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THE LUNAR SPACE ELEVATOR

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ABSTRACT

This paper examines lunar space elevators, a concept originated by the lead author, for lunar development. Lunar space elevators are flexible structures connecting the lunar surface with counterweights located beyond the L1 or L2 Lagrangian points in the Earth-moon system. A lunar space elevator on the moon's near side, balanced about the L1 Lagrangian point, could support robotic climbing vehicles to release lunar material into high Earth orbit. A lunar space elevator on the moon's far side, balanced about L2, could provide nearly continuous communication with an astronomical observatory on the moon's far side, away from the optical and radio interference from the Earth. Because of the lower mass of the moon, such lunar space elevators could be constructed of existing materials instead of carbon nanotubes, and would be much less massive than the Earth space elevator. We review likely spots for development of lunar surface operations (south pole locations for water and continuous sunlight, and equatorial locations for lower delta-V), and examine the likely payload requirements for Earth-to-moon and moon-to-Earth transportation. We then examine its capability to launch large amounts of lunar material into high Earth orbit, and do a top-level system analysis to evaluate the potential payoffs of lunar space elevators.

SPACE ELEVATOR HISTORY

The idea of a "stairway to heaven" is as old as the Bible, and includes the Tower of Babel and Jacob's Ladder. Modern thought on space elevators goes back to Konstantin Tsiolkovski, a school teacher in St. Petersburg, Russia, who did a "thought experiment" on a tower into space.

Tsiolkovski imagined tall towers on the sun and planets, and realized that, because of their rotation, gravity would decrease as you ascended such a tower, reversing at the altitude where a satellite would have a period the same as the rotation period of the body. Here the gravitational and centrifugal forces on a body in a one-day orbit are in balance. The altitude at this point is what we now call the synchronous altitude for a spacecraft. Tsiolkovski calculated the synchronous altitudes for the five visible planets and also the sun, but he concluded that building a real tower into orbit was impossible[1].

In the 1950s, Leningrad engineer Yuri Artsutanov discovered how to build a real structure for the space elevator, but did not publish an engineering article.

His ideas appeared in a Sunday supplement to *Pravda* in 1960[2], and their significance was not recognized in the West. In 1966, a group of oceanographers led by John Isaacs at the Scripps Institute re-discovered the concept, but they proposed such a thin wire that it would be cut by micro-meteoroids almost instantly, could not be scaled up, and was therefore completely impractical[3].

Jerome Pearson discovered the concept independently and published it in the international journal *Acta Astronautica*, and thus made the international aerospace community aware of the space elevator for the first time[4], in 1975. An Air Force painting of Pearson's space elevator (Fig. 1) shows

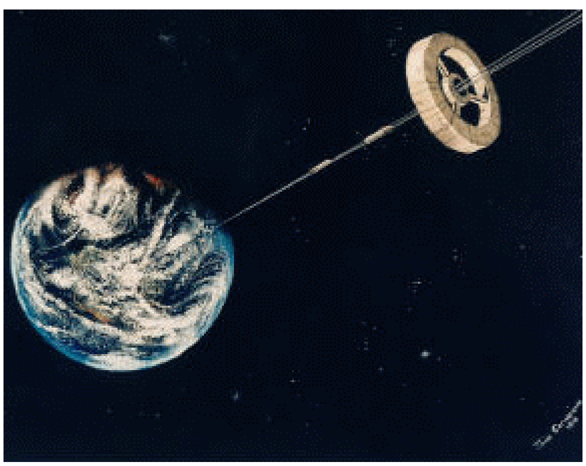

Fig. 1: The Space Elevator

capsules moving up and down from the space complex in synchronous orbit.

His discovery included using the space elevator for zero-net-energy space launching, and for launching payloads from the elevator tip to reach other planets without requiring rockets. He also was first to examine the dynamics of actually lifting payloads up the elevator, and found limitations on the speeds of ascent, akin to the critical velocities of a rotating shaft and the periodic loads from soldiers marching on a bridge. After talking with Pearson, the science fiction writer and visionary Arthur Clarke wrote his famous novel about the space elevator[5].

Pearson later extended the space elevator idea to the moon, using the Lagrangian points as balance points in lieu of the geostationary orbit, and discovered that such a "lunar anchored satellite"[6] could be used to bring lunar materials into high Earth orbit cheaply. Fig. 2 shows an Air Force artist's concept of the lunar anchored satellite with a spacecraft anchored beyond the L2 Lagrangian point on the far side of the moon, for communication with a farside astronomical observatory.

