ABSTRACT

Space Solar Power technology offers unique benefits for near-term NASA space science missions, which can mature this technology for other future applications. "Laser-Photo-Voltaic Wireless Power Transmission" (Laser-PV WPT) is a technology that uses a laser to beam power to a photovoltaic receiver, which converts the laser’s light into electricity. Future Laser-PV WPT systems may beam power from Earth to satellites or large Space Solar Power satellites may beam power to Earth, perhaps supplementing terrestrial solar photo-voltaic receivers. In a near-term scientific mission to the moon, Laser-PV WPT can enable robotic operations in permanently shadowed lunar polar craters, which may contain ice. Ground-based technology demonstrations are proceeding, to mature the technology for this initial application, in the moon’s polar regions.

Introduction

Space Solar Power technology, including Laser-Photo-Voltaic Wireless Power Transmission (Laser-PV WPT) may be used in a promising NASA space science application to power robot operations in dark craters at the moon’s North or South pole. As Figure 1 illustrates, the moon’s spin axis is nearly perpendicular to the plane of the ecliptic, so the sun never shines in the polar craters. Therefore, the craters are cold enough to preserve ice for billions of years, even in the hard vacuum of space. Radar from Arecibo and the Clementine spacecraft suggests the presence of ice in these regions, and data from the Lunar Prospector spacecraft confirms that a significant concentration of hydrogen (e.g, in frozen water) exists near the moon’s poles. Ice deposits in lunar polar craters may record a long history of major astronomical events such as comet impacts on the moon, and potentially large impacts in the Earth’s ocean’s. Lunar polar ice could become a source of water, oxygen, and propellants for future human exploration and development of space. Laser-PV WPT can beam power from a permanently sunlit mountaintop at the moon’s North or South Pole down into permanently shadowed craters, to enable long duration, "power-rich" robot operations that investigate the contents of lunar polar craters.

Lunar Polar Mission Scenario

The general mission scenario for the exploration of these shadowed craters is illustrated in Figure 2. A lunar lander descends to a selected, continually sunlit region on a mountaintop near the moon’s North or South Pole. The lander deploys a rover and photo-voltaic arrays are extended on both the rover and the lander. A laser system on the lander transmits power to the photovoltaic
receiver on the rover, initially checking out Laser-PV WPT operation and rover subsystems on the sunlit mountaintop. The rover then descends into shadowed regions along a pre-planned route using power beamed via laser from the lander. Deep in a permanently shadowed crater, the rover performs power-intensive scientific experiments, such as drilling, continuing to laser-PV WPT from the mountaintop. This beamed power provides warmth, electricity, and illumination for a robotic rover to perform scientific experiments in cold, dark craters where other power sources are impractical. The concept of using Laser-PV WPT for such a mission to the moon’s polar craters was first published by Canadian researchers (Enright and Carroll, 1997), and was independently suggested by researchers in Japan (Takeda and Kawashima, 1999) and in the USA (Potter, Willenberg, Henley, and Kent, 1999).

Data from the Lunar Prospector spacecraft’s neutron spectrometer (Figure 3) indicate that hydrogen is concentrated at the moon’s poles, presumably in the form of frozen volatile gasses, including water ice. Radar reflections suggest that water ice is indeed present in certain lunar polar craters. The total permanently shadowed area around the moon’s North and South poles is estimated at 7,500 and 6,500 square kilometers, respectively (Bussey, 2002). Ice deposited in these regions over the last 2.5 billion years may contain a stratigraphic record of tremendous value for Space Science, indicating the sequence, types, and sources of frozen volatiles, potentially derived from comets, asteroids, interplanetary dust, interstellar molecular clouds, solar wind, lunar vulcanism, and radiogenic gas production (Lucey, 2002). Earth Science may also be advanced, as comet fluxes and significant Earth (ocean) impacts, both linked to major episodes of extinction of life on Earth, may be recorded in distinct strata in lunar polar ice deposits. Ice resources at the moon’s poles could provide water and air for human exploration and development of space, as well as rocket propellant for future space transportation.

