On the use of solar power as a means of powering a Moon Base through the lunar night.

Sacramento L5 Society et al

April 23, 2015

What's the most practical way to sustain a permanent Moon base through the ~355 hour lunar night? The Sacramento L5 Society (SL5S), a California chapter of the National Space Society, has taken on the task of trying to answer that question. In early 2014, two college students, Akhil Raj Kumar Kalapala and Krishna Bhavana Sivaraju of Rajiv Gandhi University, India, proposed beaming space-based solar energy to the Earth by way of a laser beam located in geosynchronous orbit[1]. On March 14, 2014, an informal "brown bag" Moon Base Working Group (MBWG) was begun at NASA/Ames at Moffett Federal Airfield in California "to develop a cost-effective plan for establishing and operating the NASA Moon Base that would be within 10% of the total NASA budget." In March of 2014, Joseph Bland of the Sacramento L5 Society (SL5S), one of the mentors for Akhil and Krishna, suggested to Michael Abramson, a member of both the SL5S and of the NASA/Ames MBWG, that the group examine the possibility of powering a Moon base through the lunar night with a laser either at Earth/Moon Lagrange point 1 (EML1) or in lunar orbit. It was later discovered that use of a LS at EML1 had been proposed by others, including Charles Radley, president of the Oregon L5 Society[2].

It has recently come to the attention of the SL5S that a NASA concept study was undertaken in 2009 to answer the same question. The only documentation concerning the 2009 NASA study that's been available to the SL5S has been a slideshow composed of 83 slides[3], referred to below as 2009 study slides. From examination of those 2009 NASA study fragments, it seems likely that the SL5S analysis process has uncovered several relevant concepts that were not considered by the NASA study, specifically including the use of aggressive laser collimating, solar pumped lasers, orbiting energy storage, beam deflecting systems, multiple linked solar converters at the lunar poles, and solar sails for station keeping.

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1 http://spacejournal.ohio.edu/issue18/helioastra.html

2 http://lunarelevator.com/wp-content/uploads/2014/07/NASA-Lunar-CATALYST-Final.pdf

3 http://www.nasa.gov/pdf/315858main_Cheng-yi_Lu.pdf

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Appendix 1: **<u>Moon energy systems lift capacity in Falcon Heavy units and dollar equivalents</u>**

Lift Capacity (LC)

Because it takes less force to put a given mass in Low Earth Orbit (LEO) than in lunar orbit, and less mass to put a mass in lunar orbit than on the lunar surface, it is useful to use a given LC to determine relative masses in different locations. We know that it took about 5,000 lbs of propellant for the Ascent Propulsion System of the Apollo Moon lander to return about 5,000 lbs of men, materials, and Ascent Stage to lunar orbit. Assuming that a landing mass was 50% fuel and the remainder was 2/3 cargo and 1/3 landing craft, the total mass of cargo would equal (.66x.5=) 33%. Thus, approximately 3x as much mass would need to be put in orbit as would eventually be used on the lunar surface. (Note that to the extent the landing craft can be used as part of the Moon base, that number can be increased towards 50%.) We can use the proposed SpaceX Falcon Heavy (FH) to determine LC. To estimate the LC required to put one FH cargo into lunar orbit, a SpaceX fan site[4] lists the TLI (Trans-Lunar Injection) for the FH as 17,216 kg. To estimate the LC required to put one Falcon Heavy into LEO, we can use the wikipedia figure of 53,000 kg[5], or about (17216/53,000=) 33% of the mass that can be put in lunar orbit. In other words, for a given mass of cargo on the lunar surface, it would require 3 times the mass in lunar orbit, or 9 times the mass in LEO. Thus, the LC of one FH equals 53,000 kg in LEO, 17,216 kg in lunar orbit, and (17,216/3=) 5,739 kg on the lunar surface.

Use of electrical propulsion (EP)

Mass doesn't necessarily have to be lifted directly from Earth to its final destination. Called FAST (Fast Access Spacecraft Testbed) in the 2009 NASA study, use of an EP can greatly reduce the LC of any given system. As pointed out by SL5S member Mel Bulman, an EP (electrical propulsion) system could move a mass from LEO to EML1 by spiraling out over a long length of time. That method of moving a mass would have a profound impact on the required LC for objects bound beyond LEO. For an orbit raising to EML1, Mr. Bulman calculated that it requires about 25,000 ft/sec for an EP-driven spiral out. And while the transit time would be measured in years, the propellant mass, at 6,000 seconds of ISP, would only require a propellant load of about 15% of the transported mass. For our calculations, we will assume that the propellant and EP drive add 30% of the transported mass.

An EP can also be used for "orbital station-keeping", which can broadly be defined as maintaining an object in space in a preferred position or orbit. The 2009 NASA study included mass calculations for station keeping (2009 study slides 13 and 18), and those figures have been used in this study.

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4 http://www.reddit.com/r/spacex/comments/2bk5h5/i_came_up_with_falcon_heavys_tli_payload_under_a/

5 http://en.wikipedia.org/wiki/Falcon_Heavy

Energy storage systems and an Emergency Backup power System (EBS)

Our analysis examined energy storage by flywheel, electric battery, chemical, and thermal battery systems. We concluded that Lithium-Sulfur (Li-S) batteries presently appeared to have the best specific energy (0.5 kWh/kg)[6], but that other systems would benefit greatly from In Situ Resource Utilization (ISRU) and would become competitive fairly rapidly once manufacturing on the lunar surface began. A specific energy of 0.5 kWh/kg has been used in this analysis as the basis for energy storage mass calculations for all systems.

Clearly, systems that rely more on energy storage will be more positively affected by any future improvement in energy storage technology. However, all systems will be positively affected to some degree, since all systems would need some minimum amount of backup power in case of emergency. In the event of a total Moon base energy system failure, such an EBS would need to be adequate to permit evacuation of the Moon base personnel to a safe habitat, probably Earth. Also, sufficient backup energy would need to be available to effect repairs, if at all possible. In this analysis, a prudent backup quantity is assumed to be 120 kWh for a (nighttime) 15 kW continuous Moon base energy system. Using Li-S, the mass of the EBS would equal about 240 kg on the lunar surface.

Orbiting Energy Storage system (OES)

A PV-powered satellite that is not in sun synchronous Lunar Orbit (LO) will move continually into the Moon's shadow. Adding an OES permits an LS to continue beaming energy even when this occurs. This permits a completely different approach to using an orbiting LS to power a Moon base than was considered in the 2009 NASA study, where the Moon base only received beamed energy when the LS was both in line of sight with the base and in full sunlight.

Laser collimating

SL5S member Roger Arnold has suggested that collimating of the laser beam with a Fresnel optical lens could be used to dramatically reduce the diameter of a laser beam over a long distance, such as between EML1 and the lunar surface. Per Mr. Arnold, "For a given light wavelength and distance to target, spot diameter is inversely proportional to aperture diameter. For a wavelength of 500 nm (yellow light) [5 10^-7 m] and a target distance of 10^5 kilometers (10^8 m), the product of spot diameter and aperture diameter needs to be roughly 50 m2. So a 10 meter aperture would throw a 5 meter spot, and a 5 meter aperture would throw a 10 meter spot."

Collimating a laser is a useful means of reducing the divergence angle of a laser. "If we collimate the output from this source using a lens with focal length f, then the result will be a beam with a radius $y_2 = \theta_1 f$ and divergence angle $\theta_2 = y_1/f$. Note that, no matter what lens is used, the beam radius and beam divergence have a reciprocal

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6 http://www.gizmag.com/lithium-sulfur-battery-energy-density/29907/

relation. For example, to improve the collimation by a factor of two, you need to increase the beam diameter by a factor of two."[7]

Considering Mr. Arnold's rough estimate of a 50 m2 product at 50,000 km, for a laser with a wavelength of 8.3 10^-7 m (2009 study slide 14), we'd expect an aperture diameter and beam diameter product that's roughly 83 m2 over about 50,000 km. As a check, we'd expect that, at roughly 60,000 km (2009 study slide 17), a 1 meter aperture would yield a product roughly ((60,000/50,000)x83=)100 m. This compares generally with the 2009 study's estimate of 119 m (2009 study slide 18), which has some amount of collimation that may be close to a one meter beam at the collimator. Consequently, we'll assume that, over about 60,000 km, a product of aperture diameter and beam diameter of about 120 m is fairly close, and assumes a one meter aperture.

Because objects in space are in weightlessness, and because space has no atmosphere, a Fresnel optical lens can be used to collimate a laser beam. Mr. Arnold estimates that a Fresnel lens used as a collimator in space might only be a few mils thick. In addition, Mr. Arnold suggests that it would be easier to make a Fresnel lens precise than a parabolic mirror, since it's only the thickness of the film, as a function of distance from the center, that needs to be precise to a fraction of a wavelength. Further, he suggests that the film can be flexible, and can warp or twist to some degree without affecting its beam-forming ability. Accordingly, the mass of a Fresnel lens laser collimator, including the extender framework, is expected to be less than 0.25 kg/m2.

Solar Pumped (SP) Laser System (LS)

The LS system analyzed in the 2009 NASA study was a PV-powered LS. As suggested by Mr. Charles Radley of our sister chapter Oregon L5 Society, another type of LS is possible using SP lasers[8]. In an SP LS, the solar insolation is concentrated directly on the laser, bypassing the electrical conversion system. Efficiencies for the SP LS and the PV LS are expected to eventually be about the same, but the SP LS appears to have a higher specific power even at present efficiencies.

Deflecting satellite System (DS)

Use of DS satellites can in certain circumstances permit uninterrupted LS beaming, thus obviating the need for energy storage either in orbit or on the lunar surface. In one case, an LS is orbited in a sun synchronous polar orbit such that it continually sees solar insolation throughout the year. Two, three, or more laser-deflecting satellites are placed in the same polar orbit and all satellites are spaced an equal distance apart.The satellites are able to deflect the laser beam either from one satellite to another or directly to a Moon base at the one of Moon's poles. Adding a "constellation" of orbiting LS satellites with different orbits would make it possible to continually direct a laser beam to any point on the lunar surface.

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[7] http://www.newport.com/Focusing-and-Collimating/141191/1033/content.aspx

[8] http://www.asteroidinitiatives.com/Papers/files/Solar-pumped-laser-white_paper.pdf

A DS can also find use in other ways. Orbiting a DS constellation around the Earth would permit a LS mounted either in LEO or even on the Earth's surface to continually transmit laser energy to the Moon, including continually transmitting laser energy to a second DS constellation orbiting the Moon. Finally, it is possible to use a non-orbiting DS directly on the lunar surface.

Lunar Polar Multi-array System (LPMS)

The LPMS assumes that a polar Moon base at can be operated with multiple separate PV arrays connected to the Moon base via electric cables which, between them, create a continuous minimum 15 kW throughout the lunar year. Peak power output capacity would thus occasionally equal 45 kW. For our analysis, we've assumed three linked arrays.

Alternatively, it may be possible to utilize a series of DS ground stations as a means of "linking" separate solar or laser beam deflector sites at the lunar poles. In that manner, three or more low mass solar beam deflectors can "feed" a single higher mass solar converter at the Moon base throughout the lunar year. Estimates of the mass of such a system are currently in process.

Solar Sail Propulsion system (SSP) and the Gravity Winch

In certain circumstances, a solar sail arrangement can be used to enhance or even replace an EP system. An SSP is advantaged over an EP because of its ability to modify a spacecraft's position without using fuel. A related idea is the use of reels to pull in or let out either solar sails or "gravity anchors" relative to a space-based LS platform. This constitutes what might be called the concept of a "gravity winch". A gravity winch is basically a reeled tether that's dropped down a gravity well from a neutral gravity point such as EML1. In the case of an L1LS, a tether can be dropped down both the Moon's gravity well and Earth's. Shifting the gravity anchors from one side to the other allows the L1LS to "balance" between the two gravity wells, similar to the way a pole helps a tightrope walker balance. In effect, it removes the "z" vector (along the Earth-Moon axis) from consideration, allowing station-keeping to concentrate on the "x" and "y" vectors.

The 2009 NASA concept study (2009 study)

In comparing the 2009 study to the present analysis, we note that NASA studied a 5 kW per user system (2009 study slides 5 and 48). Our study has focused on a 15 kW system, which can be said to represent a 3-7 user system. For direct comparison purposes, the 2009 NASA study only requires being sized up by a factor of 3.

The NASA Cryogenic storage Regenerating Fuel Cell system (CRFC)

The preferred system recommended in the 2009 NASA study was a PV solar array-powered CRFC. NASA calculated that a 5 kW continuous delivery CRFC system would store 2,000 kW-hr (2009 study slide 48) with a system energy density of 1.14 kWh/kg (slide 51).

The NASA Fixed Orbit Laser System (FOLS)

The 2009 NASA study's alternate preferred system was a FOLS with a 16.1 hour orbit period (2009 study slide 21) that required a surface receiver installation with 525 kW-hr of energy storage. The laser was powered and fired (a) when the laser was in direct sunlight, and (b) whenever the laser was within a 30 degree minimum elevation angle of direct line of sight with the Moon base (2009 study slide 29). The FOLS system analysis presumed an energy storage architecture that was capable of only 200 W-hr/kg (2009 study slide 21). If the NASA study had used the proposed CRFC to store the energy for the proposed FOLS, then the total estimated FOLS storage mass would have been reduced by (1,140/200=) 570%, making a comparison between the two systems far more competitive. The likely reason for not including this consideration was that NASA was pitting the two technologies against one another to determine which development program would be funded.

We've included the 2009 NASA study's CRFC and FOLS systems in Table 1 for reference purposes, noting that a practical CRFC system would be applicable to reducing the mass of all systems with stored energy requirements. We've also estimated the mass of a comparable system to the NASA CRFC system that utilizes state-of-the-art Li-S energy storage. This PV-powered Lunar Non-polar Surface Mounted System (LNSMS) was calculated to have approximately 2.5 times the mass of the 2009 NASA study's CRFC system, but includes 240 kg of backup energy storage on the lunar surface that was not part of the CRFC system. Finally, we've also estimated the mass of a comparable system to the NASA FOLS system that uses Li-S energy storage and aggressive laser collimating. Such a PV-powered Lunar Orbiting Laser System (PVLOLS) is calculated to have an orbiting component mass equal to that of the FOLS system, while the PVLOLS surface component is calculated to have a mass that equals approximately 30% of the FOLS system, including 240 kg of backup energy storage on the lunar surface that was not included in the FOLS system.

Findings

Table 1, entitled "Moon energy systems lift capacity in Falcon Heavy units and dollar equivalents", collates the results of our analysis. The full table from which these results are taken can be found in Appendix 1 on the sacl5.org website. In Table 1, the systems are ranked from low cost to high cost by total FH dollars without EP. FH dollars are calculated based on $1,200/kg per the statement by SpaceX Chairman Elon Musk that "Ultimately, I believe $500 per pound or less is very achievable"[9]. Note that FH dollars do not include any costs associated with developing the various systems.

