NIGHT-TIME POWER DELIVERY TO LUNAR OUTPOSTS WITH A HIGH-POWER GROUND-BASED LASER ARRAY

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Executive Summary: Lunar temperatures range between 90˚K and 390˚K, even at the equatorial regions. Although, the drastic changes between cryogenic and room temperatures are predictable, they are done abruptly and are complete in matter of a few hours, as there is no atmosphere to smooth the thermal processes. Temperatures at permanently shadowed craters in the polar regions and the far side of the moon may be as low 40˚K. These conditions present unique engineering challenges that require active thermal management and control during the entire duration of the ~28-days lunar day. Therefore, access to a reliable power source is a key for sustained lunar exploration and science activities planned under the Artemis program. Energy storage for the 14-days long lunar nights is not feasible. While some lunar payloads and instruments could be "turned off" half of the time, they all would prefer to have access to un-interpreted power source. And certainly, any humans on the moon would require a permanent and reliable power supply. Laser power from the Earth can be a low-cost first step, before a nuclear power source or laser power from space can deliver constant power to the lunar surface.

We suggest that electric power may be delivered to lunar outposts with a high-power ground-based laser array. For that we envision to use a 18x18 array of 0.3m telescopes on the Earth, each equipped with a high-power ~1kW laser. By employing coherent beam combination techniques (developed at JPL), we will deliver over ~5kW power to the moon which is received by a 10m diameter solar panel. The panel is delivered and erected on the lunar surface as a part of the upcoming lunar landing opportunities. A simple telescope re-pointing may allow to transmit power to multiple separated lunar assets. Relying on the presently available technology, even larger amounts of electric power could be delivered to any point on the lunar sur-face that has a direct line of sight with earth. This approach could result in smart/cost effective power generation capabilities at the early phases of the Artemis program.

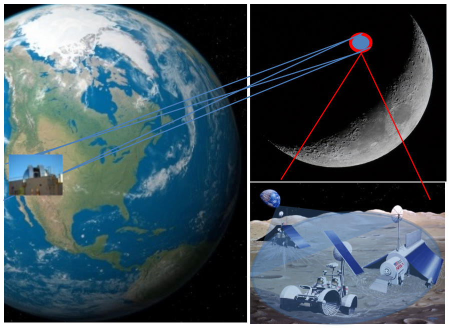

Figure 1. Concept to deliver power to the lunar surface.

Our solution relies on a coherent beam combination of many high-power CW lasers to deliver power to photovoltaic elements on the lunar surface. This approach is based on the fact that the present-day high power laser amplifiers are inexpensive. They may be combined in phased arrays for directed energy applications. Our solution will provide instruments and humans on the lunar surface with electrical power during the 14-day lunar night. Before a nuclear reactor is placed on the moon, laser beaming can supply ~5kW of power at a modest cost. To distribute power, our mission delivers and builds a changing station on the moon that could 1) supply electrical power to a nearby facility (science instrument(s)) that need power throughout the lunar night; 2) serve as an "electrical vehicle charging station" during the lunar night; 3) serve as the power source for optical power transmission to another point on the moon. High resolution differential LLR science can be a byproduct of this effort.

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1. The Nature of the Innovation

Challenge: Lunar temperatures range between 90˚K and 390˚K, even at the equatorial regions. The changes between cryogenic and room temperatures happen predictably and are done in matter of a few hours, as there is no atmosphere to smooth the thermal processes. Temperatures at permanently shadowed craters in the polar regions and the far side of the moon may be as low 40˚K.

These conditions present unique engineering challenges that require active thermal management and control during the entire duration of the ~28-days lunar day. Therefore, access to a reliable power source is a key for sustained lunar exploration activities planned under the Artemis program.

While some lunar payloads/instruments could be "turned off" half of the time, they would all prefer to have access to uninterpreted power sources. And certainly, any humans on the moon would require a constant power source. Laser power from the Earth can be a low-cost first step, before a nuclear power source or laser power from space can deliver constant power to the lunar surface.

Solution: Our propose to consider a novel opportunity of delivering significant electric power to the lunar surface via coherent combination of high-power laser beams for a subsequent transmission to the lunar surface. This process may be used to enable many critical aspects of the Artemis program, especially during the early phases of its implementation. We propose to build and operate a space-based infrastructure that relies on ground- and space-based facilities using coherent combination of many high-power lasers (~1kW each) to power lunar outposts, especially during 14-days lunar nights and locations away from human habitats.