Candidate mountain-top landing sites that appear to provide near-continuous sunlight and proximity to high hydrogen concentrations are also shown in figure 3. A landing site must be chosen carefully so that outpost remains in full sunlight over many months as the moon rotates once per month around its slightly inclined axis. Landing site selection should also consider direct, communications with Earth, and local terrain features that might obstruct local line-of-sight communications and Wireless Power Transmission to a rover on the moon’s surface.

Lunar topography near the North and South poles illustrated in Figure 4. Topographical features are significantly more pronounced at the South pole (at the edge of the Aitkin Basin, an area of particular scientific interest). In this region, the range in elevation is roughly 12 kilometers between the highest peaks and deepest craters.

The effects of local topography determine maximum laser range, as is illustrated in Figure 5. In this example, a WPT beam from a 1 km high mountain can travel 50 km before it is obstructed by the horizon. From the top of a 6 km high mountain, the WPT range increases
to 120 km before the beam grazes the horizon. The range can be extended further with laser projection into deeper craters. Relay mirrors are of particular interest as they can extend laser range and allow transmission of light into all areas of the lunar polar craters. Laser range may be also be extended by beaming between one mountain and another.

Approximate laser range from a candidate mountain-top landing site near the moon’s South pole is illustrated in Figure 6. This site, labeled as point E, allows direct communications with Earth as well as communications and laser transmission ranging up to 200 kilometers, including access to the moon’s South pole. Peaks identified as A, B, and C are closer to the South pole, but the moon’s orbital motion leaves them without direct sunlight in portions of the “winter season” (when the pole is tilted one and a half degrees away from the sun). This region also looses direct line-of-sight communications to Earth for roughly half of each month. Peaks at the D and E appear to briefly shadow each other, at least for several hours each month during the South Pole’s “winter” season. The peak labeled E has a more pronounced altitude gradient in the North-South direction, which is desired to minimize solar panel height to receive full sun during winter (deWeerd) and to enhance line-of-sight Laser-PV WPT and communications toward the Earth and the South pole. The peak F spot is high, and close to one of the deepest, most hydrogen-rich craters, but it is too far from the South pole to be in constant sunlight.

Figure 7 illustrates an example lunar roving vehicle path in the vicinity of the moon’s South pole. The rover’s primary mission proceeds from an Space Solar Power outpost on Peak E, down into a hydrogen-rich spot labelled G, deep in the bottom of the deepest crater. The rover’s path covers a traverse distance of approximately 200 km, with a 12 km decrease in altitude. Within this deep crater, Laser-PV WPT, with a line-of-sight range close to 100 km, provides the rover’s only power source. As a secondary mission objective, following thorough investigation of the crater, the rover may traverse upward, out of the crater, to reach and research other locations, potentially visiting the geographic South Pole and perhaps even returning to the original point of departure.

A large rover is needed to perform such a long distance traverse. Due to the large Laser-PV WPT ranges involved, a fairly large photo-voltaic receiver will be needed, also implying a fairly large rover. NASA’s Marshall Space Flight Center and Boeing have already developed a large rover, the Apollo Lunar Roving Vehicle (LRV, and flight-proven it over significant ranges on the moon (Figure 8). LRV units remaining from Apollo could even, potentially, be modified to perform the mission described here.

Technology Development
Technology demonstration activities are proceeding to demonstrate Laser-PV WPT technology on Earth, in advance of a lunar polar mission, as a cooperative effort between Government, aerospace industry, and academic institutions. Harvey Mudd College has developed a specialized laser beam expander (Figure 9) for precise beam pointing and focusing, allowing long distance power
transmission. Initial tests of this laser transmitter over modest ranges (Figure 10) found minor imperfections in the primary mirror, but managed to maintain near constant beam dimensions over a one kilometer range. For longer range ground demonstrations (on Earth), atmospheric transmission issues become more significant and laser wavelengths must be selected accordingly (Figure 11). Using an 830 nm laser wavelength (with high atmospheric transmissivity), and Galium Arsenide photovoltaic cells, the University of Colorado-Boulder has achieved close to 70% percent efficiency in converting laser light into electricity (Figure 12). [34% efficiency was achieved in similar Japanese research using an 805.8 nm wavelength and Silicon photovoltaic cells (Takeda and Kawashima, 1999)]. The University of Colorado-Boulder has also developed prototype photo-voltaic receivers for small remotely controlled rovers (Figure 13), including a beam-concentrating reflector, designed to efficiently receive an expanded laser beam with a gaussian intensity profile (Figure 14). Carnegie Mellon University has developed a larger photovoltaic powered rover for lunar polar technology demonstrations (Figure 15), and is assessing system modifications for Laser-PV WPT research purposes. NASA and Boeing are integrating these components for ground technology demonstrations.