[9] http://en.wikipedia.org/wiki/Falcon_Heavy

Moon energy systems lift capacity in Falcon Heavy units and dollar equivalents

Systems	Comment	Tot FH with EP	Tot FH without EP	Tot FH $ with EP	Tot FH $ without EP
ELEOLS	Beamed energy from Earth to a DS constellation in LEO	0.11	0.18	$6,994,393.08	$11,648,264.06
LOPMLS (SP)	LO Polar Multiple satellite LS - SP-powered	0.08	0.19	$5,148,061.71	$11,880,142.41
EGEOLS	Beamed energy from Earth to DS at GEO	0.09	0.20	$5,644,184.77	$12,421,191.89
L1LS (SP)	L1 based LS - SP-powered	0.09	0.20	$5,509,163.93	$12,713,455.23
LEOLS (SP)	Low Earth Orbit LS - SP-powered	0.13	0.20	$8,489,042.29	$12,797,994.22
LEOLS (PV)	Low Earth Orbit LS - PV-powered	0.14	0.21	$9,101,346.06	$13,268,997.12
LOPMLS (PV)	LO Polar Multiple satellite LS - PV-powered	0.09	0.21	$5,760,365.48	$13,293,151.11
LOPCLS (SP)	LO Polar Constellation satellite LS - SP-powered	0.09	0.21	$5,901,666.35	$13,619,230.04
L1LS (PV)	L1 based LS - PV-powered	0.10	0.23	$6,388,369.35	$14,742,390.81
LOPCLS (PV)	LO Polar Constellation satellite LS - PV-powered	0.10	0.24	$6,513,970.12	$15,032,238.75
L1LS (PV)	L1 based LS - PV-powered	0.11	0.25	$6,953,572.83	$16,046,706.53
LOPPVLS (PV)	LO Polar single satellite LS - PV powered	0.11	0.26	$7,032,073.32	$16,227,861.50
LOEPVLS (PV)	LO Equator single satellite LS - PV powered	0.12	0.29	$7,912,848.74	$18,260,420.17
L5LS (SP)	L4 or L5 based LS - SP-powered	0.46	0.46	$29,541,301.96	$28,992,040.12
L5LS (PV)	L4 or L5 based LS - PV-powered	0.49	0.48	$31,378,213.28	$30,405,048.82
LPSMS (PV)	Lunar Polar Surface-Mounted System - PV-powered	0.27	0.63	$17,427,107.34	$40,216,401.57
LOSPLS (SP)	LO SP-powered LS	0.36	0.82	$22,702,339.84	$52,390,015.01
LOPVLS (PV)	LO PV-powered LS	0.37	0.85	$23,455,944.48	$54,129,102.65
CRFC*	Cryogenic storage Regenerating Fuel Cell system - *Applicable to all systems requiring energy storage if practical	0.39	0.89	$24,515,701.01	$56,574,694.63
FOLS	Fixed Orbit Laser System - PV-powered - 2009 NASA concept study	0.96	2.22	$61,187,986.90	$141,203,046.68
LNSMS (PV)	Lunar Non-polar Surface Mounted System - PV-powered	0.99	2.28	$62,808,236.88	$144,942,085.10

Table 1

The PV-powered LOLS (PVLOLS)

The PVLOLS is basically a reworking of the 2009 NASA study's FOLS to include (a) using a collimating lens to decrease the surface receiver and (b) Li-S energy storage.

FOLS solar conversion efficiency

From the 2009 study (see slide 15):

a. A collection efficiency of 70% was assumed for a system that used a flat plate array of solar cells;
b. of that 70%, 30% was converted into electricity.;
c. of the remaining (0.7x0.3=) 21%, 95% was converted into usable energy by the laser, leaving about (0.21x0.95=) 20% net energy to power the laser;
d. the laser was rated at an efficiency of 50%, leaving (0.2x0.5=) 10% of the original energy content of the solar insolation being beamed towards the Moon;
e. an average of 65% of the laser energy was collected on the lunar surface, leaving (0.1x0.65=) 6.5% of the original solar insolation;
f. 80% of the laser energy collected was converted into electricity, leaving (0.065x0.8=) 5.2% of the original solar insolation.
g. 95% of the electricity leaving the laser was converted into usable, storable energy, leaving (0.052x0.95=) 5% of the original solar insolation.
h. The total solar insolation in orbit is therefore equal to the storable energy divided by the efficiency of the process, or (5/0.05=) 100 kW.

Effect on the FOLS of orbiting behind the Moon

What were the mass numbers for the various elements of the 2009 study's FOLS orbiting component? The FOLS orbital element is not continually beaming energy to the Moon base. As the FOLS orbits below the 30 degree minimum elevation angle with the lunar surface, a significant "gap time" is developed where a Surface Energy Storage system (SES) will need to be used (2009 study slide 21). Per the 2009 study, "…525 kW-hr of battery are required for a continuous 5 kWe output" (based on 2009 study slides 22 and 41). It is clear that, for the 2009 study's proposed 5,928 x16,149 km elliptical orbit (2009 study slide 17), a great deal of energy storage will be needed to "balance" intermittent lower power input from the laser (2009 study slide 30), increasing the required size of the SES.

Regarding the orbiting mass, there is a secondary effect from the intermittent nature of the laser beam. Since the battery requirements are not spread out evenly (2009 study slides 30 and 31), the battery for a 5 kW system will have to be charged by the laser a total of (525/5=) 105 hours, or (105/24=) 4.4 days, at the same time the system is supplying the 5 kW continuous surface output. In other words, it becomes necessary for the laser system to be enlarged beyond supplying sufficient energy storage.

The NASA study's "Functional Block Diagram and Energy Balance chart (2009 study slide 15) doesn't consider this second aspect, but it is considered in the study's "Power Beaming energy Balance with Gap Time" chart (2009 study slide 22). Consequently, the power generated by solar conversion was calculated to go up from ~21kW continuous to 27 kW continuous, or an increase of (27-21)/21=) 29% (2009 study slide 22). Thus, with a solar power conversion of 30% and a collection & concentration efficiency of 70%, or ~21% overall efficiency, if ~21 kW power generation is required from the solar array, then the solar insolence must equal (21/0.21=) 100 kW. If 27 kW power generation is required from the solar array, the incident solar energy requiring collection increases to (27/0.21=) ~130 kW.

PVLOLS orbiting array mass

Two different approaches to solar concentration are possible; concentration by parabolic reflecting mirror, and concentration by Fresnel lens. A parabolic solar concentrator can be expected to produce a reflective efficiency in excess of 90%. A lens can approach 100% pass-through.

As mentioned earlier, a Fresnel lens might only be a few mils thick in a weightless environment. It would also be easier to make a Fresnel lens precise than a parabolic mirror, since, according to Mr. Arnold, it's only the thickness of the film, as a function of distance from the center, that needs to be precise to a fraction of a wavelength. The film can be flexible, and can warp or twist to some degree without affecting its beam-forming ability.

A reflecting mirror requires keeping a parabolic shape, which will increase its mass, although theoretically, the mirror could be thin enough that the energy of the striking photons could in effect "unfurl" it and maintain its shape, much as solar sails are unfurled. From wikipedia[10]: "The least dense metal is lithium, about 5 times less dense than aluminum. Fresh, unoxidized surfaces are reflective. At a thickness of 20 nm, lithium has an areal density of 0.011 g/m^2. A high-performance sail could be made of lithium alone at 20 nm (no emission layer). It would have to be fabricated in space and not used to approach the sun. In the limit, a sail craft might be constructed with a total areal density of around 0.02 g/m^2, giving it a lightness number of 67 and a_c of about 400 mm/s^2."

Of course, the environments at EML1 and in lunar orbit aren't completely absent of the need for applied force, and a rigid framework for the mirror or Fresnel lens would be required for that force to act upon. However, such a framework could be fabricated from carbon fiber or even from mylar "balloon" structures. Consequently, total mass for a parabolic mirror in space would likely not exceed 0.25 kg/m2.

We know that the state of the art in 2009 was 30W/kg (2009 study slide 44). However, the 30% conversion efficiency shown in 2009 study slide 15 presumes a

[10] http://en.wikipedia.org/wiki/Solar_sail#NanoSail-D_2010

massive increase in efficiency over the 2009 state of the art, increasing the power to mass ratio from 30W/kg (2009 study slide 44) to 130 W/kg (2009 study slide 13). Likely, this is due largely to use of Concentrating PV (CPV) technology.

Thin Film FRESNEL Solar Energy Reflector

United Applied Technologies
Huntsville, AL

Innovation

Ultralightweight thin polymide film deployable structure integrated with ultraviolet radiation and atomic oxygen resistant thin film polymide Fresnel lenses and reflectors for use in solar thermal propulsion, large telescopes, and space solar power systems.

Accomplishments

- Development status: Prototype demonstrated
- Currently negotiating with Boeing to demonstrate concentrator on its commercial solar orbit transfer vehicle.

Commercialization

- Product/Service name or trademark name: Inflatable Space Structures & Reflectors
- Primary target/potential market sectors: Private orbit transfer vehicles and communications satellite antennas. Government large space telescopes and earth observation satellites.
- Customer interest: Private sector communications satellite producers have shown significant interest for future system designs.
- Unique competitive advantage: Space environment tolerant inflatable structures/reflectors of large size and precision not available elsewhere.

Inflatable Structure Test at MSFC/XRCF

Government/Science Applications

- Meets user need for low-cost, operationally simple, long-life inflatable solar concentrator for solar orbit transfer vehicles, electrical power generation, and high temperature materials processing in space.
- Other reflector applications are large antennas, microwave concentrators, and next generation space telescopes.
- Received NASA SBIR Phase III contract for $620K as a continuation of their Phase II effort.

Marshall Space Flight Center
Date of Update: 1/13/99
Success Story #: 8-032

Points of Contact:
- NASA (Denise Swain; 256/544-8112)
- United Applied Technologies (Rodney Bradford; 256/650-5120)

1994 SBIR Phase 2; NAS8-40649

For a 100 kW solar insolation CPV array with ~21 kW continual output, 130 W/kg gives us a PVLOLS array mass of (21/0.130=) 162 kg. For a ~130 kW solar insolation PV array with 27 kW continual output, the PVLOLS array mass equals (27/0.130=) 208 kg.

In addition to the mass of the array itself, the array will need to track the sun in its orbit, especially if it is to use CPV technology[11][12], which is being assumed in 2009 study slide 13. It will be assumed that a two axis tracking system will add at least 100 kg

[11] https://www.ise.fraunhofer.de/content/dam/ise/de/documents/publications/studies/cpv-report-ise-nrel.pdf

[12] https://en.wikipedia.org/wiki/Concentrator_photovoltaics

to the total orbiting array mass, for a total mass of ~~(208+100=) 308 kg for a 5 kW continuous system, or 924 kg for a 15 kW system.~~(162+100=) 262 kg for a 5 kW continuous system with 100 kW solar insolation. However, the laser needs to be upgraded (2009 study slide 15 versus 2009 study slide 22) by ((27-21)/21=) ~29%, in order to produce about 5 kW electric output while the batteries are being charged, and simultaneously produce an sufficient electric output to the batteries to operate when the laser is out of sight.

PVLOLS Laser mass

Per 2009 study slide 15, to produce 5 kW on the lunar surface through the lunar night will require about (5/0.95/0.8/0.65=) 10 kW from the laser (2009 study slide 15). In 2009 study slide 13, for a 5 kW continuous system, the mass of the laser module equals 12 kg/kW or (12x10=) 120 kg, the mass of the DDCU electronics equals 6.3 kg/kW or (6.3x10=) 63 kg, and the structure mass equals 18.3 kg, for a total mass of about (120+63+18.3=) 200 kg. ~~However, the laser needs to be upgraded (2009 study slide 15 versus 2009 study slide 22) by ((27-21)/21=) ~29%, in order to produce about 5 kW electric output while the batteries are being charged, and simultaneously produce an sufficient electric output to the batteries to operate when the laser is out of sight. A laser plus DDCU system mass of 50 W/kg thus equals a system mass of (12.5/0.05=) 250 kg for a 5 kW continuous system, or 750 kg for a 15 kW system.~~ (Per slide 15, laser module and dc-to-dc converter unit (DDCU) power electronics equaled a combined 50% efficiency and 50 W/kg composite specific power. 200 kg thus equals 10 kW.)

Other PVLOLS mass

For a 100 kW solar insolation system, other large system masses include: Fixed spacecraft bus = 200 kg (2009 study slide 13); propulsion system dry mass = 30 kg (2009 study slide 13); propellant mass = ~7 kg (2009 study slide 67); and station-keeping gimbal mass = 3.5 kg (2009 study slide 85). The total of these masses equals about (200+30+3.5+7=) 240 kg. For a 130 kW solar insolation system, the “other” mass would equal (240x1.3=) 312 kg for a 5 kW continuous system, or 936 kg for a 15 kW system.

PVLOLS Radiator System (RS) mass

The sum of the estimated mass for all elements of the orbiting component less the unknown RS mass is thus equal to about ~~(308+250+312=) 870 kg.~~(262+200+240=) 702 kg. We know that the orbital component of the PVLOLS equals ~~(1,000x1.286=) 1,286~~1 000 kg. Therefore, total RS mass for a 100 kW solar insolation system must equal about ~~((1286-870)=) 416 kg~~(1 000-702=) 298 kg for a 5 kW continuous system, or 1,248 kg for a 15 kW system.

(A second way to examine radiator mass is to estimate from known information. Per wikipedia: “Most spacecraft radiators reject between 100 and 350 W of internally generated electronics waste heat per square meter.” Assuming 350 W/m2, 2kg/m2 laser module heat rejection radiator areal density (2009 study slide 13), and 50% heat rejection from a laser receiving 27 kW (2009 study slide 22), we get (27/2/0.35=) ~39 m2 of radiator area and (39x2=) 78 kg mass.

However, this leaves out any photovoltaic and DCDU thermal radiation requirements. This is especially true for solar-voltaic systems that use CPV to enhance efficiency. Note that a CPV system will still generate (0.7x0.3x0.95=) 80% waste heat (2009 study slide 22), or ~~(130x0.8=) 104 kW.~~(100x0.8=) 80 kW. That's equivalent to a solar-voltaic cell area of ~~(104/0.35=) ~300 m2.~~(80/0.35=) ~230 m2.

Of course, much of the material making up the area of the receiver can be used for radiative surface. Assuming copper indium gallium selenide (CIGS) solar-voltaic cells (2009 study slice 44), and assuming the 30 W/m2 increased to 130 W/m2 due to CPV, that suggests a reduction in area to ~~(30/130=) ~23%.~~(30/100=) ~30%. The array (shown in 2009 study slide 44) covers an area of (1.048x0.546=) 0.572 m2. It has an output of 25 W on the Earth's surface, which, due to the increase in solar insolation from 1 kw/M2 to 1.367 kw/m2, would increase in space by ~40% to about 42 W, or (42/0.572=) 73.4 W/m2. For ~~(130-27=) 103 kW,~~(100-27=) 73 kW, that's an area of ~~(103/0.0734=) 1,400 m2.~~(73/0.0734=) 1 000 m2. Reducing that to 23% yields a final area of ~~(1400x0.23=) ~322 m2.~~(1 000x0.23=) ~230 m2. Assuming 2 kg/m2, that equals ~~644~~460 kg. Assuming 50% is radiated from the solar panels directly, that's about ~~322~~230 kg. Adding 78 kg for the laser yields ~~(322+78=) 400 kg,~~(230+78=) ~308 kg, which is very close to the ~~416 kg~~298 estimated above.)

<u>PVLOLS collimator mass</u>

As stated earlier, collimating of the laser beam can be used to dramatically reduce the diameter of a laser beam over a long distance, such as the distance between EML1 and the lunar surface. The 2009 study settled on a 45 degree inclination, 16 hr orbit with a maximum range of 10,731 km (2009 study slide 21) and a spot diameter of 34 m (2009 study slide 18) or ~908 m2. Using a collimator, we can increase the diameter of the aperture and correspondingly decrease the diameter of the spot on the lunar surface. Thus, if we wanted a receiver area of 32 m2 on the lunar surface, or a circular area 6.8 m in diameter, we would increase the diameter of the aperture in orbit to (34/6.8=) about 5 m in diameter. We've thus reduced our PVLOLS surface receiver area from 910 m2 to 32 m2, or (32/910=) ~3.5% of the area determined in the 2000 study for a FOLS lunar orbiting system. And since the mass of a Fresnel lens laser collimator, including the extender framework, is expected to be less than 0.25 kg/m2, the mass added to the orbiting system for a 5 kW system would equal (0.25x32=) 8 kg, or 24 kg for a 15 kW system. This is probably less or equal to the 1 m collimating lens that is being replaced, so no net change is expected in overall mass due to collimating with a thin film lens.

Total PVLOLS lunar orbiting mass

The total lunar orbiting mass configured for a 5 kW system equals 1000 kg (2009 study slide 55). However, as detailed above, the orbiting system would need to be scaled up ~30% to account for time out of line of sight, to ~1,300 kg. Total for a 15 kW system would thus equal ~3,900 kg.

