Powering a Moon base through the lunar night.

The Sacramento L5 Society et al

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What's the most practical way to sustain a permanent Moon base through the approximately 355 hour lunar night? In 2009, a NASA concept study attempted to answer that question, according to a recently discovered slideshow[1]. And in March of 2014, the Sacramento L5 Society (SL5S), a California chapter of the National Space Society, undertook the task of answering the same question, eventually resulting in a detailed analysis of 20 different potential energy delivery systems. From examination of the 2009 NASA study fragments, it seems likely that the SL5S analysis has uncovered several relevant concepts that were not considered by the NASA concept study, specifically 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.

This article is a summary of the findings of the SL5S analysis to date. The detailed analysis itself and its accompanying spreadsheet, including a full description of the 20 systems the SL5S has studied to date, can be found on the SL5S website[2].

Lift Capacity (LC)

Because it takes less force to put a given mass into LEO than into lunar orbit, and less force to put a mass into lunar orbit than onto the lunar surface, it is useful to use a given LC to determine relative masses of different systems in different locations. In the SL5S analysis, the LC is defined in SpaceX Falcon Heavy (FH) units. One FH has a liftoff mass of 1,462,836 kg[3]. It is assumed that the LC of one FH can put 53,000 kg into Low Earth Orbit (LEO), 17,216 kg into either a lunar or L1 orbit, and 5,739 kg onto the lunar surface.

Electric Propulsion system (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 reduces the LC of any given system. For the SL5S calculations, it is assumed that the propellant and EP drive used to move a mass from LEO to either LO or L1 will equal 30% of the transported mass. Since moving a mass that distance with a standard rocket approach will typically take about twice the transported mass in fuel, the potential savings are clear.

An EP system can also be used for "orbital station keeping," which can be broadly defined as maintaining an object in space in a preferred position or orbit. The 2009 NASA study included mass calculations for station keeping which have been used in the full SL5S analysis.

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

The SL5S analysis examined energy storage by flywheel, electric battery, chemical, and thermal battery systems. It was concluded that Lithium-Sulfur (Li-S) batteries presently appeared to have the best specific energy (0.5 kWh/kg)[4], but that other systems would benefit greatly from In Situ Resource Generation (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 the SL5S 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.

Laser collimating

Aggressive collimation 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 since, for a given light wavelength and distance to target, spot diameter is inversely proportional to aperture diameter[5]. Per one source, "If we collimate the output from [a] 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 relation. For example, to improve the collimation by a factor of two, you need to increase the beam diameter by a factor of two.[6]"

Accordingly, it is highly recommended that aggressive collimation be explored as a means of decreasing the divergence angle of a laser beam. Aggressive collimation may be especially practical in a weightless, weather-less environment. Because objects in space are weightlessness, and because space has no atmosphere, a space-based Fresnel collimating lens might only be a few mils thick. Also, it should be easier to make a high precision Fresnel lens than a high precision 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, the film can likely warp or twist to some degree without affecting its beam-forming ability. Finally, a Fresnel lens has a higher light transfer efficiency than a mirror. In this analysis, the mass of a Fresnel lens laser collimator, including the mounting framework, is assumed to be 0.25 kg/m2, with most of that mass assumed to be in the mounting framework.

Solar Pumped (SP) Laser System (LS)

The LS system analyzed in the 2009 NASA study was a PV-powered LS. Another type of LS is possible using SP lasers[7]. 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.

Orbiting Energy Storage system (OES)

A satellite that is not in sun synchronous Lunar Orbit (LO) will move continually into the Moon's shadow. Adding an OES system permits an orbiting 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.

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 proposed system, 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 to another satellite or directly to a Moon base at the one of Moon’s poles, thus continually powering the Moon base and obviating the need for energy storage. 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.