Ground testing of Laser-PV WPT for lunar polar applications is proceeding in the state of Hawaii (Figures 16). State-of-the-art laser research facilities exist on top of Mount Haleakala at NASA's Lunar Ranging Experiment (LURE) observatory and the Air Force Maui Optical and Supercomputing (AMOS) site, and this geometry, beaming down from a mountaintop, is similar to the geometry of the lunar polar technology application. Unique long-range power transmission experiments are possible here, similar to the ranges expected for lunar polar Laser-PV WPT applications, and the air is exceptionally clear, minimizing atmospheric effects. Candidate power receiving areas include local terrain that is similar to lunar terrain, including finely divided soils, and craters (of volcanic origin, rather than meteoritic origin). Apollo LRV operations were previously tested in this area, and it is a logical location for further research and development of a large lunar rover.

**Conclusion**

Space Solar power technology, including laser-Photo-Voltaic Wireless power Transmission, is enabling for near term robotic missions to investigate potential ice deposits in lunar polar craters. Technologies demonstrated and matured via lunar polar applications can also be used in other NASA science missions (Valles Marineris, Phobos, Deimos, Mercury's poles, asteroids, etc.) and in future large-scale SSP systems to beam energy from space to Earth. Continuing activities should increase transmission distances, power levels, and efficiencies, in preparation for a near-term space science and technology demonstration mission.
References


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Space Solar Power Technology Demonstration for Lunar Polar Applications

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October, 2002
The National Research Council recently found that a mission to the moon’s south pole-Aitken Basin has high priority for space science. A photo-voltaic-powered rover could use sunlight, when available, and laser years’ recording prior impact events on the moon (and Earth) Craters may hold frozen water and other volatiles deposited over billions of shaded craters that are believed to contain ice. A lunar polar mission could demonstrate and validate Laser-PV WPT and other SSP technologies, while enabling access to cold, permanently

NASA Marshall Space Flight Center Technology for Laser-PV Photo-Voltaic Wireless Power Transmission (Laser-PV WPT) is being developed for lunar polar applications by Boeing and

For Lunar Polar Applications Technology Demonstration Space Solar Power
Overview of Mission Concept
Lunar Polar Technology Flight Demonstration
South Pole > 85 degrees

LETTERS indicate candidate Laser-PV WPT sites

Dark Blue indicates highest Hydrogen concentration

From Lunar Prospector Spacecraft

Neutron Spectrometer Data
Note Difference in Vertical Scale!!

To the Moon's North and South Poles

Radar-Derived Topography

South Pole > 85 degrees

North Pole > 85 degrees
Laser Range Depends on Topography

Transmitter on lunar mountain could beam power > 100 km

120 km Range (to horizon)
1 km high mountain
50 km Range
Deep Crater
Relay Mirror OptIon
Further Range

WPT from Lunar Mountain top
(horizontal scale exaggerated)

Horizontal Scale
0 50 100 km
Candidate for Lunar Laser-PV WPT Mission:
Apollo Lunar Roving Vehicle (LRV):
Initial Transmission of Expanded Beam

- Mid-Range (~1 Kilometer)
- Short-Range (~1 Meter)
- Major Impurities from Diamond-cut Primary Mirror
- Image Distortion due to 3 Hole
- Mounting of Primary Mirror
- Corrected by Replacing Mirror

main beam 10 cm

aperture 10 cm
Laser-Photo-Voltaic Wireless Power Transmission

Argon (488 & 514 nm)

Cryogen (830 nm)

Krypton (1064 nm)

Wavelength, nm

0 750 1500 250 500

Atmospheric Transmission (%)

Ground Technology Demonstrations

Atmospheric Transmission Issues for

Comensation call for active

Shimming wavelengths shorter significant at shorter scattering is selection wavelength influences absorption WPT demos long distance significant in air mass is

