Lunar Space Elevators for Cis-Lunar Transportation

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ABSTRACT

Lunar space elevators could revolutionize the development of the Moon. The lunar space elevator system allows solar-powered robotic vehicles to climb a high-strength composite ribbon from the lunar surface to beyond the L1 Lagrangian point, where payloads of lunar resources could be released into Earth orbit for major space construction projects. The overall system concept includes the lunar space elevator, a robotic construction system for the components, and robotic vehicles to carry lunar products into Earth orbit for construction and for upper stage propellant, and Earth-orbit payloads to the lunar surface for lunar habitat supplies. The construction system creates building blocks from lunar materials, using automated assembly and wire forming to construct complex shapes. The lunar space elevators provide non-rocket transportation of these lunar products from polar and equatorial mining sites into Earth orbit. This architecture is a new way to create a lunar base for robotic and human operations on the surface. A lunar space elevator using existing high-strength composites with a lifting capacity of 2000 N at the base equipped with solar-powered capsules moving at 100 km/hour could lift 584,000 kg/yr of lunar material into high Earth orbit. Since launch costs twenty years from now may be $1,000/kg, this material would be worth half a billion dollars per year, creating a new era of space development.

BACKGROUND

The space elevator is a connection between the surface of a planet and a terminus beyond the stationary orbit radius, where a counterweight maintains the structure in tension and in balance between its synchronous orbit velocity and the planet's gravitational attraction. The space elevator was first invented by Artsutanov[1] in 1960, but was not noticed by the spaceflight community until the first author invented it independently and published in *Acta Astronautica* (Pearson[2], 1975). For a planet or single body, the space elevator can be balanced about any point in the geostationary orbit. For the Moon or a natural satellite, however, the three-body dynamics dictates that a lunar space elevator must be balanced about one of the collinear Lagrangian points L1 or L2. The lunar space elevator was invented first by Pearson[3], followed independently by Artsutanov[4]. The concept may have been mentioned in an early work by Tsander, but this is not available in English translation.

The space elevator must be constructed of extremely strong, lightweight materials, to support its weight over the tens of thousands of kilometers of length; even then, for minimum mass it must be tapered exponentially as a function of the planet's gravity field and the strength/density of the building material. Because of their smaller mass, Moon and Mars space elevators are far less demanding of materials than Earth space elevators; they can be constructed of existing composites, as shown in Figure 1. The required area taper ratio between the balance point and the surface is plotted in terms of the characteristic height, or breaking length of the material, which is the maximum length of a hanging cable of the material under a 1-g gravity field. Current composites have characteristic heights of several hundred kilometers, which would require taper ratios of about 6 for Mars, 4 for the Moon, and about 6000 for the Earth. The mass of the Moon is small enough that a uniform cross-section lunar space elevator could even be constructed, without any taper at all.

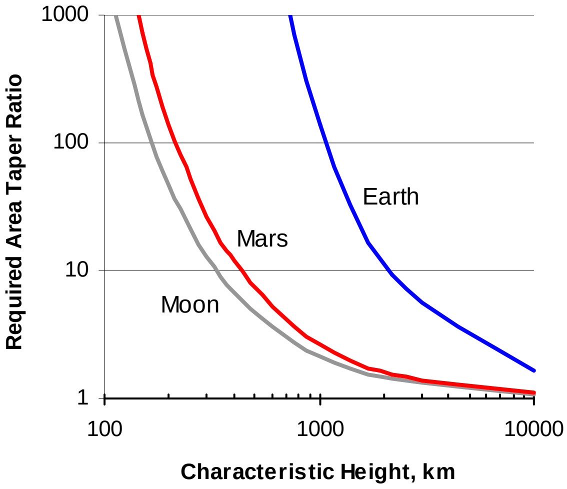

Figure 1. Moon, Mars, and Earth Space Elevators

Table 1 shows some candidate materials for lunar space elevators, with density, stress limit, and the breaking height. The Earth space elevator will require carbon nanotubes (shown in the table for comparison). All these materials, except the carbon nanotubes, are available now.

Table 1. Lunar Space Elevator Building Materials

Material	Density ρ, kg/m^3	Stress Limit σ, GPa	Breaking height $h = \sigma/\rho g$, km
SWCN*	2266	50	2200
T1000G†	1810	6.4	361
Zylon‡ PBO	1560	5.8	379
Spectra¶ 2000	970	3.0	316
M5**	1700	5.7(9.5)	342(570)
Kevlar†† 49	1440	3.6	255

*Single-wall carbon nanotubes (laboratory measurements)
†Carbon fiber from Toray
‡Polybenzoxazole fiber from Aramid, Ltd.
¶Extended chain polyethylene fiber from Honeywell
**Honeycomb polymer from Magellan (with planned values)
††Aramid fiber from DuPont

For the Moon and Mars, space elevators can be constructed of existing high-strength materials such as T1000G carbon fiber, or, with protective coatings, Spectra 2000, Zylon, or Magellan M5. These all have breaking lengths of several hundred kilometers under 1 g, and would require taper ratios of less than ten between the minimum at the base and the maximum at the balance point.

