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THE ACCELERATION OF THE HUMAN EXPLORATION OF THE SOLAR SYSTEM WITH SPACE ELEVATORS

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Space Elevators are not a new idea, the original concept dating back to Tsilokovsky, but are not commonly considered in near-term plans for space exploration. While a Terrestrial elevator would require substantial improvements in tether material, a Martian Space Elevator (MSE) or a Lunar Space Elevator (LSE) would not, and there are currently possible elevator missions that would enhance the exploration of the solar system. This paper considers two proposed missions leading to a infrastructure capable of supporting human exploration, shortening the time and lowering the cost required for exploration and enhancing the capabilities of robotic and human explorers. Both missions use planetary scale tethers, strings many thousands of kilometers long stabilized either by rotation or by gravitational gradients.

The Deep Space Tether Pathfinder (DSTP) is a 5000 kilometer long rotating tether, weighing two tons, to be sent into deep space to test the engineering of a LSE or MSE. As a test of the ability of Space Elevators to return surface samples, the rotation of the DSTP would be used to match the relative velocity between one tip and the Moon during a flyby, allowing for the collection of a surface sample in a “touch-and-go” fashion from a suitable scientific target, such as the floor of Shackleton Crater in the Lunar South Polar Region. The collected sample would then be returned to Earth by the release of a return capsule roughly one half rotation period later, when elevator tip velocity is directed towards the Earth for a direct return trajectory. After sample release, the DSTP would continue into deep space, allowing for long term observations of tether performance in the space environment.

The Lunar Space Elevator Infrastructure (LSEI), a follow-on to the DSTP, is a much longer tether extending from the Lunar Surface, through the Earth-Moon L1 Lagrange point (EML 1) and into cis-lunar space. The LSEI prototype, requiring one launch of a heavy lift vehicle, would be able to lift roughly 1 ton of lunar samples per year, and deploy a similar quantity of equipment onto the Lunar surface. The LSEI would significantly enhance the ability of a Deep Space Habitat (DSH) at EML1, for a small fraction of the total cost of a DSH by, for example, enabling on-site DSH laboratory research into Lunar samples, as well as supporting robotic exploration on the surface.

I. INTRODUCTION

A space elevator is a structure rising from at or near a planetary surface to a sufficient altitude to be held taut by gravity, rotation and orbital dynamics [1]. Typically a space elevator is intended to match its primary body’s rotation to allow for an easy transfer of material between a synchronous orbit and the surface of the primary. For a rapidly rotating planetary body, such as the Earth, a space elevator would be held taut primarily by rotation, while for slowly rotating bodies, such as the Moon[2], the elevator would be held taut primarily by tidal gravitational forces. Free-flying tethers, such as the DSTP, must rotate to stay in tension. In the inner Solar System radiation pressure and electrodynamic forces may be significant, but will generally not be dominant [3]. Free-flying tethers that rotate in such a fashion as to cancel the relative motion between the tip and a planetary or satellite surface are called rotovators [4]; such tethers may be used to set up transportation systems moving material to and from the surface without the expenditure of fuel [5, 6]. Shorter (<< 1000 km) tethers have been flown in a variety of experiments, are covered generally in the *Tethers in Space Handbook* [7], and will not be considered further here.

The long term exploration and development of space would greatly benefit from the use of planetary-scale tethers, both as dynamic tools and for space elevators, a more static means of access to and from planetary surfaces. As with any complicated new technology, these tools will not be used without gaining experience in their use in space. Unlike much new technology, the appropriate experience with space megastructures (both free-flying tethers and space elevators) will require the deployment of full-sized prototypes. The only way to properly test a structure the size of the Earth (or larger) will be to build and deploy it. Such large-scale tethers are likely to have dynamical features hard to predict from ground based simulations and laboratory tests, and their radiation and micrometeorite protection will also be hard to test except in a full-scale mission. Pathfinder and prototype missions are thus essential to gain experience with real planetary-scale tethers, and, in the current very competitive space funding environment, any initial megastructure missions must also have a solid scientific return and be justified on their own merits, without relying on possible future developments. Only in this fashion can the technology advance to a sufficient Technology Readiness Level (TRL) to enable its widespread use.

