Combining Laser Communications and Power Beaming for use on Planetary Probes

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ABSTRACT
Two aspects of any planetary mission is the ability to transmit and receive data, and generate power. Laser communication has the ability of increasing data received by a factor of 100, with a small power and mass penalty. This technology has been demonstrated on the ground as well as in space, with an image successfully transmitted to the Lunar Reconnaissance Orbiter (LRO) [1]. Laser power transfer has the potential to be a way to "recharge" a probe along side, or instead of traditional power generation methods. For planetary missions, this can supplement existing solar arrays, or provide bursts of high-voltage power that Radioisotope Thermoelectric Generators (RTGs) fail to provide. This technology has also been demonstrated on the ground, but has yet to be attempted in space.

The core of these technologies is the laser itself. Creating a system that fulfills two roles has the potential to save power, mass and volume in an individual system. Using base stations, a network of probes has a centralized location for data and power storage and transmission. Creating an infrastructure that can provide power and communications coverage into deep space opens a new door into solar system exploration.

This paper investigates the use of both laser communications and laser power transmission, their applicability for planetary missions, and models a small satellite that acts as a “base station” for a laser communications/power demonstration. This mission is designed as a "technology demonstration", which can be expanded upon for future use as a base station in a Lunar or Martian environment.

1. INTRODUCTION
Two of the biggest needs for deep-space missions are data transmission capability and sustainable power. As sensors and experiments improve, the need for higher data rates increases, likewise, advanced sensor suites also consume more and more power.

Laser communications promise much faster data rates than traditional RF (radio frequency) transmissions. This is critical to missions that provide large amounts of data, and are a large distance away from Earth.

Laser power transmission technology is a step toward a Deep Space Power Grid. Being able to wirelessly transfer power from one satellite to another can boost the available power for deep space probes.

Combining these technologies into one unit saves mass, spacecraft volume, and mechanical complexity. Likewise, a standardized laser system will save money and development time if a power and communications grid is to be established.

2. LASER COMMUNICATIONS
Laser communications work very similar to a digital RF transmission. Digital data is transmitted via a laser (instead of the traditional radio frequency waves) to a special receiver (which consists of a photodiode or photovoltaic cells). Once the energy is received, the signal is decoded back to the original data. Lasers can provide a data rate 10-100x faster than current RF methods [2].

Laser communications have been demonstrated successfully. Terrestrially, the military is experimenting its use for ship-to-ship and air-to-ground communications. In space, Ground to Space transmission has been achieved with the Lunar Reconnaissance Orbiter (LRO), and Space to Ground transmissions are planned for the Lunar Atmosphere and Dust Environment.
Explorer (LADEE) mission, to launch in September 2013 [3].

3. LASER POWER TRANSMISSION

Space-borne wireless power transmission has been a topic of discussion for decades. Research began in the 1960’s with Peter Glaser and the idea of beaming power for use on earth using Microwave transmission methods. Glaser patented methods of microwave power transfer in the early 1970’s [4]. While the concept was not developed further, due to a lack of technical knowledge, the concept has been brought up again since the late 1990’s due to rising energy costs on Earth, and their effect on some growing economies (mostly in Japan, India and China). This new crop of wireless transmission technologies also include the use of lasers for transmission instead of microwaves.

While much of this research has been in the area of Space-based Solar Power (SSP), there are also important applications for Space to Space power transfer. With wireless power transfer, a “deep space power grid” can be created, enabling large amount of high voltage power to be utilized in deep space (where photovoltaic cells are impractical). Also, orbiting “gas stations” can be set up to provide power when the satellite may not be able to generate power on it’s own (during periods of darkness). This concept has been proven in Space, with a laser link made with the JAXA OCIETS satellite and the ESA Artemis satellite [5].

Laser-based power transfer is very similar to laser communication; in fact the hardware used is the same. The only difference is how the laser energy is processed – communications data is decoded, whereas laser light can also be converted into electrical energy in the same matter as solar energy (photovoltaic cells).

4. COMBINING LASER COMMUNICATIONS WITH POWER TRANSFER

There are many things Laser Communications and Laser Power Transfer have in common. Most notably is the laser itself. The design parameters for the two technologies are the same: low beam divergence, high beam quality, and high wall-plug efficiency.

Beam divergence is the angle at which the laser beam deflects once it leaves the source.

Figure 1: Beam Divergence

This property is important because it governs energy density, the required target size, and the distance between the laser and it’s target. The beam divergence of most lasers is very small – on the order of single-digit milliradians. While this angle is very small, when the laser is traveling over a very long distance (as it would in most spaceflight applications), the beam diameter at the target is much larger than at the source.

Figure 2: Scale representation of a 3U CubeSat with deployable target panels vs. the beam of a 7mrad laser 500m away.

For power transfer purpose, this requires a large target array to gather all of the energy. On the other hand, this also means the energy density of the target is much lower than at the source, which can be helpful for thermal considerations and sensitive components.

Beam quality ($M^2$) is simply, the quality of the beam. While the conventional interpretation of lasers is a spot that is concentrated at the center and diffuses outward, this is not always the case. Due to lensing, refraction and other optical effects, lasers can have different transverse electromagnetic modes.
Figure 3: Transverse Electromagnetic Modes (TEM$_{xy}$) [6]

The closer the laser spot is to the ideal TEM$_{00}$ mode, the higher the beam quality.