For the Earth space elevator, recent advancements have been made in the construction system, the cargo lifting system, and especially in materials[5]. However, there are two very difficult problems to be overcome in building the Earth space elevator—carbon nanotubes are required for the engineering material, which may not be available for decades, and the problem of interference with all other spacecraft and debris in Earth orbit. Because the space elevator is a fixed structure that extends from the equator to beyond the geostationary orbit, every satellite and every piece of debris will eventually collide with it, typically at greater than orbital velocity. This means that for safety the Earth space elevator must be constantly controlled to avoid these obstacles, or all spacecraft and debris must be removed, requiring an enormous space cleanup.

For transporting masses to and from the Moon, shorter rotating tethers have been proposed by Moravec, and by Hoyt and Forward[6] as propulsion systems, but there are several difficulties in achieving their visions. They are based on momentum exchange tethers, catching and throwing masses from their tips, and touching down instantaneously at several points on the lunar surface. This requires precise control of the tether tip, precise rendezvous with the target masses, and precise catching of the incoming masses from another rotating tether. The low lunar orbit rotating tether's orbit must be carefully controlled and adjusted to precisely touch the surface. Also, the rotating tethers require that the mass flow be balanced between Earth and the Moon, or they must make up the momentum by other means, usually by solar power and electric propulsion. Finally, the incoming masses are on hyperbolic orbits, so if a catch is missed, the payload is lost; there is no second chance.

In contrast, lunar space elevators are passive, fail-safe, involve no high-speed rendezvous catches or throws, and have no need for balancing the mass flow or for re-boosting. Masses are carried up and down the lunar space elevators by electrically driven, wheeled vehicles, gripping the ribbon of the space elevator and using solar or beamed laser power. These cargo carriers would move at a moderate speed to provide a constant mass flow, like a pipeline. Robotic vehicles released from the top of the lunar space elevator would carry payloads of radiation shielding, building materials, and finished constructions from the lunar surface to

Earth orbit. From there, they could be used in LEO or carried to the surface of the Earth for terrestrial uses. Lunar space elevators also function to make the Lagrangian points L1 and L2 stable for space stations and transport nodes, rather than unstable and requiring constant stationkeeping.

LUNAR SPACE ELEVATOR DESIGN

The architecture for a lunar space elevator (LSE) system consists of three systems: lunar space elevator ribbons, robotic climbing and orbit transfer vehicles, and a lunar construction system. The potential configurations of the lunar space elevators are shown schematically in Figure 2.

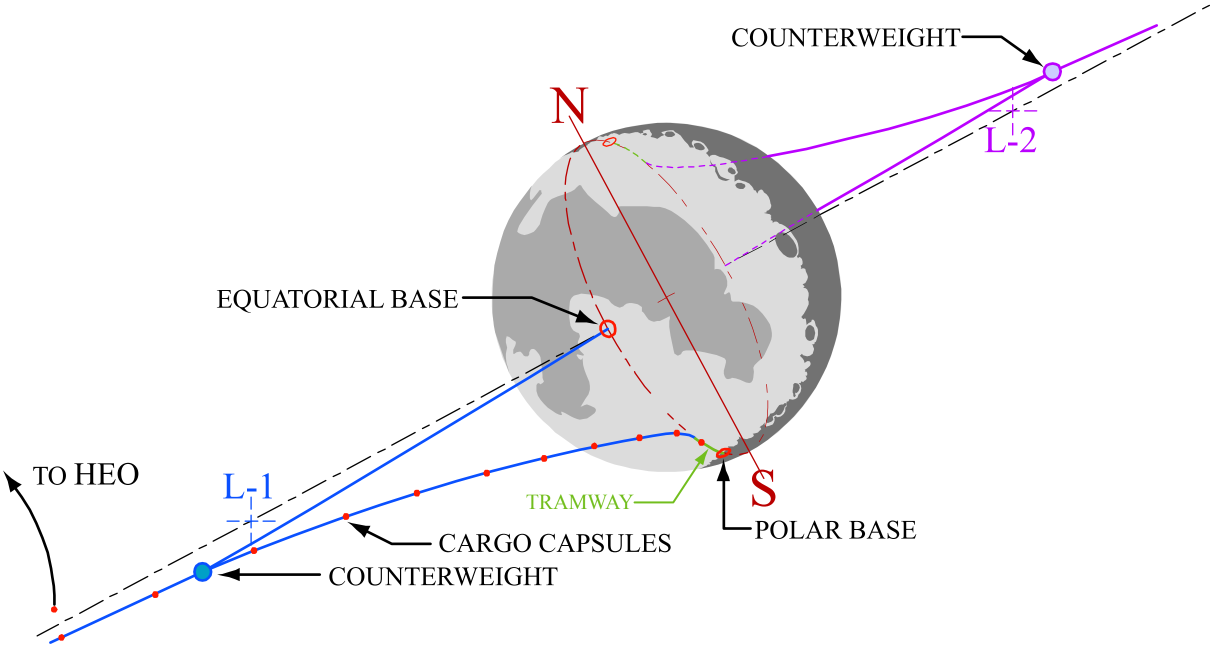

Figure 2. Lunar Space Elevators

The space elevators are balanced about the collinear Lagrangian points L1 and L2 to provide connections from the gateways of L1 and L2 to the lunar nearside and farside. Vertical sections connect to the equator, and curved extensions could reach toward the poles. Solar-powered vehicles climb the space elevators to take payloads beyond the Lagrangian points with excess orbital energy. From there, the solar-powered climbers can double as robotic space tugs to take them to high Earth orbit for use in construction, shielding, habitats, and solar power satellites.