Initial deployments should be based on existing technologies, and not dependent on future evelopments in material science, which means that a terrestrial space elevator is not a realistic prospect for a near-term prototype mission. Of the practicalable near-term space elevator missions, a Lunar Space Elevator (LSE) is undoubtedly the most technically feasible. Even a prototype LSE, deployed by a single launch of an existing launch vehicle, would serve as the linchpin in a Lunar Delivery Service, the Lunar Space Elevator Infrastructure (LSEI) [8], capable of transporting up to a tonne (t) of material to and from the Lunar surface per year and supporing a wide variety of scientific research, including on and near the Lunar surface, at the Earth-Moon L1 Lagrange point (EML1), and deep into cislunar space at the counterweight.

While the initial, prototype, LSEI will not be able to deliver human passengers to and from the Lunar surface, a functioning LSEI prototype would provide a substantial addition to the capabilities of Human explorers in a Deep Space Habitat (DSH) in a Lissajous orbit around EML1, as is envisioned in the 2011 Global Exploration Roadmap [9]. One purpose of having a human presence at EML1 would be to simulate long duration exploration voyages, such as to an asteroid or to the planet Mars. The LSEI would enable astronauts to deliver rovers and instruments to the Lunar surface, teleoperate that equipment from only 56,000 km altitude, lift selected surface samples to EML1, evaluate those samples, and use that evaluation to direct the acquisition of further samples. All are these are functions likely to be required on future voyages into deep space; and all could be performed by astronauts and cosmonauts at EML1, given a deployment of the LSEI.

The prototype LSE will be a very long structure (the current LSEI planning envisions a 278,000 km elevator weighing over 48 t) and is realistically going to require a lighter weight precursor mission as a pathfinder, to test the general engineering and specifically the performance of certain aspects of the radiation and micrometeorite protection. The Deep Space Tether Pathfinder (DSTP) [10] is intended to provide the technological development required for this LSE while itself possessing a solid scientific justification. The current DSTP planning is for a 5000 km tether with a total system mass of 2.3 t rotating every 2.18 hours. The DSTP would be the first rotovator actually deployed, using this technique to match the velocity of one tip with the Lunar surface to perform a "touch-and-go" sample return from a permanently shadowed region at the Lunar poles, such as the interior of Shackleton Crater. Approximately 2 hours after sample collection the DSTP would then use its rotational velocity to sling-shot the sample back to Earth, with no expenditure of fuel, and continue on into deep space for a long-duration exposure test of the radiation and micrometeorite resistance of the tether's design.

A logical follow-on to the DSTP and the LSEI would be a Phobos-Anchored Martian Space Elevator (PAMSE) [11], which would use the mass of the Martian moon as a counterweight, considerably shortening the length, and reducing the total mass required, at the cost of not being able to anchor to the Martian surface. A PAMSE with the same carrying capacity of the prototype LSE (150 km maximum static load) would be 5800 km long and weigh 5.8 t, only 12% of the mass of the prototype LSE. (This is for an elevator reaching down towards the surface; a similar elevator heading away from Mars on the opposite side of Phobos could be used to retrieve and launch payloads to and from Earth [11].)

The orbital eccentricity of Phobos amounts to 283 km, which is by coincidence comparable to the effective depth of the Martian atmosphere for satellite drag [12] (typically ~ 170 km, but subject to variations due to atmospheric events such as dust storms). The average relative velocity between the lower tip and the surface of Mars is only 534 m/sec, roughly Mach 2 in the cold Martian atmosphere, and slow enough that it should not cause significant heating of the tip. This raises the interesting possibility that the PASME tip could dip down deep into the atmosphere to leave or recover payloads or perform reconnaissance, acting as a supersonic airplane for the period near periapse when it is near the surface.

II. DESIGN OF SPACE MEGASTRUCTURES : INTEGRATING THE TETHER

Any space megastructure in the near or medium term future will be made out of tethers (strings), capable of withstanding tension but not compressive or lateral forces. Such megastructures rely on some external forcing to keep them taut and in tension.

