SETTLING SPACE

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Summary

An ongoing collision between population growth and a burgeoning demand for resources is presently afflicting the Earth's environment. Lunar Surface Resource Utilization (LSRU) is of immediate importance to humanity because there are at least three ways it can help mitigate the impact of this collision: First, LSRU is inherently friendly to Earth's environment, since the development of space resources takes place off-planet on the lunar surface. Second, LSRU will increase the availability of resources, offsetting the need for Earth-based resources with high environmental impact. Third, over time, LSRU can help humanity move towards full-scale space settlement, thus solving permanently the issues raised by unfettered population growth.

Settlement of space and the development of space resources are mutually synergistic. Only the Moon has both massive space resources and the ability to realistically meet all the requirements for full-scale space settlement. However, the Moon has one major drawback; it has two weeks when essentially the whole Moon sees no sunlight. The solution to that problem is Aggressively Collimated Technology (ACT), which permits solar-powered lasers to beam energy to the lunar surface economically and constantly.

ACT can reduce the cost of energy on the lunar surface, but it will require the creation of a publicly-owned Lunar Power Utility (LPU) to establish reasonable rates for that power. These reasonable rates would in turn foster the development of Lunar Surface Resource Utilization (LSRU). LSRU will, in its turn, help establish the foundation for massive lunar settlement. In time, massive lunar settlement will establish the foundation for full-scale settlement of space.

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Acronyms	**Meaning**
ACT	Aggressive Collimating thin-film Technology
AU	Astronomic Unit
$(C_2H_4)_n$	Polyethylene
CC	Copper Cable
CO2	Carbon dioxide
CRFC	Cryogenic storage Regenerative Fuel Cell
ACDS	Aggressively Collimated Deflecting System
EM	Earth/Moon
EML	Earth/Moon Lagrange point
EML1	Earth/Moon Lagrange point 1
EML2	Earth/Moon Lagrange point 2
EML3	Earth/Moon Lagrange point 3

EML4	Earth/Moon Lagrange point 4
EML5	Earth/Moon Lagrange point 5
EP	Electrical Propulsion
ESA	European Space Agency
FH	Falcon Heavy (LC unit)
FOLS	Fixed Orbit Laser System
GPS	Global Positioning System
GSO	GeoSynchronous Orbit
H2	Hydrogen molecule
H2O	Water
Isp	specific impulse
ISRU	In Situ Resource Utilization
ISS	International Space Station
JAXA	Japan Aerospace eXploration Agency
kg	kilogram
km	kilometer
kW	kiloWatt
LC	Lift Capacity
LEO	Low Earth Orbit
LO	Lunar Orbit
LPMS	Lunar Polar Multi-array System
LPN	Lunar Power Node
LPR	Lunar Power Rover
LPR1	Lunar Power Rover 1
LPU	Lunar Power Utility
LSRU	Lunar Surface Resource Utilization
m	meter
m^2	meter squared
mSV	milli-Sievert
mGy	milli-Gray
N2	Nitrogen molecule
NASA	National Aeronautics and Space Administration
NEO	Near Earth Object
NSS	National Space Society
O2	Oxygen molecule
OLO	Oscillating Lagrange point Orbit
PVRP	Photovoltaic Receiver Panel
R&D	Research and Development
SE	Sun/Earth
SEL1	Sun/Earth Lagrange point 1
SEL2	Sun/Earth Lagrange point 2
SEL3	Sun/Earth Lagrange point 3
SEL4	Sun/Earth Lagrange point 4
SEL5	Sun/Earth Lagrange point 5
SL5S	Sacramento L5 Society
SRU	Space Resource Utilization
SSTO	Single Stage To Orbit
W	Watt

The problem: How can we survive overpopulation?

The human race has a problem: For the last 50 years, our population has been growing linearly at the rate of almost 80 million people a year (Figure 1)[3], stretching to the limits our planet's resources and our civilization's ability to handle environmental impacts. As these countering forces impinge upon one another in a mighty collision, global warming is just one negative result. Almost as threatening is the fracturing of fruitful cooperation between people and nations, as competition for resources heats up.

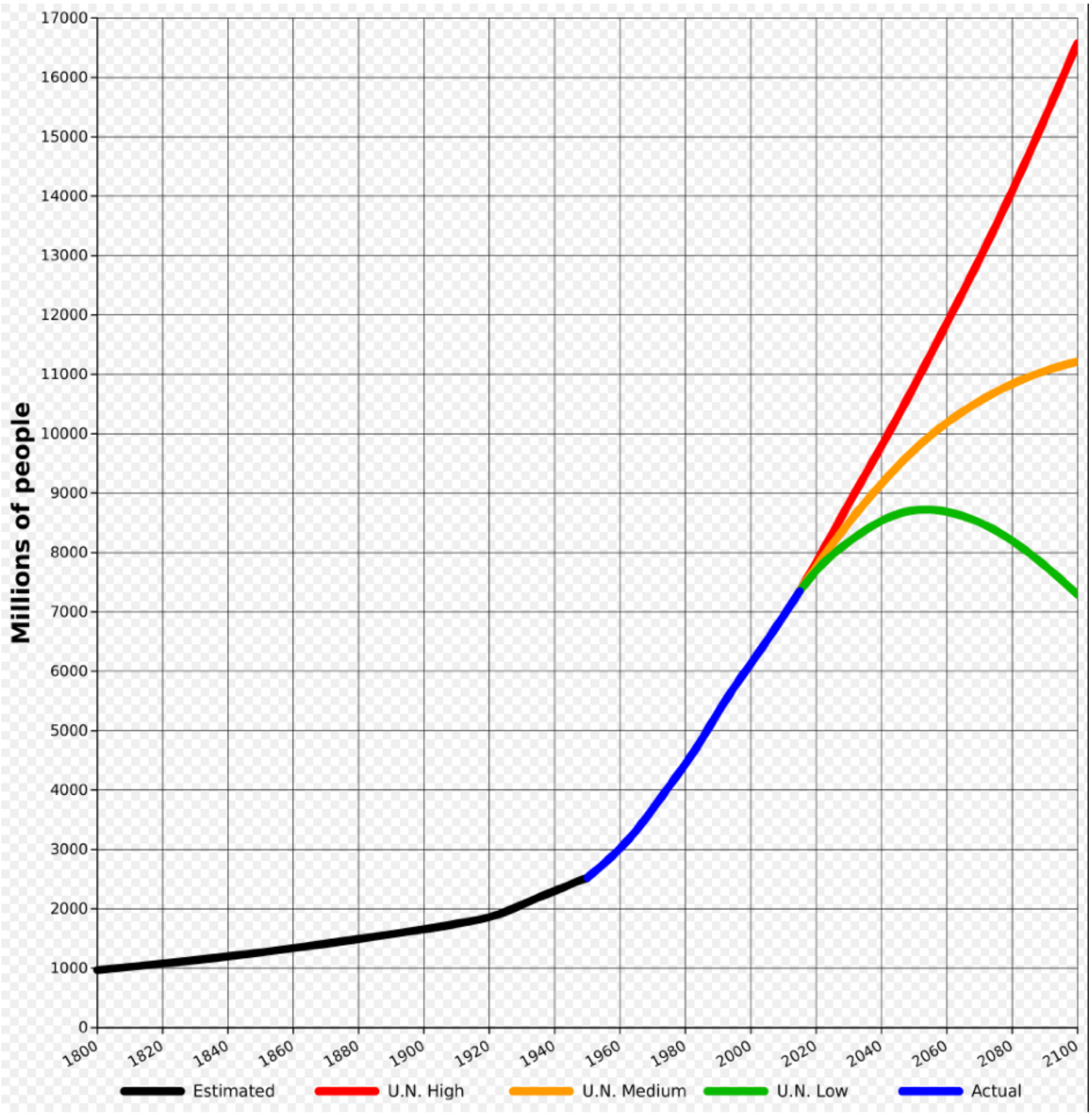


Figure 1

The solution: Open up a new frontier

In the human race's distant past, one of the most powerful forces available to mitigate the collision of population growth and resource restriction was resettlement. Early man's world was effectively boundless.

The Sacramento L5 Society, one of the National Space Society's oldest chapters, is herein proposing nothing less than the recreation of early man's world of boundless resources and growth.

What is a Lagrange point?

It's odd to think of points in space as being islands, but that's a pretty good way to think of Lagrange points. However, these "islands in space" have no physical existence, being defined by the gravity fields of any two spacial bodies in rotation around one another.

There are five Lagrange points for each such two body system, such as the Sun/Earth (SE) system and EM system. The EM Lagrange points, labelled L1 thru L5, are represented in Figure 2 below, but all Lagrange points would have the same general relationship. There is also a sixth common point, called the barycenter, which the two bodies rotate around. (The EM system's barycenter is located about 4,700 km from the Earth's center and is thus located about 1,700 km below the Earth's surface.) For the EM system, we will refer to the first three Lagrange points as EML1, EML2, and EML3. And since Lagrange points 4 and 5 are also often referred to as "trojan points", we will refer to EML4 and EML5 collectively as the EM trojans.

All five Lagrange points rotate around their barycenter at exactly the same rate as the two bodies. Thus, in the case of the EM system, they rotate at the same rate at which the Moon and Earth orbit the EM barycenter, or about once a month. The EML1 point lies on the line connecting the centers of the two bodies and it orbits inside the two orbiting bodies. The EML2 point also lies on the line connecting the centers but orbits outside the two orbiting bodies. The EML3 point orbits in about the same path as the smaller orbiting body and once more on the line connecting the centers of the two bodies, but is 180 degrees opposed to the smaller body. The EML4, and EML5 points are in approximately the same orbit as the smaller body. Viewed from the barycenter, the EML4 point leads the smaller body by 60 degrees, and the EML5 point trails the smaller body by 60 degrees.