Wall plug efficiency is a term used to relate a laser’s efficiency in practical terms. Since there are many parts of a laser, there are many different efficiency values of interest (the laser medium, lenses, mirrors, etc). The wall-plug efficiency is simply the energy put into the laser (the energy from the “wall outlet”) versus the energy output of the laser [7]. While this exact value varies between laser models, general values hold for most different types of laser.

Table 1: Laser Wall Plug efficiency

<table>
<thead>
<tr>
<th>Type of Laser</th>
<th>Wall-plug efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diode</td>
<td>30-50%</td>
</tr>
<tr>
<td>Diode-pumped</td>
<td></td>
</tr>
<tr>
<td>Solid State</td>
<td>~10%</td>
</tr>
<tr>
<td>Gas (CO$_2$)</td>
<td>5-10%</td>
</tr>
<tr>
<td>Gas (HeNe)</td>
<td>0.1-1%</td>
</tr>
</tbody>
</table>

The similarities of the two technologies still hold for the receiving end as well. Both power and data can be received using photodiodes or photovoltaic cells. Photovoltaic cells are extremely common in spacecraft for gathering solar energy. These same cells (that can be modified for use at specific wavelengths) can be used for either task. The difference lies in the demodulation of the laser energy. A simple switch can be used to switch the energy flow from the photovoltaic cell to either the electrical control system or to the data decoder system.

In order to prove this technology in a low-cost way, small satellites can be utilized for a technology demonstration mission. These missions are typically short in duration, and light on experimental data, but are important in mitigating risk for future large missions.

This mission would include two small satellites, one acting as the transmitter (the “Pitcher”), and one as a receiver (“Catcher”). Along with the typical suite of satellite systems (main computer, attitude control, electrical power, etc), the Pitcher would include a laser payload. The Pitcher would also be pre-loaded with many experimental data packets. These packets would mimic the data that many probes would receive (high-resolution pictures, radiation measurements, spectrometer measurements, etc). The Catcher would not have a laser but a deployable “Target” photovoltaic array payload.

After deployment, these satellites would orient themselves so as to transmit data/power. Using a conventional RF communications system, the satellites would handshake, and then initiate data or power transmission (depending on the experiment). For data experiments, the data received on the Catcher will be sent to ground (using conventional RF methods), and the quality of the data will be compared to the sent data. For power experiments, the increase in battery charge during the experiment will be measured and stored, then sent to ground for analysis.

One benefit of the CubeSat bus is the reusability of components. Instead of spending time developing new avionics for each mission, previously flown hardware designs and some off-the-shelf components can be used. For this mission, the command and data handling and RF communications systems are the same as those used on TechEdSat, a 1U CubeSat designed at San Jose State and flown in 2012. Attitude control is managed by the off-the-shelf MAI400 unit from Maryland Aerospace (a self-contained 1U-sized unit).

5. TECHNOLOGY DEMONSTRATION MISSION
Table 2: Pitcher Satellite specifications

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Mass</th>
<th>Size</th>
<th>Payload</th>
<th>Power</th>
<th>Communications</th>
<th>ADCS</th>
<th>CD&amp;H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitcher</td>
<td>8 kg</td>
<td>6U, 100x200x300 mm</td>
<td>Coherent Matrix Laser</td>
<td>Laser off – 10W, Laser on, &gt;100W.</td>
<td>Stensat Beacon, UHF (420-450 MHz)</td>
<td>MAI400 ADCS suite (3x magnetorquers, 3x reaction wheels)</td>
<td>AAC Microtek OBCLite (TechEdSat bus), nanoRTU (watchdog)</td>
</tr>
</tbody>
</table>

Table 3: Catcher Satellite specifications

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Mass</th>
<th>Size</th>
<th>Payload</th>
<th>Power</th>
<th>Communications</th>
<th>ADCS</th>
<th>CD&amp;H</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catcher</td>
<td>4 kg</td>
<td>3U, 100x100x300 mm</td>
<td>Deployable Target Array</td>
<td>7-10 W (nominal and transmitting), Laser Target = 768 cm², Solar Array = 896 cm²</td>
<td>Stensat Beacon, UHF (420-450 MHz)</td>
<td>MAI400 ADCS suite (3x magnetorquers, 3x reaction wheels)</td>
<td>AAC Microtek OBCLite (TechEdSat bus), nanoRTU (watchdog)</td>
</tr>
</tbody>
</table>

From an area-point of view, the satellites are broken up as follows:

Figure 4: Pitcher satellite volume breakdown

Figure 5: Catcher Satellite volume breakdown

6. CONCLUSION

As sensor technology develops, communication technology must follow suit. As we become more and more able to explore regions greater than 1.5 AU from the sun, we need a reliable source of high voltage power. Lasers can be used for both of these purposes, furthermore, using one laser for two different roles saves on satellite mass, volume and power. These developments in power and data transfer can enable both power and data networks in deep space to facilitate multiple missions at once. In order for such a large-scale mission to succeed, a small, low-cost demonstration mission can be used to improve the technology’s TRL and mitigate technological risk.

7. REFERENCES