will fall towards the Moon under gravity, much of that tether might survive and could be recovered and reused. The portion which is free flying would go in one of three places:

1) Earth orbit
2) Lunar orbit
3) Earth atmosphere entry
4) Interplanetary trajectory [farside LSE only]

In the case of Earth atmosphere entry or Interplanetary trajectory, the LSE tether would be lost. In the case of Earth orbit or Lunar orbit, it would be feasible to recover the tether, and return it back into service.

- EML station

The fate of the EML station depends on the location of the break. If the LSE tether breaks between the EML station and the counterweight, then the EML station would tend to fall towards the Moon. Since the EML station is high value, it is desirable to prevent it from impacting on to the surface of the Moon. One scenario would be for the EML intentionally to either separate from the main tether, or to sever the tether midway between the EML and the Moon. In that case, the EML station should enter a lunar orbit, from which it could be recovered and returned back into service. If, on the other hand, the break occurs between the EML and the Moon, then the EML might suffer the same fate as the counterweight, as described above. In that case, the biggest concern is if the EML station enters the Earth's atmosphere; in that case, it would be desirable for the EML station to separate from the section of tether attached to the counterweight. That would allow the counterweight to enter Earth's atmosphere, but the EML station would enter orbit around the Earth, from which it could be recovered and placed back into service.

- Third party Lunar surface installations

In any failure scenario, part of the tether will remain attached to the lunar surface, and that portion will fall back to the lunar surface, perhaps with one or two climbers attached to it, the other climbers could be rescued by a secondary tether described above. There will be some residual lateral velocity [due to Coriolis forces] which will cause the tether to fall across some finite distance away from the surface attach fixture location. The tether material would be very thin, less than 1mm for the early versions, and that is small enough that it is not likely to make contact with any lunar surface installations in the area. In any case, the fall to the lunar surface would be fairly slow, taking a few hours, there would be some time, but not much, for humans on the surface to take evasive action. The high end tip of the tether would impact the lunar surface with the highest velocity, and might cause some cratering and dust cloud at the point of impact. Once the tether has settled on the lunar surface it should be possible to recover and reuse most of the material.

- Lunar orbiting spacecraft

The probability of collision of the free flying LSE fragment with lunar orbiting spacecraft is quite small, and the velocities slow enough that evasive action should be possible if needed. In any case, for an LSE operating nominally it will be necessary for a situational awareness [SA] system to be in place to make sure that lunar orbiters phase their orbits such that they avoid impacting the static LSE. This SA system should be able to modifying the orbiter phasing to avoid collision with a drifting LSE fragment.

VII.**Near Term Commercial Markets for Lunar Resources**

The first near term market for a LSE will probably be science data[5]. LSE will enable cheaper access to the lunar environment, enabling more science to be done, and reducing the cost of science experiments. It will also enable new types of science which were previously impossible or prohibitively expensive, such as Very Long Basline Interferomtetry, and Farside radio astronomy. Other short term markets would mostly derive from commercial and industrial lunar resource utilization.

Crawford[14] has suggested that there is probably no single commodity of lunar origin which by itself could justify the substantial investment needed for any lunar mining system. . However, Crawford does suggest that a basket of multiple commodities could afford sufficient financial and economic justification, and that a profitable business plan could be developed. Crawford suggested some ingredients to such a basket, but there are probably additional products which could be commercially developed. An LSE would reduce the cost of a lunar mining system ninefold in terms of cost of retrieving lunar material; nevertheless, it is likely that Crawford's hypothesis could remain true.

The value of lunar commodities is somewhat counterintuitive. The price and value of commodities on Earth, for example, will be very different for lunar materials. Market demand for lunar materials will be very different than for terrestrial materials, due to the very different abundance of the various items at the respective locations. Moon rocks themselves would have intrinsic commercial value purely for their rarity and novelty attributed. Lunar meteorites are widely available and traded between private collectors at high prices. In commercial market places such as eBay it is not unusual to see lunar meteorites selling for hundreds of Euros per gram. There is an immediate market for such material, how elastic that market will be as supplies increase, is difficult to predict. But as increased volumes of raw lunar material come on to the market, other derived or refined materials with higher value will become available.

Helium-3 currently sells on Earth for $2,000 per liter[15], or $30,000 per gram, there is strong demand in various industries for neutron detectors, including hospital MRI machines, homeland security, and natural gas exploration. In the future it might have increased value for nuclear fusion fuel, but even today, demand is strong, and terrestrial supplies are dwindling. Helium-3 is abundant on the Moon, it has been measured from Apollo samples, and detailed maps of Helium-3 distribution on the lunar surface have been made by the Chinese Chang'e-1 spacecraft[16,17]. This market is immediate, and can be engaged once technology has been deployed on to the lunar surface to scoop large quantities of lunar regolith, heat it to 800 degrees C extract the volatiles, then use Superleak type isotope separation, to separate the more common Helium-4 from the Helium-3[18]. The cost of delivering such technology to the lunar surface will be considerably reduced by using LSE, and the cost for sample return to Earth will also be reduced versus chemical rockets.