A DS can also find use in other ways. Orbiting a DS constellation around the Earth would permit an 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. Also, it is possible to use a series of non-orbiting DS modules directly on the lunar surface to transfer beamed energy to other locations. Finally, it is possible to mount laser systems at the lunar poles and beam solar-powered laser energy to orbiting DS constellations, distributing lunar pole-generated laser energy to Moon bases anywhere on the Moon.

Lunar Polar Multi-array System (LPMS)

The LPMS assumes that a 15 kW continuous polar Moon base can be operated with three separate PV arrays situated on high lunar mountain peaks, or so-called “peaks of eternal light,”[8] each connected directly to the base via multi-kilometer long electric cables. Periods of darkness as long as 36 hours are still likely[9], requiring an estimated additional energy storage capacity of 540 kWh. Peak power output capacity of the three PV arrays would thus occasionally equal 45 kW.

As an alternative to energy transfer by electric cable, it may be possible to deflect and transfer solar beams directly to a Moon base from multiple distant (polar) sites. The transfer would be accomplished with a series of surface-mounted DS modules, each module composed of an arrangement of lenses and mirrors. Estimates of the mass and efficiency of such solar beam deflection systems 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 L1. 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.

Figures 1-3 illustrate a possible space-base L1LS that uses a solar sail and a gravity winch for station-keeping. 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.

The 2009 NASA concept study

The preferred system recommended in the 2009 NASA study was a PV solar array-powered Cryogenic storage Regenerating Fuel Cell system (CRFC). NASA calculated that a 5 kW continuous delivery CRFC system would store 2,000 kW-hr with a system energy density of 1.15 kWh/kg. The study's alternate preferred system was a Fixed Orbit Laser System (FOLS) with a 16.1 hour orbit period that required a surface receiver installation with 525 kW-hr of energy storage. The laser was powered and fired (a) when it was in direct sunlight, and (b) whenever it was in direct line of sight with the Moon base.

The 2009 NASA study's FOLS system analysis presumed an energy storage architecture that was capable of only 200 W-hr/kg. If the NASA study had used the proposed 1.15 kWh/kg CRFC to store the energy for the proposed FOLS, then the total estimated FOLS energy storage system mass would have been reduced by 83%, making a comparison between the two systems far more competitive. A probable 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.

Findings

Table 1, entitled "Moon energy systems lift capacity in Falcon Heavy units and dollar equivalents," collates the results of our analysis. The CRFC and FOLS systems are included for reference purposes only. It is presumed that any advances in battery technology will be applied across the board to all systems. To aid in such, a comparable system to the CRFC system but using Li-S energy storage is included as the Lunar Non-polar Surface Mounted System (LNSMS). Also, a comparable system to the FOLS system but using Li-S energy storage and aggressive laser collimating is included as the Lunar Orbiting PV-powered Laser System (LOPVLS).