One can think of Lagrange points as being the tops of frictionless gravity "hills". If an orbit were perfectly circular, and no nearby body perturbed the orbit, an object placed a the top of the hill could balance there relatively easily. However, most orbits, including the EM orbit, are not circular but elliptical. An object placed at an L1, L2, or L3 point is effectively placed on a frictionless hill that is constantly moving out from under it. Consequently, an object placed at L1, L2, or L3 would need to apply work just to keep the object in the vicinity of the Lagrange point.

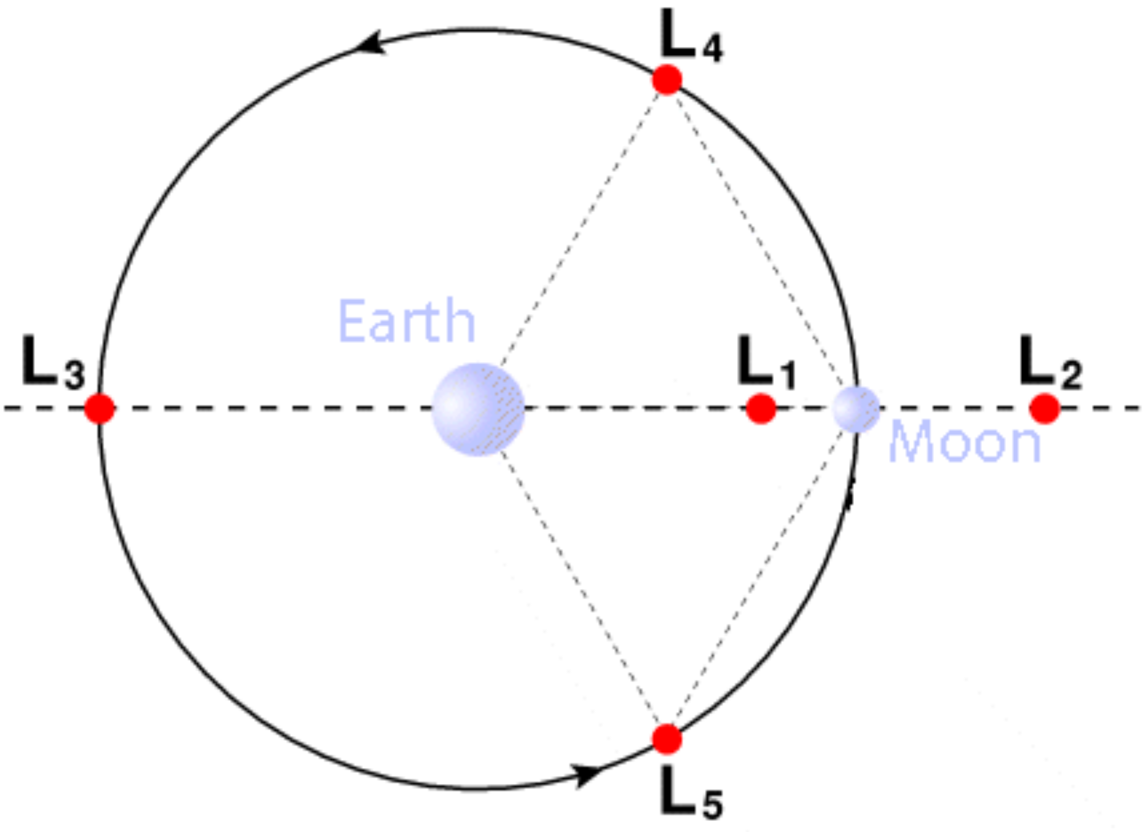


Figure 2

The trojan points, are different; relative to the other 3 points, they are considered “stable”. Each trojan point can be thought of as each having a small “dish” shape at the top of it’s hill. If an orbit were perfectly circular, and no nearby body perturbed the orbit, anything placed at one of these trojan points would stay at the bottom of the dish. However, the EM orbit, being elliptical, causes an object at one of the trojan points to be sloshed about in it’s dish. Even so, the object will stay permanently in the dish, and thus in the general neighborhood of the trojan point.

In September, 1974, Princeton University physics professor Gerard K. O’Neill published his seminal paper "The Colonization of Space,” in the scientific journal Physics Today. In that paper, O’Neill proposed establishing large space habitats at the Earth/Moon system’s L5 point. A year later, the L5 Society was incorporated, with the long range goal of establishing a space settlement at Earth/Moon L5, or EML5. In 1987, the L5 Society merged with the National Space Institute to form today’s National Space Society (NSS), the parent organization of the Sacramento L5 Society.

David Brandt-Erichsen of the NSS has this to say about those heady early days of the L5 Society:

"It is difficult today to realize the excitement that was generated in the early years of the L5 Society. Every issue of the L5 News contained reports of new studies and progress in the field...L5 members at the time thought that they would really get the chance to personally live in space within their lifetimes."

What happened to the L5 Society's vision? Over the decades since humanity began to lift into space, a cold, hard reality has slowly dawned on us. Space, it turns out, is filled with a constant sleet of highly energetic particles, some of which are massive and traveling at nearly the speed of light. Some of these particles are radiating from our sun, but the most dangerous ones, called cosmic radiation, are coming from all directions. The Earth is protected from this radiation by the Earth's magnetic field. Consequently, if humanity wants to settle space outside that magnetic field, humanity will have to live behind permanent, heavy-duty shielding 5 to 6 meters thick in all directions.

Unfortunately, in light of the severity of the radiation issue we've since discovered, the initial choice of settling EML4 or EML5 turns out to have been a major mistake. Apart from their ability to maintain an object in their vicinity, there is no particular usefulness associated with them. More importantly, because they are isolated in space (they 384,000 kilometers from both the Earth and the Moon), there is no source of raw material in relatively easy reach with which to construct the required massive barriers against radiation.

Does this mean the dream of settling space is finished? Far from it. We just have to reprioritize our goals. There are other areas of space far better suited to large scale space settlements than EML4 and EML5.

Space: The final frontier

Space's frontiers will remain limitless when all other frontiers are gone. However, some of space's frontiers will be easier to settle than others. In fact, "grading" space's frontiers from easiest to hardest is extremely important if we are to accomplish settling as expeditiously as possible. Starting from those closest to Earth and moving outward, the candidates for early space settlements include:

1. Low Earth Orbit (LEO).
2. GeoSynchronous Orbit (GSO).
3. Earth/Moon (EM) Lagrange point 1 (EML1).
4. Lunar Orbit (LO)
5. The Moon's surface.
6. EM Lagrange points 3 (EML3), 4 (EML4), and 5 (EML5).
7. EM Lagrange point 2 (EML2).
8. Sun/Earth (SE) Lagrange point 1 (SEL1).
9. SE Lagrange point 2 (SEL2).
10. Mars (about half an AU at closest approach).
11. SE Lagrange points 4 (SEL4) and 5 (SEL5) (about 1 AU from Earth)
12. Ceres the dwarf planet (about 1.75 AU from Earth at closest approach)
13. SE Lagrange point 3 (SEL3) (about 2 AU from Earth).

Besides these possible candidates for space settlements, there are many other space objects that might be included on the list, including asteroids, comets, and the moons of Mars.

Clearly, they would need to be graded in a similar manner as, say, Ceres. Near Earth Objects (NEO's) are particularly interesting, since they can come quite a bit closer to Earth than SEL1 or SEL2.[4] However, their orbits do not keep them permanently close to Earth, meaning that the distance to them will vary considerably. In addition, very little information about their makeup is known. Finally, only a few of them would make good habitats for anything but very small space settlements. As more information becomes available regarding their nature, other space objects may be included on the list.

LEO

LEO can be defined as orbiting the Earth within the Van Allen radiation belts (ending about 500-1,000 km above sea level). NSS member Al Globus has recently written a paper entitled "Space Settlement: an Easier Way" that does an excellent job of pointing out both the advantages and disadvantages of a space settlement at LEO[5].

Perhaps the single most important advantage for LEO concerns radiation. Globus proposes orbiting the Earth at an altitude of less than 500 km (slightly higher than the International Space Station) and in an equatorial orbit. Barring radiation from rare but still possible massive solar storms, Globus calculates that relatively low mass shielding, on the order of 10 kg/m^2 of polyethylene, will be sufficient. More massive solar storm shelters, like lifeboats on an ocean liner, will still be essential, which will add to the required mass.

One drawback to LEO settlements is the need to continually boost the structures back to a higher orbit. Over time, elements of Earth's atmosphere will want to drag LEO habitats deeper and deeper down Earth's gravity well.

A second drawback to LEO settlements is the increasing proliferation of space debris. As of 2008, space was filled with on the order of 5,500 tons of orbiting space debris, 1,500 tons of which was classified as orbiting in LEO[6]. That has undoubtedly increased significantly since. Space junk poses a significant danger to long term LEO settlements. On the other hand, orbiting space junk can also be considered a potential high value resource, even a kind of In Situ Resource Utilization (ISRU) material, provided that many hurdles, both technological and political, can be overcome.

The biggest disadvantage of LEO settlement is the nearly complete absence of ISRU material. Every successful resettlement effort in history has been based on the ability of the settlement to eventually "live off the land". It is difficult to imagine the development of a massive settlement of LEO in the absence of ISRU material. Of course ISRU material does exist in space. Unfortunately, the only material that presently exists in orbit near the bottom of Earth's gravity well is man-made.

One resource that does exist in LEO and throughout space is solar energy. It's possible that a settlement at LEO can find a way to use the plentiful solar energy there to benefit the settlement. (One intriguing possibility is the use of the "MiraSolar" concept[7]. In this concept, several constellations of 18 "mirror satellites" are parked at an orbit of about 1,000 km. These mirrors are used to augment the solar energy of an array of ground-based solar electric stations distributed around the world. The mirrors will provide an additional 2 $kWh/m^2/day$ to the ground-based stations.)