Total PVLOLS lunar surface mass

The lunar surface mass for a 5 kWh FOLS is stated in the 2009 study as equal to 3,997 kg (2009 study slide 55). Only 1,372 kg of this mass is solar collector, the remainder being energy storage. The net result is to increase the mass required on the surface by 2,625 kg in energy storage. Using Li-S would reduce the 2009 study's storage mass to (525/0.5=) 1,050 kg. To that needs to be added the EBS mass of 240 kg. (NOTE: This mass is not included in the FOLS calculations. It is used in this analysis across all systems for comparative purposes.) The total equals a combined energy storage total of (1050+240=)1290 kg for a 5 kW system, or (1,290x3=) 3,870 kg for a 15 kW system. In addition, thanks to collimation, the mass of the surface solar collector can be decreased to 8% of the former amount; that is, to about (1,372x0.08=) 110 kg. That reduces the overall lunar surface mass to (110+1,290=) 1,400 kg for a 5 kW continuous system, or (1,400x3=) 4,200 kg for a 15 kW continuous system.

Total PVLOLS mass

When the surface component is originally in lunar orbit, it would mass about 3 times the mass on the lunar surface, including the fuel and equipment necessary to land it there. The 5 kW PVLOLS surface component in orbit would thus mass (1,400x3=) 4,200 kg, while the 15 kW continuous surface component of the PVLOLS in orbit would mass about (4,200x3=) 12,600 kg. Thus, the total mass to lunar orbit of the 5 kW PVLOLS system would equal about (4,200+1,300=) 5,500 kg, and the 15 kW PVLOLS system would equal about (12,600+3,900=) 16,500 kg.

The SP-powered LOLS (SPLOLS)

Another type of LS is possible using solar pumped (SP) lasers. In a Solar Pumped Laser System (SPLS), the solar insolation is concentrated directly on the laser. A laser radiation of 80 W has been obtained from a single 3.7 cc (6mm dia x130 mm) ND3+:YAG rod installed in the multi-element secondary concentrator of the Big Solar Furnace (BSF) in Uzbekistan[13], and a conversion efficiency of solar energy into laser radiation was shown of up to 25% of the solar flux energy. The total solar flux energy collected can thus be calculated to equal about (80/0.25=) 320 W.

SPLOLS solar conversion efficiency

In the 2009 NASA study, a collection efficiency of only 70% was assumed for the orbiting solar array (2009 study slide 22), and presumed 130W/kg specific power using (2009 study slide 13). Like an PVLOLS, an SPLOLS would use a solar concentrator.

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[13] http://www.asteroidinitiatives.com/Papers/files/Solar-pumped-laser-white_paper.pdf

However, the concentrator would have a conversion efficiency to laser energy in the PVLOLS of (0.7x0.3x0.95x0.5=) 10%, while the SPLOLS would have a conversion efficiency of 25%, or 2.5x as much. The required solar insolation for the SPLOLS would equal (130/2.5=) ~52 kW for a laser with 10 kW conversion to laser efficiency, or (52/130=) 40% of the required PVLOLS solar insolation.

SPLOLS orbiting concentrator mass

The mass of the solar power collection and concentration system would be a function of the mass of the concentrator, since there are no photo-voltaic cells. A thin film lens with a mass of 0.25 kg/m2 and a solar insolation area of (52/1.367=) 38 m2 would equal (38x0.25=) 9.5 kg. Assuming a two axis tracking system will proportionally add (100/308=) 32.5% additional mass to the total concentrator mass, total mass for the SPLOLS orbiting concentrator would equal (9.5x1.325=) ~12.6 kg.

SPLOLS Laser mass

Assuming fiber bundle coupled lasers powered by small scale solar concentrators, a single laser module with a 2 m2 concentrator and a solar insolation of 1.4 kW/m2, total solar insolation would equal about 2.8 kW. From that, we can calculate that our laser rod would be (2.8/0.32=) 8.75 larger than the one used at the BSF, or measure about (3.7x8.75=) 32.4 cc. YAG has a specific gravity of about 4.5. 32.4 cc's of YAG would thus mass about (32.4x4.5=) 146 grams for a 2 m2 system. For a 38 m2 solar concentrator system, the (38/2=) 19 fiber bundled, coupled, and phase matched laser rods would collectively weigh about (19x0.146=) 2.8 kg, not including housing and electronics. Per 2009 study slide 13, the PV-powered laser module plus DDCU system mass of 50 W/kg. Assuming an equal mass for the SPLOLS laser thus equals a system mass of (12.5/0.05=) 250 kg for a 5 kW continuous system. However, since no electronics are required to produce the laser energy, it is considered likely that mass will be appreciably reduced, and so it is assumed the actual system mass for a 5 kW continuous SPLOLS laser system will be <125 kg.

SPLOLS RS mass

Assuming 350 W/m2, 2kg/m2 laser module heat rejection radiator areal density (2009 study slide 13), 25% efficiency from a laser putting out (27/2=) ~13.5 kW and thus heat rejection of (13.5x3=) ~40.5 kW, RS area equals (40.5/0.35=) ~116 m2 and RS density equals (116x2=) ~232 kg. For a 15 kW system, the mass would thus equal ~696 kg.

SPLOLS collimator mass

Assuming a 5 m diameter Fresnel aperture that is (2.5x2.5xpi=) 20 m2 in area, and assuming 0.25 kg/m2 mass for the aperture and the aperture frame, the total mass added might be 5 kg.

Other SPLOLS mass

Other SPLOLS mass includes fixed bus, propulsion system dry mass, station-keeping gimbal, and propellant masses. These are expected to be proportional to the “other” masses in the PVLOLS, which equaled 312 kg. Since the non-other mass for the PVLOLS equals (208+308+250+416=) 1,182 kg Total mass of the SPLOLS components equals (13+125+232+5=) ~375 kg. The relative proportion to PVLOLS thus equals (375/1,182=) 32%, the SPLOLS other mass equals (312x0.32=) ~100 kg.

Total SPLOLS orbit mass

Total calculated 15 kW continuous SPLS orbiting component mass equals (375+100=) 475 kg.

Total SPLOLS lunar surface mass

Like the PVLOLS system, the overall lunar surface mass for the SPLOLS system including EBS equals 1,400 kg for a 5kW continuous system and 4,200 kg for a 15 kW continuous system.

Total SPLOLS mass

Total lunar surface mass to lunar orbit of a 5 kW continuous SPLOLS with SES and EBS would equal about (1,400x3=) ~4,200 kg. For a 15 kW system, the total mass in lunar orbit would equal about (4,200x3=) ~12,600 kg.

Beamed energy from EML1 (L1LS)

An EML1-based LS (L1LS) is highly advantageous for a number of reasons, including:

• The laser represents a point location in the Moon's sky that moves very little in relation to a Moon base.

• The laser can beam energy to the Moon's Earth-facing surface continuously, excepting total eclipses of around 5 hours maximum perhaps twice a year.

• Since all proposed solutions include a 120 kWh EBS, which would be good for 8 hours at 15 kW and thus sufficient to see the Moon base through any total eclipse plus plenty of safety margin, no other surface-based battery system will be required.

• Since energy is continuously delivered, it is not necessary to oversize the laser system or the systems that power the laser system.

• With no atmosphere, there is no extraneous absorption or diffraction of laser energy.

• With no ecology in harms way, the laser beam can be increased in intensity.

• The L1LS can be grown in a modular manner, that is, it is possible to increase the output on the Moon by adding modular systems at EML1. Thus, if we orbit a second L1LS that is equal in all respects to the initial L1LS, we will double the input to the main surface receiver with no change to the surface receiver whatsoever.

•Power plant modularity inherently builds in a redundancy that is very important to ensuring a Moon base’s long term survival.

• Use of a beam redirecting apparatus would permit a laser beam to be directed at the floor of Shackleton Crater on the Moon’s south pole.

In most respects, the L1LS system would be analogous to the LOLS 100 kW insolation system. The differences include:

• A collimating lens ~2x the LOLS diameter (9.6 m - see below) & ~4x the LOLS mass.

• A receiving lens ~2x the LOLS diameter (12.5 m - see below) & ~4x the LOLS mass.

• A reduced orbiting target tracking mass requirement.

• A reduced lunar surface laser tracking mass requirement.

• Assuming a standard halo orbit and standard thrust generation by electric power, a 6x increase in fuel mass for station-keeping.

<u>L1LS collimator mass</u>

As stated earlier, collimating of the laser beam with a Fresnel optical lens can be used to dramatically reduce the diameter of a laser beam over a long distance, such as the distance between EML1 and the lunar surface. Assuming a 120 m product of a 1 m diameter aperture, as was assumed in the 2009 study, if we wanted a receiver area of 125 m2 on the lunar surface, or a circular area ((125/pi),sqrt,x2=) ~12.5 m in diameter, we would increase the diameter of the aperture in orbit to (120/12.5=) about 9.6 m in diameter. We've thus reduced the area determined in the 2009 study for a laser powered lunar generating system orbiting at EML1 from (119x119xpi=) 44,488 m2 (2009 study slide 18) to (6.3x6.3xpi=) 125 m2. The mass of a laser collimator at EML1 is expected to be less than 0.25 kg/m2. For a 9.6 m diameter lens, that would equal 72 m2, or about (72x0.25=) ~<u>20 kg</u>.

<u>PVL1LS</u>

A PVL1LS uses a photo-voltaic system to electrically charge the LS.

<u>PVL1LS orbiting array mass</u>

For a 100 kW solar insolation PV array with (0.3x0.7x0.95=) 20% overall efficiency and a specific power of 130 W/kg, the PVL1LS array mass would equal (20/130=) ~153 kg. In addition to the mass of the array itself, the array will need to track the sun in its orbit, especially if it is to use Concentrating PV (CPV) technology, which is being assumed in 2009 study slide 13. Assuming a two axis tracking system will proportionally add (153/208=) 74% additional mass to the total concentrator mass (compared with the PVLOLS), total mass for the PVL1LS orbiting concentrator would equal (153x1.74=) ~<u>266 kg</u>.

PVL1LS Laser mass

To produce 5 kW continuous on the lunar surface through the lunar night will require about (5/0.95/0.8/0.65=) 10 kW from the laser (2009 study slide 15). In the 2009 study slide 13, the mass of the laser module and the mass of the DDCU electronics equals 50 W/kg, for a total laser system mass of (10/0.5=) ~200 kg for a 5 kW continuous system, or 600 kg for a 15 kW system.

Other PVL1LS mass

For a 100 kW solar insolation system, other large system masses include: Fixed spacecraft bus = 200 kg (2009 study slide 13); propulsion system dry mass = 30 kg (2009 study slide 13); station-keeping gimbal mass = 3.5 kg (2009 study slide 85); and propellant mass = ~7 kg (2009 study slide 67) times 6 (2009 study slide 18), or (7x6=) ~42 kg. The total of these masses equals about (200+30+3.5+42=) ~276 kg, or 828 kg for a 15 kW system.

PVL1LS Radiator System (RS) mass

Because there is no "gap time" (2009 study slide 22) at EML1, the RS for the PVLOLS system is 29% larger than the PVL1LS system, whose mass equals 416 kg for a 5 kW continuous system. For the PVL1LS system, the RS mass would thus equal (416/1.29=) 322 kg, or 966 kg for a 15 kW system.

Total PVL1LS mass

Total calculated 5 kW continuous PVLS orbiting component mass equals (20+266+200+276+322=) 1,084 kg.

SPL1LS

An SPL1LS uses concentrated solar illumination to directly charge the LS. The SPL1LS resembles the SPLOLS and requires significantly less solar insolation than the PVLOLS and PVL1LS (52 kW vs 130 kW).

SPL1LS collimating lens

The thin film laser collimating lens, like the PVL1LS, is about 9.6 m in diameter (72 m2) and has a mass of about 20 kg.

SPL1LS orbiting array mass

Total SPL1LS orbiting concentrator mass would equal that of the SPLOLS concentrator, or ~13 kg.

SPL1LS Laser mass

Total SPL1LS laser system mass will be the same as for the PVL1LS system: 200 kg for a 5 kW continuous system, or 606 kg for a 15 kW system.

Other SPL1LS mass

Total SPL1LS other mass will be the same as for the SPLOLS system: 100 kg for a 5 kW continuous system, or 300 kg for a 15 kW system.

SPL1LS RS mass

Total SPL1LS mass will be the same as for the SPLOLS system: 232 kg for a 5 kg system, or 696 kg for a 15 kW system.

Total PVL1LS mass

Total calculated 5 kW continuous SPLS orbiting component mass equals (20+13+200+100+232=) 532 kg.

Station-keeping at EML1 by EP, solar sail and gravity winch

At EML1, L2, and L3, station-keeping is an on-going process. That is largely because these three Lagrange points are constantly moving due to the elliptical orbit of the Moon. In the 2009 study, a 3,700 km "halo orbit" is presumed. A halo orbit runs roughly circularly around the axis of the centerline between the center of the Moon's mass and the center of the Earth's mass. As shown in the 2009 study, station keeping can be accomplished by EP units. Those units would require both a source of electricity and a source of mass to be expelled. For an L1LS, the mass for EP fuel may be calculated as equal to 6X that of the propellant for a lunar orbiting FOLS (2009 study slide 67). We know that, for a 5 kW system, the propellant mass of the FOLS equals ~7kg (2009 study slide 67). The propellant mass at EML1 would thus equal about (7x6=) 42 kg. We also know that, for a 5 kW system, the propulsion system dry mass for a lunar orbiting FOLS equals 30 kg (2009 study slide 13). The propulsion system dry mass for an L1LS would be expected to mass about the same, since the FOLS would only intermittently need to use its EP units. Total EP mass at EML1 for a 5 kW LS system would thus equal (30+42=) 72 kg, and total EP mass at EML1 for a 15 kW LS system would equal (72x3=) 216 kg. In addition, there would need to be some additional electric power available to power the EP units, although it is not expected to add much additional mass.

However, there are alternative approaches for station keeping. Solar sails[14] would require no replenishment of fuel and only a very small source of electricity. In effect, station keeping is accomplished by using a solar sail to act as a kind of sea anchor in space or "space anchor", pulling against one gravity well or the other as EML1 rotates around the Earth. "Tacking" can be accomplished as well, just as on the sea, to "pull" one way or the other as EML1 rotates relative to the solar rays. Tacking can be accomplished by angling the solar sail so that the solar rays hit it obliquely rather than straight on. A system of tethers perhaps hundreds of kilometers long, could be hauled in or let out by reels situated on the L1LS core to angle the whole, or a portion, of the solar sail.

Figures 1-3 illustrate a possible space-base L1LS that uses a solar sail for station-keeping. Note that the actual solar sail would be much larger and much farther away compared to the relative size and position of the L1LS in the illustration. In effect, the solar sail elements shown in Figures 1-3 represent a single panel of a large array of panels that can be "angled" by pulling in or letting out various attached tethers.