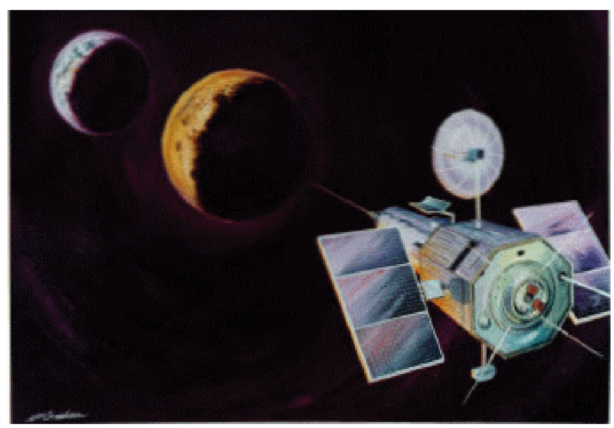

Fig. 2: The L2 Lunar Space Elevator

Interestingly, Artsutanov[7] published a paper on a lunar space elevator just one month later than Pearson, without either author being aware of the other! To compound the mutual lack of awareness, Levin points out that the Russian scientist Tsander conceived of a lunar space tower[8] in 1910, although the ideas were not published until 1978.

John McCarthy and Hans Moravec of Stanford University had been thinking about space elevators in the 1970s, and seeing the Pearson orbital tower publication led Moravec to propose rotating space tethers unconnected to a planet or moon, for catching and throwing space payloads to different orbits[9]. Artsutanov had also proposed this concept earlier[10], but it was not known to Moravec. Forward[11] also proposed rotating tethers for cislunar transportation a decade later, and Oldson and Carroll showed the cost savings from tether transport[12] with short tethers. Pearson[13] showed the synergism of combining longer tethers with rockets or guns.

The rotating tethers proposed by Moravec, and by Hoyt and Forward[14] as propulsion systems for transporting masses to and from the moon are beset with several difficulties. 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, are stabilized by counterweights beyond the L1 or L2 points, and have no need for balancing the mass flow or for re-boosting. Masses can be carried up or down the lunar space elevators by electrically driven, wheeled vehicles, gripping the ribbon of the space elevator and using solar or beamed laser power[7]. These cargo carriers would move at a moderate speed, but provide constant mass flow, like a pipeline. A robot station at the top would launch payloads of radiation shielding, building materials, and finished constructions from the lunar mine to high Earth orbit. From there, they could be further moved to LEO or to the surface of the Earth for other uses.

One fundamental problem of building the space elevator is the phenomenal strength of materials required to support its mass over the 35,800-km height to geostationary orbit. Artsutanov and Pearson recognized that carbon "whiskers" representing perfect-crystal structures, might be one way to achieve the required strength. When carbon nanotube structures were discovered, it was realized immediately by Richard Smalley at Rice University in Houston, Texas and by Boris Yakobson at North Carolina State University that these super-strength materials would make the Earth space elevator possible.

Because a space elevator is hanging from stationary orbit, it must support its own weight over this enormous distance. In a uniform 1-g gravity field, a uniform cable of a specific material can attain a "breaking height" $h = \sigma/\rho g$, where σ is the stress limit of the material and ρ is its density. Since no material has a breaking height as high as synchronous orbit, the space elevator must be tapered from a maximum at the synchronous height to minima at the base and at the top.

Table 1 shows candidate materials for space elevators, with their breaking heights. The Earth space elevator will require carbon nanotubes, but lunar space elevators can be constructed with these existing materials.

Building Material	Material Density ρ, kg/m^3	Stress limit σ, GPa	Breaking Height $\sigma/\rho g$, 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	342
M5 planned	1700	9.5	570
Kevlar†† 49	1440	3.6	255

* Single-wall carbon nanotubes (lab measured)
† Toray carbon fiber
‡ Aramid, Ltd. polybenzoxazole fiber
¶ Honeywell extended chain polyethylene fiber
** Magellan honeycomb-like 3-D polymer
†† DuPont aramid fiber

Table 1: Candidate materials

The amount of taper required is an exponential function of h and the radius, mass, and rotation rate of the planet, as shown in Figure 3. This figure shows that the Earth space elevator is very demanding of materials, but space elevators for Mars and the moon are much easier.