Levine [3] provides a comprehensive review of the dynamics of space tethers, a simplified version of which is used in the LSEI and DSTP tether design [see also 13,14] . In the design process, first a nominal mission is chosen, and then the conditions of maximum tension are determined (for an LSE, this would be at the time of Spring Tides, and for the DSTP, this would be at the time of sample collection, when one tip is close to the Moon). In the modeling, the tether string is assumed to be made of many hundreds of substrings, and a minimum string segment size is chosen (currently, 2 km), together with an estimate of any non-gravitational force on the tip. The static load includes the force from the payload, which for the purposes of the integration is assumed to be at the string location with the maximum forcing (typically, the tip). It is straightforward to estimate the required thickness for any given segment; the force per unit mass exerted on a segment by gravity (direct and tidal) and rotation is calculated for the mid-point of the segment. The thickness of the segement is adjusted (by adding or subtracting substrings) to account for that force plus the static load imposed by the aggregate of the string sections previously considered, keeping the segment as close as possible to the desired string stress. Once the segment size is deterimined, the mass used for the segment is removed from the total mission string mass available. The force on the segment is added to the static load (the sum of the forces from the segments previously considered), and the integration moves to the next segment along the tether. At each point, the software tests whether all forces would be balanced if the counterweight plus remaining available string mass was added to the end of the segment, This process is repeated until it all forces are balanced, or until all of the string mass is consumed (which represents a failed design). Once a successful string design is found, the integration is interated, changing parameters to find, e.g., the maxmum payload for given mission parameters.

This process yields a string taper (Figure 1 and Figure 2) which is very close to optimum. The tapering of the DSTP and the LSE reach a peak at the point where forces balance (the center of mass for the DSTP and EML1 for the LSE). The tapering (and stress) for the PAMSE peak at the surface of Phobos.

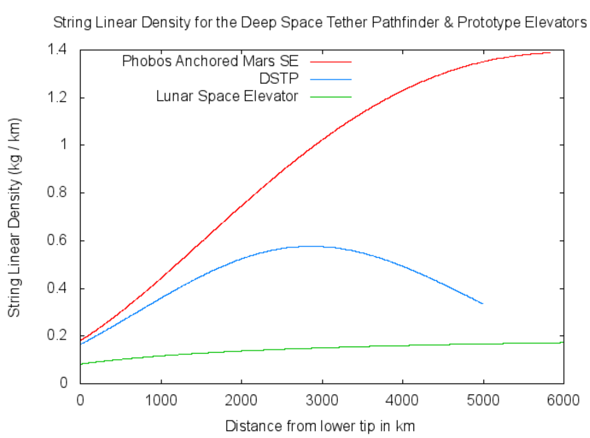

Figure 1: Tapering of (top to bottom) the Phobos Anchored Martian Space Elevator, the DSTP and the Prototype LSE. (Note that the LSE curve continues offscale to the right.) The DSTP will prove design aspects of both elevators in realistic conditions in deep space.

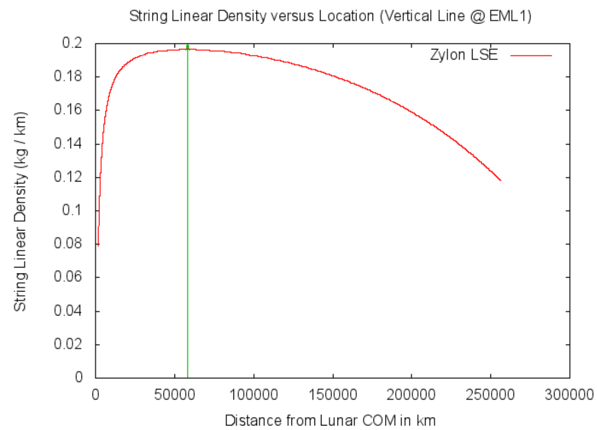

Figure 2: The complete tapering of the LSE. The Vertical line represents the Earth-Moon L1 Lagrange Point. The difference between this piecewise linear tapering and an ideal tapering is indistinguishable at the scale of the Figure.