The initial lunar space elevator will be balanced about the L1 Lagrangian point, and a second LSE could be built about L2. L1 is about 58,000 km from the center of the Moon toward the Earth, and L2 is about 64,500 km from the center of the Moon away from the Earth. The L1 LSE is slightly easier to build and is constantly visible from the Earth; the L2 LSE facilitates communication with farside observatories.

Robotic vehicles would climb the lunar space elevator by gripping the ribbon with large, soft wheels driven by electric motors with power from the articulated solar arrays. The climbers would carry lunar regolith and minerals for constructions in Earth orbit, and water for propellant, derived from the polar ice deposits. The concept is shown in Figure 3.

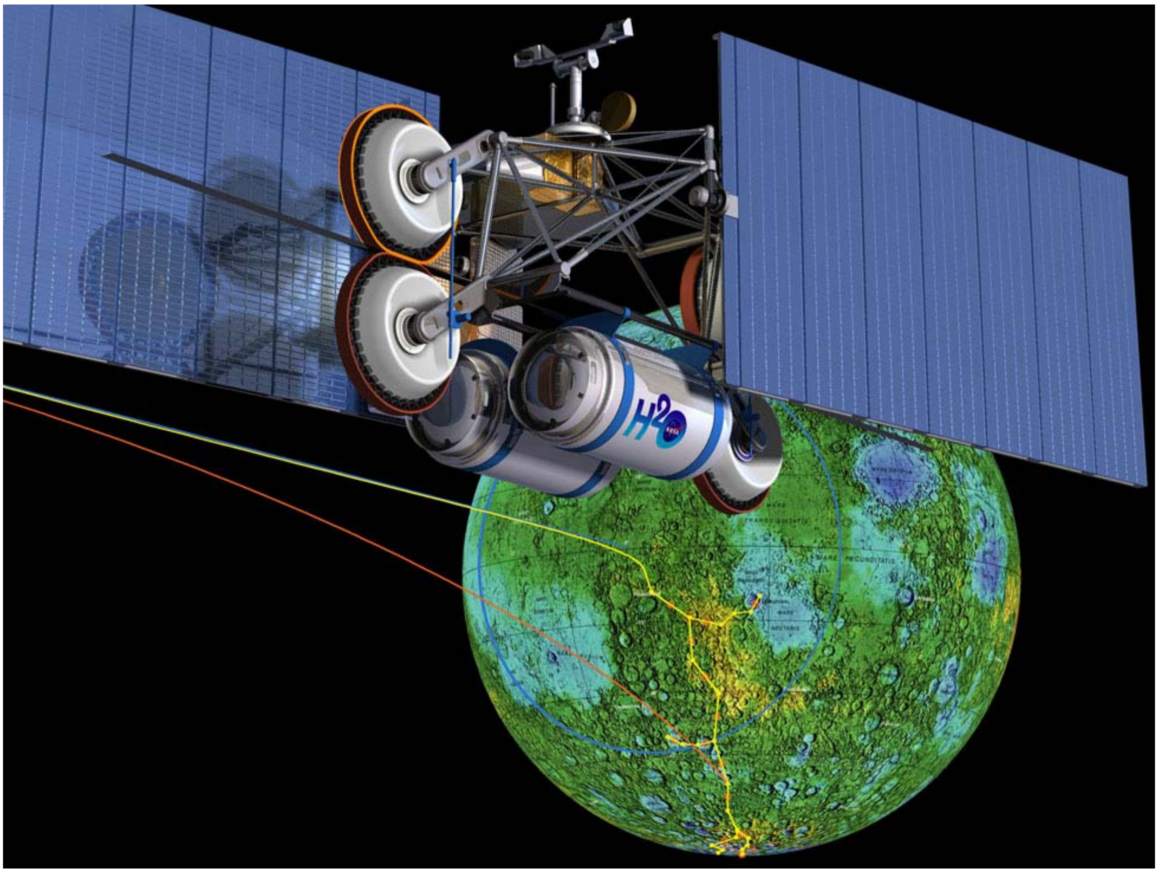

Figure 3. Artist's Concept of Climbing Vehicle on the Lunar Space Elevator

The lunar products include lunar-derived propellants that can be emplaced in LEO cheaper than propellants can be launched from the Earth's surface. The cislunar transportation system operates in both directions, taking non-urgent Earth materials from LEO to the lunar surface via the space elevator. The construction system is a unique and streamlined method for creating the basic building blocks for lunar and orbital construction. It allows the robotic construction of lunar habitats, vehicles, and support towers for the tramway system to the poles. The lunar space elevator could become literally a "highway" from Earth orbit through L1 to the lunar surface, carrying cargo in both directions.