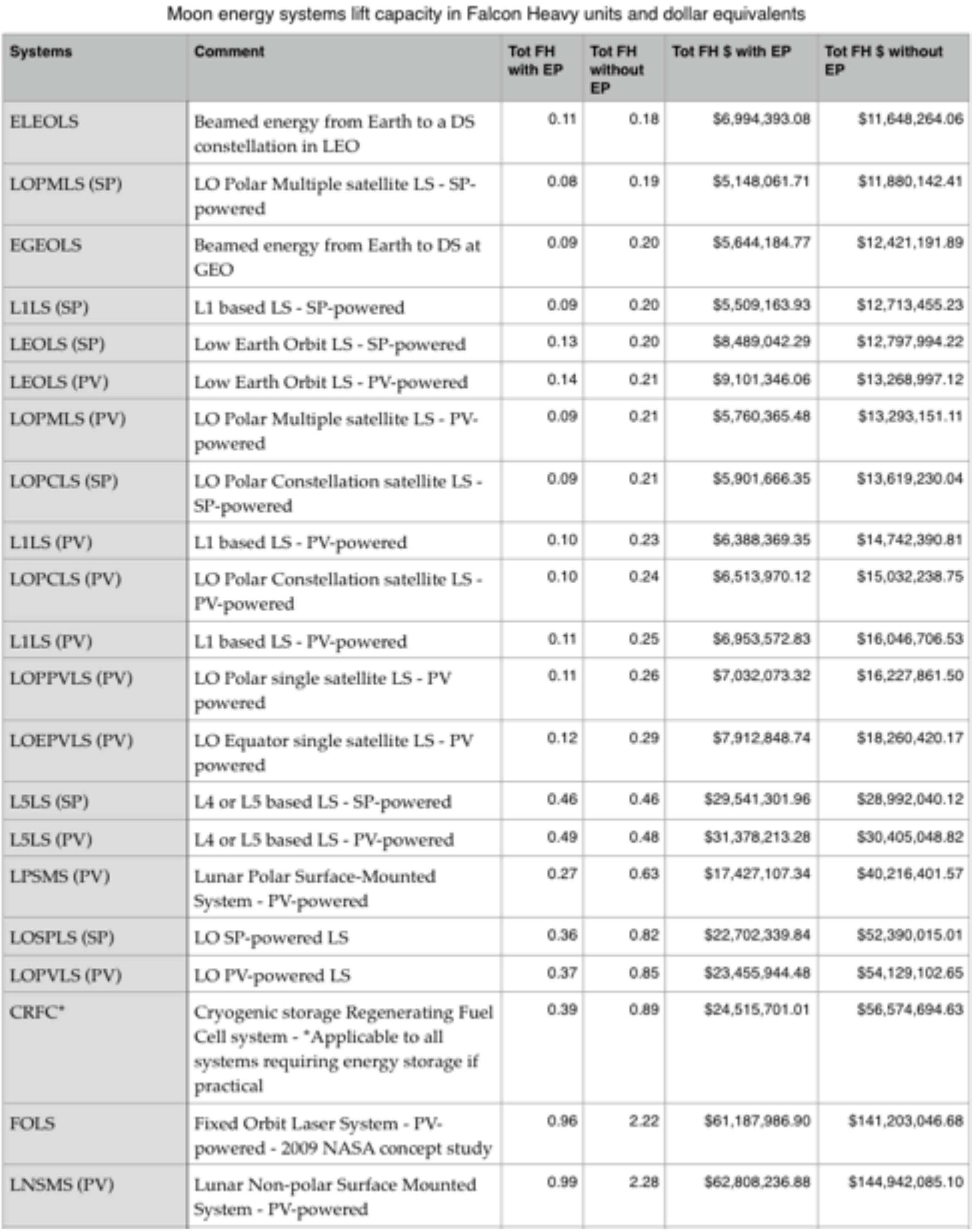
In Table 1, the systems are shown ranked from low cost to high cost by the column "Tot FH $ without EP". It is assumed that, for an initial Moon base, electronic propulsion will not be used to deliver the payloads to their ultimate destinations. FH dollars are calculated based on $1,200/kg in accordance with the statement by SpaceX Chairman Elon Musk that "Ultimately, I believe $500 per pound or less is very achievable"[10]. It's important to note that FH dollars do not include any costs associated with developing the various systems shown in the table.

Conclusions

The findings of the SL5S 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 article 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.

History of this analysis

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[11]. 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 L1 or in lunar orbit. It was later discovered that use of a LS at L1 had been proposed by others, including Charles Radley, president of the Oregon L5 Society[12].