III. THE SCIENTIFIC GOALS OF THE DEEP SPACE TETHER PATHFINDER

The Deep Space Tether Pathfinder (DSTP) [10] will be a 5000 km long free flying tether using existing tether materials to serve as a engineering test-bed for all future megastructure missions. The cost of this 2.5 ton structure is intended to fit within a Technology Demonstration or Explorer Mission cost cap. The scientific justification of this mission is primarily based on a lunar sample return, with the current baseline targeting the shadowed regions of the Lunar South Pole using the “rotovator” technique (although an open consideration of all possible sampling locations would be an important part of the actual pre-mission planning).

The search for Lunar Volatiles consistently ranks high in the decadal surveys of planetary science[15]. Permanently Shadowed Regions (PSRs) on the Moon are the easiest such locations to access in the solar system, similar to the conditions at the poles of Mercury and also on certain minor planets, and of course in the outer solar system; findings from the Lunar volatile regions would thus apply across the Solar System. The PSRs contain an important scientific record of the history of volatiles in the inner Solar System, information on processes, hard to simulate in terrestrial laboratories, that are important throughout the Solar System, and a potential resource for future economic development. These regions have been the target of intense scientific interest in the last decade, and including being the target of the LCROSS impactor, which attempted to find evidence for water in the South Polar region.

The DSTP offers both a means of developing and proving the engineering and scientific capabilities of planetary-scale tethers, and accelerating the scientific and economic development by the Moon, by collecting and returning roughly a kilogram of samples from a PSR in the Lunar polar regions, and by collecting images and scientific data in the course of this sample collection. (While there are a number of apparently suitable PSRs for this sample collection, typically at the bottom of craters near the Lunar poles, I will focus on Shackleton Crater as a preliminary target, as it has been proposed for sample collection and has been fairly extensively studied in the last decade.) The DSTP will collect samples in a touch-and-go manner, as has been proposed for a number of cometary and asteroid missions, and as is planned for the OSIRIS-Rex sample collection mission. Figure 1 (a and b) shows the Moon, Cislunar space and the DSTP in a 2 body gravitational simulation, both one hour before and at the time of sampling. The rotation and orbital velocity of the tether must be matched to enable a near zero-relative-velocity sampling, taking into account both tether elongaton under varying stress and thermal expansion; a successful sample collection will require monitoring or controlling the tether length to within one part in 10^5.

In the local reference frame the tether descends almost vertically to perform sampling (Figure 2), enabling sampling from topographically rough regions. In addition, there is a clear line-of-sight back to the counterweight on the other tip, and so there should be no trouble with direct communication with Earth at the time of sampling, even for regions that permanently lack line of sight to the Earth,

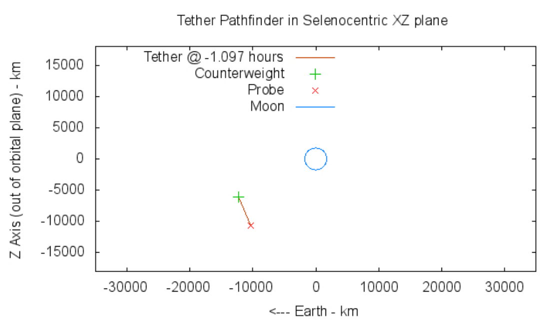

Figure 3a: The DSTP in a 2-body simulation one hour before the touch-and-go sampling. The small circle is the Moon, and the Earth is off to the left.

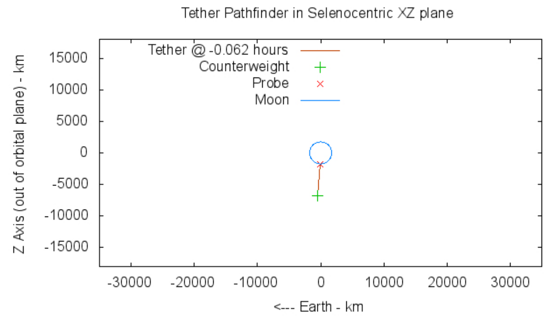

Figure 3b: The DSTP in a 2-body simulation at the time of the touch-and-go sampling.