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[14] http://en.wikipedia.org/wiki/Solar_sail

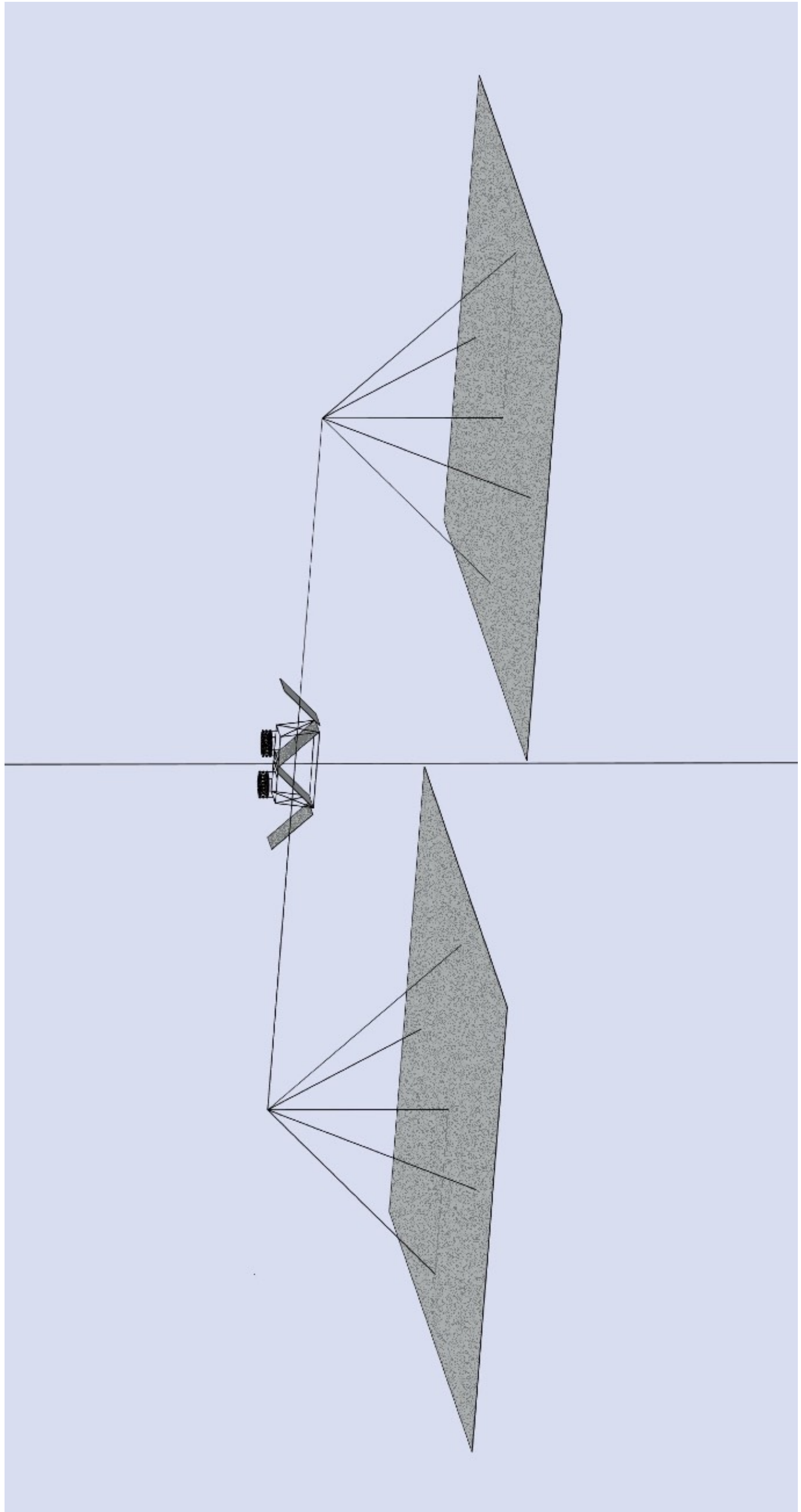
In the illustrated approach, an outrigger boom is used to connect two solar sail panels to the L1LS. Many more panels can be attached in a similar manner. The two solar sails can be angled and hence moved apart by the sun's pressure. That allows the laser to continually target the Moon's surface without being blocked by the sails when the Earth is between the Sun and the Moon (Figure 2). Figures 1 and 3 show the position of the solar sails and the rotating reflecting mirrors when the Moon is directly between the Sun and the Earth. Figure 2 shows the position of the solar sails and the rotating reflecting mirrors when the Earth is directly between the Sun and the Moon. Figure 3 is a close-up showing the main framework, the main boom, the system of rotating and non-rotating reflecting mirrors, two arrays of collimated solar-pumped lasers, and the tether winches.

In addition, the solar sails, which would be at the ends of tethers perhaps hundreds of kilometers long, could be hauled in or let out by reels situated on the L1LS core. As the solar sail is hauled in, it may effectively be pulled out of one gravity well and towards the other. The long term result would be to reduce the overall pull of gravity from that direction. Conversely, if the solar sail is let out, then it sinks farther down the gravity well in question, the long term result of which is to increase the overall pull of gravity from that direction.

Developing this idea, it's possible to view long tethers dropped down gravity wells as "gravity anchors", particularly if they have a weighted mass on the end. Note that outfitting such a gravity anchor as a "gravity winch" doesn't necessarily require a solar sail. A gravity winch is basically a reelable tether that's dropped down a gravity well from a neutral gravity point such as EML1. In the case of EML1, a tether can be dropped down both the Moon's gravity well and Earth's. Pulling in or letting out the gravity winch increases or decreases the long term pull from one direction or the other. In addition, the process of shifting the gravity anchors from one side to the other allows the L1LS to "balance" between the two gravity wells, similar to the way a pole helps a tightrope walker balance. In effect, it removes the "z" vector (along the Earth-Moon axis) from consideration, thus allowing station-keeping to concentrate on the "x" and "y" vectors. Note that a mass can be placed at the end of the tether or tethers to increase the effectiveness of this approach. In Figures 1-3, the line running left to right represents a single gravity winch tether balanced between the Moon and the Earth's gravity. Finally, note that this line may also be considered to represent the tether of a possible "lunar space elevator"[15].

In the illustrated system, an 118 m2 SP-powered L1LS would be composed of 60 individual solar pumped lasers, arranged in two separate LS arrays of 30 each. An individual Fresnel collimator and an individual Fresnel solar concentrator would be rigidly attached to each laser, and both LS arrays would be held in a single rigid

15 http://en.wikipedia.org/wiki/Lunar_space_elevator



framework or core unit. The additional core unit framework for attaching solar sails and gravity anchors might add 200 kg to the total mass.

Figure 1

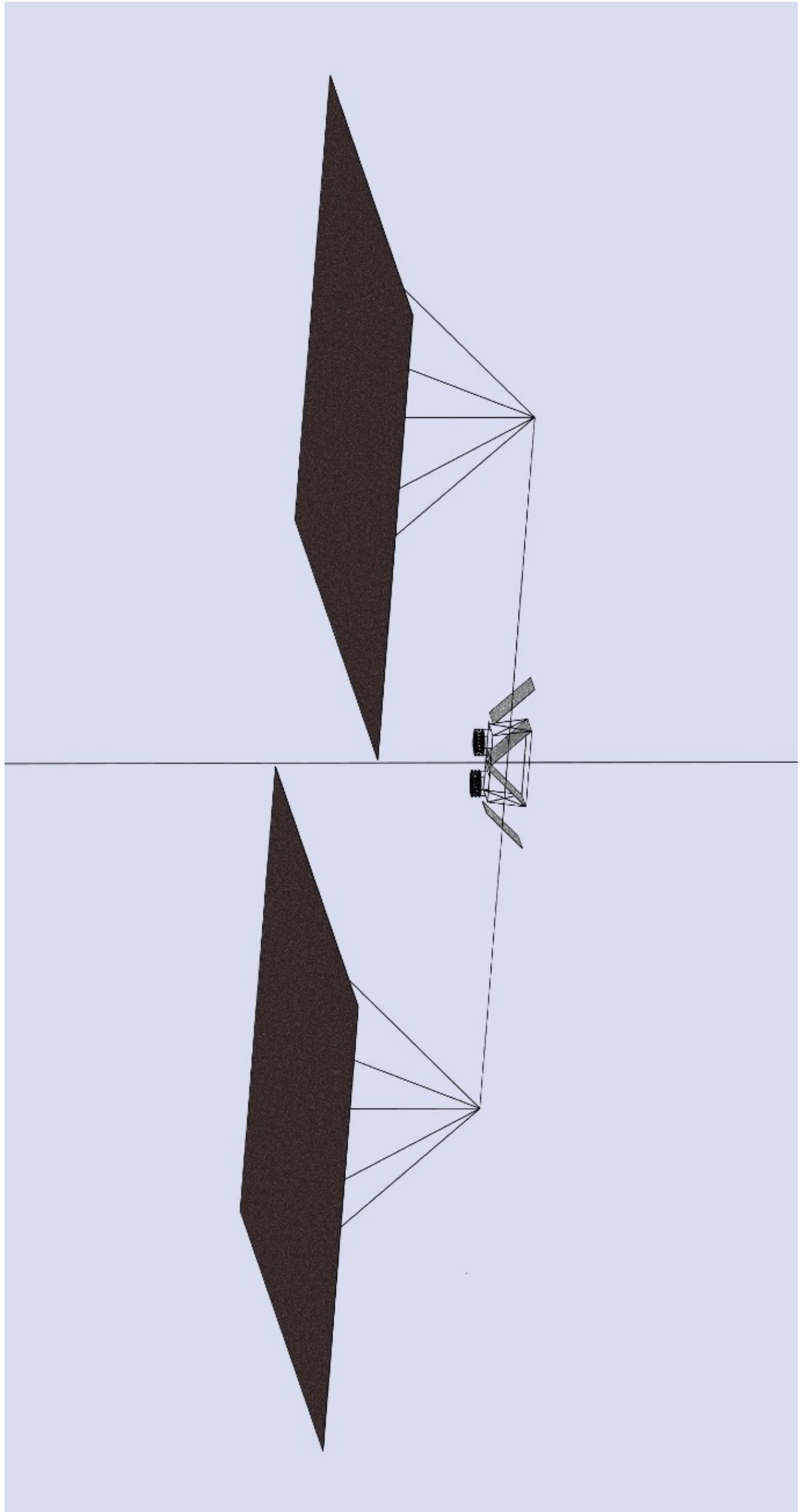


Figure 2

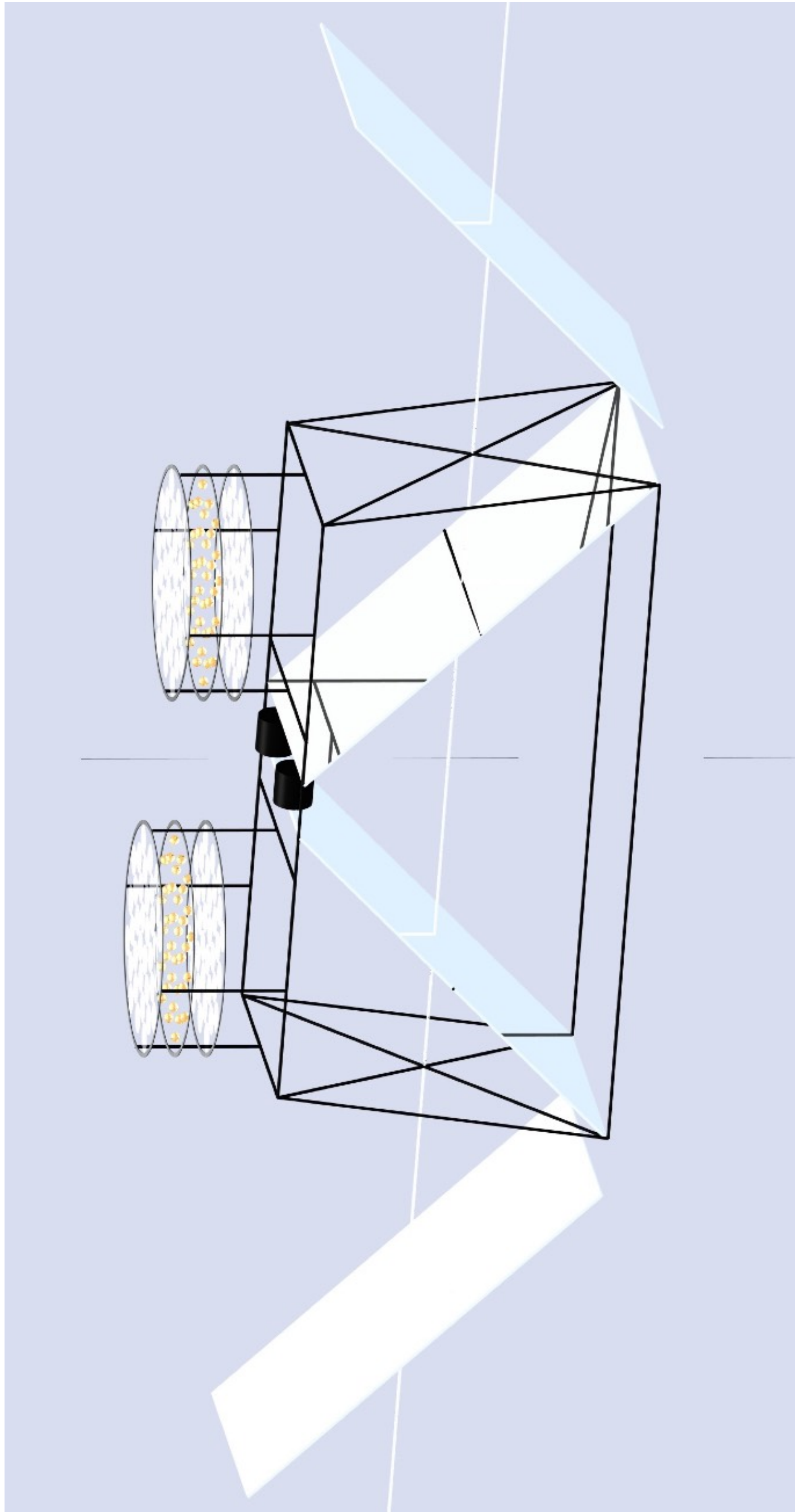


Figure 3

By definition, the solar concentrators would need to accurately track the sun. The proposed system would use an "outrigger" support beam to accomplish this. The outrigger beam would extend in opposite directions with the core unit in the middle. The outrigger beam would be run perpendicular to the Earth/Moon plane. At the end of each outrigger would be a gimbal that rotated 360 degrees over the course of one EML1 orbital rotation, thus tracking in the Earth-L1 plane. A second gimbal would be attached to each 360 degree gimbal. It would rotate through an inclusive angle of about 5 to 6 degrees to enable tracking in the Sun-L1 plane. Each secondary gimbal is attached rigidly to a flat solar reflector. The two gimbal-attached reflectors would be set at an sun beam incident angle of about 45 degrees and continually track the Sun. Each rotating reflector would reflect a 12.5 meter minimum diameter solar beam without interference to a companion non-rotating flat solar reflector, also set at an incident angle to the reflected beam of 45 degrees. The two non-rotating reflectors would in turn direct a 12.5 meter minimum diameter solar beam onto the surface of the two LS arrays' Fresnel concentrators. The non-rotating reflectors would be rigidly attached to the core unit along with the two LS arrays. In effect the two rotating reflectors and the two rigid reflectors would continually serve to deflect the solar beam through ~90 degrees throughout the lunar orbit and throughout the year, thus permitting the LS beam from EML1 to continually stay focused on and continually beam to a single spot on the surface of the Moon. For a 15 kW system, each reflector would be about 15 meters in width and about 35 meters in length. The mass of the mirror surface, like the mass of a solar sail, can be nominal (for example, it could be formed of lithium formed in space into a sheet a few nanometers in thickness - see "SPLOLS solar conversion efficiency" above). The outrigger beam, however, would be more substantial as it will also need to rotate other elements, although it will probably mass no more than 50 kg. A minimal PV solar system would be required for any electrical demands, and the PV panels would be ideally mounted to the rotating reflector in order to always point directly at the sun. We can expect the electrical system to mass about 50 kg. In addition, the radiator panels for the solar pumped lasers and ancillary cooling requirements would be advantageously mounted behind the rotating reflecting mirrors in order to keep them continually in shade. However, these larger masses would only need to rotate at most (360/30=) 12 degrees in a single day. Consequently, the outrigger gimbal systems would probably mass less than 50 kg each or 100 kg total.

The outrigger could also serve for attaching the solar sails, one per outrigger end. The two sails would be attached by lightweight tethers extending tens or even hundreds of kilometers away. Assuming two sails, the two sails would be canted off the end of each tether at a slight angle to one another such that the force of sunlight acting through the tethers would move them somewhat away from one another. Thus, as the rotating mirrors and solar sails rotated relative to the L1LS, the Sun's light and the laser beams would never be blocked by the solar sails. The total weight of the solar sails and their rigging might only come to 100 kg or so. Total for core unit/outrigger/electrical/gimbal/solar sail mass thus equals (200+50+50+100+100=) 500 kg. This would supplant the EP system and its fuel. See Figures 1-3 for an example system.