Oxygen is a valuable resource in cislunar space and in LEO. Oxygen is relatively easy to produce from lunar soil anywhere on the Moon. The principal market for Oxygen is for propellant. Every chemical rocket launched using current technology is comprised about 80% by weight of Oxygen or Oxidizer. Delivering oxygen from the Moon to the surface of the Earth makes no economic sense, since it is abundant and cheap on Earth. However, there would be a strong market for delivering oxygen from the Moon to LEO. Ishimatsu T., et al.,[19] have shown that for launching a mission to Mars, the launch weight will be reduced 68% by using lunar oxygen versus launching all the propellant directly from Earth; that means the payload weight budget is increased more than three fold. There is currently no commercial market for Mars missions, with uncertain outlook, however, similar methodology can be used to reduce the cost of missions to Geostationary orbit, which is an active multi-billion dollar annual market.

Let us quantify the benefits of using lunar oxygen for supplying the large market for boosting commercial communications satellite from Low Earth Orbit [LEO] to their final Geosynchronous Earth Orbit [LEO].

We consider a case study example of the Inertial Upper Stage [IUS] which was a two stage tug, with perigee stage which injected from LEO to GTO, then a second apogee kick stage which injects from GTO to GEO. IUS transfers the payload from LEO to GEO with two large impulsive burns.

Thus IUS is an excellent basis for a case study, assuming that the specific impulse of the IUS propellants are typical of chemical rockets in general.

IUS launch weight into LEO excluding payload: 10,400 kg

GEO Payload of IUS using conventional terrestrial propellants: 2,270 kg

=> IUS total stack weight in LEO = 10,400 + 2,270 = 12,670 kg

Assume 80% of IUS unladen weight is oxygen, 20% is fuel and inerts, therefore:

Oxygen = .8 x 10,400 = 8,320 kg

Fuel+inerts = .2 x 10,400 = 2,080 kg

For a valid comparison we keep the IUS total stack weight constant.

For a vehicle refueled in LEO with lunar oxygen, the payload weight is increased then the percentage of fuel required [in the IUS stack] will be increased:.

The ratio of fuel weight to payload weight is as follows: 2,080 / 2,270 = 0.9163,

So by removing the oxygen we have a fuel mass fraction of 2,080 / (2,080+2,270) = 47.82%

So using lunar oxygen, the total stack of IUS launched from Earth comprises:

Fuel = 47.82 % of 12,670 kg = 6,058.3 kg

Hence useful payload delivered to GEO is: total IUS stack minus the fuel = 12,670 - 6,058.3 = 6,611.7 kg

Hence the ratio of payload to GEO using terrestrial oxygen, versus payload using lunar oxygen, is:

6,611.7 kg / 2,270 kg = 2.913 times

The tanker with oxygen from Moon will weigh about: 5 x 8,000 = 40,000 kg, which is about 3.5x the weight of the IUS stack. Therefore, it would use less fuel to maneuver the IUS than to maneuver the lunar tanker. If the accuracy of injection of the IUS and the tanker are sufficiently accurate, then the amount of maneuvering propellant would be rather small.

In fact, in LEO, it will be possible to use electrodynamic maneuvering using a long tether, such as the EDDE tug design[20]. The EDDE is parked in LEO. Using zero propellant the EDDE can rendezvous with the IUS, then it can pull the IUS to make it rendezvous with the lunar tanker.

As for other resources on the Moon, there is new data to suggest that water is ubiquitous over the entire lunar surface[21], contained in spherules of pyroclastic glass, and such water resources in Sinus Medii would be readily accessible via LSE, and greatly improve the economics of space transportation in the cislunar region.

VIII. Conclusion

A 48 ton Lunar Space Elevator [LSE] can be built with currently available materials and technologies and packaged on to a single SLS vehicle launch. LSE is affordable and can pay for its launch cost within one month, assuming a climber speed of 0.7 km/sec can be sustained. Six evenly spaced climbers can travel on the tether simultaneously, achieving 80 ascents and descents per month, resulting in payload throughput of 8 tons per month in each direction. A cost reduction of at least nine times [probably much more] for lunar sample retrieval missions is possible versus using chemical rockets. Cost reduction for soft landing will exceed three times. These large cost reductions are game changing and will enable major expansion of human activities beyond Earth orbit, and establish profitable lunar based industries. A novel system of tethering the climbers together is proposed which could result in survivable abort modes for astronauts.

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