Because of the peculiarities of the three-body system, the lunar space elevator requires a larger counterweight for the same relative distance beyond the balance point, and the balanced lunar space elevator is longer than the balanced Earth space elevator. Paradoxically, the longer the lunar space elevator is, the less massive the system becomes. This is because the counterweight must be very large if it is close to L1, but may be much smaller if it is far beyond L1. Figure 4 shows the relative masses of the ribbon and counterweight.

Besides being less massive, a longer lunar space elevator has another advantage: payloads carried up the lunar space elevator and released beyond the L1 balance point will be in elliptical Earth orbits. The final orbit perigee depends on the length of the lunar space elevator, and for long elevators could reach as far down in the Earth's gravity well as LEO. Conversely, payloads from circular LEO orbits could be raised into elliptical orbits that just touch the lunar space elevator, and could be attached to the elevator and carried down to the lunar surface for supply of lunar bases.

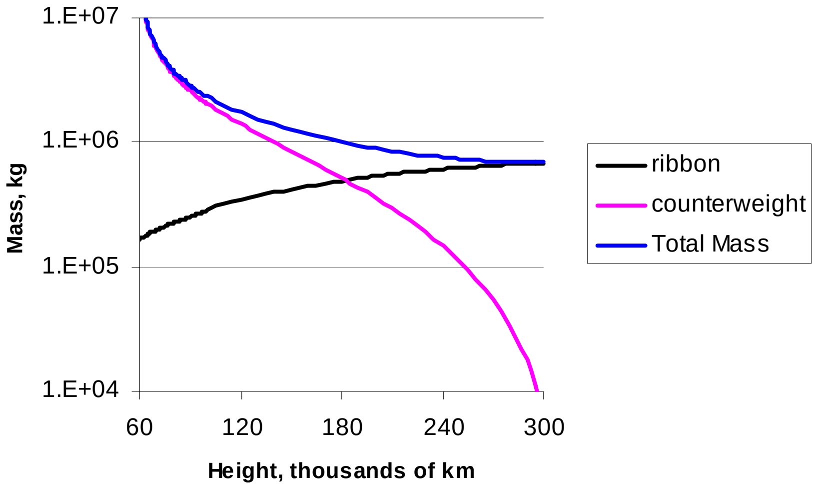

Figure 4. LSE Ribbon and Counterweight Mass vs. Height

Lunar "Sling" for Launching Payloads to L1

For the shorter lunar space elevators, the counterweight is very massive, which could be very expensive if the mass were launched from Earth. In addition, after the initial ribbon is constructed, the lunar space elevator can carry additional material to increase its area, mass, and carrying capacity. However, a faster and cheaper way to accomplish this is to sling the counterweight material, and lunar-derived ribbon material, to L1 using a lunar-surface rotating tether, as shown in Figure 5.

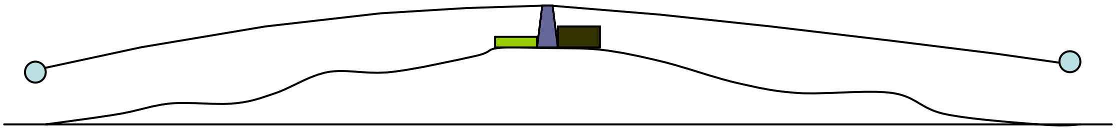

Figure 5a. Lunar Sling on Mountaintop

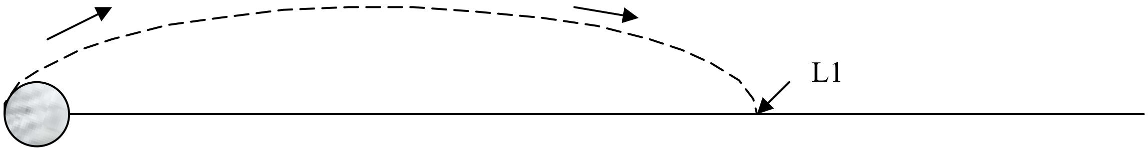

Figure 5b. Payload Trajectories from Lunar Sling to L1

Table 2 shows the parameters of the sling, with its capabilities for launch. If the sling is located on top of a mountain 4 km high, then for orbital launches the tether could be up to 118 km long, and for parabolic launches, it could be up to 236 km long, without dragging the ground at the tip. The table shows the tip velocities required for circular orbit velocity and for escape. For a tip acceleration of 24 g, fairly low for cargo, the lengths required are 12 and 24 km, respectively. If 500-kg payloads are launched every 4 hours, the power required to spin the tether is 100 kW, and the throughput is an impressive 3 tonnes per day. The ideal location is on the lunar equator on the farside, although a polar location is also possible, with an adjustment in velocity and plane of rotation.

Table 2. Lunar Sling Parameters

Type	h, km	r, km	V_{tip}, km/s	a_{tip}, g's	P, kW	Tons/day
Low Orbit	4	12	1.68	24	100	3
Escape	4	24	2.38	24	100	3

Reaching the Lunar Poles

We would like to connect the Lagrangian points directly to the lunar poles, but that is impossible, even for an infinitely strong material in a straight-line configuration. Using strong ribbon materials would allow the LSE to be curved from the equator toward the poles. The maximum latitude that can be reached is a function of the material strength/density, which was described theoretically by one of us (Levin[7]). Therefore, to reach the polar ice-mining bases, it will be necessary to provide a tramway-like connection made of a series of catenary ribbons suspended from towers.