Total mass for L1LS space components with and without solar sails plus gravity winches may now be calculated. We know that the core unit (minus the additional mass of the larger collimators and the extra station-keeping elements) would be the same as that for a similar orbiting LS. Thus, total mass for a PV L1LS space component with solar sail plus gravity winch equals (3,000+500+20=) 3,520 kg. Likewise, total mass for a SP L1LS space component6 with solar sail plus gravity winch equals about (2,050+500+20=) 2,570 kg. Also, total mass for a PV L1LS space component with EP equals (3,000+605+20=) 3,625 kg. Likewise, total mass for an SP L1LS space component with EP equals about (2,050+605+20=) 2,675 kg. In short, the mass for the solar sails plus gravity winch system is about the same as the mass for an EP system. Total EP mass at EML1 for a 5 kW LS system would thus equal (30+42=) 72 kg, and total EP mass at EML1 for a 15 kW LS system would equal (72x3=) 216 kg.

Total PVL1LS lunar orbiting mass

The total lunar orbiting mass configured for a 100 kW solar insolation system equals (269+200+240+120+20=) 849 kg. Total 15 kW continuous PVL1LS orbiting mass would equal (849x3=) 2,547 kg.

Total SPL1LS lunar orbiting mass

The total SPL1LS orbiting mass configured for a 100 kW solar insolation system equals (50+200+240+120+20=) 630 kg. Total 15 kW continuous PVL1LS orbiting mass would equal (630x3=) 1,890 kg.

Other non-propellant means for maintaining EML1, L2, and L3 position

The Oscillating Lagrange point Orbit (OLO)

There may be yet another low energy orbit in the vicinity of EML1. In 2015, SL5S member and contributor Roger Arnold wrote the following to the author:

"Your description of how the L1 point changes distance from the moon as the moon itself changes distance from the earth is correct. But note that tracking the L1 point as it moves is not a requirement for the L1 station…The metastable neutral point that the station should track is not the L1 point, wherever it happens to be at any given moment. Rather, it's a point in the 6D phase space for the system (x, x-dot, y, y-dot, and z, z-dot). I.e., both position and velocity vectors must be right. When they are, the station describes an oscillating "orbit" that passes through the L1 point twice per month. Once the station achieves the neutral point, I believe the only station keeping that's needed is to correct for drift due to measurement errors and unaccounted solar radiation pressure. The neutral point that the station follows will oscillate with the L1 point, but with lesser amplitude and lagging in phase. The proper analogy is to balancing a weight atop a pole whose base is oscillating back and forth. The weight does not precisely track the base and remain positioned exactly above it."

Figure 3 illustrates what an OLO might look like. It is mapped out along the course of the movement of EML1 during its approximately 6,400 km journey along the EM centerline between the Moon's perigee and apogee.

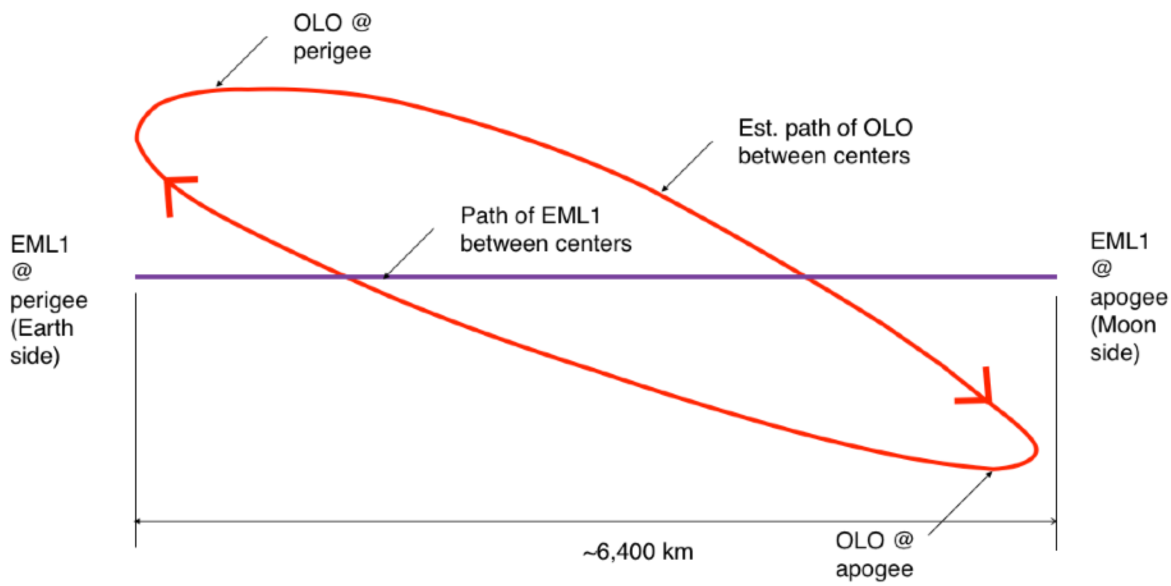


Figure 4

<u>"Surfing" EML1</u>

In 1963, Giuseppe "Bepi" Colombo published "The Stabilization of an Artificial Satellite at the Inferior Conjunction Point of the Earth -Moon System".[16] Colombo is best known for his work on the planet Mercury, and it was his calculations on how to get a spacecraft into a resonant orbit with Mercury with multiple fly-bys that led to the success of the Mariner 10 mission. Indeed, the upcoming "BepiColombo" joint mission of the European Space Agency (ESA) and the Japan Aerospace eXploration Agency (JAXA) to the planet Mercury was named after him.[17]

One striking aspect of Colombo's 1963 paper was his proposal that EML1 stabilization can be accomplished with very little force. One way to think of how Colombo's proposed systems would work is to think of the way a surfer balances on a wave. After "catching" the wave, the surfer can "fall" in advance of the wave or "pull out" of the wave simply by changing his center of gravity on the board, tipping it backward or forward to "surf" the power of the wave.

Like a surfer's wave, the EML1 point can also be "caught". The elliptical orbit of the Moon as it moves towards and away from the Earth over the course of a month

16 http://articles.adsabs.harvard.edu//full/1963SCoA....6..213C/0000213.000.html

17 https://en.wikipedia.org/wiki/BepiColombo

causes the EML1 point to move as well. Similar to the surfer, we can think of a craft as balancing just in front of the moving EML1 point. When the Moon moves towards the Earth the craft would “balance” slightly more away from Moon than the EML1 point, balancing between the Earth’s gravity and the Moon’s gravity to keep our craft at the edge of the point. When the Moon moves away from the Earth, our craft would “balance” slightly more towards the Moon than the EML1 point, “riding” the imbalance back towards the Moon.

However, as Colombo says, balancing in this manner would require a Global Positioning System (GPS) system that “could detect displacements of the order of 2 km”. In 1963, those didn’t exist. Today, they do.

Non-momentum stabilization

The paper proposes two EML1 stabilization systems that can be built “without using momentum”, by which Colombo means without expelling a jet of some material. It can also be thought of as “non-propulsive station-keeping”. In the preface Colombo states: “The devices considered [for stabilizing] are a solar sail of relatively small dimensions, and a mechanical autonomous device.”

The first non-propulsive station-keeping system Colombo proposes involves the use of solar sails.[18] In section 5, Colombo speaks of “the proposed orbit around L1”, and then states the following: “This means that for a 200-kg satellite we need a maximum reflecting area of $19x10^5$ cm^2 or 190 m^2.” The “reflecting area” he is referring to is the area of a solar sail. Thus, a solar sail approximately 15.6 meters in diameter would be sufficient to position a 200 kg satellite in the vicinity of EML1 indefinitely, with no need for any propulsive station-keeping.

The second stabilization system Colombo proposes uses what he calls a “mechanical autonomous device”. Section 6, entitled “Autonomous stabilization of a system of two points” begins with the following:

“Since we are considering only the theoretical possibilities, at least for the present, we should like to discuss one other method for stabilizing a satellite at the inferior conjunction point without consuming momentum…Let us consider the motion of [two points] of equal mass, and suppose that [the points] are constrained…To build this constraint we need only a position sensor and an internal device to change the distances between the points as necessary. We can change the exterior force that acts on the system by changing only (with interior force) the distance [between the two points]. We will need only energy without loss of mass for the system.”

Colombo ends Section 6 and the article with this statement:

“Obviously, we need a highly sensitive control complex. It is interesting to note that it is possible, in principle, to change the exterior gravitational force acting on the complex by using only an interior force and information from outside.”

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[18] https://en.wikipedia.org/wiki/Solar_sail

The mechanism for accomplishing Colombo's "mechanical autonomous device" appears to be something as simple as weighted tethers. The tethers, perhaps a few tens of kilometers long, would be hauled in or let out by winches situated on a platform located near a Lagrange point. Assume that the platform is at a perfect point of balance, falling neither towards the Earth nor towards the Moon. If a tether is reeled in, it is effectively pulled out of one gravity well and towards the other. This has short and long term results. The short term result is for the platform to begin to fall in the direction of the tether being reeled in (action/reaction). The mass of the tether versus the mass of the platform and the time involved in the reeling process will determine the degree of that movement. The long term result, however, is to reduce the overall pull of gravity from that direction, since the weighted end has been pulled towards the point of gravity balance. Conversely, if the tether is reeled out, then the end of the tether sinks farther down the gravity well in question. As the tether is released, the platform will temporarily fall in the direction opposite to the tether being let out. The long term result, however, is to increase the overall pull of gravity from the direction of the tether that was let farther down the gravity well.

A reelable tether dropped down a gravity well from a neutral gravity point such as EML1 might be termed a "gravity winch". In the case of EML1, a tether can be dropped down both the Moon's gravity well and Earth's. Pulling in or letting out either tether with the gravity winch increases or decreases the long term pull from one direction or the other. The process of shifting the gravity anchors from one side to the other thus allows the craft at EML1 to "balance" between the two gravity wells, similar to the way a pole helps a tightrope walker balance.

Note that "unreeling" of tethers could be amplified by using a solar sail. Since solar sails may be furled and unfurled, as well as canted at an angle, some combination of gravity winch and solar sail may prove to be optimal for station keeping.

<u>L1LS lunar surface mass</u>

The lunar surface mass for a PVLOLS is stated in the 2009 study as equal to 3,997 kg (2009 study slide 55), of which 2,625 kg was a SES. Use of a SES in the 2009 study arrangement also increased the size of the orbiting system by 23%. Thanks to the constant position of EML1 in the lunar sky, an SES is not necessary with an L1LS. In addition, as spoken of above, the size of the laser beam at the lunar surface can be vastly decreased by the use of collimation to 125 m2.

Assuming a mass based on 0.5 kg/m2 (2009 study slide 14), a system with an area of 125 m2 would weigh (125x0.5=) 63 kg. Note that this would be the same for a 5 kW system or for a 15 kW system. As a solar cell receiver, 125 m2 would receive about 1.4 kW/m2 in solar insolation on the lunar surface, or 175 kW continuous input. That is, a 15 kW which delivers ~20 kW of laser beam to the receiver would be under-powering the receiver by a factor of (175/20=) about 9. One solution is to beam the laser thru a thin film concentrator lens with a 125 m2 area. That can appreciably reduce the area and thus the mass of the laser cell receiver placed at the focal point of said concentrator. Since the laser is being beamed from EML1, the concentrator will not need to track. For now, we will assume that the mass would equal that of a non-concentrating 125 m2 system, although it would clearly mass much less.

To the mass of the receiver needs to be added the EBS mass of 240 kg, equalling a combined total of (63+240=) 303 kg.

Surface lift mass to LO/EML1 for the 5-15 kW continuous L1LS = (303x3=) 909 kg.

<u>Total PVL1LS mass</u>

Total PVL1LS mass to EML1 = (849+909=) 1,758 kg for the 5 kW system and 5,274 kg for 15 kW system.

<u>Total SPL1LS mass</u>

Total SPL1LS mass to EML1 = (630+909=) 1,539 kg for the 5 kW system and 4,617 kg for the 15 kW system.

<u>**Beamed energy from LO**</u>

As noted above, the 2009 study looked at a FOLS, which we have improved somewhat as a PVLOLS. Recall that the PVLOLS is basically a reworking of the 2009 NASA study's FOLS to include (a) using a collimating lens to decrease the surface receiver and (b) Li-S energy storage.

However, other approaches to building an orbiting PVLOLS are possible. This includes the possibility of storing energy on the orbiting LS as well as on the surface. In addition, for a Moon base either located along the equator or at either of the poles, as at the Shackleton Crater on the Moon's south pole, a nearly circular orbit at relatively low altitudes is possible. A low altitude orbit allows the amount of energy storage on the lunar surface to be reduced substantially, since the non-beaming time is greatly reduced. Another advantage that was overlooked by the 2009 study is that, with a PV-powered system, electrically generated energy can easily be stored on the orbiting craft until the LS comes back in sight of the Moon base. That in turn means that the overall size of the PV system can be reduced, since all solar energy does not have to be converted into electricity during the process of beaming the energy. (Note that storing energy during orbit is an advantage of a PVLOLS over a SPLOLS; with a solar pumped laser, it is not possible to "store" solar-produced energy for use at a later time, as when the laser orbits the Earth or the Moon and is thus blocked from a direct line-of-sight to the Moon base.)

Finally, systems have been explored that use orbiting laser beam DS satellites. Such satellites permit the use of SPLOLS in an orbiting array, which can remove the need to store energy either in orbit or on the lunar surface.

For our analysis we will assume a circular orbit of 400 km above the Moon's surface in all instances. We can calculate the period of a 400 kg orbit thus:

The speed of a satellite in circular orbit is:

v=SQRT(G*M/r)

G*M equals the Standard gravitational parameter. For the Moon, that equals 4,903.

The mean radius of the Moon is 1,737 km.

v=SQRT(4,903/1,737)

v=SQRT2.823

v=1.68 kilometers per second at the Moon's surface.

v=SQRT(4903/(1737+400))

1737+400=2137

v= (SQRT(4903/2137)=) 2.29 kilometers per second at 400 km orbit above Moon's surface.

circumference of orbit = (pix2137x2=) 13,427 kilometers.

orbit period equals 13,427/2.29 = 5,863.4 seconds = 97.7 minutes = 1 hr and 37.7 minutes (1.63 hr).

Lunar Mass Concentrations (mascons)

There is a real problem trying to orbit close to the lunar surface. The Moon has mass concentrations (called "mascons") buried under its surface that make achieving a controlled orbit challenging, and potentially expensive in regards to propellant. Fortunately, close orbits have been found that are much more stable, thanks to mapping of the Moon's gravity field (see "Bizarre Lunar Orbits" https://science.nasa.gov/science-news/science-at-nasa/2006/06nov_loworbit/ and "Grail" https://en.wikipedia.org/wiki/GRAIL). From "Bizarre Lunar Orbits":

""There are actually a number of 'frozen orbits' where a spacecraft can stay in a low lunar orbit indefinitely. They occur at four inclinations: 27º, 50º, 76º, and 86º"—the last one being nearly over the lunar poles.""

LO Equator PV-powered single satellite LS (LOEPVLS)

Per Figure 5, the Moon base will be in line of sight for about 71.4 degrees or (71.4/360x1.63x60=) 19.4 minutes per orbit. Assuming an unobstructed view and a tracking receiver reduces access to about 43 degrees, total beam time would equal (43/360x1.63x60=) 11.7 minutes per orbit. During that time, sufficient energy needs to be sent and converted to power the Moon base with 5 kWh constant electricity over a time period of 1.63 hours, or a total electricity delivered of (1.63x5=) ~8.15 kW. Thus, over the 11.7 minutes, or 0.2 hours, electricity must be delivered at a rate of (8.15/11.7x60=) ~**41.8 kW/hour**.

Surface mass

While it's possible to create a flat plate laser cell receiver system on the lunar surface, to reduce mass both the orbital system and the surface system would ideally track one another in both the horizontal and vertical axis. The surface system would thus be composed of an ultra-light thin film fresnel lens that focuses on a small array of laser-tuned PV cells.