The space elevator must be constructed of extremely strong, lightweight materials, and for minimum mass it is tapered exponentially with of the planet's gravity field and the strength/density of the building material. Using the M5 fiber with their advertised stress limit of 9.5 Gpa gives a breaking height of 570 km under 1 g. For the L1 lunar space elevator, this requires a taper ratio of just 2.66 in cross-sectional area between the maximum at the L1 point and the minimum at the lunar surface. For Mars and Earth, M5 fiber would require taper ratios of 81 and 5800, respectively, because of their higher gravity fields.

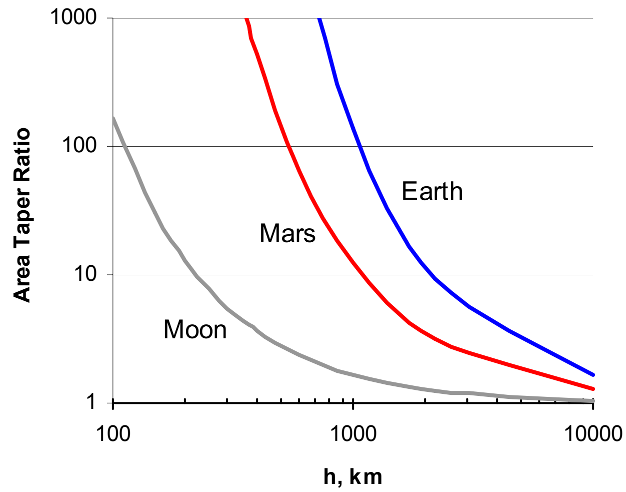

Figure 3: Space elevator area taper ratios vs. breaking height for Earth, Mars, and the moon

Physicist Bradley Edwards proposed a practical scheme for constructing a space elevator about the Earth, and received NIAC funding for a study[15]. The Earth space elevator concept has now been advanced in the construction system, the cargo lifting system, and especially in materials[16]. However, there are two very difficult problems to be overcome in building the Earth space elevator—the necessity for a material such as carbon nanotubes, which may not be available for construction 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 they must be removed, requiring an enormous space cleansing.

On the other hand, it is possible to build Pearson's lunar space elevator now, and use it to develop lunar resources and for lunar farside communication. It could also be constructed of existing composite materials, and does not require the super-strength of carbon nanotubes. Because of the moon's lower gravity, far less material would be required than the Earth space elevator[17].

LUNAR SPACE ELEVATOR SYSTEM CONCEPT

Vision

We propose to develop lunar resources and make them available for large-scale operations in cislunar space, by using lunar space elevators. The architecture for this vision consists of three systems: a lunar construction system, a lunar space elevator system, and a cislunar transportation system.

The construction system is a unique and streamlined method for creating the basic building blocks for lunar and orbital construction, and will be detailed in a later paper. The lunar space elevators use both Lagrangian points to provide access to nearside and farside equatorial regions and the polar regions as well. Solar-powered vehicles climb the space elevators to take payloads beyond the Lagrangian points with excess orbital energy. From there, small robotic space tugs complete the cislunar transportation system, taking lunar materials to high Earth orbit (HEO) for use in construction, shielding, habitats, and solar power satellites.

The effectiveness of this vision will depend on the kinds and amounts of material flows that such a system could support, and the potential uses and payoffs of the final products for operations in Earth orbit, as well as the mass required for the lunar space elevators compared with the expected annual throughput.

We have begun to identify the most likely lunar products for developing and industrializing Earth orbit, and to define and analyze the space elevator operating concept, including the cargo vehicles for carrying lunar materials. We have also examined taking the lunar products from the elevator vehicles and propelling them into high Earth orbit. This allows an evaluation of the payoffs of the entire system for cislunar development.

Figure 4 shows our concept for lunar space elevators to develop lunar resources. Lunar space elevators allow access to both the equatorial maria and the polar mountains, and inherently includes a non-rocket propulsion system to take the material to HEO.

Two lunar space elevators (LSE) will meet the needs—one balanced about the L1 Lagrangian point, and one about the L2 Lagrangian point. L1 is 58,021 ± 3183 km from the center of the moon toward the Earth, and L2 is 64,517 ± 3539 km from the center of the moon away from the Earth. The variations are due to the 0.055 eccentricity of the lunar orbit. The L1 LSE is slightly easier to build and is constantly visible from the Earth; the L2 LSE is slightly better for launching masses into Earth and lunar orbits, and can communicate with lunar farside outposts.