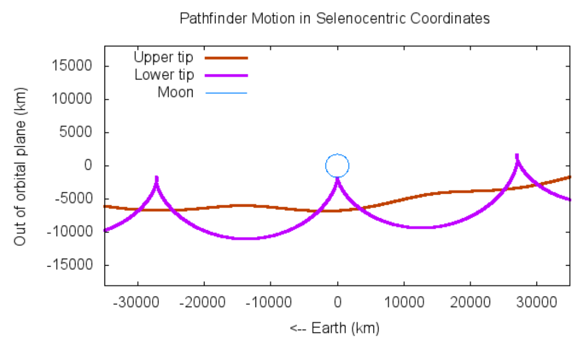

Figure 4: Trajectories of the two tips of the DSTP during the Lunar Sample return period, as seen from a selenocentric reference frame. In this model, the sample tip has about 1/10th the mass of the counterweight, and thus undergoes a much larger motion about the center of mass. This Figure represents 6 hours of total motion.

The Japanese *Selene* orbiter imaged the interior of Shackleton Crater (using light reflected by the Crater rim, see Figure 3) and found the albedo in the Crater interior to be similar to that of the non-shadowed Lunar highland surface [16], indicating that the crater floor was not simply covered with pure water ice. It may be that there are no volatiles in the PSR, or they may be covered with dust or mixed with other surface material [17]. (Repeated meteorite impacts on the cold PSRs may cause the formation of a cyro-regolith, with a mixture of silicate and volatile dust.) Even a failure to find any volatiles in returned samples would be very important both scientifically and for the future direction of the Moon's economic development.

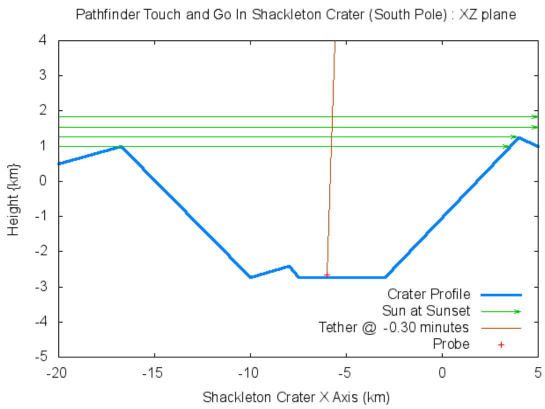

Figure 5: A cross sectional view of Shackleton Crater at the moment of sampling. The DSTP probe has roughly 5 seconds within 50 meters of the surface for sample collection. The green lines indicate the portion of the crater illuminated by the Sun at one time of the Month; the crater interior below that is permanently shadowed. The resulting “rim-light” on the floor of the Crater is considerably brighter than the Full Moon.

Shackleton Crater sits on the boundary of the older and much larger South Pole-Aitken Basin, an ~ 2500-km diameter impact basin which brought up material from deep inside the Lunar interior. Orbital surveys reveal that this basin contains different material from any found on the near-side; this distinctive material has yet to be sampled and so any returned samples would be of intense geological interest. Given the surface albedo results from *Selene*, it is highly likely that a sample collection from the floor of Shackleton Crater would include rock or regolith samples from the South Pole-Aitken Basin. As Shackleton Crater is roughly 4 km deep, non-volatile surface samples returned by the DSTP may include material from deep within the South Pole-Aitken Basin crater rim, and could conceivably include material from the Lunar mantle, if the South Pole-Aitken Basin impact excavated all the way through the Lunar crust.

A proposed South Pole–Aitken Basin Sample-Return (SPA-SR) mission was highly ranked by the National Research Council Planetary Science Decadal Survey [15] and was suggested for continued consideration as a “New Frontiers” class mission, with a cost cap of $ 1.0 billion. The proprosed SPA-SR mission would not land in a PSR and would not address any scientific or economic issues related to volatiles. The DSTP would provide a first look at both South Pole-Aitken Basin material, and at the volatiles in the PSR, for less than one fifth the SPA-SR cost.

The DSTP Lunar Scientific Goals address every one of goals in the *Lunar Polar Volatiles and Associated Processes* white paper submitted to the 2011 Decadal Survey [15]:

• Determine types of sources of volatiles: This will be facilitated by sample return, especially by isotopic and trace element analysis.

• Infer timing of delivery: Timing of volatile delivery will require dating of the volatile sample, for example through their galactic cosmic ray exposure history. This goal will probably require keeping samples cold until their return to Earth.