Levin calculated the maximum lunar latitude achievable as a function of the characteristic height of the ribbon material. These calculations are more complicated than the Earth space elevator, because of the 3-body problem of the Earth-Moon system. The result is that curving the lunar space elevator takes a large fraction of the material strength, as shown in Figure 6. In this figure, the abscissa is η, the ratio of the square of the transverse wave velocity of the material, $v_t^2 = T/\rho$ (tension over density), to the square of the circular velocity at the lunar surface, $v_0^2 = \mu/r_0$ (lunar gravitational parameter over lunar radius).

Using a ribbon of M5 fiber with a safety factor of 2, $\eta \approx 1$, and the LSE bottom end could be towed to a latitude of about 36 degrees and retain about half its strength for lifting payloads. The maximum latitude attainable by M5 is 52.5 degrees, but that takes all its strength, leaving no margin for lifting payloads. Even carbon nanotubes could reach only 76° latitude, which still leaves a distance of 426 km overland to the pole. This means that a tramway will be required to reach the poles, no matter what the material.

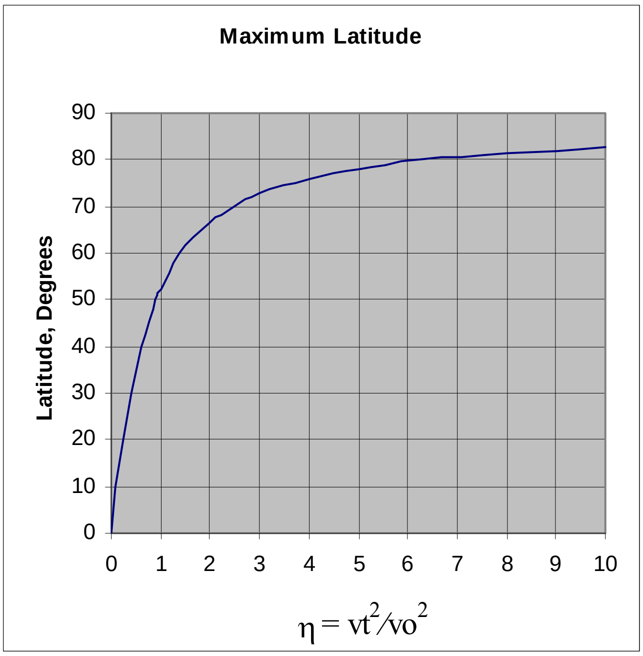

Figure 6. Maximum Latitude Touchdown for Curved Lunar Space Elevators

Using half the stress limit to reach 36° latitude saves only about 1000 km of tramway, but it halves the throughput of the entire system. Much higher productivity can be obtained by just using a vertical configuration, and taking the tramway the entire 2700 kilometers from the equator to the pole.

The ribbon could be simply extended in the form of a lunar tramway, as shown in the sketch of Figure 7. Over perfectly flat terrain, catenary towers 1 km high could span 91 km; that means that only about 30 towers would reach all the way from the equatorial touchdown point to the polar ices. Many of the towers might be erected on local mountain peaks or crater rims to increase the spans. The path of the catenary could also deviate to pass through mineral deposits, for access to lunar resources.