GSO

GSO is an interesting choice for a space settlement. GSO is an orbit about 36,000 km above sea level that rotates at exactly the same speed as the Earth.

What are the problems with GSO?

• As Globus pointed out in "Space Settlement: an Easier Way", radiation outside the Earth's magnetic field is quite literally a "massive" problem. Any human settlement located there would require 6 to 7 tons of water or it's equivalent in radiation-blocking material per square meter of habitat. And because the most dangerous radiation is cosmic radiation, that material would need to permanently surround the settlement in all directions. A second drawback to GSO is that, like LEO, there are essentially zero ISRU materials at GSO, other than what might be scavenged from space debris.

What are the advantages of GSO?

• Similarly to LEO, we already have some debris material there that could be used to fabricate the beginnings of a space settlement.

• GSO isn't as far down Earth's gravity well as LEO, and thus resource materials from the Moon, asteroids, and comets should be easier and less expensive to procure.

• GSO has been proposed as the locus of solar power satellite systems[8]. A nascent GSO settlement could find employment constructing or repairing any equipment operating there.

Recall that GSO refers to GeoStationary Orbit, or an orbit that doesn't move in relation to the surface of the Earth. There are several proposals for beaming energy from GSO to a specific point on the Earth's surface, where the ecologically friendly energy is converted back into a useful form.[9, 10] Such a solar power beaming system would be enormous, and would clearly require a substantial human presence during construction.

EML1

The EML1 "island" varies between about 55,000-61,000 km from the Moon's center, and always sits directly on the Earth/Moon centerline.

One disadvantage EML1 has compared to LEO and GSO is obvious; it's almost as far away from Earth as the Moon is, which means it will take significantly more fuel and/or time to get to it from Earth than to either LEO or GSO. It also has all the issues with radiation that GSO has. But it also has many advantages, as will be shown below.

LO

It takes about as much fuel to get from Earth to LO as it does to get to EML1, so in that regard the two possible space settlements are a wash. There could be a slight radiation advantage to a LO settlement over a GSO or EML1 settlement, since, assuming the LO settlement was not in a "sun synchronous" orbit (i.e., always in the sun), the Moon would effectively block the sun for part of the settlement's orbit, reducing the sun's radiation accordingly.

The Moon

The Moon, obviously, has a tremendous advantage in being a massive source of ISRU material. It also has at least three disadvantages: First, it's much farther from Earth than LEO; second, it is at the bottom of a gravity well, albeit not a very deep one; third, most of the surface is subjected to radiation unhindered by a magnetic field, although the bulk of the Moon shields any surface settlement from half the cosmic radiation of a settlement orbiting outside Earth's magnetic field.

EML2

EML2, like EML1, always sits directly on the line that connects the gravitational centers of the Earth and the Moon, and is on the opposite side of the Moon from the Earth. It takes only slightly more energy to get to EML2 than EML1 or LO. It also has all the issues with radiation that EML1 has. However, a major drawback to settlement or even utilization may be an international agreement setting aside the far side of the Moon as "shielded from terrestrial electronic transmissions" and thus potentially removing both EML2 and the far side of the Moon from consideration as space settlements.[11]

Mars

Like the Moon, Mars has a tremendous advantage in being a massive source of ISRU material. However, it has three major disadvantages: First, it is at the bottom of a substantial gravity well; second, like the Moon, it is subjected to radiation unhindered by a magnetic field, although that may be mitigated; third, it is very distant from the Earth, so much so that humans traveling there would require a vehicle that itself is massively shielded from radiation.[12]

Ceres

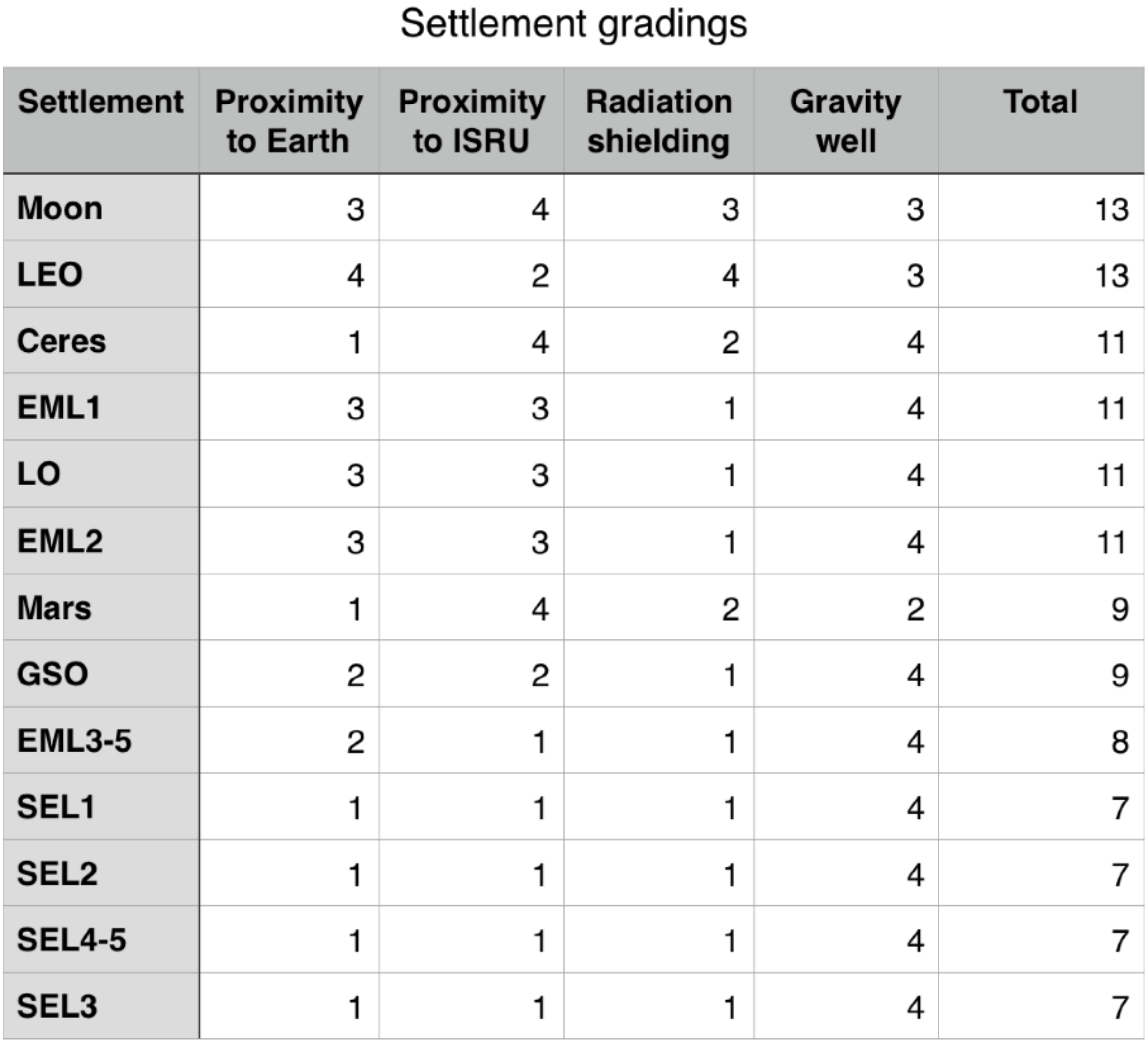
Like the Moon and Mars, Ceres has a tremendous advantage in being a massive source of ISRU material. Additionally, Ceres has a minute gravity field, which means tapping into it's resources doesn't require dropping into and out of a substantial gravity well. On the negative side, like the Moon and Mars, it is subjected to radiation unhindered by a magnetic field, but that may be mitigated. Finally, it is even more distant from the Earth than Mars. Thus, like Mars, traveling there would require a vehicle that's massively shielded from radiation.

Other Lagrange points

We will group the other Lagrange points together (choices 6, 8, 9, 11 and 13). Their collective disadvantages are their distance from the Earth, their distance from a source of ISRU material, and their requirement for massive radiation shielding. However, one Lagrange point, SEL2, does have an intriguing advantage; it is the closest point for a way station between the EM system and Mars and/or Ceres.

Grading the settlement options

The simplistic grading system in Table 1 below is far from sufficient as a means of determining the best places to begin settling space. However, Table 1 can still be useful in a rudimentary way. We have roughly graded the options (Table 1 is sorted by "Total") on the basis of their distance from Earth, their ability to shield settlers from radiation, the availability of In Situ Resource Utilization (ISRU) material, and the depth of their gravity well. Proximity to Earth grades on how much energy is required to reach the settlement location, while proximity to ISRU grades on how much energy is required to reach ISRU.



Settlement gradings

Settlement	Proximity to Earth	Proximity to ISRU	Radiation shielding	Gravity well	Total
Moon	3	4	3	3	13
LEO	4	2	4	3	13
Ceres	1	4	2	4	11
EML1	3	3	1	4	11
LO	3	3	1	4	11
EML2	3	3	1	4	11
Mars	1	4	2	2	9
GSO	2	2	1	4	9
EML3-5	2	1	1	4	8
SEL1	1	1	1	4	7
SEL2	1	1	1	4	7
SEL4-5	1	1	1	4	7
SEL3	1	1	1	4	7

Table 1

The gravity well grade varies for several reason. Even though LEO is closest to Earth and material coming from Earth can get there at the lowest cost, it has no ISRU material other than solar energy, and it is expensive getting material from outside LEO down the Earth’s gravity well. The Moon has the exact opposite problem: Because the Moon is basically made out of ISRU material, it doesn’t have to be concerned about importing space resources, but any non-ISRU material meant for the Moon’s surface has to first get up Earth’s gravity well and then get down the Moon’s gravity well. LEO and the Moon’s surface have been given an equal grade on the issue of gravity wells. Note that Ceres has the highest gravity well grade; it has lots of ISRU material and almost no gravity well. Similarly, all the EML points have a high gravity grade, since it will be easier to get space resources to them than to any point down a gravity well.