• Determine historical fluxes of volatiles in Cislunar space: The relative proportion of silica and volatiles, plus the space weathering history of the returned samples, and the relative proportion of volatiles with different evaporation temperatures, will directly provide estimates of the cumulative flux and loss of volatiles in the last few Gyr.

• Study physics / chemistry / astrobiology/ geology in extreme environments: This can best be facilitated by the analysis of returned samples.

• Assess global processes measured/studied specifically within PSRs: The collection and return of samples using electrets elevated off of the crater floor would provide the first direct sampling of the globally important electrostatic levitation and transport of dust in the lunar environment.

• Feed forward to missions/observations of other planetary environments: The DSTP will both provide data on sample returns from permanently cold regions, and engineering, operational and scientific information on the use of planetary-scale tethers in the exploration of the solar system.

• Assess implications for operations on the Moon: Assessing the existence and quantity of volatiles at the Lunar PSR may be the most important single goal for the economic development of the Moon, and it can be done mostly directly through a sample return. Near-surface imagery returned during the sample collection process will help to assess the nature and distribution of volatiles, even if sample return is not successful.

The other major scientific goal of the DSTP is to deploy the first radio interferometer for the spectral region between 10 kHz and 1 MHz, which is largely unexplored for radio astronomy as these wavelengths do not penetrate the Earth’s Ionosphere. The proposed radio interferometer, the Dark Ages Pathfinder (DAP), would consist of two 10-km dipoles attached to either end of the DSTP tether, providing an interferometric baseline of ~ 5000 km to be used for rotational synthesis as the tether rotates. At a frequency of 1 MHz this baseline would allow for an angular resolution of approximately 1 degree, which would allow for the detection of point sources and a limited mapping of extended sources. The DAP would complement the proposed Dark Ages Radio Explorer [18], which is planned to operate over a higher frequency radio bandpass of 40–120 MHz. DAP data would be primarily acquired during the cruise-phase part of the mission as the DSFP receeds from Earth; its ability to distinguish solar system, galactic and cosmological sources from terrestrial interference will improve as the distance to the Earth increases.

IV. THE PROTOTYPE LUNAR SPACE ELEVATOR

Unlike a Terrestrial Space Elevator, the LSE is technically feasible and could be built using commercially available string materials such as Zylon or M5. Pearson et al. [2] developed many of the crucial concepts of a LSE, but their proposed mission is much more elaborate than LSEI, with a total mass of order 10^6 kg, enough to require a functioning Lunar transportation system as a prerequisite. The LSEI is intended to achieve both a functioning LSE and to provide a solid scientific return in one mission, based on one launch from an existing or planned Heavy Lift Launch vehicle. The LSEI currently is planned to be executed in a single Discovery class mission, starting with the delivery of 58,500 kg of Zylon HM fiber plus associated equipment to the L1 Lagrange site. While the fiber could be changed if better choices become available, Zylon is sufficient for LSEI [2, 19], and is also commercially available in sufficient quantities for the LSEI.

Figure 6 shows to scale (although with greatly enhanced visibility) the major components of LSEI, the string, the Landing Platform, the supply depot at EML1, and the CounterWeight (CW). The CW would use the emptyTrans Lunar Injection (TLI) stage for mass, which would provide as much as 5 t of “free” CW mass and this an important increase in payload mass. In order to improve the mass ratio delivered to the L1 Lagrange Point, it is planned to use Solar Electric Propulsion, a lunar gravity assist and a Weak Stability Boundary (WSB) trajectory [20], yielding a substantially enhanced LSE mass, and thus a substantially increased surface lift payload, at the cost of taking up to one year to get from LEO to EML1.