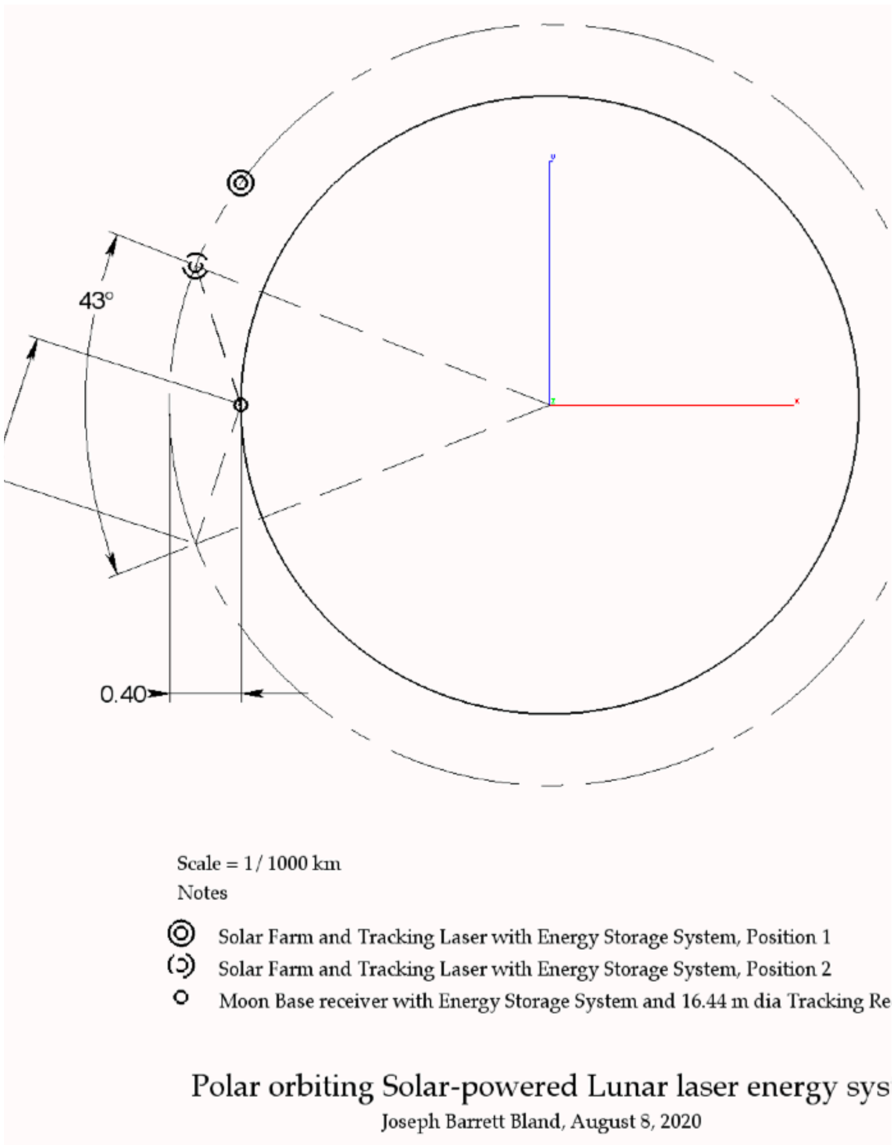

Figure 5

The 2009 study assumes thin-film (CIGS) photovoltaic technology for the laser receiver with 1,367 W/kg specific power (2009 study slide 14). We know the laser-tuned cells will need to output 41.8 kW/hour (for 11.7 minutes). At 1.367 kW/kg based on 0.5 kg/m2, the photovoltaic receiver cells equal a mass of (41.8/1.367 =) 30.6 kg~~.~~ and the area would equal (30.6x2=) 61.2 m2, or a circular area ~9 m in diameter. Doubling mass for a one axis tracking structure, then doubling it again for a second axis tracking structure, the mass of a complete system for tracking and receiving sufficient energy for 5 kW continuous electricity would likely equal about (30.6x4=) **122.4 kg**.

Turning now to the dimensions of the collimating system and receiver, with a 1 m dia. collimating lens as in the 2009 study and a lunar equatorial orbit (2009 study slide 18), the beam surface area over an 11,041 km distance equaled 23 m (2009 study slide 17). Using the same size collimator and decreasing the maximum distance to 833 km (minimum distance equals 400 km, see Figure 1) or (833/11041=) 0.075%, we reduce the maximum diameter of the spot size to (23x0.075=) ~1.73 m. Reducing the collimating lens will allow us to increase the size of the spot diameter to match the ~9 m diameter of the target. To increase the spot diameter by (9/1.73=) ~5.2x, we would reduce the size of the collimating lens to (1/5.2=) ~0.2 m.

~~Assuming a 2m dia thin film fresnel lens of negligible mass and a 2m x 2m (4 m sq) fresnel lens frame mass of 0.5 kg/m2, the surface receiver array would weigh 2 kg. Doubling that for a one axis tracking structure, then doubling it again for a second axis tracking structure, the mass of a complete system for tracking and receiving sufficient energy for 5 kW continuous electricity would likely equal about (30.6+8=) **38.6 kg**.~~

During the 11.7 minutes when the laser can acquire the target, the target must receive both sufficient laser energy to power the rover for 11.7 minutes and sufficient additional laser energy to store ((97.7-11.7)/60=) 1.43 hours of power. Assuming 5 kW per hour continuous required, that comes to (5x1.43=) 7.17 kW battery storage on the lunar surface. As stated above, Li-S batteries have a specific energy of 0.5 kWh/kg. Power storage requirement absent backup power would thus equal (7.17/0.5=) ~14.3 kg.

<u>Size of laser in orbit</u>

Per slide 22 of the 2009 study, 80% of the laser energy is converted by the laser-powered cells into electric power, and 95% of that is converted into stored electric power. Total conversion of received beamed energy thus equals 76%. Delivering 41.8 kW/hour to the storage battery, that means the laser needs to deliver (41.8/0.76=) ~55 kW/hour to the laser-powered photocells. Again from slide 22, approximately 65% of the laser energy that leaves the laser actually makes it across space to the laser-powered cells, increasing the required output from the laser to (55/0.65=) 84.6 kW/hr. The electricity consumed by the laser, operating at 50% efficiency, then doubles that energy requirement to (84.6/.5-) ~170 kW/hr. Of course, the laser only fires for 11.7 minutes, or (11.7/60=) 0.2 hrs, so the total energy required by the laser is (170x0.2=) ~34 kW.

To estimate the mass of the laser system to a first order, we can borrow from the 2009 study, as estimated above. The mass of the laser module and the DDCU electronics equals about 50W/kg (2009 study slide 13). At an output of 84.6 kW/hr, the laser would need to mass (84.6/0.05=) 1,692 kg. To that must be added the laser radiator system mass, estimated at 150 kg. Total laser module mass would equal ~1,842 kg for a 5 kW electric delivery on the lunar surface.

Note, however, that the mass is in orbit. The alternative PVLOLS system requires 4,000 kg on the lunar surface, which equals 12,000 kg in lunar orbit, and 36,000 kg in low earth orbit.

Multi-satellite system

It's possible to bring down the size of the laser by building a multi-satellite system. Assume 8 satellites, each satellite would cover 12.3 minutes. Each would be responsible for 1 kWh. Each laser would then need to output (1/(0.95x0.9x0.7)=) 1.7 kW and would mass (1.7/0.05=) 34 kg. However, 1.7 kW are delivered from batteries for 12.3 minutes, but have 98 minutes to create that energy. The energy that needs to be stored will equal (2x1.7=) 3.4 kW. It will take 17 kWh of solar insolation to make 3.4 kW of stored energy over 1.63 hours. That's (17/1.63=) 10.43 kW of solar cells, and would equal a (10.43/1.367=) ~7.63 m2 area. At 130W/kg and an output of (1.367x0.7x0.3x0.95=) ~275 W/m2 or 2.1 kW total, the solar power systems would mass 2.1/0.13=) 16.15 kg each. You could send 4 in the opposite direction, spaced evenly apart, so that the tracker on the ground would sweep back and forth continually. However, you'd need 8 tracking systems.

Note that a single satellite could deliver 1 kWh to the surface, which per orbit would average (1/1.63=) 613 W/hr continuous per satellite.

Orbiting solar panel

The 5 kW delivered NSS system required 100 kW/hr of solar insolation, and massed about 169 kg. And there was no battery storage capacity.

Other orbiting mass

For a 100 kW solar insolation system, other large system masses include: Fixed spacecraft bus = 200 kg (2009 NASA study slide 13); propulsion system dry mass = 30 kg (2009 NASA study slide 13); station-keeping gimbal mass = 3.5 kg (2009 NASA study slide 85); and propellant mass = ~7 kg (2009 NASA study slide 67). The total of these masses equals about (200+30+3.5+7=) 240 kg. For a 123 kW solar insolation system, the mass would equal (240x1.23=) 295 kg for the NSS 5 kW continuous system. Again, assuming twice the mass for the proposed system due to the 0.01% smaller size, other mass would equal about (590x0.01=) ~6 kg.

Sum of orbiting laser & receiver masses

Not including the lunar rover itself, the mass on the lunar surface related to supplying a continuous 50 W output would equal about 10 kg. The lunar mass in orbit, assuming a propellant-based orbiting maneuvering system, would equal about (8+3.4+6=) less than 20 kg.

Surface mass

While it's possible to create a flat plate laser cell receiver system on the lunar surface, to reduce mass both the orbital system and the surface system would ideally track one another in both the horizontal and vertical axis. The surface system could then be composed of an ultra-light thin film fresnel lens that focuses on a small array of laser-tuned PV cells.

The 2009 NASA study (slide 14) assumes thin-film (CIGS) photovoltaic technology for the laser receiver with 1,367 W/kg specific power. We know the laser-tuned cells will output 420 W/hour (for 11.7 minutes). At 1,367 W/kg, the photovoltaic receiver cells equal a mass of (420/1,367 =) 0.3 kg.

Turning now to the dimensions of the collimating system and receiver, with a 1 m dia collimating lens as in the 2009 NASA study, the beam surface area over a 16,000 km distance equaled 34 m (slide 18). Using the same size collimator and decreasing the maximum distance to 833 km (minimum distance equals 400 km) or (833/16000=) 0.05% (see Figure 1), we reduce the maximum diameter of the spot size to (34x0.05=) 1.77 m.

Assuming a 2m dia thin film fresnel lens of negligible mass and a 2m x 2m (4 m sq) fresnel lens frame mass of 0.5 kg/m2, the surface receiver array would weigh 2 kg. Doubling that for a one axis tracking structure, then doubling it again for a second axis tracking structure, the mass of a complete system for tracking, receiving, and storing laser energy would likely equal about 10 kg.

During the 11.7 minutes when the laser can acquire the target, the target must receive both sufficient laser energy to power the rover for 11.7 minutes and sufficient additional laser energy to store ((97.7-11.7)/60=) 1.43 hours of power. Assuming 50 W per hour continuous required, that comes to (50x1.43=) 71.7 W battery storage on the lunar surface, or a negligible mass.

<u>Size of laser in orbit</u>

Total wattage delivered per orbit would equal (50x1.63=) 81.5 W. It needs to be delivered in 11.7 minutes, requiring a surface receipt of (81.5/11.7=) ~7 W/min or 420 W/hr.

Regarding power requirements, per slide 22 of the 2009 NASA study, 80% of the laser energy is converted by the laser-powered cells into electric power, and 95% of that is converted into stored electric power. Total conversion of received beamed energy thus equals 76%. Using our 420 W/hour target, that means the laser needs to deliver (420/.76=) ~550 W/hour to the laser-powered cells. Again from slide 22, approximately 65% of the laser energy that leaves the laser actually makes it across space to the laser-powered cells, increasing the required output from the laser to (550/.65=) 846 W/hr. In other words, the laser required for powering a project on the lunar surface that requires 50 W/hr would have an output capacity of less than 1 kw/hr. The electricity consumed by the laser then doubles that energy requirement to ~1.7 kW/hr. Of course, the laser only fires for 11.7 minutes, so the total energy required by the laser is (11.7/60x1.7=) ~332 W.

To estimate the mass of the laser system to a first order, we can borrow from the 2009 NASA study, as estimated in the SacL5 study. To produce 5 kW stored energy on the lunar surface for use during the lunar night required about 12.5 kW from the laser (study slide 15). The mass of the laser module and the DDCU electronics equals about 50W/kg, for a total laser system of 250 kg (study slide 13). To that must be added the laser radiator system mass, estimated in the SacL5 study at 150 kg, for a total of 400 kg for a 5 kW continuous electrical output system. If we double that due to the smaller size of the 50 W continuous system being proposed, which is (50/5000=)0.01% the size, we can estimate the mass of the proposed laser system would equal about (800x0.01=) 8 kg.

Note that replacing the 1 m dia glass optical lens of the NASA system with a 1 m thin film lens will actually reduce the mass of the overall system.

Orbiting solar panel

The 5 kW delivered NSS system required 100 kW/hr of solar insolation, and massed about 169 kg. Again, assuming twice the mass for the proposed system due to the 0.01% smaller size, solar PV mass would equal about (590x0.01=) ~3.4 kg.

Other orbiting mass

For a 100 kW solar insolation system, other large system masses include: Fixed spacecraft bus = 200 kg (2009 NASA study slide 13); propulsion system dry mass = 30 kg (2009 NASA study slide 13); station-keeping gimbal mass = 3.5 kg (2009 NASA study slide 85); and propellant mass = ~7 kg (2009 NASA study slide 67). The total of these masses equals about (200+30+3.5+7=) 240 kg. For a 123 kW solar insolation system, the mass would equal (240x1.23=) 295 kg for the NSS 5 kW continuous system. Again, assuming twice the mass for the proposed system due to the 0.01% smaller size, other mass would equal about (590x0.01=) ~6 kg.

Sum of orbiting laser & receiver masses

Not including the lunar rover itself, the mass on the lunar surface related to supplying a continuous 50 W output would equal about 10 kg. The lunar mass in orbit, assuming a propellant-based orbiting maneuvering system, would equal about (8+3.4+6=) less than 20 kg.

In this approach, the orbiting solar-powered laser is placed in an equatorial orbit (most likely the 27^{o} orbit mentioned above) that passes closely over the Moon base once per orbit. By definition, that will be bases located in the approximate middle of the Earth-L1-Moon plane, or Moon equator. This plane is about 2.5 degrees off in either direction (about 5 degrees total) from the Sun-Earth plane (known as the ecliptic). (Note that Earth eclipses occur infrequently in this orbit because of the Moon's rotation about the Earth.)

LOEPVLS orbiting mass

An orbit that is 722 km above the Moon's surface gives the orbiting LS sunlight for about 75% of the orbit. Energy storage in orbit is necessary since electricity will be generated for 3/4 of the orbit, but will be transferred by laser beam to the lunar surface, and occasionally for the 1/4 of the orbit when the LOEPVLS is not in the sunlight. We know from above calculations that, for a 15 kW continuous system, a PVLOLS would have a solar insolation to surface generation efficiency of 5%. Also, like the PVLOLS, the LOEPVLS will have a mass of 3,000 kg, since the LOEPVLS orbit carries itself out of sunlight approximately 1/4 of the orbit, and it is thus necessary to build a larger solar array to achieve the same amount of power delivered to the Moon base.

We know from the above calculations that a PVLOLS would have a solar insolation to surface generation efficiency of 5%, and would require 300 kW of solar insolation. At a solar insolation to laser output net efficiency of (0.7x0.3x0.95=) 20%, that would generate (300x0.2=) 60 kWh of electricity. In its 3 hour orbit, a surface-generated 15 kW LOEPVLS would need to store about (3x60=) 180 kWh. Using Li-S with a mass of 0.5 kg/kWh, we can calculate the storage mass as (180/0.5=) 360 kg.

The total orbital mass of the LOELS would thus equal (3,000+360=) 3,360 kg.

<u>LOEPVLS lunar surface mass</u>

Because the LOEPVLS can use a collimator to reduce the size of the beam diameter on the lunar surface, it is possible to use a tracking system to track the orbiting LS. At an altitude of 722 km, a laser beam traveling at a tangent to the surface (90 degrees from vertical) would travel a maximum distance of 1,768 miles to reach the lunar base. Over that short a distance, a receiver can easily be reduced to less than 25 m2 (5.64 m diameter). Assuming a mass based on 0.5 kg/m2, the surface receiver array would weigh (25x0.5=) 12.5 kg. Doubling that for a support structure and single axis tracking system, then doubling it again for a tracking structure and two axis tracking system, the mass of a complete system for tracking and converting LOEPVLS energy would equal about (12.5x4=) 50 kg or less.