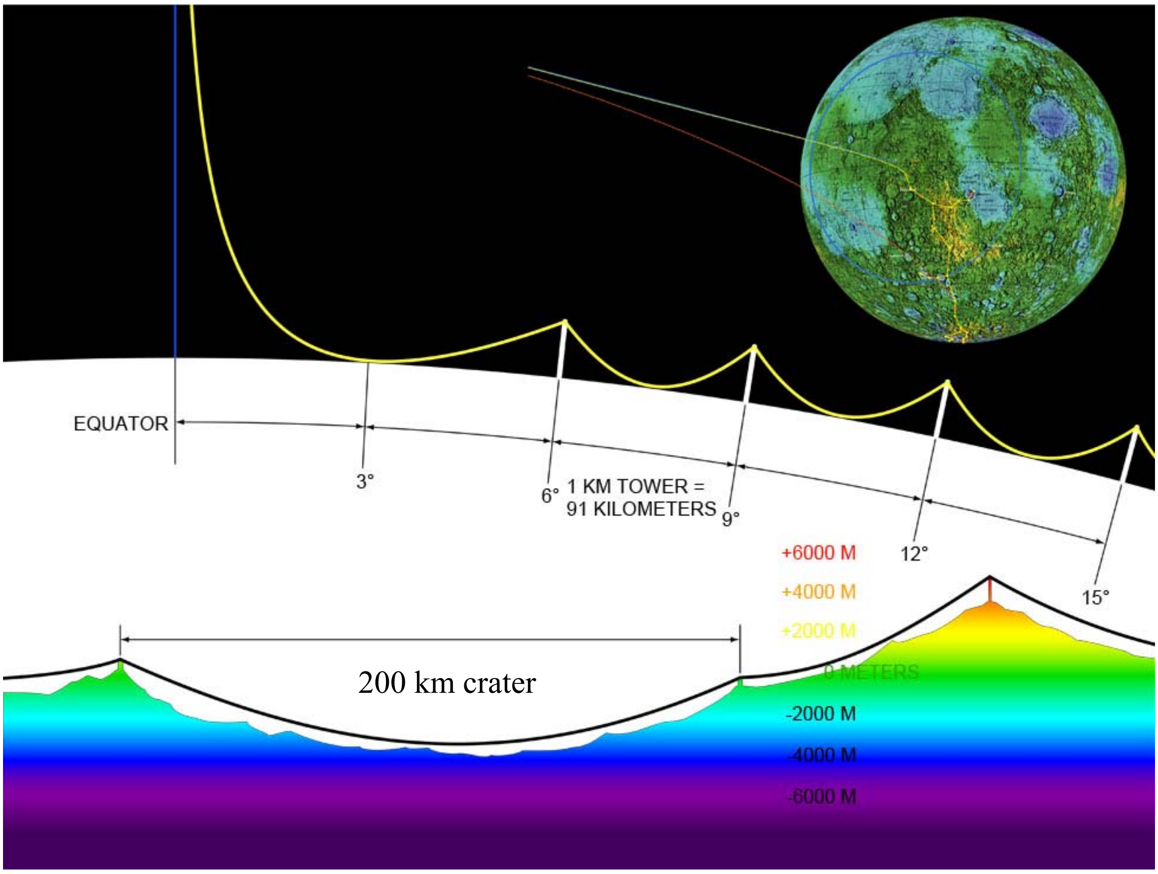

Figure 7. Lunar Tramway for Reaching the Poles

The same solar-powered vehicles that climb up and down the vertical ribbon could move along the horizontal catenary, taking individual cargo payloads all the way from the pole to past L1 and launch to Earth orbit. The vehicles are equipped with articulated solar panels to generate power to drive their wheels over the surface, and would therefore be limited to lunar daytime operations, but the panels also double as the power source for orbit transfers.

OPERATIONS AND PERFORMANCE

Using high-strength material launched from Earth, the lunar space elevator will be constructed from the L1 balance point, extending ribbons in both directions until the lower tip of the space elevator ribbon reaches the surface at the equator. From this point, robotic surface vehicles can carry the ribbon toward the poles, and anchor it on towers at convenient crater rims or mountain peaks, with way stations near deposits of lunar resources. The ribbon will be extended from tower to tower until it reaches the polar mining bases. This will connect the polar mining bases, various mineral deposits, and the elevator base to the launch stations beyond L1, and thence to Earth orbit.

To minimize the amount of mass that must be transported from Earth, we can use indigenous lunar materials, including the lunar regolith, or weathered rock. For construction purposes, we propose that a wide variety of complex structures can be built using just two basic shapes combined in innovative ways. The basic shapes are beads and wires. The problem we solved was the creation of space filling geometries based on these two extremely simple shapes. The building beads are small compression blocks of about 2 cm or less on a side. The beads must be small enough to make practical partitions but suitable for multiplication into structural hull sections or beams of any required length.

Although the concept of the building bead was inspired by “lunarcrete,” the beads might be produced from a variety of available materials, including ceramics, an aggregate material that could be sintered or bonded, powder metallurgy, cast iron or aluminum, or even cut and machined rock. This flexibility means that the bead production process can be adapted to fit the resources available; the assembly equipment and the support system designs can remain the same. If the material available is strong only in compression, a web of tension wires can pass through or between the beads, and the resulting composite structure will exhibit both properties.

Robotic mines at the base of the elevator could prepare these building materials, and assemble them into towers to support the ribbon catenary. A robotic vehicle could move over the surface, carrying tower elements and the ribbon, and erect the towers vertically in place, without the requirement for swinging them erect and using guy wires. The concept is shown in Figure 8, with a terrestrial example pictured.