The radiation shielding grade also varies for several reason. LEO has the highest grade since the least shielding will be required, and the Moon has the second highest grade since (a) it only needs to shield from half the cosmic radiation, and (b) massive amounts of shielding are readily available. Mars and Ceres also have massive amounts of shielding. However, they have a substantially lower grade because these potential settlement sites, being extremely distant from Earth, will require massive vehicle shielding for settlers journeying there, making them extremely expensive to settle. Once there, the availability of ISRU and the blocking of half the cosmic radiation means that they have a higher grade than the EML points or LO. The EML points and LO have no naturally occurring ISRU capacity and cosmic energy would attack them from all directions, forcing them to have massive shielding that completely surrounds any prospective settlement.

Grading is by 4 levels. A grade of 4 signifies the requirement is largely met, a grade of 3 that the requirement is partly met, a grade of two that the requirement is partly not met, and a grade of 1 that the requirement is largely not met. The top contenders for settlement with a grade of 13 are LEO and the Moon's surface. In second place with a grade of 11 are Ceres, EML1, EML2, and LO. In fourth place with a grade of 9 is Mars.

<u>Mitigating issues</u>

There are many aspects of each choice that mitigate these grades. For example:

- The original goal of our settlement effort is "to expand humanity's resources and reduce environmental impacts". A settlement's ability to more directly promote development of space resources mitigates the cost of that settlement.
- As this proposal will show, EML1, EML2, LO, and the Moon's surface can be viewed as being intimately interrelated and interdependent. That is, developing any one of them lends strength to the possibility of developing all the others. Another example of interrelated and interdependent relationship would be the moons of Mars, Phobos and Deimos. Settling these two bodies doesn't require descending into the Mars gravity well. Unfortunately, little is known about the resources on either moon. Should they prove to have valuable resources, they would immediately be good candidates to add to the list.
- In the case of Mars and Ceres, distance from Earth incurred a penalty from the requirement for massive vehicle shielding for settlers, thus rating a 2 grade rather than a 3 grade like the Moon. This shielding penalty can be mitigated by at least four means:
    1. Space craft transferring humans could make use of "hibernation" technology, should that eventually become practical.[13] Hibernation technology, by requiring shielding of just the hibernation area, would theoretically reduce the area that needs to be massively shielded during transportation.
    2. "Cyclers" could be built that slowly ferry humans from Earth to the Moon, Mars, Ceres, or any other distant permanent habitat, permitting the use of massive shielding for most of the journey while greatly reducing propulsion mass.[14, 15]

3. Slower orbit-altering techniques are possible that can be used in conjunction with hibernation technology and/or cycler technology.
    - Electrical Propulsion (EP), such as an ion drive, can move through cis-lunar space slowly but much more efficiently than chemical rockets.[16]
    - Even more slowly yet even more efficiently, mass may be moved by solar sails.[17]
    - A third intriguing possibility, in light of the essence of this proposal, is the use of "laser propulsion".[18] It's possible that two laser, one at EML1 and one at EML2, could continuously "boost" a craft from LEO to EML1 in an orbit spiraling out from LEO, and vice-versa.

4. Lightly shielded humans can be moved from safe haven to safe haven if they can be moved quickly enough. One possible high-efficiency orbit-altering technique is the use of atomic energy to power human transports. Of course, sending massive amounts of radioactive material into space from Earth's surface is not acceptable. However, the Moon may have radioactive material that can be mined and refined there, with no chance of polluting the Earth.[19]

- Advanced lunar surface-to-orbit technologies are now within technological reach that can drastically reduce the cost of dropping down or lifting out of the Moon's gravity well. Note that some of these may be possible on Mars as well. Technologies include:

1. Lunar elevators. Lunar elevators are a subset of the space elevator concept.[20] Basically, it involves dropping cables from points in space onto the surface of the Moon and constructing an apparatus for hauling mass to and from orbit without the need for a rocket. EML1 and EML2 are seen as instrumental in developing this approach.

2. Mass drivers and mass landers.[21] Mass drivers are generally electromagnetic systems, although technically a really large mechanical catapult on the lunar surface could accomplish the same task. The U.S. Navy has a next-generation aircraft carrier that will use an electromagnetic launcher (EMALS) for it's aircraft slated to be operational in 2017.[22] Building such a device on the Moon would allow solar energy to be used to launch SRU material and possibly even humans into lunar orbit.

    Mass landers are the opposite of mass drivers. Consider a Navy jet "landing" into an EMALS and slowing the aircraft with electromagnetic force. In effect, the EMALS becomes a generator. This basic idea lies behind SL5S member Roger Arnold's concept of the Spaceport.[23]

3. Cislunar tethers.[24] In this system, a "skyhook" operating between the Moon's surface and a low lunar orbit tether facility "catches" payloads sent from Earth and deposits them with zero velocity relative to the lunar surface.[25] Simultaneously the deposited cargo is "replaced" with lunar cargo of the same mass, bringing that cargo out of the Moon's gravity well. The lunar cargo can then be sent back to Earth

where a second tether "catches" it, replaces it with a cargo from Earth, and sends the Earth cargo back to the Moon.[26]

Requirements for settling space

For our purposes, we will define a successful settlement as one that can eventually become economically viable. That is, the worth of the settlement must at least balance it's cost. The major costs of any settlement are the costs of the basic requirements for a continual human presence. They include:

- Shelter
- Air
- Water
- Arable land/food
- Gravity
- Trade goods
- Energy

In this proposal, we will consider these requirements for both lunar surface and LEO settlements.

Shelter

On the Moon:

Short of an Earth-like planet, space is an exceptionally hostile environment. At a minimum, a shelter would contain all the elements necessary to survive in that environment.

Essential for a livable environment is the need to be protected from radiation. We take this need for granted on Earth, since we are constantly protected from radiation by the Earth's magnetic fields. Early life on Earth, having begun deep in Earth's oceans, was even more protected from radiation.

The Moon has a far less robust magnetic field. Shelter on the Moon can only be found through exploiting natural features, by construction with imported materials, by construction with ISRU materials, or by some combination of these three. Natural features would include walls, caves, and lava tubes. Natural features would have portions that can partially or even completely shield a prospective settlement from direct sunlight, solar storms and cosmic radiation. In Table 2 of his paper "Orbital Space Settlement Radiation Shielding", Al Globus has calculated the wall thickness required on the lunar surface to shield from radiation as less than 20 mSV/year or 6.6 mGy/year.[27] If the shielding were polyethylene ($(C_2H_4)_n$) or water, then the shielding might need to be 6,000 to 7,000 kg/m^2. If the shielding were regolith, the mass would increase to 11,000 kg/m^2. Roughly speaking, we can assume 2 g/cm^3 or 2,000 kg/m^3 for regolith mass density.[28] That suggests the regolith would need to be about 5.5 m or 18 feet thick to adequately protect a lunar settlement from radiation.

Shelters would also provide for warmth during the two week long lunar night. In extreme cases, such as a settlement situated in Shackleton Crater at the Moon's south pole, shelters would need to be provided warmth on a continual basis.

Shelters or portions of shelters imported from Earth are obviously possible but expensive, since they need to be moved to lunar orbit and then dropped down the Moon's gravity well. Over time, ISRU can greatly reduce those shelter portions that require the importing of material.

Shelter on the Moon can also be constructed by drilling, digging, or boring holes or tunnels, then sealing them afterwards, or by covering shelters with large amounts of lunar soil. Shelters would be one of the first uses of ISRU by lunar inhabitants.

One of the best radiation barriers is water. Long before a large lunar settlement would be expected to exist, water would be sought out and mined by robot prospectors. If the quantities of lunar water prove large enough, settlers might begin beneath artificial reservoirs used to temporarily store mined and refined water.

In LEO:

With the exception of "lifeboat" shelters for protection from the inevitable massive solar storms, shelters in LEO can be far less massive than on the lunar surface, assuming settlement at about 500 km in altitude and circling the equator. In Table 4 of the Globus paper "Orbital Space Settlement Radiation Shielding", it is calculated that polyethylene shielding could be as little as 0.01 tons/m^2 at an orbital altitude of 500 km. However, as was pointed out earlier, other than materials converted from space debris, shelter will depend entirely on materials imported from either Earth, passing asteroids/comets, or the Moon.

Air

On the Moon:

There is a large amount of oxygen (O2) available in lunar material.[29] In addition, once obtained, air can be recycled, especially if an ecosystem can be created using lunar farming to generate O2 from carbon dioxide (CO2) expelled by human and animal settlers.

One vital volatile for any settlement of humans and plants that isn't likely to be easy to acquire via SRU or ISRU will be nitrogen. One possible method for acquiring nitrogen might be to "harvest" it from the Earth's atmosphere. One possible means for harvesting it would be to utilize a Liquid Air Cycle Engine (LACE).[30] In the LACE engine, a heat exchanger chilled by liquid H2 liquifies a quantity of the air it passes through. The air is then separated into O2, N2, H2O and CO2. Finally, the now-warmer gaseous H2, the liquid N2, and the H2O and CO2 solids are dumped overboard, while the liquid O2 is burned in the rocket engine, theoretically reducing the mass of the rocket for a given lift capacity. However, if the non-O2 constituents were stored rather than dumped, it would constitute an important cargo. Thus, an intriguing possibility would be the development of a rocket that literally gathers it's cargo as it achieves orbit!

In LEO:

For a LEO settlement, all non-recycled air would need to be imported from either Earth, the Moon, or a nearby asteroid/comet.