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

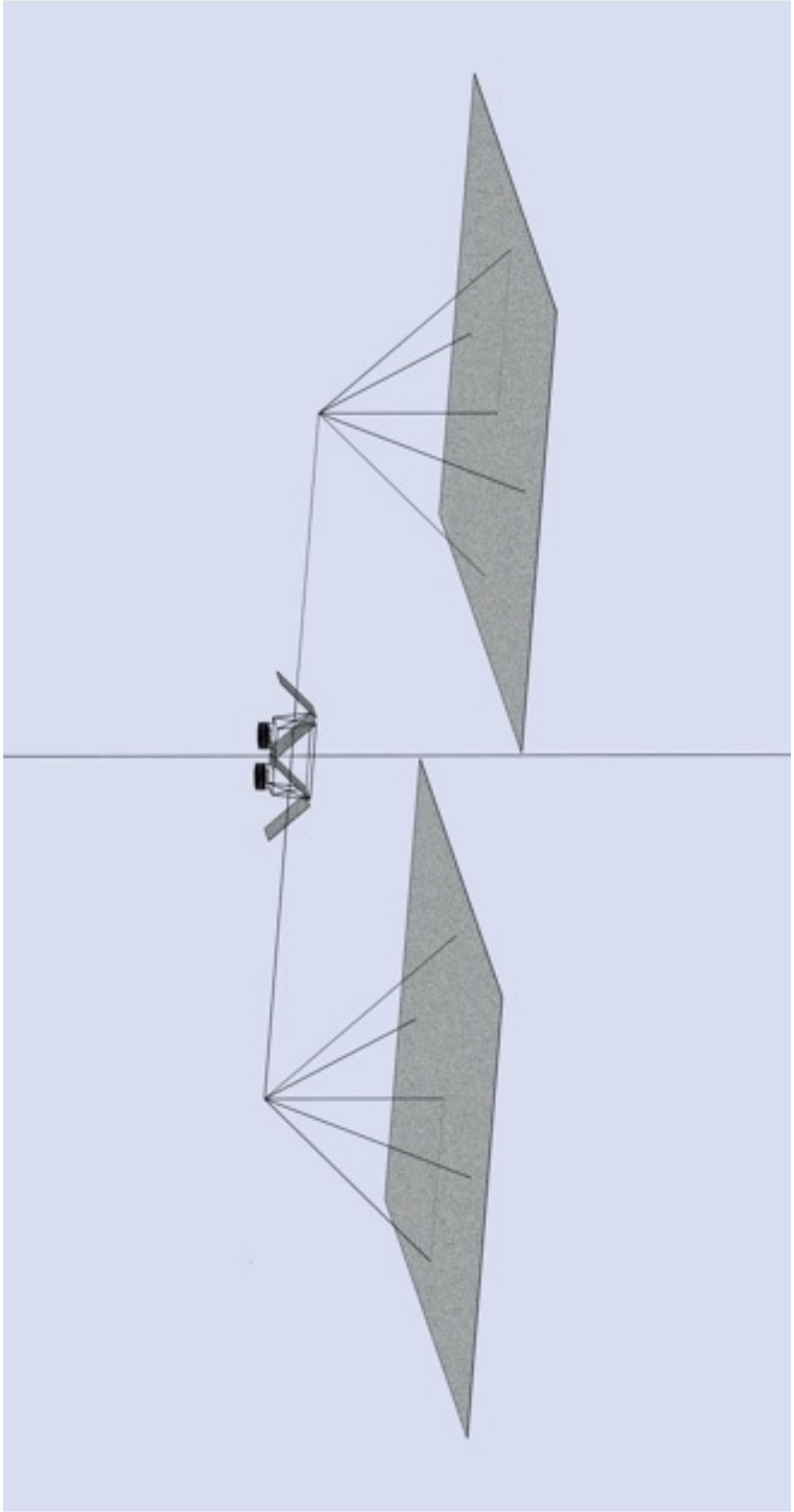


Figure 1

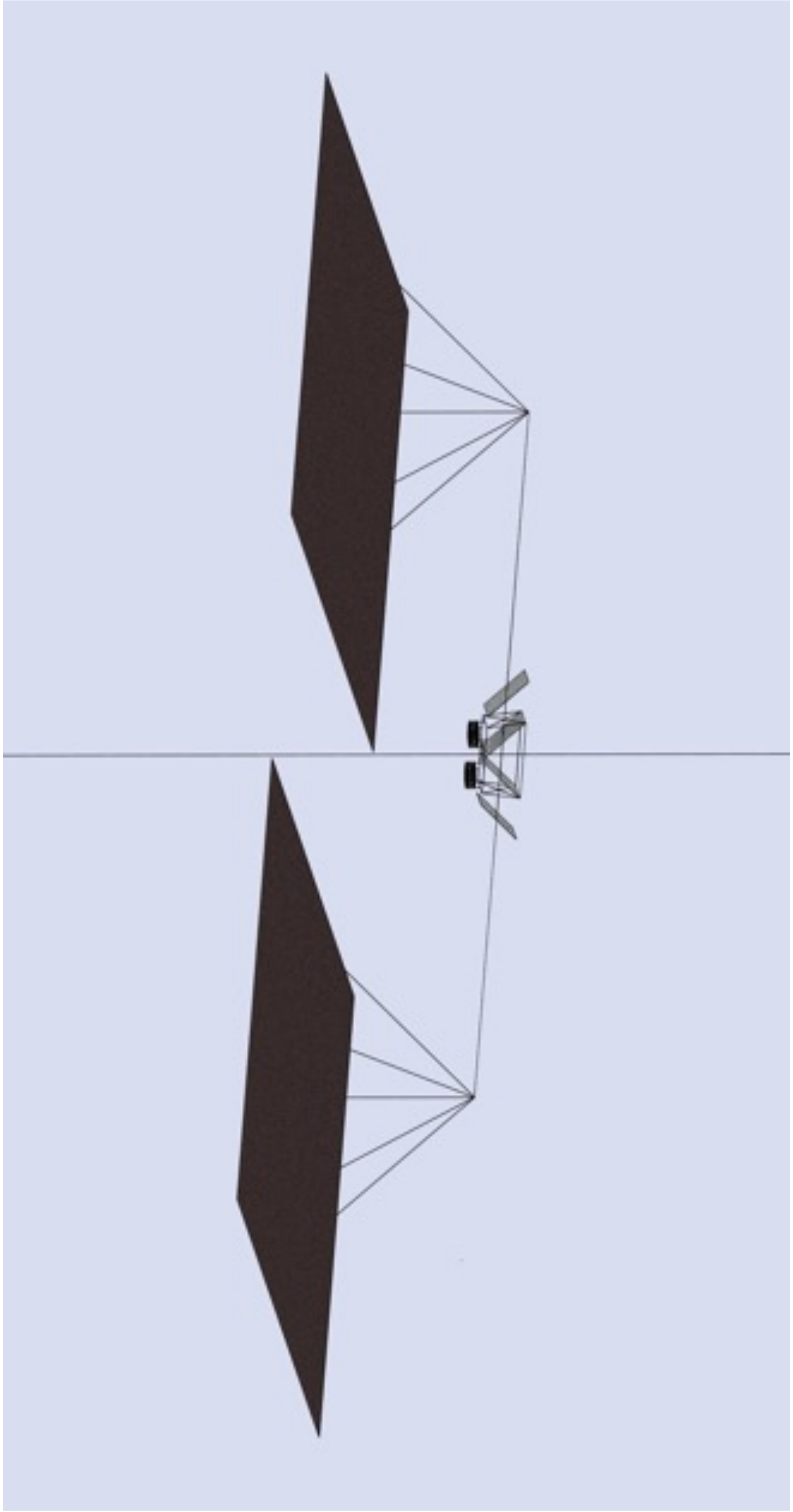


Figure 2

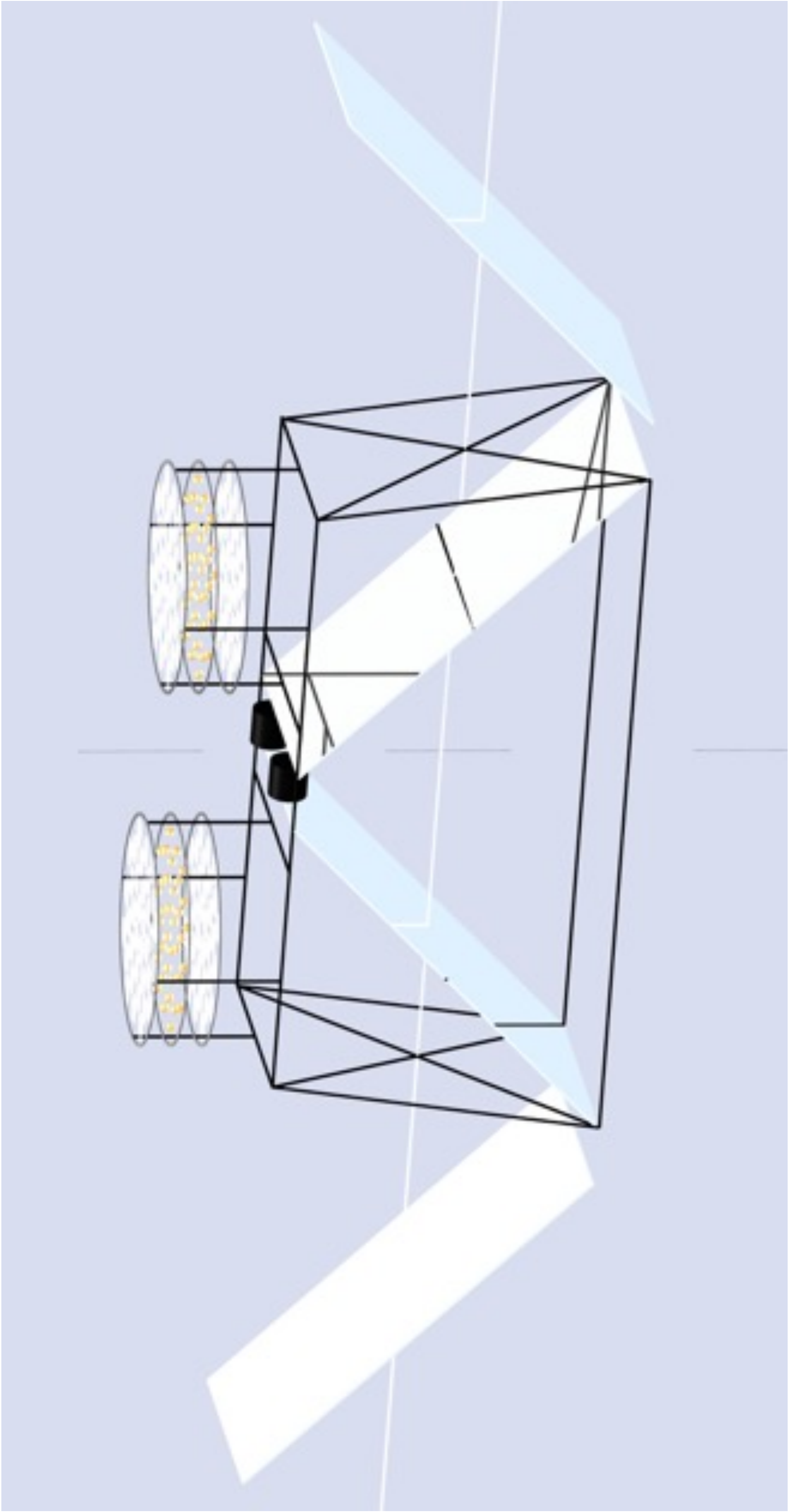


Figure 3

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[1] http://www.nasa.gov/pdf/315858main_Cheng-yi_Lu.pdf

[2] sacl5.org

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

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

[5] SL5S member Roger Arnold

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

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

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

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

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

[11] http://spacejournal.ohio.edu/issue18/helioastra.html

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