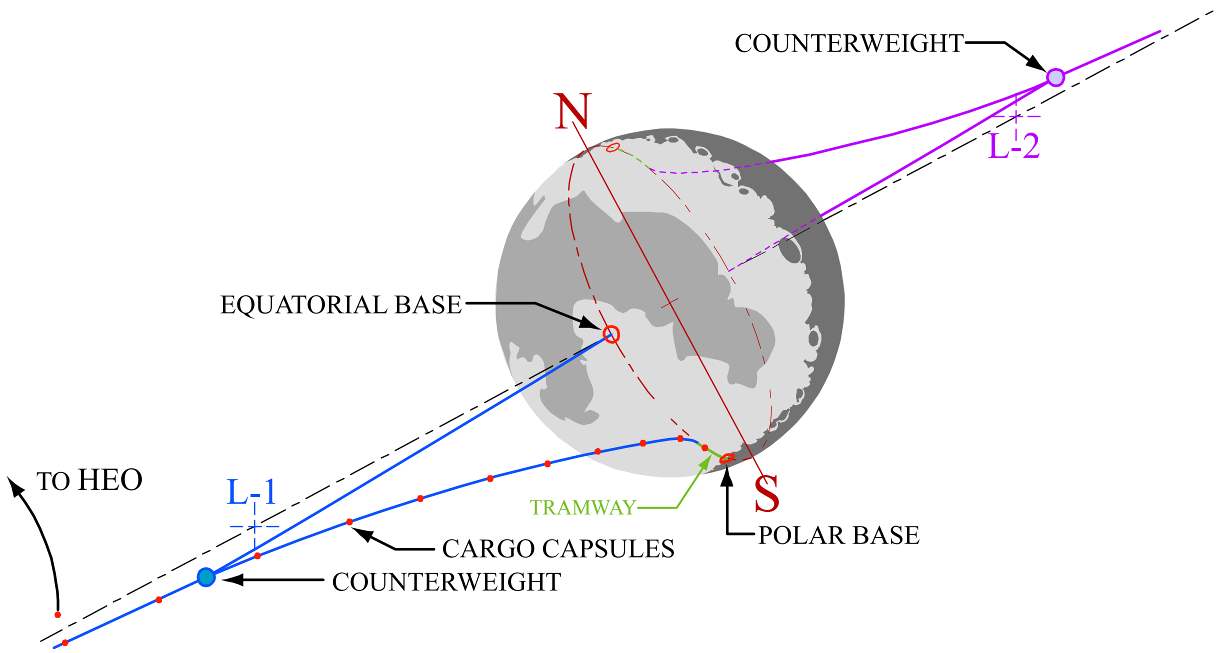

Figure 4: Lunar space elevators about L1 and L2, with equatorial and polar bases

<u>Lunar space elevator design</u>

Vertical lunar space elevators balanced about the L1 and L2 Lagrangian points provide access to the lunar maria on both the near and far sides of the moon. Providing access to the polar regions requires multiple attachment points, multiple ribbons, and continuation of the space elevator across the surface to reach polar mines for lunar hydrogen. Finally, launching material into high Earth orbit without rockets for their most useful applications requires space elevator extensions beyond L1 and L2.

The complete lunar space elevator system requires a basic structural ribbon, climbing vehicles, and tramways. The self-powered climbers carry the cargo from the construction sites up the elevators. The tramways connect the lower ends of the elevator legs to the polar sites for continuous power and hydrogen, the nearside maria for ilmenite, and the farside highlands for astronomical observatories unaffected by interference from the Earth's electromagnetic radiation.

To access the poles, the space elevators have non-vertical segments that curve away from the equator and toward the poles, connecting the resources near the lunar poles with the transportation system. The maximum latitude that can be reached is limited by the material breaking height, which was demonstrated theoretically by one of us (Levin[18]). Depending on how close the space elevator building material allows the base to be moved toward the pole, a certain length of tramway will be required to reach the polar mining base.

The lunar space elevators are built from the L1 and L2 balance points, by extending the space elevator ribbons until the lower tips reach the surface at the equator. Additional ribbon strands can then be lowered and towed by a surface vehicle toward the poles, and anchored at convenient mountain peaks at the latitude where they are tangent to the surface. These additional ribbons not only make the lunar space elevator redundant and fail-safe, but they will be extended from lunar mountain peak to peak until they reach mining bases near the poles. This creates direct connections between the polar mining and refining bases and the launch stations beyond L1 and L2.

Figure 4 shows the total mass of the ribbon and the counterweight required to balance the L1 lunar space elevator using the expected values for M5. The values for L2 are very slightly higher.