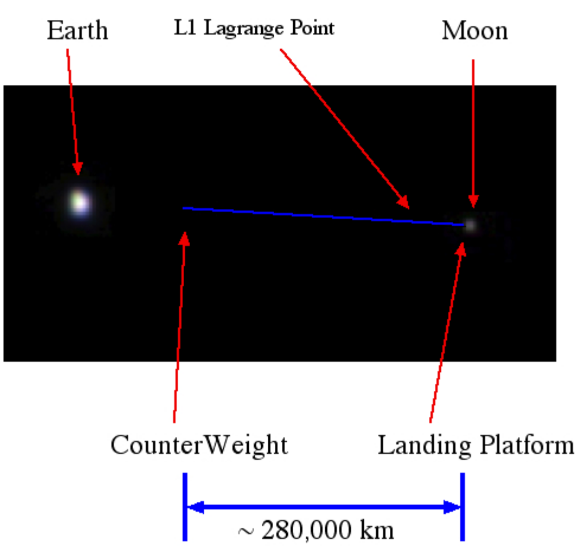

Figure 6. The components of the LSEI LSE, to scale, superimposed on a image of the Earth-Moon system from the Juno spacecraft, taken August 26, 2011 at a distance of 9.66 million km. (Note: the actual LSE would not be visible to the naked eye such distances.)

A Lunar elevator has an inverse relationship between length and weight. Given the low mass available from a single heavy launch vehicle, the LSEI prototype will be quite long, ~ 280,000 km, and can be expected to exhibit substantial transverse and longitudinal waves. Good string instrumentation will be crucial in measuring the effects of these normal modes. There are 3 natural locations for LSEI observations, the Landing Point (LP) on the surface, the deployment platform at EML1, and the Counterweight (CW) at the far end of the elevator. All 3 locations (CW, EML1 and LP) can and should be instrumented, both for the scientific return and to monitor the elevator’s performance.

The Landing Platform (LP) is attached to the string descends to the Lunar surface in the initial prototype deployment. It has to be embedded in the Lunar surface firmly enough to anchor the elevator. Once it lands, it will referred to as the Landing Station (LS); the planned LS location is Sinus Medii, near Latitude = 0 Longitude = 0 on the Lunar surface.

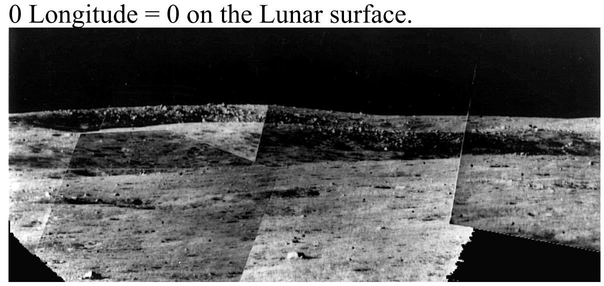

Figure 7. Sinus Medii from Surveyor 6, taken about 44 km from the proposed landing site [21].

This LS point (see Figure 7). was chosen to minimize the complexity of the prototype mission. If there was need, it should be possible to move the Landing Point by up to hundred km either North-South or East-West without causing undue difficulties.

The primary initial science goal of the LSEI prototype mission is the return of the Lunar samples to Earth. LSEI will take a core sample upon landing and will deliver one or more microrovers to the Lunar Surface to assist in collecting surface samples. LSEI should have the ability to return up to 100 kg of samples from the first Lift from the Lunar Surface, using a reusable solar-powered lifter. These samples can be returned without the expenditure of any fuel by simply lifting them to about 220,000 km altitude on the elevator, and releasing a sample return capsule at the right moment for a direct reentry trajectory to a desired landing location. This same technique could be used to return high value ore samples or mining products from a Lunar mining enterprise. With volumne, it could be possible to lower the cost of returned material to as low as $ 50,000 / kg.

LSEI plans to use Single Cube Retroreflectors (SCR) as Laser ranging targets for navigation during deployment of the LSE and the Landing Platform. Once it reaches the surface, the SCR would remain as a permanent addition to the Lunar Laser Ranging (LLR) retroreflector network.While the Apollo astronauts installed 3 LLR corner cube reflector arrays on the lunar surface, and two more French corner cube arrays were carried on the Soviet Lunakhod rovers, these arrays are all ~ 40 years old, and are beginning to show signs of degradation with age. Their performance is now the limiting factor in LLR accuracy. The LSEI should deploy modern single corner-cube retroreflectors [22] at Sinus Medii, extending both the life and the extent of the LLR reflector array on the Moon; these corner cubes would also be used for navigation during deployment. The LSEI prototype mission would thus become an essential component to LLR studies of both basic physics, Lunar dynamics, and Earth-Moon celestial mechanics.