What would be the mass of the lunar surface energy storage system? In its 3 hour orbit, an LOEPVLS would need to store about (3x60=) 180 kWh. However, the laser can be downloading energy to the receiver for 25% of that orbit. Thus, the total surface energy storage requirement for the 15 kW continuous LOEPVLS equals (180x0.75=) 135 kWh. Using Li-S, our storage mass would thus equal about (135/0.5=) 270 kg. To that needs to be added the EBS mass of 240 kg, equalling a combined total of about (50+270+240=) 560 kg.

<u>Total LOEPVLS mass</u>

Surface lift mass for the 15 kW continuous LOEPVLS: (560x3=) 1,680 kg
Total LO lift mass for the 15 kW continuous LOEPVLS: (3,360+1,680=) 5,040 kg

<u>LO Polar PV-powered single satellite LS (LOPPVLS)</u>

The orbit of the laser satellite system may begin such that the plane of the orbiting LS is perpendicular to the sun's rays midway through a lunar Fall or Spring; that is, when the Moon's equator is within the plane of the Earth/Moon ecliptic. As a first approximation, the satellite orbit is a hoop fixed in inertial space. Each month, therefore, within the Earth-Moon plane, the hoop of the orbiting laser satellite effectively rotates once around the Earth and thus stays relatively perpendicular to the solar rays throughout the month. Of course, the hoop of the orbiting laser satellite also rotates once around the sun per year, and so will require a retrograde orbit adjustment of approximately 1 degree per day. Such a 1 degree retrograde orbit can be accomplished with a "sun synchronous orbit"[19], which effectively creates an orbit slightly tilted towards the equator.

This system would require energy storage in orbit since, although it sees solar energy throughout the orbit and throughout the year, it needs to store that energy until it is within line-of-sight of the Moon base. That means it isn't efficient to use a SP laser with this system. Thus, it would require the same mass of orbiting energy storage, and the same mass of Moon base, as the equator-orbiting laser satellite system. However, since its orbiting LS is never blocked from the sun by the Moon's shadow, the mass of the orbiting system's PV panel is reduced slightly in comparison to the equator-orbiting system.

<u>LOPPVLS orbiting mass</u>

For a 15 kW system a LOPPVLS orbital mass would equal (3,000/1.23=) 2,439 kg. Like the LOEPVLS, to that would be added the orbiting storage requirement of 360 kg, for a total mass in orbit of (2,439+360=) 2,799 kg, including EP for station keeping.

<u>LOPPVLS lunar surface mass</u>

Like the LOEPVLS, the lunar surface mass of the LOPPVLS receiver would probably be about 50 kg, and the storage mass would equal about 270 kg. To that needs to be added the EBS mass of 240 kg, equalling a combined total of about (50+270+240=) 560 kg.

<u>Total LOPPVLS mass</u>

Total mass for the 15 kW continuous LOPPVLS orbiting component: 2,799 kg.

Surface lift mass for the 15 kW continuous LOPPVLS: (560x3=) 1,680 kg

Total LO lift mass for the 15 kW continuous LOPPVLS: (2,799+1,680=) 4,479 kg

<u>**Multiple satellite LS**</u>

Two different systems are possible that permit efficient use of a SPLOLS or PVLOLS in a lunar orbit without the need for energy storage either in orbit or on the lunar surface. In the first approach a single orbiting LS plus two, three, or more laser DS satellites orbit over the lunar poles. In this approach, the DS satellites are able to deflect the laser beam either from one DS satellite to another or down to the Moon base at the Moon's pole. Thus a Moon base may be supported at either of the poles. The second approach would add a second series of DS satellites orbiting around the Moon's equator. Such a "constellation" of satellites would make it possible to continually deflect a laser beam to any point on the lunar surface.

Because both systems are able to see the sun throughout the year, the orbiting LS component would equal the LS component of the EML1 system.

<u>**LO Polar Multiple satellite LS (LOPMLS)**</u>

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[19] http://en.wikipedia.org/wiki/Sun-synchronous_orbit

A single LOPMLS is placed in a polar orbit at a minimum of 722 km over the Moon's surface. As explained above for the LOPPVLS, this can be done in such a manner that the orbiting satellite can always be kept in full sunlight by using a sun synchronous orbit. The LOPMLS is placed in an orbit that passes closely over the Moon base once per orbit. By definition, the Moon bases would be located only on the lunar poles.

In addition to one LS satellite, from two to three much less massive DS satellites are placed in the same orbit, approximately 90 degrees apart if there are three DS satellites and 120 degrees apart if there are two DS satellites (a two DS satellite configuration would need to be in a higher orbit than a three DS satellite configuration). A DS is basically a combination of de-collimators, prisms, mirrors, and re-collimators. This analysis will examine a three DS (four satellite total) configuration. Since the LOPMLS will always see the sun, the Moon base can be continually bathed in either direct or deflected laser light, thus removing any requirement for energy storage at the Moon base.

There are negatives to this approach; the LS and DS satellites, as well as the surface receiver, need to be capable of two axis tracking in order to maintain laser beam contact with the receiver, adding complexity. Also, each individual satellite would need its own station-keeping system. However, there are some positives as well, besides no requirement to store energy: First, all the elements of the system are relatively close to the Moon itself, possibly permitting a repair of the laser generator system by Moon base personnel, should that become necessary. Second, such a system can take advantage of the decreasing energy cost of any ISRU-developed lunar resources to enhance or grow the system. Third, bases may be placed at either or both lunar poles. Finally, the LOPMLS can use a solar-pumped laser, potentially enhancing efficiency and decreasing mass.

<u>LOPMLS orbiting mass</u>

The mass of an SP-powered LOPMLS satellite will match that of the SP L1LS base unit, or 2,049 kg. The mass of a PV-powered LOPMLS satellite will equal (3,000/1.23=) 2,439 kg.

The DS de-and-re-collimators, as discussed before, will mass very little but will permit a large reduction in the size and mass of the prisms and mirrors making up the heart of each DS. Total mass for the core DS system will be assumed to be less than 50 kg. Energy will be required for the tracking, computation hardware, and the EP motor, so a solar power system will be required. A 5 kW continuous system should be more than adequate. Using the 130 W/kg specific power of the 2009 NASA study (slide 13), a solar array would mass about 38.5 kg, or (38.5/538=) 7% the mass of a PVLOLS solar array. Assuming a DS core of about 50 kg and a solar array of about 38.5 kg, or a total of about (50+38.5=) 90 kg, the mass of a DS would be approximately a tenth of the mass of a PVLOLS. Each DS will need an EP motor and a supply of fuel. Per the 2009 NASA study, fixed spacecraft bus, propulsion system dry mass, station keeping gimbal mass, and propellant mass equaled 240 kg (see “Other PVLOLS mass” above). However, that was for a lunar satellite approximately ten times more massive than a DS. The corresponding DS mass would thus equal about (240/10=) 24 kg, suggesting an overall mass of perhaps 120 kg per DS.

LOPMLS lunar surface mass

Like the LOELS, the lunar surface mass of the LOPMLS would probably be less than 50 kg. However, no surface energy storage is required. To that needs to be added the EBS mass of 240 kg, equalling a combined total of about (50+240=) 290 kg.

Total LOPMLS mass

Total mass of three DS satellites: (120x3=) 360 kg.

Total mass for the 15 kW continuous PV LOPMLS orbiting component: (2,439+360=) 2,799 kg.

Total mass for the 15 kW continuous SP LOPMLS orbiting component: (2,049+360=) 2,409 kg.

Surface lift mass for the 15 kW continuous LOPMLS: (290x3=) 870 kg

Total LO lift mass for the 15 kW continuous SP LOPMLS: (2,409+870=) 3,279 kg

Total LO lift mass for the 15 kW continuous PV LOPMLS: (3,360+870=) 4,230 kg

LO Polar Constellation satellite LS (LOPCLS)

In this system, a single LS satellite would be served by between 5 and 7 orbiting DS satellites. This analysis will examine a 7 DS configuration. Half the satellites (2 to 3 DS and a single LS) would circle between the poles and would continually see sunlight by using a sun synchronous orbit, while half the satellites (3 to 4 DS) would circle the equator and only see sunlight for half the day. The result is that any point on the lunar surface would always be in line of sight of either a DS satellite or the LS satellite itself, and would thus be able to receive a continuous supply of laser energy.

LOPCLS orbiting mass

The mass of the LS and DS satellites for a LOPCLS will match those of the LOPMLS satellites. Disadvantages and advantages remain the same as for the POMLS, except that, due to the extra DS satellites, the LOPCLS will mass slightly higher but be able to serve the entire lunar surface.

LOPCLS lunar surface mass

Like the LOELS, the lunar surface mass of the POMLS would probably be less than 50 kg. However, no surface energy storage is required. To that needs to be added the EBS mass of 240 kg, equalling a combined total of about (50+240=) 290 kg.

Total LOPCLS mass

Total mass of LOPCLS DS satellites: (120x7=) 840 kg

Total mass for the 15 kW continuous PV LOPCLS orbiting component: (2,439+840=) 3,279 kg.

Total mass for the 15 kW continuous SP LOPCLS orbiting component: (2,049+840=) 2,889 kg.

Surface lift mass for the 15 kW continuous LOPCLS: ((290x3=) 870 kg

Total LO lift mass for the 15 kW continuous SP LOPCLS: (2,889+870=) 3,759 kg

Total LO lift mass for the 15 kW continuous PV LOPCLS: (3,279+870=) 4,149 kg

Other beamed energy systems

As far back as the 1980's, the idea of using lasers to beam energy through space was studied[20]. That included space-to-space, Earth-to-space, and Earth-to-Moon studies at the very least. It probably included space-to-Moon and Earth-to-space-to-Moon studies as well. However, a few interesting variants look particularly promising.

Beamed energy from Earth to an LEO LS (LEOLS)

One approach to reducing the throw weight of an LS is to orbit the LS in LEO. Moving an LS from EML1 to LEO would reduce the throw weight required to orbit the LS by two thirds. To avoid the Earth blocking the LEOLS from the sun, and thus making it more expensive to use a solar pumped laser, a sun synchronous orbit will be required for the laser satellite. Alternatively, a PV-powered LS with energy storage could be used. This analysis will assume the use of an LS system in a sun synchronous orbit. In addition to the main LS satellite, a multiple DS satellite system would be required for continuous power beaming. Alternatively, multiple LS satellites can be used to achieve continuous power beaming. This analysis will assume the use of a single LS system.

Assuming a rotation of the DS satellites in the Earth-Moon plane, only one LS satellite and two DS satellites would be required. The DS satellites would orbit somewhat less than 180 degrees apart such that they are always in line of sight with one another at the same time one or the other will always be in line of sight of the Moon. The LS satellite may be in a higher orbit than the DS satellite in order to ensure that one or the other of the DS satellites is always in line of sight with the LS satellite. In this way, whenever the LS is hidden from the Moon by the Earth, the laser beam can always be relayed around the Earth and then to the Moon.

LEOLS collimator mass

The LEOLS will use a collimator to reduce the size of the beam diameter on the lunar surface. The Moon is 407,000 km from the Earth at its apogee. For a laser with a wavelength of 830 nm (2009 NASA study slide 14) or 8^-10 m, we'll assume a 120 m product of a 1 m diameter aperture over a 60,000 km distance (see above). Over a 407,000 km distance, the product of the aperture and the spot would grow to about (407,000/60,000x120=) about 814 m.Thus, if we wanted a receiver area of, say, 625 m2 on the lunar surface, or a circular area ((625/pi),sqrt,x2=) ~30 m in diameter, we would increase the diameter of the aperture in orbit to (814/30=) about 27 m in diameter, or

[20] geoffreylandis.com/laser

572 m2. Assuming a mass based on 0.25 kg/m2, a LEO-orbiting LS collimator with an area of 572 m2 would weigh about (572x0.25=) 143 kg.

<u>LEOLS orbiting mass</u>

The mass of the core of an SP-powered LEOLS satellite will match that of the LS at EML1, or 2,049 kg, excluding any extra mass required for station-keeping and the mass of the larger collimator. The mass of a PV-powered LEOLS satellite will equal (3,000/1.23=) 2,439 kg, excluding those same masses.

In addition to the mass of the LS satellite, the individual mass of the two LEOLS DS satellites will be increased due to the structural requirements of much larger de-collimators and re-collimators. We will assume the de-collimators and re-collimators will each mass as much as an LS collimator, being of a similar size. For each DS, therefore, it will require (143x2=) 286 kg of de-collimators and re-collimators. Total mass of the core lens and mirror arrangement is estimated to be about 24 kg (see LOPMLS above). Therefore, not including station-keeping, each LEOLS DS satellite should mass about (286+24=) 310 kg

Total mass of the PS LEOLS orbiting component, not including DS station keeping, will thus equal (2,049+143+310+310=) 2,812 kg. Total mass of the PV LEOLS orbiting component, not including EP units or their fuel, will thus equal (2,439+143+310+310=) 3,202 kg.

<u>LEOLS lunar surface mass</u>

The lunar surface laser receiver would equal 625 m2. It would not need tracking, but would need support structure as it approaches the lunar poles. At the lunar poles, the support structure can be assumed to double the mass of the receiver. Per the 2009 NASA study, the receiver masses 0.5 kg per m2, or 1 kg per m2 for the receiver and its support structure, or 625 kg. To that needs to be added the EBS mass of 240 kg, equalling a combined total of about (625+240=) 865 kg. (From lunar orbit, it would mass about (865x3=) 2,595 kg. From LEO, it would mass about (2,235x3=) 7,785 kg.)

<u>Total LEOLS mass</u>

Total LEO lift mass for a 15 kW continuous PV LEOLS: (3,202+7,785=) 10,987 kg*

Total LEO lift mass for a 15 kW continuous SP LEOLS: (2,812+7,785=) 10,597 kg*

*Does not include DS solar sail or EP mass.

<u>Beamed energy from Earth to Geostationary Earth Orbit (EGEOLS)</u>

A second approach has been recommended to reduce the cost of a laser based system. In an EGEOLS, laser energy is beamed from the Earth's surface to a deflecting satellite orbiting at Geostationary Earth Orbit (GEO). From there, the beam is deflected either to another orbiting deflecting satellite or directly to the Moon's surface. There are some problems with a EGEOLS. First, the beam must pass through the atmosphere. As a result, it will probably require "adaptive optics" to correct for the effects of air turbulence. Second, there will be times when the weather at the laser site may obstruct the laser sufficiently to shut power delivery down, so emergency power backup systems on the Moon will be essential. Third, there is the question of wildlife or aircraft accidentally flying through the laser. A possible site for such an Earth-based LS has been proposed near China Lake, California[21].

EGEOLS collimator mass

The EGEOLS will use a collimator to reduce the size of the beam diameter on the lunar surface. The Moon is 407,000 km from the Earth at its apogee. At its farthest distance from the Moon, a DS at GEO would be 26,200 miles from the center of the Earth. A laser from Earth would have to travel to the GEO, back past the Earth, and then to the Moon. The distance will vary, but will approximate (407,000+26,200+26,200=) 460,000 miles at its farthest distance. For a laser with a wavelength of 830 nm (2009 NASA study slide 14) or 8^-10 m, we'll assume a 120 m product of a 1 m diameter aperture over a 60,000 km distance (see above). Over a 460,000 km distance, the product of the aperture and the spot would grow to about (460,000/60,000x120=) about 920 m.Thus, if we wanted a receiver area of, say, 625 m2 on the lunar surface, or a circular area (625/pi),sqrt,x2=) ~30 m in diameter, we would increase the diameter of the aperture in orbit to (920/30=) about 31 m in diameter, or 755 m2. Assuming a mass based on 0.25 kg/m2, a collimator with an area of 755 m2 would weigh about (755x0.25=) 188 kg.