In the ground-to-lunar surface architecture, an array of 350 small (30cm) telescopes on the Earth enables transmission of 320kW, resulting in ~5kW power received on the moon by a 100 m^2 photovoltaic (PV) panel. A moon-based laser beacon common to all lasers in the array is used to enable coherent beam combination. As such, our concept is new and relies on architectures within a space mission context that includes delivery, deployment, and operations of such a power facility.

2. Technolgical Foundation

Synergistic Efforts: Engineering of coherently combined high-power laser beaming systems with active phase control has been demonstrated to produce 10-100kW power level in laboratory conditions (Sprangle et al., 2015). To date there was no successful coherent laser beam combination in free space with a precision wavefront control correction for the air turbulence. No high-power laser beams were used to power a spacecraft in Earth-orbit and especially instruments on the moon. Until recently, it was not possible due to the lack of reliable high-power fiber amplifier technology and optical elements with required quality. Progress in the development of high-power continuous wave (CW) lasers, led to major advances. Today, 1-25 kW fiber amplifiers are available at the cost ~$65-110K, with many optical components being commercial-off-the-shelf (COTS) at affordable costs. Many space-qualified components for various laser wavelengths are also available.

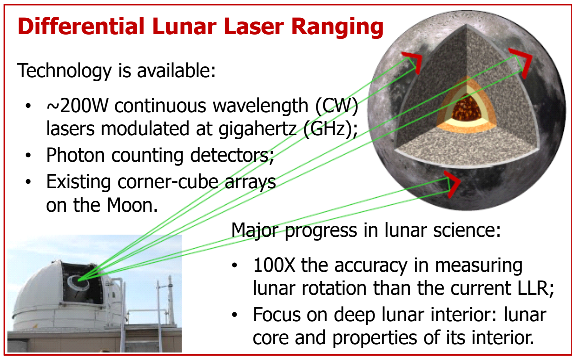

Figure 2. The schematics of the differential LLR.

These innovations were used to develop JPL's high-power lunar laser ranging (LLR) facility at the Table Mountain Observatory (TMO), CA (Figure), that we operate since 2016. This LLR facility uses a CW laser with a 1.1 kW average power at 1.6 nm. We amplitude-modulate the laser at ~0.1GHz frequencies to conduct differenced LLR measurements accurate to 30 μm (limited by atmosphere) – precision not achievable by other means.

The operational logic for our LLR facility is as follows: The seed laser is first amplitude-modulated to produce the chirp modulation that provides ranging information. Then its phase modulated to broaden the linewidth to ~10-20 GHz to avoid the stimulated Brillouin scattering (SBS) in the 1.1kW power amplifier. On return from the moon, a CCD is used to roughly point the telescope. Narrow bandpass and Fabry-Perot filters are used to limit the IR detectors to the laser bandwidth.

The IR camera provides the fine pointing information. The APD/SCNW is an IR photon-counting detector with ~1nsec time resolution. The return flux from the moon is ~10^4 phot/s as opposed to ~0.3 phot/s received by the current best LLR facility at the Apache Observatory, NM. With high photon flux, the fundamental limitation to the accuracy of the LLR is then no longer sqrt(N), but the atmospheric delay. The delay from Earth's atmosphere (~2.3 m at zenith) produces a ranging uncertainty of ~8 mm after correction using the temperature, pressure, and humidity. However, the *differenced* delay error from TMO to two or three sets of lunar corner-cube retroreflectors (CCR) can be as small as ~30 µm, not possible with other LLR means.

Figure 3. High-power fiber laser amplifier tested at 1.1KW in water-cooled beam dump.

Our experience with high-power lasers and design of the LLR facility led us to propose a practical solution for Breakthrough Starshot Photon Engine (BSPE), which would be an array of small (15-30cm) telescopes all transiting high-power fiber laser (HPFL) signals that are then coherently combined on the $4m^2$ laser sail to propel the Starshot laser sailcraft to 20% of the speed of light, see https://breakthroughinitiatives.org/initiative/3. Our solution relies on three critical elements: i) digitally controlled optical delay lines at each of the telescopes in the array, ii) fiber-enabled signal distribution approach within the widely distributed BSPE array, and iii) use of an active optical beacon for wavefront sensing purposes. We have proven that this design could lead to a practical solution of building/operating a BSPE that will be capable to coherently combine 1000 telescopes and to project a few GW of laser-power on a moving 4-m sail.

Our LLR facility and the relevant JPL technology was the basis of the solution found for BSPE. Now the same approach could be used to provide the critical capabilities of power transmission/reception at lunar outposts during lunar night-time within the context of the Artemis program. The affordable HPFL amplifiers that recently become available (Fig. 3) offer a novel opportunity to provide lunar power to the moon.