The electrostatic levitation and transport of dust is thought to be important in regions near the Lunar terminator [23], and may be important in the covering of PSR volatiles over geologic time. The LSEI will maintain a thread stretching from the surface and up though the entire near-surface regime, and this sample though the Lunar atmosphere can in principle be accessed at any time. For example, aerogel sample collectors could be suspended on the LSE thread at any desired altitiude throughout the Lunar night. If electrostatically-levitated dust is present at the time of collection, it should be possible to sample it *in situ* with passive collectors using electrets (permanently charged materials), which could also be exposed at various locations along the thread near the surface. After Sunrise, the next lifting elevator climber could simply collect these samples and bring them back to Earth.

The EML1 Lagrange point is where the Earth and Moon gravity and orbital dynamics balance, yielding a microgravity environment. The LSEI prototype will be deployed from there, extending the tether both towards and away from the Moon in a balanced fashion. Once the LSEI elevator is operational material and supplies would be stored there either before they were shipped to the lunar surface or after they were transported up from the lunar surface. EML1 has a much quieter dynamic regime than low Earth orbit and is thus a natural location for a Picogravity Laboratory (pGL), allowing experiments (from physics, material sciences, even biology) to experience both a very low non-gravitational acceleration environment together with the large changes in gravitational potential resulting from inertial motion in Cislunar space). As an example of the scientific utility of scientific research at EML1, consider the ability to perform a gravitational red shift experiment there. The JPL Deep Space Atomic Clock (DSAC), with a fractional frequency stability of up to 10^{-16} [24], has been selected for a game-changing development to bring it to qualifiation for deep space operations. One such clock installed at EML1, could improve on NASA's Gravity Probe A [25] by 3 orders of magnitude (for the Earth's gravity) and 2 orders of magnitude (for the Sun's gravity) by taking advantage in its large Gravitational potential changes relative to the Earth (see Figure 7). In addition, EML1 is a logical location for the observation of the near-side of the Moon. In particular, one fairly small optical telescope (20 cm) could continuously observe the entire Near Size, searching for meteorite impacts and transient lunar phenomena, but also able to detect and characterize the orbits of all close lunar orbiters. All of these activities would be facilitated by having the LSEI with regular deliveries to and from EML1.

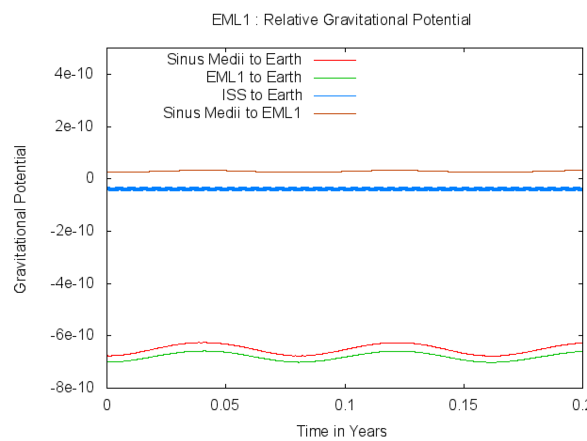

Figure 8: The time-varying gravitational potential for various locations including (bottom) the LSEI prototype.

The Counterweight (CW) will be in a position to observe the Earth from a little more than 100,000 km away, outside of the existing satellite constellations,. It will be able to observe the magnetic and charged particle environment as the CW goes in and out of the Earth's magnetosphere twice per lunar month. A variety of Earth observations could be performed from the CW; for example the phase of the GPS signals from satellites being occulted by the Earth could be monitored to determine atmospheric and mesospheric conditions through the inversion of radio occultations.

V. CONCLUSIONS

The entire purpose of planetary scale tethers is to accelerate and facilite the exploration of space. In order to realize their full potential it will be necessary to advance their technological readiness level, and for such large structures this can only be done by deployment of actual tethers in space and, for planetary scale tethers, in deep space. The DSTP and the LSEI are crucial first steps in the development of space elevators, and in future tether missions, but can and must be justified on the basis of returned science, in addition to its engineering return. Building the DSTP is feasible, has an exciting scientific return and should lead to the construction of the LSEI and thus to future Martian elevators and in due course the development of a true transportation infrastructure for the inner solar system.

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