If the counterweight is placed just beyond the L1 point, a very large counterweight is required to balance the space elevator ribbon, and this gives a very large total system mass. If the ribbon is extended much beyond the L1 balance point, the required counterweight is much smaller, and the total system mass declines. However, the system mass is dominated by the counterweight, even out to lengths of 120,000 km.

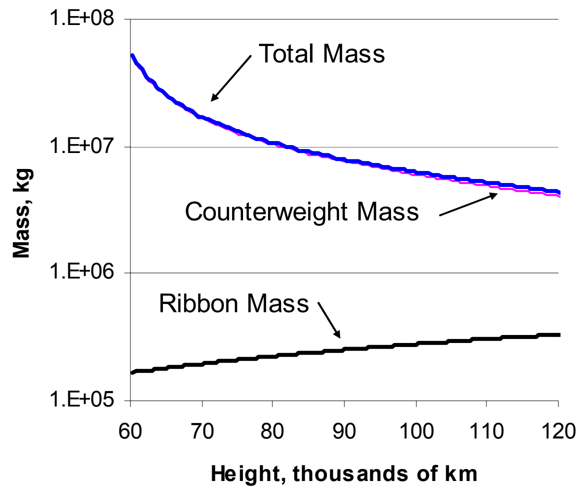

Figure 4: Lunar space elevator ribbon and counterweight mass

Lunar space elevator construction

A flat ribbon of M5 material, 30 mm wide and only 0.023 mm thick, similar to aluminum foil, could support a mass of 2000 kg at the lunar surface, or 100 cargo vehicles of 580 kg each spaced evenly up the length of the elevator ribbon. The average velocity of the cargo vehicles might be reasonably maintained at 100 km/hour for the ascent, without producing undue wear on the elevator ribbon.

Climbing vehicles to carry payloads up to L1 and L2 could grip the ribbon-shaped lunar space elevator, as shown in Figure 5. The climbers would be equipped with large wheels that press against the ribbon of the space elevator from both sides, providing enough frictional force to support the weight of the payload.

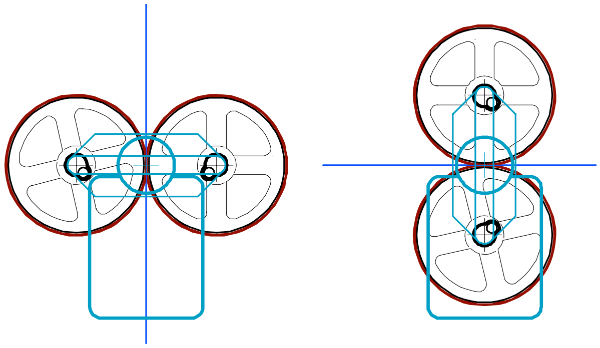

Figure 5: Climbing vehicles grip the ribbon, vertically or horizontally

With this climbing vehicle mass and speed, the resulting Coriolis force on the ribbon would total just 7.9 N for 100 vehicles, or less than 0.02% of the tension. This speed is also less than 1% of the transverse wave velocity, and therefore the vehicles will not excite the ribbon flexible modes.

Maintaining this velocity would require 26 kW at the surface, but would halve at 600 km height, and halve again at 1741 km. One-fourth of the way to L1 the power would be down to 290 W. Most of the journey would require very little power, and so the capsules might have less than 1 kW of solar array capacity, allowing for losses from efficiency of sunlight on the single-axis-control of the hanging arrays. Their initial acceleration could be provided by laser power beamed at much higher than solar power density from a surface laser, or they could simply start at lower speed.

Lunar space elevator operations

Lunar mining, refining, and construction plants will be built on the surface, with useful objects constructed from lunar resources, carried up the lunar space elevators by solar-powered cargo capsules, and dropped from the tip of the space elevator into high Earth orbit for use in the next phase of space development. Lunar space elevators will revolutionize the way we operate in cislunar space, and will greatly reduce the cost of getting lunar materials into Earth orbit.

The lunar space elevator will also be a stepping stone to the Earth space elevator. Lunar space elevators do not require super-strength materials, and do not endanger all Earth satellites. Lunar space elevators are twice the length of the Earth space elevator, but because of the moon's much smaller mass they 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 traveling 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 vehicles climbing rapidly along their great lengths.

Lunar space elevators will provide abundant raw materials and manufactured products that can be continuously delivered into Earth orbit for development of extensive space facilities, space stations, space hotels and tourism centers, 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, will 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.

The chart shown here, reproduced from Pearson (Reference 6), shows the half-regions of accessible orbits from the lunar space elevators.