Boeing

NASA
Laser-Photo-Voltaic Wireless Power Transmission

vs. Laser Wavelength (μ, Colorado-Boulder)

Gallium Arsenide Photo-Voltaic Cell Efficiency
Rover Teleoperation
Condition monitoring
Radio transmission of visual data from rover
On-board display (Current, Voltage, Temp.)
Concentrates light on PV array
Even Gaussian laser intensity profile
Photovoltaic Array surrounded by reflector
Larger radio-controlled rover
Dark Landscapes (2001-2002)

Project MEDL: Moon/Mars Explorer of Small rover with photovoltaic cells
Initial Laser-PV WPT efficiency tests
Moon/Mars Rover (2000-2001)
Project LAMAR: Laser-Powered (University of Colorado at Boulder)
Experimental Laser Receivers & Rovers
Laser-Photo-Voltaic Wireless Power Transmission

- total power (60% of power in main lobe)
- 19% of main beam lobe, to collect its 50% of smaller photo-voltaic receiver intercepts
- Km distance from 25 cm
- 808 nm laser beam at 100
- Radius (cm) from center of

Normalized
Beam Intensity

at Receive. 0.8
0.6
0.4
0.2
0
-40
-20
20
40

0.4
0.6
0.8

-40
-20
20
40

- More even illumination of photo-voltaic array improves efficiency
- linear polar applications (>1/5 the PV area for >1/2 the power output)
- Smaller receiver, allowing beam spill-over, may be advantageous for Gaussian Laser Beam Intensity Distribution
Lasers

Photo-Voltaic Wireless Power Transmission

- Possible system revisions (e.g., PV receiver)
- Large, cooperative target for long distances
- Wireless power transmission
- Demonstrations of Laser-Photovolatic near-term applications in ground
- Currently under study for potential
- Autonomous ops in constant sunlight
- the Canadian Arctic in Summer, 2001
- Circumnavigated Haughton Crater in
  Lunar Polar Mission
- Demonstrates technology for a future
  Carnegie Mellon University to
  Developed by the Robotics Institute at

(Carnegie Mellon University)

Photo-Voltaic Rover for Further Research
Potential for end-to-end technology demonstration/validation

- Relatively low humidity; excellent night-time visibility
- Similar to lunar polar geometry; laser beams down from mountaintop
- Candidate site on Hawaii was used to test Apollo rover
- Small craters exist at volcanic vents
- Large areas have fine volcanic ash soils (similar to lunar regolith)
- Barren terrain, similar to mooncape, can simulate mission operations
- Photo-Voltaic Power Reception at site(s) on Maui, Lanai, or Hawaii
- Laser telescope operated by the University of Hawaii
- NASA Lunar Ranger Experiment (LURE) Observatory
- World-class laser facilities with large, high-quality optics
- Air Force Maui Optical and Supercomputing (AMOS) Site

Laser Power Transmission from established site(s) on Maui

- Horizontal scale (vertical scale exaggerated)
- 100 km
- 50 km
- 0 km

-Hawaii: Mauna Kea & Mauna Loa (4 km high mountain)
-Lanai: Haleakula (3 km high mountain)

For Technology Demonstration and Lunar Mission Simulation

Wireless Optical Near-Field Directed Energy Relay
Overview of Laser Beaming from Haleakala to Receiving Sites near Kihei and on Lanai

Elevation Ranges (feet)
- 0 - 1000
- 1000 - 3000
- 3000 - 5000
- 5000 - 7000
- 7000 - 9000
- 9000 - 10025
Perform lunar mission (technology flight demonstration)
• Test prototype flight hardware in simulated mission operations
• End-to-end technology demonstration (power from sunlight)
  • Increase range, efficiency, apertures and power levels

Potential future steps:
• Next step: Initialize power beaming over modest distances
• Current status: Small scale benchtop tests initiated at AMOS

Ground demonstration is prerequisite for flight demo

Science and Human Exploration and Development of Space
• While investigating ice deposits with high value for space
  • Lunar application can mature Laser-PV WPT technology
  • Near the moon's North and South Poles can enable access to permanently shadowed craters

Conclusions