Water

On the Moon:

Provided it isn't misused, water on the Moon is not expected to be an issue for settlers. It is estimated that the Moon has hundreds of millions of metric tons of water near it's poles.[31, 32] However, the issue of "water rights" is predicted to become a major issue as lunar settlement goes forward. Peter Kokh of the Moon Society views shipping H2 off the Moon as "a crime against the Moon's future".[33]

In LEO:

For an LEO settlement, all non-recycled water would need to be imported from either Earth, the Moon, or a nearby asteroid/comet.

Arable land

Once a sheltered area on the Moon is secured, a portion of it can be set aside for growing vegetation. All human and animal waste could be recycled into the readily available lunar soil. A farm on the Moon might resemble one on the Earth, albeit with sunlight being artificially provided for at least two weeks out of every month. Alternatively, hydroponic gardening could be used, although it would require substantially more fabricated equipment.

For a LEO settlement, all soil would need to be imported from either Earth, the Moon, or a nearby asteroid/comet. Consequently, some form of hydroponic gardening would almost certainly be used.

Gravity

On the Moon:

Gravity has become an important issue for the future of any space settlement. In the Globus paper "Space Settlement: an Easier Way", only a little attention was paid to gravity issues on the Moon (pages 12, 13). Some assumptions were made as well.

Assumption 1: Lunar settlements cannot be rotated as easily as free space settlements can.

Rebuttal: The Moon has no atmosphere. With proper magnetic levitation, any structure can be put into rotation and stay in rotation for very long periods with only a tiny amount of energy. With the full use of ISRU, it will prove far less expensive to build rotating lunar settlements on the Moon than it would in free space.[34]

Assumption 2: Living full time in the 1/6th lunar gravity would give the inhabitants "very weak muscles and bones".

Rebuttal: It is unknown at this time the degree of tolerance that humans have for 1/6th gravity. In fact, it's possible that a "Earth gravity" rotating lunar area will be required for only part of the time. It may be that lunar settlers will be required to sleep in a 1 g environment, or possibly only be required to spend part of their time "working out" at 1 g in a rotating gym. This might simply need to become a way of life for lunar settlers - exercise at 1 g every day for two hours out of every twenty four.[35]

In LEO:

In the Globus paper "Space Settlement: an Easier Way", a good case is made for much smaller diameter, faster spinning habitats than has previously been felt necessary. However, the most striking reduction in mass for LEO habitats has less to do with spin speed and diameter reduction than with elimination of radiation shielding. And there is at least one argument in favor of a larger, slower spinning habitat at LEO:

For a 112 m diameter torus with a height of 20 m and a width through the torus of 10 m, the total habitat area is equal to 3,204 m^3. If we assume a torus with the same height and width but 4 times the diameter, the edge-on surface area is also 4 times larger. Assuming rotation in the orbital plane, the area of both habitats impacted by remnant air at 500 km over the Earth's surface, thereby requiring station keeping, would be proportional. However, the total habitat volume has increased to 13,760 m^3, or 4.3 times larger. Note that this difference is magnified significantly if the width through the torus is increased. That is, a larger habitat will have a proportional requirement for station keeping, but will have a larger area for habitation.

Trade goods

On the Moon:

A viable settlement will also have something worth trading for. Clearly, ISRU materials represent a huge source of trade goods. In return for those goods, a moon settlement gan trade for:

- Materials, such as nitrogen.
- Equipment, including all manner of items not easily manufactured on the Moon. These will decrease as the Moon settlement creates it's own manufacturing plants.
- Professionals (doctors, teachers, equipment maintainers, etc)
- Repair/refurbishment facilities.

There is another key aspect of "trade goods" that needs to be mentioned here. By far the most likely route to settling the Moon is to first send our robots to begin exploring and mining it. Thus, many of the requirements for a Moon settlement won't apply at this stage, since robots generally don't require shelter, gravity air, water or arable land. Robots won't even be required to "earn their way" at first, since there exists more than enough reason for sending them to the lunar surface in the interest of science.

There is the possibility of eventually using Moon material for constructing a settlement at LEO. Unfortunately, until advanced lunar surface-to-orbit technologies are available, Moon material will be very expensive. Consider the cost of sending fuel meant for a settlement in LEO from the lunar surface to LO: In the 2015 SL5S analysis, we assumed a lunar lander/launcher would need 1/3 of it's mass in fuel, 1/3 of it's mass in rocket elements, and 1/3 of it's mass in cargo. To get 5,000 kg of "cargo" into LO (or to the lunar surface from LO), the transporting rocket will require 5,000 kg in fuel and 5,000 kg in rocket mass (engines, pumps, tanks, fuel tanks, etcetera). However, assuming the rocket will be reused, the rocket must then return to the lunar surface to pick up it's next load and will need fuel for the return trip. It lifted 15,000 kg and it's returning 5,000 kg. If it required 5,000 kg in fuel to get 10,000 kg in orbit, it will require 2,500 kg in fuel to put 5,000 kg back on the surface. Thus, the actual delivered fuel mass to LO will equal only 2,500 kg. And by the time it reaches LEO, it will be substantially less than that.

If the settlement were on the lunar surface in the first place it could avoid the cost of "burning" 7,500 kg of fuel plus wear and tear on the rocket just to put 2,500 kg of fuel into LO. Moreover, it could simply use the total mass of fuel and rocket for growing the lunar settlement, especially since the 10,000 kg of fuel would probably be made from lunar water, which would then be consumed, disappearing forever as a resource.

In LEO:

Unless solar power plants exporting energy to Earth are located at LEO rather than GEO, the only trade goods settllers will possess will be tourism and repair/refurbishment facilities.

Energy

In LEO:

Energy availability is not a problem for most of space up to about the orbit of Ceres, since the sun shines everywhere in vast profusion. Consequently, energy availability will not be a problem for LEO. The energy storage issue is comparatively tiny for an object in orbit around the Earth at an altitude of 500 km.

On the Moon:

For any slowly rotating body in space, energy availability can be an issue. The Moon is a classic case. Since the Moon rotates about once a month, almost every location on it's surface sees the sun for two weeks, and then no sun at all for two weeks. Fortunately for the Moon, EML1 is only about 60,000 km away.

The Lagrange point solution

Advantages of EML1 and EML2

EML1 and EML2 have many advantages:

First, because EML1 and EML2 are inherently unstable, their orbits are naturally free of space debris In the case of EML1, anything that isn't capable of station-keeping will inevitably fall either towards the Earth or towards the Moon. In the case of EML2, anything that isn't capable of station-keeping will inevitably fall towards the Moon or be hurled into space.

Second, EML1 is between the Earth and the Moon, and thus is a natural staging area between the two bodies.

Third, EML1 and EML2 have easy access to the Interplanetary Transport Network or ITN. As a result, EML1 and EML2 are logical sites for a space-based propellant depot that can transfer fuel manufactured on the Moon to orbiting spacecraft.

Fourth, EML1 and EML2 are potential sites for a lunar elevator. A lunar elevator will revolutionize access to the lunar surface.

EML1 and EML2 have one other potential advantage that happens to be crucial to developing LSRU; the potential to deliver continuous, affordable laser energy anywhere on the lunar surface. However, this advantage depends heavily on the ability to economically perform station-keeping in their vicinity.

Station-keeping at non-trojan Lagrange points

Fortunately, there appear to be several ways to keep an object in the vicinity of EML1 and EML2 with little expenditure of reaction material. In fact, it may just possibly require no reaction material whatsoever.

Halo orbits

In the late 1970's, it was discovered that use of a special type of orbit called a "halo orbit" can keep a satellite in the general vicinity of non-trojan Lagrange points with very little station keeping. A halo orbit is a three-dimensional orbit circling roughly perpendicular to the center line connecting the Earth and the Moon. One can visualize a halo orbit as resembling the child's toy of a button being spun at the middle of a string by both ends, like a jump rope. The button represents the orbiting craft and the string ends represent the gravity's of the Earth and the Moon. After much computation, it was determined that there are stable varieties of these halo orbits. Stable halo orbits in the vicinity of EML1 are about halfway between EML1 and the Moon.[36, 37, 38, 39]

"Surfing" EML1

In 1963, Giuseppe "Bepi" Colombo published "The Stabilization of an Artificial Satellite at the Inferior Conjunction Point of the Earth -Moon System".[40] 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.[41]

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 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 causes the EML1 point to move as well. Similar to the surfer, we can think of craft as balancing just in front of the moving EML1 point. When the Moon moves towards the Earth our craft would "balance" slightly more away from Moon than the EML1 point, using the Earth'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.

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 it's approximately 6,400 km journey along the EM centerline between the Moon's perigee and apogee.

Non-momentum stabilization

There is a second, perhaps even more striking aspect of Colombo's 1963 paper. In the preface Colombo states:

"The devices considered [for stabilizing] are a solar sail of relatively small dimensions, and a mechanical autonomous device." 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".