EGEOLS orbiting mass

We will assume the de-collimators and re-collimators will each mass as much as a collimator, being of a similar size. For one DS at GEO, therefore, it will require (188x2=) 376 kg of de-collimators and re-collimators. As with the LEOLS, total mass of the core lens and mirror arrangement is estimated to be about 24 kg. Therefore, not including the EP or fuel for station-keeping, each LEOLS DS satellite should mass about (376+24=) 400 kg at GEO. Per Wikipedia, a Falcon Heavy can lift 21,200 kg to GTO (Geostationary Transfer Orbit). Its LC would thus be (53,000/21,200=) 2.5x. The DS mass to GEO of an EGEOLS would thus equal (400x2.5=) 1,000 kg, assuming no EP used.

EGEOLS lunar surface mass

The lunar surface mass for the EGELOS would be the same as for the LEOLS, or about 7,785 kg from LEO.

Total EGEOLS off-Earth mass

The total LEO mass for the EGELOS would equal (1,000+7,785=) 8,785 kg.*

*Does not include DS solar sail, EP mass, or mass of LS.

Beamed energy from Earth to a DS constellation in LEO (ELEOLS)

Assuming multiple laser systems on the Earth, a DS constellation could be created that would also permit beaming from Earth. In that instance, the maximum distance the laser beam would have to travel would be reduced to around 410,000 miles. Multiple laser systems could be expected to improve the likelihood of weather

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[21] http://www.thelivingmoon.com/46exuberant/03files/Laser_Power_SELENE.html

cooperating for at least one of the systems. In addition, there would be times when all of the systems could send energy to the lunar surface, increasing the energy availability during the lunar night to accomplish tasks.

ELEOLS orbiting mass

The DS satellites in this system are comparable to the mass required of a DS in LEO. Assuming a constellation of six DS satellites with a mass of 310 kg, the total mass in LEO for am ELEOLS would be (310x6=) 1,860, not including the mass of the EP units or their fuel.

ELEOLS lunar surface mass

The lunar surface mass for the ELELOS would be the same as for the LEOLS, or about 7,785 kg from LEO.

Total ELEOLS off-Earth mass

The total LEO mass for the ELELOS would thus equal (1,860+ 7,785 =) 9,645 kg.*

*Does not include DS solar sail, EP mass, or mass of LS.

Beamed energy from Earth/Moon L4 or L5 (L5LS)

L4/L5 are approximately the same distance from the Moon as is the Earth. It is thus possible to put an LS there that would mass about the same as an LEOLS. It would have the advantage of a much easier job of station-keeping, and would always be in sunlight (excepting eclipses). However, its orbiting mass would be about three times that of an LEOLS. Its lunar mass would approximately equal that of the LEOLS, or about 7,785 kg from LEO.

Total LEO lift mass for the 15 kW continuous PV L5LS: ((3,202x3)+ 7,785 =) 17,391 kg*

Total LEO lift mass for the 15 kW continuous SP LEOLS: ((2,812x3)+ 7,785 =) 16,221 kg*

*Does not include DS solar sail or EP mass.

Lunar surface-mounted systems (LSMS)

For comparison purposes, we need to consider solar energy systems that are mounted on the Moon's surface.

Lunar Polar Surface-Mounted System (LPSMS)

A "peak of eternal light" is a point on a body within the Solar System which is always in sunlight. Per wikipedia, "no peaks of eternal light have been positively identified on the moon[22]". (This is almost certainly due to the seasonal tilt of the Earth-Moon orbital plane relative to the Sun-Earth orbital plane.) Also, "…two points about 8 km from each other along a straight ridge extending from the Shackleton Crater at the Lunar South Pole are illuminated a combined ~94% of a lunar year. This is because both points cast shadows upon each other during different times of the lunar year and only a few times of darkness occur when further peaks throw shadows over both of these

[22] http://en.wikipedia.org/wiki/Peak_of_eternal_light

points simultaneously". Per the wikipedia chart and the accompanying picture, the minimum illumination at one peak can be as little as 44%, while at the other peak it can be as little as 56%. Neither peak is illuminated over 82% of the year.

A second (NASA) analysis has recently come to light[23]. From the abstract: "Every year, a location near the Shackleton crater rim in the south polar region is sunlit continuously for 240 days, and its longest continuous period in total darkness is about 1.5 days. For some locations small height gains (10 m) can dramatically improve their average illumination and reduce the night duration, rendering some of those particularly attractive energy-wise as possible sites for near-continuous sources of solar power."

We will assume that a Moon base at Shackleton Crater can be operated with three separate PV systems which between them create a minimum of 15 kW nearly continuously to the Moon base via electrical cables. The system would thus have a maximum generating capacity of 45 kW and a minimum generating capacity of 0 kW. There is ample time for such a system to store enough energy to get through some acceptable number of hours of darkness. We will assume that time is equal to 1.5 days or 36 hours. Using the figure from the 2009 NASA study of 130 W/kg specific power (slide 13), one 15 kW PV array power plant placed on the Moon would mass about (15,000/130=) 115 kg, not including support structure. The PV array would need to stand almost perfectly vertically off the lunar surface to face the sun. In addition, it would need at least a single axis system to track the sun, and possibly a two axis system. The support structure will be assumed to double the mass of the PV array to (115x2=) 230 kg. The first axis tracking system will be assumed to double that total to about (230x2=) 460 kg. We will assume a third axis is not required. For three systems, the mass will triple to (460x3=) 1,380 kg.

Some mass would be required by the connecting cable. It has been estimated that the cable might mass about 10 kg/km. If we assume two of the systems are set up on the previously mentioned peaks 8 km apart, and that a third peak is no more than 20 km distant, it may be possible to use as little as 30 km of cable. However, it should probably be assumed that a minimum of 100 km of cable will be required. At 10 kg/km, that would indicate a cable mass of (100x10=) 1,000 kg.

Added to this would be the mass of the required energy storage to get through the longest period of darkness. Assuming 36 hours, that would equal (15x36=) 540 kWh. Using Li-S, the mass of the EBS would equal about (540/0.5=) 1,080 kg on the lunar surface. To that needs to be added the EBS mass of 240 kg, equalling a combined lunar surface energy storage total of (1,080+240=) 1,320 kg.

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[23] see http://ntrs.nasa.gov/search.jsp?R=20120010094

The total mass of our LPSMS would thus equal (1,380+1,000+1,320=) 3,700 kg. In lunar orbit, the mass would equal (3,700x3=) 11,100 kg. Note, however, that peak power output capacity would equal 45 kW.

Lunar Non-polar Surface Mounted System (LNSMS)

The main problem with a LNSMS is that it requires stored energy when sunlight isn't available. If we assume the proposed Moon Colony will require 15 kW continuous during the lunar night, then it is clear that we will need to generate considerably more than 15 kW continuous during the lunar day in order to have sufficient power to charge the energy storage system and output 15 kW continuous at the same time.

Like a LPSMS, an LNSMS would need to track in at least one axis. Assuming an LPSMS has the same mass as a single LPSMS array, in order to "net" approximately 15 kW continuous day and night and still have 15 kW of capacity during the day to charge the storage system, a 30 kW PV array system would appear to be required. However, since it will be difficult to capture solar energy at precisely dawn or dusk, even with a tracking system, and since an average synodic lunar day takes about 29.5 earth days, a good assumption is that, even for tracking solar devices, 17 day's worth of energy would need to be stored to get completely through the lunar night.That would equal (15x17x24=) about 6,000 kWh for a 15 kW system. This compares well with the 2,000 kWh for a 5 kW system in the 2009 NASA study (2009 NASA study slide 48). Note that 17 days of zero energy input infers (29.5-17=) 12.5 days total for energizing the batteries. That's (12.5/29.5=) 42% of the total lunar day, not 50% as was originally assumed above. Since a 15 kW output single axis tracking array will mass about 460 kg, a 37.5 kW system will mass about (460/0.42=) 1,095 kg.

Using Li-S, the mass of the EBS would equal about (6,000/0.5=) 12,000 kg on the lunar surface. To that needs to be added the EBS mass of 240 kg, equal to a combined lunar surface energy storage total of (12,000+240=) 12,240 kg. The total mass of our LNSMS would thus equal (1,095+12,240=) 13,335 kg, or (13,161x3=) 40,005 kg in lunar orbit.

Energy storage systems

Energy storage by flywheel

In the case of our baseline energy system of 15 kW continual output, to store sufficient electrical energy for 17 days of lunar "night", we would need to generate about 6,000 kWh of stored energy over the course of 13 days or 312 hours. Taking the figure of Earth-produced flywheels at 0.22 kWh/kg, we'd need (6,000/0.22=) 27,273 kg of Earth-produced flywheels on the lunar surface to get through a lunar night. To that would need to be added 240 kg of EBS.

Note: To the degree that flywheels can be manufactured on the Moon using lunar material, the required amount of mass that would need to be transferred from the Earth could be vastly reduced.

Energy storage by electric battery

For comparison purposes, A Model S Tesla with a 244 mile range carries a 60 kWh battery pack. We can estimate a Model S battery pack at 600 kg each. Thus, the system would require between (6,000/60=) 100 Model S Tesla batteries, for a total mass of (100x600=) 60,000 kg in batteries.

Recently, a second type of battery has been proposed by SL5S member Michael Abramson, namely lithium-sulfur batteries[24]. This type of battery can develop a specific energy of 500 Wh/kg. For 6,000 kWh, that would require (6,000/0.5=) 12,000 kg in batteries.

Note: To the degree that batteries can be manufactured on the Moon using lunar material, the required amount of mass that would need to be transferred from the Earth could be vastly reduced.

Chemical energy storage

Fuel cell are worth considering. The obvious problem is that they require a fuel. The high heat of combustion of H2 is 142 Mj/kg. Using the 2009 NASA study's specific energy figure of 1.153 kW-hr per kg (slide 54), to produce 2,000 kWh would require about (2,000/1.153=) 1,735 kg of cryogenic regenerating fuel cell. That would include 87 kg of H2 and 692 kg of O2. For a 15 kW output system, it would require (87x3=) 261 kg of H2 and 2,076 kg of O2. If we don't regenerate the fuel cell, we'd require that much landed on the lunar surface every month.

Alternatively, we could "mine" the O2 on the Moon's surface. That would drop the required shipment from Earth to the lunar surface to 261 kg of H2 per month.

Clearly, there are strong incentives to "solve" the problem of the regenerating fuel cell.

Energy storage by thermal battery

By increasing the temperature of the thermally isolated mass to about 1,300 deg F, one can power a very efficient heat engine. High temperature heat engines are commonly used on the Earth today to create energy from concentrated solar energy. Stirling Cycle-based engines are typically used in these applications.

Can we use refined lunar metal as a storage medium for a thermal battery? Iron, with a melting point of 2,800 deg F and a heat of fusion of 272 kJ/kg, and Aluminum, with a melting point of 1,221 deg F and a heat of fusion of 398 kJ/kg, are particularly interesting.

It's well known that unoxidized iron exists on the Moon. It seems reasonable to assume, therefore, that unoxidized aluminum exists there as well. Should that prove to be the case, then mining for either of these metals should be very simple: Melt the lunar regolith, and physically separate the metals. As an added benefit, oxygen and other useful materials can be separated as well.

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[24] http://www.gizmag.com/lithium-sulfur-battery-energy-density/29907/

Molten iron could be used to store high grade heat and could power a very efficient heat engine. Most heat engines won't be able to effectively use heat energy at 2,800 deg F, but it's easy to "step down" the temperature to a more reasonable 1,300-1,500 deg F by increasing the flow rate of the heat transfer medium. Aluminum is useful in that it doesn't require a step down process, allowing a simpler, more robust heat exchanger design (basically a bunch of stainless steel tubes that are run through the molten aluminum).

Energy storage by laser beaming the lunar regolith

Finally, it may be possible to create a heat engine that operates from heat from both the laser and incident solar that is stored in the lunar surface. Beamed energy from a an orbiting laser fired at a maximum angle of 71.5 degree increases the beam area about 2.7 times. That area would then increase until the LS was exactly overhead. Alternatively, a laser at EML1 would be able to pass through a de-collimator and focus a generally set beam area on the lunar surface. If this were to occur during the Lunar day, the total amount of radiation of the lunar surface would be increased. Consequently, the temperature of the lunar surface in the center of the irradiated mass would climb much higher than the average of 380 K near the equator. It's even possible that the targeted mass could become molten, thus storing heat in a phase change. If one were to then thermally isolate the mass at night, for example by closing mirrored louvers suspended over it that reflect radiated heat back to the surface, then it might remain molten through the entire lunar night, serving as a heat source for a heat engine.

Note that sufficiently concentrated solar radiation can accomplish the same goal without the need for a laser system (see "Energy storage by thermal battery" above).

Thermal battery and trough concentrators

Note that it isn't necessary to use beamed energy to get to 1,300 deg F. Consider trough concentrators: Trough concentrators, if they are laid out perpendicular to the sun's path across the lunar sky, only require a single-axis (sun-tracking) mechanism. On the Earth, trough concentrators can rarely achieve peak concentrating temperatures of 1,000 deg F. On the Moon, it should be no problem to achieve at least 1,300 deg F. On the Earth, trough concentrators use a synthetic oil as a heat transfer fluid, which is limited to temperatures around 750 deg F. Molten salts have been proposed for use in solar trough concentrators, but still appear to be limited to a temperature of around 1,000 deg F. A better approach on the Moon is to use a gas working fluid[25].

If the gaseous heat transfer fluid for such a trough system were pressurized, it would have multiple benefits. First, pressurizing increases the mass flow through the system per unit of time. That will reduce pumping losses per unit of heat transferred. Second, using a gaseous heat transfer fluid potentially simplifies the heat engine design. Such a simplified system would run pressurized gas through a solar heater, such as a

[25] http://social.csptoday.com/technology/aora-hybrid-'tulip'-tower-system-be-switched-spain

series of single axis tracking solar trough concentrators, elevating the gas temperatures to approximately 1,300 deg F. This gas would then be partially directed into a thermal battery and partially directed into a heat engine.

Assuming we use a regenerating Brayton Cycle engine, the high pressure, high temperature gas flowing from the solar trough concentrators will be directed to the heat engine. There, the gas would (1) be dropped in pressure through an expander to create work, (2) heat would be removed from the expanded gas via a regenerative heat exchanger, (3) more heat will be removed from the gas via a cooler, (4) the gas would be recompressed, and (5) the regeneratively removed heat would be used to preheat the compressed gas. Meanwhile, the fraction of gas circulated through the battery would be flowed into the hot end, flowed out of the cold end, and then be pumped into the cold side of the solar trough concentrators. It thus would require only sufficient added work to overcome pumping losses. Finally, the recompressed heat engine exhaust would be mixed in with the (cooled) gas exiting the cold end of the battery, and the recombined gas will be sent back to the solar heater (note that this mixing may advantageously occur prior to regenerative heating if the gas exiting the thermal battery is cooler than the gas exiting the compressor).

The gas flow will be reversed, with the trough concentrators taken out of the loop. Exiting at high temperature and pressure from the hot end of the thermal battery, the gas will flow through the Brayton Cycle heat engine, will go through processes (1) through (5) above, and will be pumped back into the cold end of the thermal battery at high pressure and low temperature to complete the cycle.

Low temperature system

Another intriguing possibility is to use a low-temperature heat engine to generate the power for the Moon base. The temperature swing from hot to cold on the Moon differs by 467 deg F (-243 to +224). A heat engine can be made to operate with that large a temperature difference, albeit not as efficiently as a high temperature engine. By arranging that a large area of lunar regolith in direct sunlight be "heated" to 224 deg F by lunar day, then covered with a reflective foil to keep the trapped heat from radiating away, it might be possible to continuously remove heat at close to 224 deg F from tubes buried in the regolith from the lunar soil for the 20 days required to get through the lunar "night". That could serve as the heat "source" for a low temperature heat engine. Note that this area and a similar large “cooler” area which does not see sunlight during the lunar day would ideally be located immediately adjacent to the heat engine. That second shaded area would serve as the heat engine's heat “sink".

Conclusions

The findings of this analysis are very much first order approximations. In addition, the analysis is still a work in progress. However, in light of the dramatic nature of those findings, it is felt that the systems in question merit a far more in-depth analysis than the S5LS is capable of delivering. It is hoped that this analysis will inspire the undertaking of such an in-depth analysis by NASA or some other interested party, to the benefit of all who dream of mankind moving outward into the universe.