Opportunity: There is an opportunity to construct and operate the ground-and-lunar space infrastructure described in this white paper within the context of the Artemis program. The proposed facility will be able deliver significant amounts of electric power (~5kW) to lunar outposts relying on the ground- or/and space-based arrays of high-power lasers that have their output beams coherently combined at the lunar receiver with a beacon to compensate for atmospheric turbulence. The lunar receiving/charging stations will be delivered to the moon within the context of the NASA CLPS program thus enabling a significant participation from the private industry. The high-energy laser beam is received by the PV elements, transformed into electric energy and either stored locally and/or delivered to end users to ensure their survival through 14-days lunar nights. This approach could result in effective power generation capabilities, especially important at the early phases of the Artemis program. It may become a critical part of the BPS activities on the moon.

3. Potential of the Concept and Impact

How may it be used? As our system relies on an array of small, 0.3 m telescopes it has major advantages compared to conventional high power laser transmitters. For starters, conventional adaptive optics (AO)-based systems are very complex and expensive to build and operate. Conventional moderate (3+ meter) telescopes are also expensive. They also are designed to operate in a broad-spectrum (i.e., "white light") regime. Major simplification is possible when laser light is used and when there is a cooperative beacon that may be used to compensate for wave-front errors to atmospheric turbulence. Also, a conventional deformable mirror (DM) will not survive when illuminated with a 300+KW beam. Wavefront sensor and reconstruction computer needs very fast sensors/computers. In the case of laser light with a cooperative beacon, one makes direct phase measurements and control phase and delay without a DM, thus enabling reliable operations.

To distribute power, our mission delivers and builds a changing station on the moon that could 1) supply electrical power to a nearby facility (science instrument(s)) that need power throughout the lunar night; 2) serve as an "electrical vehicle charging station" during the lunar night; 3) serve as the power source for optical power transmission to another point on the moon.

Potential Impact: There are two key elements of a lunar power infrastructure – generation, storage and distribution. Once power is available, power distribution can be done via wireless charging using laser PV capabilities. Thus, power generation is the key to success.

Previous "watts on the moon" ideas include: 1) Deliver/operate on the moon a nuclear power plant; 2) Deliver/erect large vertically oriented solar panels and/or Fresnel-lens sun light concentrators; 3) Use large solar arrays on a spacecraft in lunar orbit to capture solar light, convert it to electric power and transmit energy to the assets on the lunar surface via high-power laser transmitter.

There are technology gaps for these ideas: 1) No power from solar arrays during the lunar nights (i.e., 50% of the time). 2) One cannot solely rely on nuclear reactors to power every instrument. In fact, powering multiple separated lunar assets is another identified challenge. 3) Some solutions require specialized robotic technology not yet available. Other challenges for these concepts exist.

Although some ideas above may mature in 20-25 years, they are not practical for the Artemis program in the near term. Even at the earlier phases of lunar exploration (when we do not have a sustained human presence on the moon), we already need to operate instruments and equipment. This is why our hybrid approach offers significant advantages as we rely on power generation capabilities available on the Earth, significant laser power transmission to the moon through Earth's atmosphere and power distribution on the lunar assets – a technically much simpler task compared to the alternatives. This is the nature of our white paper.

Why is it exciting? Our solution relies on a coherent beam combination of many high-power CW lasers to deliver power to PV array elements on the moon. It is scalable. The HPFL amplifiers may be combined in phased arrays for directed energy applications. We were awarded a grant from the Breakthrough on phasing multiple high-power lasers for their BSPE. A similar approach will work for laser power transmission to the lunar surface. Our solution will provide instruments/humans on the moon with electrical power during the 14-day lunar night. Before a nuclear reactor is placed on the moon, laser beaming can supply ~5kW of power at a modest cost.

Phasing an array of lasers through the Earth's atmosphere is more difficult than phasing such an array in space powered by large solar panels. But the architecture can also be used for future space to lunar night facilities. The phasing techniques describe in this proposal can phase a large aperture laser transmitter in space that is assembled with millimeter accuracy but phase to 10's nanometer. Transmitting a shorter distance (e.g., 40,000km instead of 400,000km) would mean power transmission efficiencies of up to 50%, supplying 10s of kW, potentially a medium-term substitute for nuclear reactors. Because of the shorter distance, e.g., from L1 to lunar surface or L2 to backside of the moon, could transfer 50kW to the moon. This allows for significant commercial activities in cis-lunar space that may involve several private space companies offering power as a service.