The first non-propulsive station-keeping system Colombo proposes involves the use of solar sails.[42] 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 19×10^5 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:

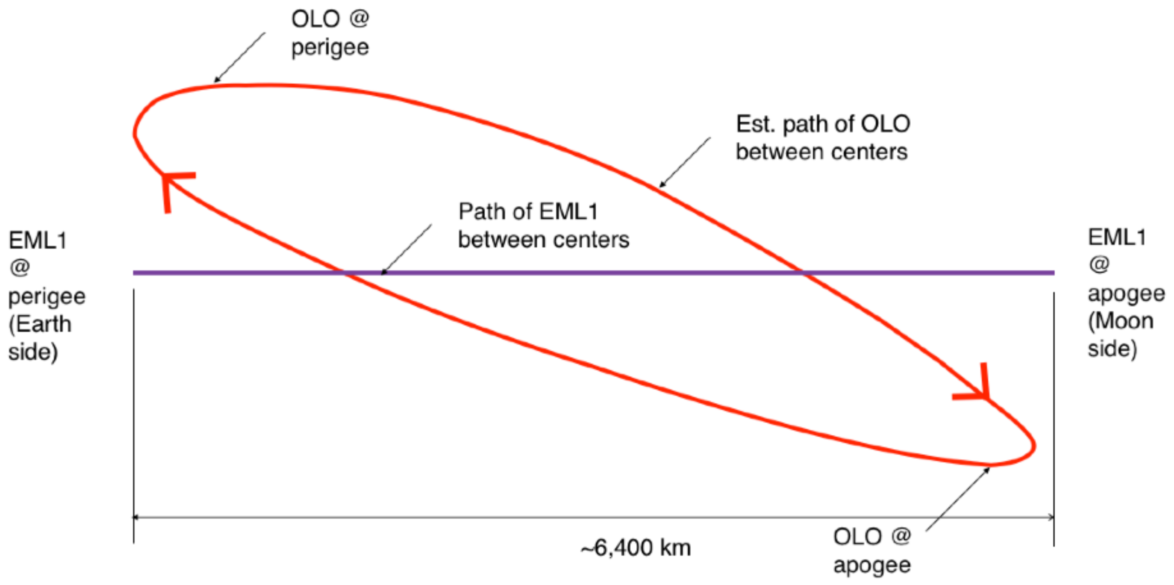


Figure 3

“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.”

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 or 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 L1 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.

Energizing the Moon

History of the 2015 SL5S analysis

What's the most practical way to sustain a permanent Moon base through the ~355 hour lunar night? On April 23, 2015, the SL5S published an analysis entitled “On the use of solar power as a means of powering a Moon Base through the lunar night” which undertook the task of trying to answer that question.[43, 44] A summary of that analysis was published in the online magazine “The Space Review” on December 14, 2015.[45]

In early 2015, as the SL5S analysis neared completion, slides of a 2009 NASA concept study were discovered which essentially paralleled the SL5S analysis to a remarkable degree.[46] Consequently, the 2009 NASA study’s slides were integrated into the SL5S analysis and used as a baseline for comparing the two approaches.

To properly compare systems between the NASA analysis and the SL5S analysis, it became necessary to develop a common “Lift Capacity” (LC) to determine relative masses in different locations. Since it takes less force to put a given mass in Low Earth Orbit (LEO) than in either EML1 or lunar orbit, and less mass to put a mass in lunar orbit than on the lunar surface, an LC is needed. The LC of one Falcon Heavy (FH) was approximated as capable of putting 53,000 kg in LEO, 17,216 kg in either EML1 or lunar orbit, and 5,739 kg on the lunar surface.

Solar energy storage systems

Assuming for the moment that the energy source for the lunar settlement is solar energy that literally disappears for two weeks on the Moon, it seems obvious that the solution is to somehow store energy up in the two weeks when the sun’s energy is available. Both the 2009 NASA study and the 2015 SL5S analysis looked at storage in general.

Cryogenic storage Regenerative Fuel Cell (CRFC) system

The preferred solution in the 2009 NASA study was the use of a “Cryogenic-storage Regenerative Fuel Cell” (CRFC) system. It was theorized, in a mature configuration, to be able to operate at a specific energy of 1,153 W-hr/kg. A mature CRFC with a mass of approximately 1,735 kg on the lunar surface would store sufficient electricity for a 5 kW continuous flow throughout the lunar night. The LC for the 2009 NASA study’s theoretical 5 kW CRFC system would equal about 0.3 FH units. For comparison purposes, a Model S Tesla 60 kWh lithium ion battery pack masses about 600 kg, equaling a specific energy of 100 W-hr/kg. That would require 20,000 kg on the lunar surface for a 5 kW continuous system, or an LC of 3.5 FH units.

One might legitimately ask where this CRFC battery technology is that has 11.5 times better specific energy than Tesla’s battery tech. The reality is, it doesn’t exist. It’s a theoretical model, and as such would require a major R&D effort to be made real, if then. For this reason, the SL5S study chose to assume yet another battery technology for all comparisons. We concluded that, using cutting edge but existing technology, Lithium-Sulfur (Li-S) batteries presently appeared to have the best potential specific energy (0.5 kWh/kg).[47] Just as importantly, issues with longevity appear to be close to solution.[48]

LO laser systems

An alternative system to the pure energy storage approach studied in both the 2009 NASA study and the SL5S analysis proposed the use of a LO solar powered laser system to fire a beam at a receiver on the lunar surface. However, the two LO laser systems were markedly different in approach.

The 2009 NASA concept study's approach 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. (Interestingly, if the NASA study had used the proposed CRFC to store the energy for the proposed FOLS, then the total estimated FOLS storage mass on the lunar surface would have been reduced by 570%, making a comparison between the two systems far more competitive.)

In the 2015 SL5S analysis, several different lunar orbiting laser systems were proposed. The simplest system, which would be useful for settlements situated either on the lunar equator or at the lunar poles, would orbit far closer to the lunar surface than the NASA system, with an orbit period of about 3 hours. It proposed an energy storage system both on the lunar surface and in orbit. In an equatorial orbit, energy would be stored for the roughly 75% of the orbit the lunar satellite was in sunlight, while in a sun-synchronous polar orbit, energy would be stored for 100% of the orbit. The stored energy would be released as a laser beam when the orbiting laser cleared the lunar horizon from the viewpoint of the Moon base, or for roughly 25% of the total orbit. Using Li/S storage technology, and assuming a 5 kW continuous delivery, the SL5S system would mass about 90 kg on the lunar surface or 0.016 FH units, and about 1,120 kg in LO or about 0.065 FH units, for a total of about 0.08 FH units, or 27% of the preferred and highly theoretical NASA CRFC system.

Lunar power generation from EML1

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.[49] On March 14, 2014, an informal "brown bag" Moon Base working group 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, then President of the Sacramento L5 Society (SL5S) and one of the mentors for Kumar and Sivaraju, suggested to Michael Abramson, a member of both the SL5S and of the NASA/Ames working group, that the group examine the possibility of powering a Moon base through the lunar night with a laser either at EML1 or in lunar orbit., since an EML1-based laser system can be used to continuously energize any point on the Earth-facing side of the Moon. Likewise, an EML2-based laser system can be used to continuously energize any point on the opposite side of the Moon.

Laser collimating

The single most striking difference between the 2015 SL5S analysis and the 2009 NASA concept study was how much less massive the SL5S analysis laser systems were when compared to the NASA study's laser systems. Indeed, while NASA analyzed the possibility of using a laser at EML1 or EML2 to power a Moon base, that possibility was rejected on the basis of how large the receiver on the lunar surface would need to be (for EML1, 11,122 m^2). The SL5S analysis posited an alternative approach that reduced the area of the lunar surface receiver for a solar-powered laser based at EML1 to a fraction of the NASA estimate.

The process for reducing the size and thus the mass of the laser receiver on the lunar surface for both LO laser systems and laser systems at EML1 and EML2 was suggested by SL5S Moon base analysis contributor Roger Arnold; laser collimating.[50] Equally as important, Arnold suggested that the collimating lens be fabricated as a thin film membrane.[51] This process is termed "Aggressive Collimating thin-film Technology" (ACT).

With ACT, the size of the EML1 LS receiver on the lunar surface could be reduced dramatically. In our calculations, we determined that a 9.6 m diameter collimating lens would reduce the lunar surface receiver dimensions to 125 m2, or 1.1% the size assumed by the 2009 NASA study. Using the 2009 NASA concept study Ground Rules and Assumptions (slide 14), a laser receiver employing "thin film (CIGS) photovoltaic technology" would possess a specific power of 1,367 W/kg and a 0.5 kg/m^2 areal density. Note that, for a laser located exactly at L1 and pointed exactly at the middle of the Moon, the receiver would be non-tracking and perfectly stationary, vastly reducing mass. For that case, the receiver mass on the lunar surface for a laser system orbiting at EML1 was estimated at about 63 kg, not including an emergency power backup system.

The laser collimating lens itself could also be reduced substantially in mass by using a thin film fresnel lens. It is estimated that a thin film fresnel lens 9.6 m in diameter might only mass about 20 kg, especially if thin film deployable structures were utilized for the lens mount.[52]

For a 5 kW continuous system, the total mass at EML1 is estimated at about 870 kg. The LC for the lunar surface portion would thus equal 0.01 FH units, and the LC for the EML1 portion would thus equal 0.050 FH units, for a total of 0.06 FH units, or (0.06/0.3=) 20% of the preferred and highly theoretical NASA CRFC system.

Aggressively Collimated Deflecting System (ACDS)

ACT can also be seen to be useful in at least two other ways. It is clear that, in space, a lightweight lens can be used to concentrate light energy, including laser energy and solar energy, with a much lower mass system than with a reflecting mirror, and with less loss of energy. But it can also reduce the mass of the reflectors/lenses required for a "deflecting system". Thus, in one use, a collimated laser beam can (1) be "condensed" by an ACT, (2) be redirected through a series of small reflectors/lenses, (3) magnified back onto a second ACT and in effect re-collimated, and be thus deflected in a different direction. Such an Aggressively Collimated Deflecting System (ACDS) would have very low mass and very low energy loss.

An ACDS could also theoretically be used to efficiently transmit solar energy from point to point, albeit over a smaller range due to the much larger diffusion angle of sunlight. In such a system, solar energy would be condensed with ACT onto a small lens, exiting as a generally parallel beam that can be redirected and transferred on toward a distant target, where the beam could be utilized or once again be condensed with ACT.