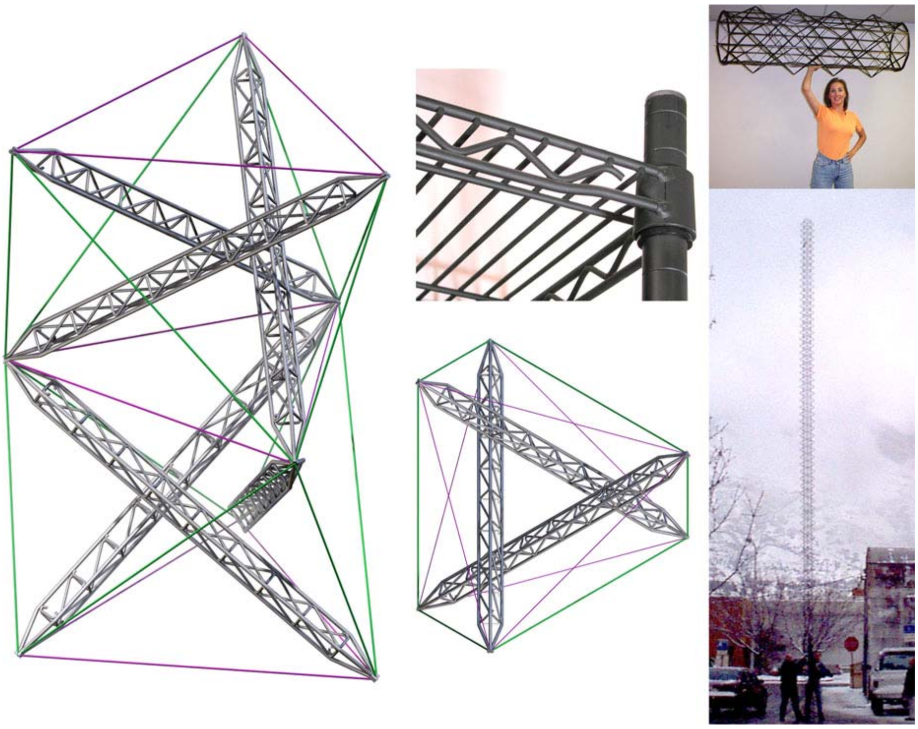

Figure 8. Lightweight Towers for Tramway Support

If the average climber velocity could be maintained at 100 km/hour for the ascent, this would produce a total throughput of 385,000 kg of material per year into high Earth orbit. This amount of material per year is based only on the initial strand of the lunar space elevator. If we can use lunar material to construct additional ribbon, perhaps with indigenously available spun basalt, the annual tonnage could be multiplied many-fold.

Lifting the payloads at this velocity would require a little over 10 kW at the surface, but would halve to 5 kW at 600 km height, and halve again at 1741 km. One-fourth of the way to L1 the power would be down to 100 W. Most of the journey would require very little power, so the capsules might start slowly, to require far less than 10 kW solar array capacity, leaving more of their mass for payload. Their initial acceleration might be helped by auxiliary power generated at the base, or by a catapult launcher.

Lunar materials shipped to Earth orbit will consist of a variety of lunar resources:

- Lunar regolith to HEO for shielding and general construction
- Lunar plagioclase, feldspar, anorthite, etc., for Earth-orbit construction
- Lunar water, oxygen, aluminum, and sulfur to LEO for propellant depots
- Lunar water from the poles to lunar bases for life support

Earth payloads shipped to the LSE and the lunar surface will include potential counterweight masses for LSE construction, return of lunar climber solar arrays to the surface for re-use, and Earth-launched materials bound for the Moon. Note that the LSE is like a pipeline, with large but slow throughput, so it will not carry human cargo. However, the LSE could carry a large quantity of materials and supplies to complement the human passengers who will move by faster chemical rockets to and from the Moon. The result will be a large reduction in the cost of moving payloads from LEO to the Moon, and the availability of lunar materials at a reasonable cost in Earth orbit.

To carry this large tonnage, we could use a fleet of about 50 tugs, using ion rockets or electrodynamic thrusters, to take the Earth supplies from LEO to the LSE and bring the lunar products back to LEO. Each tug would consume about 10-20 kW of solar power, produce 0.5-1 N of thrust, and transfer 500-kg payloads in about 2 months. Each tug could move 1.5-2.5 tons per year, and 50 tugs could move 75-125 tons per year, or a million kg per decade.

To support the tugs, we would need to launch 10 tons each month to LEO, of which 10% is fuel for the tugs. The tugs will be departing daily; for the first few years, they will be carrying only LSE parts, but later some of them could deliver lunar fuel to other spacecraft. The tugs could be scaled to the most efficient size and power, which might be as high as 300 kW in some scenarios.

COST ANALYSIS

The performance of the lunar space elevator depends on the carrying capacity of the ribbon material, which is a function of the available material strength and the total mass of the ribbon. The cost of the lunar space elevator depends on Earth-orbit launch costs, orbital transfer to lunar trajectories, and the cost of developing and operating the system.

Launcher cost projections

A simple spreadsheet cost model for the lunar space elevator was developed, using a strategy from Nock[8] et al. in their work on Moon-Mars transport economics. Launch mass to LEO is used as the standard parameter for costing. Rather than attempting to project launch costs to LEO well into the future, we use three values, low ($0.3M/t), medium ($1M/t), and high ($3M/t), to convert launch mass to cost. The high end of this range is based on the published cost and performance of the Falcon V launch vehicle, currently under development by SpaceX (www.spacex.com), and scheduled for launch during the second quarter of 2006. The current estimated cost is $15.9M plus range fees, and the payload to a Cape Canaveral inclination, 200 km altitude circular orbit is 6020 kg, which gives a cost per tonne of $2.64M. Allowing a modest amount for range fees, we round this up to $3M/t.

Taking this cost as the upper end of the range seems reasonable, but actual demonstration of flights at these rates is needed. Note this is a big reduction from the $10M/t of current launchers, which was the value used by Nock. Given the published goal of SpaceX founder Elon Musk to develop even lower cost vehicles, assuming the midrange of $1M/t to LEO is probably a conservative cost for the time frame of the LSE. The low end is consistent with the ambitious goals of various paper studies of advanced launchers, but is not out of line looking two or three decades in the future.