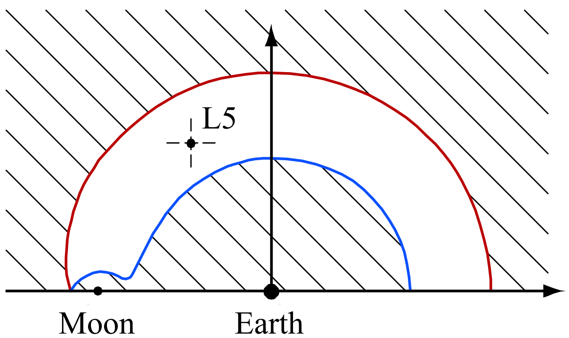

Figure 6: Accessible regions in the Earth-moon space from payloads released from the L1 and L2 points

Payloads carried up the lunar space elevator and released beyond L1 or inside L2 could reach the inner hatched region of Figure 6; payloads released from beyond L2 could reach the outer hatched region. Basically, the accessible regions cover all of cislunar space except an extended region encompassing the Lagrangian points L3, L4 and L5.

If the L1 lunar space elevator is extended far enough, payloads released from the top would fall into lower Earth orbits—the longer the L1 lunar space elevator, the lower the Earth orbit perigee.

Figure 7 shows the perigee of typical Earth orbits reached by payloads released from the L1 lunar space elevator. The L1 point is 58,000 km from the lunar surface, or about 0.15 lunar distance units. If the payload is released from 130,000 km high, its HEO perigee will reach GEO. This should be the limit, because any lower would interfere with geostationary satellites.

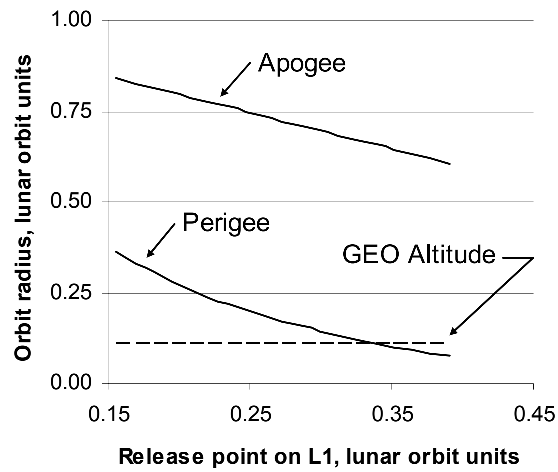

Figure 7: High Earth orbits reached by payloads from the L1 lunar space elevator

Lunar Space Elevators for Cislunar Development

The construction of lunar bases and habitats using lunar resources[19] was considered extensively in the 1970's after the Apollo missions provided information about the composition of lunar maria and highlands. The lunar materials available include the basaltic lavas of the nearside maria, with their silicates and iron-titanium oxide ilmenites, and the feldspars of the highlands. More recently, the Clementine and Lunar Prospector missions have shown the likely presence of lunar hydrogen in permanently shadowed areas near the south pole, probably as water ice. The lunar space elevators provide a means to develop all these resources.

The poles may be the key to lunar resource development. The Clementine and Lunar Prospector missions indicated that there may be valuable deposits of water ice in permanently dark craters near the poles. These could be invaluable as a source of rocket propellant for propulsion in cislunar space. There are also permanently sunlit mountain peaks near the lunar south pole, allowing for the generation of continuous solar power, even through the 14-day lunar night. This could greatly assist a mining base near the south pole.

The lunar space elevator allows us to re-discover the moon for space habitats, after the romance in the 1970s with space colonies at L4 and L5. With virtually continuous solar power from mountain peaks, and valleys of permanent darkness for mining condensed ices, the poles provide a range of lunar resources. The moon also provides a constant gravity force to keep the muscles, bones, and vestibular systems of the inhabitants in better shape while requiring less exercise than the zero gravity of space stations.

Mining lunar regolith and launching it from beyond L1 using a constant stream of climbing vehicles on the lunar space elevator could provide a total throughput of more than 755,000 kg of material per year into high Earth orbit.

CONCLUSIONS

The lunar space elevator can be a key piece in the development of the moon and the use of its resources for advanced space development, and it can contribute greatly to the new vision for a moon-Mars initiative announced by President Bush in January of 2004. We expect lunar space elevators to enable us to take advantage of these positive attributes by creating a paradigm shift leading to bold moves for lunar development, sending humans to Mars, and on into the solar system.

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