Why is it credible? Delivering an instrument to the moon does not represent a challenge. NASA/JPL have done that before. Now, working with many commercial partners, under CLPS program and especially the Artemis program currently unfolding, these efforts are going to be even more exciting. We have also studied the deployment and operations of multiple instruments on the moon (new CCRs, magnetometers, seismometers, etc.) for Lunar Geophysical Network (LGN). The experience from the ongoing lunar efforts (LLR, GRAIL, LRO) and LGN studies have told us that deploying and operating power station on the moon is feasible.

Specifically, the proposed work draws on our experience of working with the HPFLs at the advanced LLR facility that we built at the JPL TMO facility and the development of new CCR instrument for a deployment on the moon (Turyshev et al, 2012). That facility is used in our ongoing study of the BSPE facility to accelerate a chip-size spacecraft to 20% of the speed of light.

Current kW-class fiber lasers have up to ~10 GHz linewidths. The 10 GHz linewidth is typically generated by starting with a narrow line laser. In our current setup with a 1.1 kW laser at JPL's TMO we start with a < 1 kHz linewidth. Another starting point is the use of a 1 GHz thermal white noise source and an electro-optical modulator (EOM). How to obtain the desirable 10 GHz broadening of the 1 kHz laser with a 1 GHz thermal source? One does that by overdriving the EOM.

When the phase modulation of the EOM is > 2π, this leads to generating harmonics that produce a laser linewidth that is 10 GHz wide even though the RF signal to the EOM is only 1 GHz wide.

Our approach of phasing a multi-component high-power laser had solved the Breakthrough's Photon Engine problem. The presence of the common laser beacon is a key to coherently combine many high-power lasers beams at a PV array on the moon. This differentiates our approach from other proposals (Enright & Carroll, 1997; Landis 2020; Grandidier et al., 2021) that only present conceptual designs and lack means of practical implementation in realistic conditions either from the ground or space. The same approach could be used to deliver high power to the lunar surface.

4. Technical Approach & Methodology

Potential implementation: To provide electric power to a user on the moon via a coherent combination of high-power lasers, the power must be generated, delivered, and distributed. Power delivery to the lunar surface may be done relying on three different architectures 1) ground-to-surface (g2s), 2) space-to-surface (sp2s), and 3) surface-to-surface (s2s). As the s2s architecture suffers from the same power outage challenge during 14-days lunar nights, it will not be considered here.

The ground-to-surface laser power facility consists of three main elements:

1. A ground-based array of high-power lasers that are coherently combined to transmit a high-power laser beam toward the moon (Xmit)
2. A receiver on the moon with photovoltaic (PV) elements (Receive)
3. Power distribution system (either wired or wireless) to deliver power to end users.

The relevant ground-to-space power infrastructure is broadly discussed next: We envision that laser power generation is done with the ground-based high-power laser transmitter array that uses an array of *N*=350 of small (30cm) telescopes, each equipped with a high-power ~1kW laser, transmitting 320 kW of beamed power. By employing coherent beam combination techniques, the facility will allow for delivery of ~5kW power to a 100 m^2 receiver with PV elements separately built on the lunar surface (Table 1). To avoid weather interference with power delivery, several arrays may be built in different deserts around the globe. Power to operate the array is sourced from local power plants. We will explore solar energy as a source of green operations with renewable energy.

Table 1. Anticipated power xmit efficiency.

	Earth-Moon
Total xmit, W	3.20E+05
Wavelength, um	1
Apperure, m	0.3
N of telescopes	350
Total dia, m	5.612
Spread, rad	1.78E-07
Distance, km	400,000
Footprint, km	0.071
Solar panels, m	10
Linear loss	0.140
Quad loss	0.020
Cell efficency	0.8
Total eff	0.016
Power avail, W	5,040

The receiver on the moon, is an inflatable 100m^2 PV panel with high-reception power capability, low mass, suitable for robotic deployment, and ability to support multiple lunar users. The PV elements are optimized to work at the chosen laser wavelength. A bank with space rigidized rechargeable LiNe batteries is used to store the energy locally.

Power transmission efficiency is optimized by using a cooperative beacon at the receiver to correct for the wave-front errors (WFE) due to atmospheric turbulence. The proposed system also relies on distributed wavefront sensors (*N*=350) to measure both the delay and phase of the wavefront from the beacon. Corrected delays and phases are distributed to an array of fiber amplifiers (*N*=350) to combine coherently on the moon. A sensors/transmitter share the same ground-based telescope (~30cm, with 1 arcsec seeing limited performance). Optical heterodyne detection (common for the seed and acousto-optical modulator (AOM) is used to detect the phase delay associated with local fiber network for *N* channels. The system uses an arbitrary waveform generator (AWG)/pseudo-random code to broaden bandwidth of each fiber amplifier and correct the phase delays by a timing offset. (Note that without the cooperative beacon on the target, the ground-based array may not be used for other directed energy applications.)