Orbital Transport

A magnetoplasmadynamic (MPD) thruster system currently being developed at JPL[9] is assumed for the LEO-to-L1 leg. The assumed Isp was 4000 seconds, with an efficiency of about 82% and a thrust of 12.5 newtons. A total mass/power ratio of 10 kg/kW was assumed for sizing the inert mass of the system. The payload and inert mass were sized at 20 and 2 t, respectively, and performance computed with these numbers. Round trip transit time, returning empty to LEO, is about 6 months.

Two additional components must be added: The mass required on the lunar surface, and the transport needed to go from L1 to the lunar surface. It is somewhat less costly, in terms of total mass in LEO, to use high Isp electric propulsion to low lunar orbit, then switch to a chemical rocket needed for a soft landing, However, for simplicity, we chose to use oxygen/hydrogen chemical rockets for the entire trip. An Isp of 465 s was assumed for an RL-10 class engine. Also, return trip propellant was assumed to be available on the lunar surface, where it would be derived from polar ice. Larger or smaller use of lunar derived propellants could change the mass required for this leg by significant amounts, but lunar propellants would only have a major impact overall if they are available in LEO for the transport to L1.

The Delta-V's used are based on Earth to escape and Moon to escape, and are therefore a bit conservative. Actual systems would have losses not accounted for which would balance out these assumptions.

The orbit transfer delta-V's assumed were:

LEO to L1 high thrust: 3350 m/s
LEO to L1 low thrust: 7800 m/s
L1 to lunar surface: 2640 m/s (includes some margin for soft landing)

Elevator Mass and Transport Cost

The current mass estimate for the lunar elevator, with an added 10% margin, is just over 6100 t, plus an additional 100 t on the lunar surface. Adding in the xenon propellant for the cargo transport, plus oxygen-hydrogen chemical propellant for the lunar surface transport, gives a total LEO mass of 8000 t. Multiplying by the assumed range of transport costs gives a total cost for launch of 2.4 B$ at the low end, to 24 B$ at the high end, with a mean of perhaps $10 billion.

These estimates could be significantly lower if stronger materials become available in the next 10-15 years. Composites reinforced with carbon nanotube fibers, or even de-rated carbon nanotube composites, could multiply throughput without increasing system mass.

APPLICATIONS AND SIGNIFICANCE

These space elevators can support development of the lunar maria resources on the near side, and astronomical observatories at the poles and on the far side, away from the Earth's electromagnetic interference. The poles may be the key to lunar resource development. The Clementine and Lunar Prospector missions indicated that there may be valuable deposits of hydrogen ices in permanently dark craters near the poles. These could be invaluable as a source of rocket propellant for propulsion in cislunar space. There may also be permanently sunlit mountain peaks near the lunar poles, allowing for the generation of continuous solar power, even through the 14-day lunar night. This could greatly assist a mining base near the pole to recover lunar ices and water.

Using lunar space elevators, lunar mining, refining, and construction plants on the surface will create useful objects from lunar resources; solar-powered cargo vehicles will carry these resources up the lunar space elevator; and robotic orbit transfer vehicles will carry the payloads from the top of the space elevator into high Earth orbit to revolutionize the next phase of space development. Lunar space elevators will change the paradigm for development of cislunar space, and will greatly reduce the cost of getting building material into Earth orbit.

A radical paradigm shift for the development of cislunar space will occur when abundant lunar raw materials and manufactured products can be continuously delivered into Earth orbit, for development of extensive space facilities, space stations, space hotels and tourism centers, and space power stations and manufacturing facilities. The use of lunar material, without the heavy burden of lifting the material out of the Earth's deep gravity well, could allow the production of power and materials without encroaching on the Earth's biosphere, and could provide attractive and radiation shielded destinations in cislunar space. The use of lunar hydrogen could also provide propellant to greatly reduce the cost of expeditions to Mars.

CONCLUSIONS

The lunar space elevator has the potential to become a high-payoff space project. By providing low-cost delivery of lunar resources and materials into Earth orbit, it could significantly transform the paradigm for space development over the next decades. The lunar space elevator could also be a key to the development of the Moon and the use of its resources for advanced lunar bases and Mars expeditions, thereby contributing greatly to the new vision for a Moon-Mars initiative announced by President Bush in January of 2004. The desired developments described by Klaus Heiss[10] of lunar polar and farside observatories and solar power satellites constructed from lunar materials are made much easier by the lunar space elevator. The lunar space elevator is also a stepping stone to the Earth space elevator, because it can be constructed of existing materials. In addition, there are few satellites in lunar orbit, no man-made debris, and fewer meteoroids are expected. The Earth space elevator and the lunar space elevator both need climbing vehicles to carry cargo along their ribbons of material, and they are both orders of magnitude longer than any structure yet constructed in space. For these reasons, the lunar space elevator is an excellent testbed for examining many of the technology challenges of the Earth space elevator, including the dynamics and stability of long structures in space, control of the lateral and longitudinal oscillations, and the dynamics of vehicles climbing rapidly along their great lengths.

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