One laser ACDS use case would involve surface-to-surface power transfer. In NASA paper entitled "Lunar Surface-to-surface Power Transfer" by Thomas W. Keslake, three systems are compared for transferring power across the lunar surface, including the use of a laser.[53] In the Keslake paper, it is assumed that the power source is on the lunar surface, and the preferred Copper Cable (CC) system basically involves reeling out a cable from a central source of energy. Consequently, the mass of the laser system was considered equal to the total mass of the power source and the total mass of the laser system. If, however, the power source were located in space, that is, either in LO or at EML1 or EML2, the whole equation changes.

We can estimate the mass of a laser ACDS on the Moon, which would be made up of an ACT beam condenser, a deflecting system, and an ACT re-collimating lens as massing perhaps 50-100 kg. Using the calculations from Figure 43-46 of the Keslake paper, the mass of the laser power transfer subsystem (Figure 45) would only change by 50-100 kg, increasing from 1,777 kg to 1,827-1877 kg. That would be the total mass of the lunar surface system. In comparison, the total mass of the CC lunar surface system would equal 2,907 to 4,075 kg (Figure 46).

Of course, there is still a mass in space to be accounted for. Assuming a 15 kW delivery system from EML1 as was studied in the 2015 SL5S analysis, that mass would equal approximately 2,600 kg. However, to put a mass on the lunar surface requires, as we have said, about three times that mass in LO. Thus, the mass on the lunar surface for the CC system would equal 8,721 kg to 12,225 kg in LO, while the total comparable mass for the laser ACDS system would equal 8,081-8,231 kg. Clearly, as long as the second surface site were in line of sight, the laser ACDS system would be competitive to the CC system. And if the second surface site were a mobile device, then the laser ACDS system would be far more practical.

Lunar Polar Multi-array System (LPMS)

The Moon's polar regions represent a particularly rich source of solar energy, since the Moon's axis of rotation is almost perpendicular to the ecliptic plane. As a consequence, the Moon's "polar circles" are less than 50 km in diameter. That implies that one can place two solar receivers 50 km apart, connect them with electric cable, and send continuous solar power to a Moon base, removing the need for energy storage except as an emergency backup system. 2015 SL5S analysis contributor Michael Abramson has gone further and suggested that such a system could then "grow" away from the poles, essentially creating a lunar "power grid" of continual energy.

In Situ Resource Utilization (ISRU) on the Moon

Colonization of the Moon will be driven by ISRU development of the Moon, since ISRU development will dramatically decrease the cost of settling. Simultaneously, the more lunar settling there is, the more lunar ISRU development there will be.

Energy production and storage on the Moon will be just as inextricably bound by ISRU development. There are many ways to produce or store energy once materials are available. The "cost" of energy will drop as energy production and storage via ISRU increases, which in turn will make settlements cheaper, and so on.

The SL5S analysis concluded that, assuming ISRU were in place, many alternatives could become highly competitive to the best chemical energy storage technology.

Atomic energy on the moon

Atomic energy devices with excellent mass to power ratios are possible. However, in Earth's democratically-controlled countries, there is much resistance to the orbiting of radioactive materials. The main argument against atomic energy as a means for developing SRU is that solar can provide sufficient energy at least as economically, and with iron-clad safety.

There is one major alternative that side-steps the problem with atomic energy in space; mine and refine radioactive materials that are already in space. Radioactive materials from SRU are obviously preferable to radioactive materials launched from the Earth's surface into space. Also, atomic-powered spacecraft will eventually need to become a reality, if Mars and Ceres are ever to be settled. Atomic-powered rockets will need a fuel source that doesn't entail continuous dangerous launches of radioactive material from the Earth's surface.

There may be deposits of the radioactive element thorium on the Moon.[54] Also, significant deposits of Helium-3 may exist.[55] Helium-3 is desirable as a way to approach "Aneutronic fusion".[56]

Location, location, location: Where to begin settling the Moon?

Settling played-out lunar mines

By far the most likely route to settling the Moon is to first send our robots to begin exploring and mining it, since many of the requirements for a human-inhabited Moon settlement won't apply to robots. Mining leaves two things behind; holes in the ground, and tailings. Abandoned holes, tunnels, and tailings can supply inexpensive radiation shielding for humans interested in settling the Moon, and possibly ready-made soil for lunar farms.

Settling lava tubes

Perhaps the most desirable location for human habitation on the Moon would be old lava tubes.[57] Lunar lava tubes with a diameter as large as 500 meters may exist. It isn't hard to envision a 500 meter diameter lava tube sealed and fitted out as a lunar farm. At this time, their discovery awaits a far more aggressive exploration of the lunar surface.

One long term problem for lava tube settlements will be energy. Unless such a lava tube is located fairly close to the lunar poles, it may not be accessible at first to the LPMS grid. Fortunately, it will be accessible to a laser at EML1.

Settling Shackleton

Shackleton Crater is advantageously placed for an initial lunar settlement.[58] Shackleton Crater itself may harbor vast amounts of volatiles, since most of Shackleton Crater never sees the sun. Also, there are several other candidates for volatiles in the general area. Thus, the Shackleton area is a major candidate for future ISRU development.However, a long term settlement, in or out of Shackleton crater, will still require substantial radiation shielding, since cosmic radiation will have to be mitigated.

The intense cold that results from never seeing the sun is also Shackleton's biggest negative, even for exploratory robots. To survive in the crater itself, thermal energy will need to be continuously supplied, night and day. Short term, electricity and laser beams can supply heat. Laser beams, for example, can be converted back into electricity with very high efficiency (~80%), but waste heat will also be generated (~20%). Longer term, thermal energy is fairly easy to capture, store, and transfer with good efficiency. Use of a "chemical heat pipe" would let vast quantities of heat be chemically absorbed from solar energy during daylight hours.[59] The converted chemicals would be stored in a large "thermal pond" at the solar input site. The chemicals would then be pumped through pipes heated en route by small amounts of the pumped chemicals.

Initially, Shackleton can receive continual energy from lasers at EML1 and/or EML2. Note that the rim of Shackleton is on a massif that's raised 1-2.5 km above the general surface. That massif appears to permit the rim to continually see EML1 even at EML1's closest approach to the Moon.

Over time, the laser power from EML1 and/or EML2 can be supplemented with solar power plants situated on the highest peaks of Shackleton's rim, which will also form the beginnings of Abramson's LPMS. Eventually, the Shackleton area can expect to be plenteously and continually supplied with electrical and thermal energy both from EML1 and EML2 and from an LPMS grid extending out from Shackleton in all directions.

Establishing the Lunar Power Utility (LPU)

What is the LPU?

The LPU would be a single body which coordinates the development of lunar power as a utility or basic service. The LPU's primary importance rests in it's ability to foster the establishment of Lunar Surface Resource Utilization (LSRU).

Why is LSRU important?

- Given time, LSRU can help reduce Earth's resource and environmental pressures.

Earth's need for continued growth in resources to keep up with it's growing population is resulting in increased environmental impact and reduced quality of life. Acquiring some of the resources Earth needs from space takes pressure off the Earth for two reasons: First, LSRU will increasingly make new resources available to Earth's growing population. Second, since LSRU is inherently environmentally friendly, the Earth's environment will benefit from the acquisition of those new resources.

•LSRU can jump start full space settlement, and vice versa. As explained above, perhaps the most important reason for the failure of the original 1970's movement towards full space settlement, defined as millions of people living and working in space, was an underestimation of the problem cosmic radiation presented for people living outside the magnetic fields of the Earth. Since the only realistic way to have full space settlement is to shield against cosmic radiation, and the only presently practical system for shielding against cosmic radiation outside the Earth's magnetic field is by developing LSRU, developing LSRU is essential to the eventual achievement of full space settlement.

Why settle space?

People in space are always going to be valuable. There will inevitably arise the need to assemble and repair space-based mechanisms.

Manned missions may give more bang for the buck. How many robotic missions would it take to match the scientific impact of the Apollo Moon landings? It would be interesting to determine if, within cislunar space, manned missions are more cost-effective than unmanned missions because manned missions accomplish more.

Real time interaction with robots is important. It takes about 2.5 seconds for a signal to travel from the Moon to the Earth and then back to the Moon. That lag time will negatively impact any attempt to put LSRU into place.

Space settlement and LSRU development appear to be mutually synergistic. As shown above, ISRU development will be essential for space settlements to become practical. Since ISRU development will aid LSRU development as a whole, space settlement and LSRU development can be seen to be mutually synergistic.

Settling space can eventually help reduce the pressure of population growth on Earth. It is essential that our resources and our environmental needs be matched to our population growth. While clearly a long range goal, reducing the planet's population by settling space is a legitimate long term approach to managing humanity's burgeoning population.

Why is the Moon important?

Radiation and resources. Due to the unavoidable issue of cosmic radiation, the two most affordable candidates for space settlement are Low Earth Orbit or LEO, and the surface of the Moon. LEO's major advantage is the low mass requirements for radiation shielding. LEO's disadvantage is that the only physical resource it possesses is solar energy. The Moon's advantage is that it offers substantial physical resources, both for radiation shielding and for LSRU in general. The Moon's disadvantages are that it's farther away than LEO from Earth, and it's resources exist down a minor gravity well.

The inconvenience of the Moon's minor gravity well is outweighed by the promised access to massive lunar resources. However, to permit full-scale human settlement, the disadvantage of the Moon's distance from Earth may eventually require some form of mitigation. As mentioned above, these may include hibernation technology, the development of a lunar cycler, the development of advanced orbit-altering technologies, and various forms of "momentum exchange" transportation.

Why is the an LPU important?.

An LPU can be exceedingly competitive. Aggressively collimated laser technology doesn't rely on surface energy storage to get through the two week lunar night. As a result, it has major advantages over energy storage systems:

- Less massive and thus far less costly to transport than even the best theoretical energy storage systems.
- Will require relatively little R&D to move from theory to practice.
- Continuously projects energy to any point on the lunar surface.
- Can easily be re-targeted, while an energy storage system or atomic fission system must stay where it is landed.
- Allows for redundancy by simply adding more orbiting laser components for a given target. Large stationary systems have no inherent redundancy.
- Lasers can be used directly on the Moon for many purposes, such as prospecting and mining.