A smaller gimbaled laser transmitter integrated with the receiver will be used to transmit power to lunar assets, also with PV elements, that are in direct line of sight and separated by up to 1km.

The receiver itself will be delivered and erected on the lunar surface as a part of an upcoming lunar landing opportunity. For that, a small lander with a robotic arm will be used to deliver the inflatable panel to the moon, place it on the surface and orient it toward the Earth.

With technology presently available, even larger amounts of electric power could be delivered to any point on the lunar surface using space-based solar panels. In this case, the space-to-surface laser power facility essentially consists of four elements:

1. A space-based solar power plant located either at L1 (to serve the near side and polar assets) or at L2 (for far side and polar assets) with PV elements to convert sunlight into electric power.
2. A space-based array of high-power lasers that are coherently combined to transmit a high-power laser beam toward the moon (Xmit). This array is co-located with the powerplant.
3. A receiver on the moon with laser PV elements
4. Power distribution system (either via a wired or wireless) to deliver power to end users.

The space-based solar power essentially collects solar energy in space with reflectors or inflatable mirrors onto solar cells that directly convert sunlight into electricity. This space-based component needs no protection from terrestrial wind or weather but will have to cope with space hazards such as micrometeors, solar flares, and degradation due to the space environment.

Laser power transmission through the atmosphere requires that we correct for atmospheric turbulence. We propose to use EOM to control the phase/delay instead of more expensive high power deformable mirrors (DM). A number of $N x$ AWGs with a single pseudo-random code (with timing offset) can be used to match delay/phase. A cooperative beacon uses a chirped signal to measure the absolute geometric delay, and to correct for the wave front errors (WFE) associated with air turbulence. To broaden the linewidths of the lasers, we use *of a pseudo random noise source*. Finally, our solution also uses *a chirped laser source as the beacon*. We also use *a fiber-enabled signal distribution* with the widely distributed array. (Technical details on the design of the proposed facility will be provided to the NAS BPS Decadal upon request.) To access the full potential of the proposed concept, a technology demo mission to the lunar surface may be developed to demonstrate power transmission and distribution on the moon with a smaller 5x5 array (~100We).

Deployment/representative mission: The receiver with an inflatable $100m^2$ photovoltaic panel described here, with its high-reception power capability, low mass, and suitability for robotic deployment, could support multiple lunar missions. Among those is the development of the Artemis program and CLPS program activities where power on the moon is identified among the highest priorities. Commercial opportunities include SpaceX, Astrobotic, Masten Aerospace, Blue Origin, and others that plan to land on the Moon in the next 6 years. Our receiver instrument could support these missions either via NASA's Discovery, New Frontiers or SALMON Programs.

The receiver instrument must be deployed to point at the mean Earth to ~15° and have the largest dimension to be parallel with the Earth's equator. An enclosure would be designed to provide lifting points for the lander robotic arm to pick up and deploy on the surface. After landing, the robotic arm lifts the enclosure from the lifting point specific to the actual landing location. To simplify deployment, the instrument would be mounted at the lander external panel. A dedicated mission to deploy several such panels on the moon from a lunar orbit is possible. Thus, our facility includes ground and space-based segments that will be investigated within a mission context.

As the next phase, we envision the "all-in-space" architecture where power generation will be done in space by a farm of PV elements that use solar power to generate electricity. That power may be stored in space using a bank of LiNe batteries for a subsequent transmission to the users on the lunar surface. In this confirmation, the beacon is less critical but still an important part for coherent beam combination and power transmission. Our analysis suggests that we may be able to deliver up to 50kWe to the lunar-based segment. We will investigate such an important extension.

Cost and Schedule: A tech-maturation effort required for the ground segment as a verification of generation of high power in a typical Earth's atmospheric conditions. A ROM cost/schedule estimation for the key tech-maturation of the ground segment is $5M/2year. A lunar tech-demo mission with a scalable architecture is recommended before the full implementation. A ROM cost/schedule estimate for a 3x3 array tech-demo mission (~80We) is $75M/3 year and the full scale 18x18 array facility (~5kWe) is $165M/4.5 year. The cost estimate is based on the actuals of the NASA's Deep Space Optical Communication (DSOC) mission. The cost and schedule information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.

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