The only system capable of similar or better overall specific energy than aggressively collimated laser technology is an atomic fission power plant, which requires the launching of radioactive material from the Earth's surface. Thus, aggressively collimated laser technology will be extremely competitive with all other approaches to powering the Moon through the two week lunar night. Hence, a LPU based on the SL5S approach would have no shortage of customers.

Over time, an LPU can pay it's own way. Once established, the orbiting component of the LPU is expected to quickly become self-sufficient, generating net income. The expected income for the LPU would accrue from the price charged for energy delivered to projects on the lunar surface, creating a revenue stream that both secures funds for further LPU expansion and, eventually, pays back early investors. secures funds for further LPU expansion and, eventually, pays back early investors.

Jump-starting an LPU can jump start LSRU. The use of ACT will immediately create the potential for continuously available energy over the entire lunar surface and jump-start the LPU, which will in turn jump-start LSRU. Jump-starting LSRU is seen as a critical step towards reducing the pressure on Earth's environment and resources in a timely fashion.

The LPU can keep lunar energy affordable. Since the Moon typically has two full weeks in a row when there is no sunlight available to create energy, one of the keys to developing the Moon's resources in a timely fashion will be making affordable energy continuously available during the formative stage of lunar resource development. A publicly-owned LPU coordinating lunar power as a utility ensures that essential property for the development of lunar energy won't be controlled by a single individual, corporation, or country

The proposed LPU can start small. A complete system would require two components; an orbiting laser, and a receiver on the lunar surface. However, the initial LPU probably won't need to develop lunar surface components, since there are many entities planning to launch solar-powered instruments to the lunar surface over the next several years.[60][61] Any one of these can become a “target” for the orbiting laser. In fact, these entities can possibly both verify the usefulness of an ACT-based system and become the LPU’s first customers.

What would be the size of an initial orbiting component? The answer depends completely on whether the surface component is stationary or moving.

Assuming a lunar rover similar to the Spirit Mars Rover, the lunar rover would mass about 180 kg.[62] The Spirit Mars rover required only 0.56 kW every 24.72 hours or 0.023 kW continuous. In the 2015 SL5S analysis, the orbital component of an EML1-based laser system was estimated to mass about 2,000 kg for a 15 kW continuous system. A Spirit-sized rover would require only 0.15% of that. In theory, the mass of the EML1-based laser system would thus equal about 3 kg.

However, the mass of the collimating lens in orbit at EML1 is not related to the power of the laser. Per the SL5S analysis, to get a laser beam to the Moon with a diameter of about 13 m would require a 9.6 m diameter (72 m2) collimating lens, which is far too large for a lunar rover. The solution is to oversize the laser. As the laser beam power increases, the portion of the arriving beam that the rover needs to capture decreases. Thus, if the captured segment of the 13 meter diameter beam is 1 meter in diameter, and the amount that needs to be captured is 0.023 kW, we can calculate how much energy needs to be in the total beam.

1 m dia = 0.785 sq m.
13 m dia = 132.732 sq m.
132.732/0.785 = 169
0.023x169= 3.887 kW.

Therefore, the relative size of the EML1-orbiting component being proposed to power a lunar rover would be about 20% of the SL5S EML1-orbiting component, or about **400 kg**. That is, a 3.887 kW output laser beam on the lunar surface would have an orbital component with a specific mass of 103 kg/kW.

There is another contributing factor to the size of an initial orbiting component; it’s location. Recall that there are two possible locations for an initial orbiting laser system; in lunar orbit, and in the vicinity of EML1/L2. A lunar-orbiting laser system would require an additional energy storage mass. On the other hand, being much closer to the Moon, the arriving beam could be far smaller than one sent from EML1/L2, greatly reducing the laser system’s required output. Countering that, however, is the increase in mass required for a sophisticated tracking system on the orbiting component.

Technically, an EML1/L2 system would be much simpler, but only if it can stay in very close proximity to EML1/L2. A laser system in a halo orbit would require a sophisticated tracking system on the orbital component. In addition, in a halo orbit, depending on the lunar target (as for example a rover operating at the lunar poles), it may be necessary to have three orbiting lasers spaced approximately 120 degrees apart around the halo orbit to continuously bath the surface rover in laser light. That would increase the total mass of the orbiting system to approximately **1,200 kg**, not including the extra mass of the three tracking systems.

Note that, in the case of a lunar rover, the orbiting laser component/components is/are massively overproducing for the rover. Eventually, the laser beam(s) would expect to be redirected to a central location, where the full energy could be redistributed where it is needed.

One interesting alternative to building a full 10 m diameter ACT lens is to build only that portion of the lens that will actually be received by a small rover on the moon. Note that the laser itself would still need to be massively overproducing, but the segment of lens that is required to be orbited could be just as massively reduced in diameter. In essence, the lens could be 1/13th the diameter of a full lens, or (9.6/13=) 0.74 m in diameter. Since a 9.6 m diameter lens would be 72.4 sq m in area and a 0.74 m diameter lens would be 0.43 sq m in diameter, the 0.74 m diameter lens would be (72.4/0.74=) 1/168th the size.

It is also possible to consider a lens that was fabricated from a series of small lenses placed next to one another in a grid. While the grid would block some of the beam, the vast majority of the beam would be sent on. Thus, the 0.43 sq m lens might be constructed of 43 10 cm sq lenses. This "bee's eye" approach, coupled with the large reduction in overall lens diameter, would greatly reduce the costs for the required lens, including R&D costs, manufacturing costs, and orbiting costs. In order to create an approximation of a circular lens with a minimum area of 0.43 sq m, we'll use 55 lenses (see Figure 4 below). The diameter of the final lens assembly would be approximately 1 m.

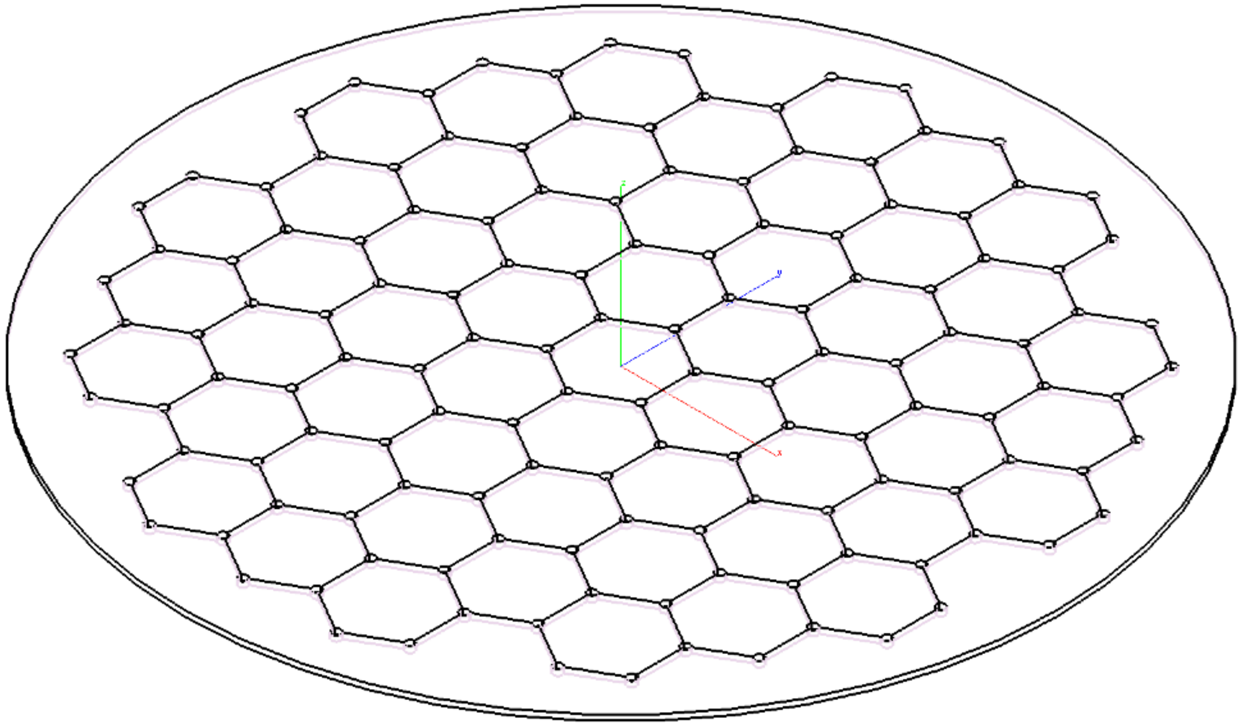


Figure 4

The proposed LPU can quickly upscale. A 400 kg orbiting laser component would massively overproduce at first. A single lunar rover similar to the Mars Spirit rover would utilize less than a tenth of one percent of the total laser beam energy ~~impacting the lunar surface~~. Over time, the laser beam could be redirected to a central location, ~~where~~and the 1 m diameter lens could be replaced with the final 10 m diameter lens, permitting the full energy of the laser beam ~~would~~to be redistributed to where it is needed with cables, microwaves, or a laser deflector system.

Undertaking a major space settlement effort will unite humanity across the planet in a common purpose such as the human race has rarely if ever seen, jump-starting the development of space's enormous cache of environmentally friendly resources that will, over time, bountifully flow back to the mother world.

The Sacramento L5 Society believes it is possible to bring that early L5 Society excitement back to full flame, and this time on a global scale. All it will take is a tiny spark at the right time and the right place. That time is now, and the Moon's surface is the place. ACT will provide the spark, and the Moon's resources will provide the tinder.

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