Technology Demonstration of Wireless Power Transfer in Space

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TECHNOLOGY DEMONSTRATION OF WIRELESS POWER TRANSFER IN SPACE

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Abstract

This paper illustrates a mission concept for a technology mission to demonstrate wireless power transfer. Different methods of wireless power transfer are discussed and traded, with laser transmission being chosen. A system of CubeSats is designed to both generate and transfer power, and to receive beamed power. These satellites are broken down into subsystems, and parts are preliminary selected. Finally a link design for the laser transmission system is presented, along with an overall end-to-end efficiency value.

Acknowledgements

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Table of Contents

List of Figures

List of Tables

Nomenclature

A_{beam}	Area of the laser beam spot
A_{target}	Area of the target array
ADCS	Attitude Determination and Controls
BW	Bandwidth
BW_{rel}	Relative Bandwidth
c	Speed of Light = 3.0 x10
CO_2	Carbon dioxide
COTS	Commercial Off the Shelf
C&DH	Command and Data Handling
d_{beam}	Diameter of the laser beam on the target
DC	Duty Cycle
DPSS	Diode Pumped Solid State laser
E	Energy [J]
E_{laser}	Energy of the laser beam [J]
E_{photon}	Energy of one photon [J]
EDSN	Edison Demonstration of Smallsat Networks
eff	Efficiency
Er	Eritium
eV	Electron Volt =
f	Frequency [Hz]
Ge	Germanium
h	Plank's Constant = 6.63 $x10^{-34}$ [Js]
HAM	Amateur radio
He	Helium
He-Ne	Helium-neon
I	Current
InGaAs	Indium-gallium-arsenide
IR	Infrared
JAXA	Japan Aerospace Exploration Agency
l	Satellite Separation Distance
LEO	Low Earth Orbit
LV	Launch Veichle

NASA	National Aeronautics and Space Administration
NORAD	North American Aerospace Defense Command
Nd	Neodymium
$n_{photons}$	Number of photons
NRC	National Research Council
P	Power [W]
P_{peak}	Peak Power [W]
P_{avg}	Average Power [W]
PV	Photovoltaic
$Q_{battery}$	Battery charge [mAh]
R_{crg}	Charge rate
RF	Radio Frequency
RFID	Radio Frequency Identification
RR	Repetition Rate [Hz]
RS	Receiver Satellite
S2G	Space to Ground
S2S	Space to Space
SSP	Space Solar Power
t	Time
t_{trans}	Transmission time
t_{pulse}	Pulse length
TS	Transmission Satellite
UV	Ultraviolet
V	Voltage/Volts
W	Watt
Xe	Xenon
YAG	Yttrium aluminum garnet ($Y_3Al_5O_{12}$)
YLF	Yttrium lithium fluoride ($YLiF_4$)
YVO_4	Yttrium vandate
#U	CubeSat Units (1,2,3 or 6)
UHF	Ultra-high frequency
UTJ	Ultra Triple Junction
λ	Wavelength [nm]
Δλ	Emission Bandwidth
ϕ	Divergence angle [mrad]

1 INTRODUCTION

1.1 Goals and Objectives

The goal of this paper is to show a conceptual mission design for a demonstration of Space to Space wireless power transfer. The Space Solar Power idea is outlined, additionally with background on small satellite technology, used for this mission. The wireless power transmission technology is explained, along with the underlying satellite subsystems. Finally, future work for the next semester is presented.

1.2 "What is Space Solar Power?"

In general, Space Solar Power (SSP) is the idea of a power plant in space that can gather solar power at higher rates than on earth, and transmit that power wirelessly elsewhere. The concept was born in science-fiction, when in 1941, Issac Asimov penned the idea in a short story called "Reason", where a large power station was providing energy to nearby planets. Years later, when space discovery was at the forefront of American technological enthusiasm, the idea of SSP sprung up again. Lead by the likes of Dr. Peter Glaser, research in the late 1960's lead to developments in the early 1970's, including Dr. Glaser's patent on a massive, microwave based system in 1973 [4]. Early studies concluded that the technology was not ready yet, but in a couple decades, it might be [12]. In the 1980's, when the price of oil sank, interest in alternative energy systems diminished. When prices started rising again, and environmentalism starting regaining momentum in the 1990's, more studies were performed, and the results were still concluding that the technology was not ready [13]. In the late 1990's and early 2000's, other counties including Japan, India, and China (all countries with low natural power resources) began looking into SSP [10][16]. A study in the US preformed in 2001 made many recommendations to both NASA and private industry about where development should be headed, many of the recommendations focusing on how to make the system cost-effective enough for commercial use [13]. Currently there have been no large-scale demonstrations of wireless power transfer. There have been some terrestrial demonstrations [19] and demonstrations of laser communications, a related technology [1].

In order to further the development of SSP, the technology must be developed, tested, and demonstrated, and small-scale demonstration missions help in that regard.

2 THEORY

2.1 Wireless Power Transmission: Microwaves and Lasers

Wireless power transmission technology has been in the development ever since electricity itself has been in development. In 1891, Nikola Tesla demonstrated wireless power transfer using means of electromagnetic induction. Since then, many methods of wireless power transfer have been developed. Some are widespread, such as RFID chips and wireless charging pads for cell phones. Most have just been shown in a laboratory.

While many old, proven technologies exist, most of them require a medium to travel through (air, water, or the Earth itself). In a space environment, these methods are mostly useless since there is no physical medium for the energy to travel through. Two technologies that stand out are those that utilize electromagnetic radiation – radio wave (microwave) transmission and lasers.

2.1.1 Microwave Technology

Microwave transmission was the method used in the original patent for a Space Power Satellite [4]. The actual transmission mechanism is no different than a RF communications transmission in the microwave band (which is commonly used for satellite TV, military communications, and satellite radio). The difference between communications and power transfer is in the receiver. Much like satellite TV, a large antenna (usually called a rectenna, due to its receive-only nature) on the ground is used to gather up the RF energy. That energy is converted to electrical energy by ways of a magnetron or klystron, which act as signal amplifiers.

A large antenna transmits the RF energy to another large antenna (often called a rectenna, due to its receiving nature) on the ground. Because of these large structures, it is difficult to scale the microwave technology down. At the microwave end of the spectrum however, (around 5.8 GHz) the Earth's atmosphere is almost transparent. This allows transmission in almost any weather without significant path loss. It is estimated that the end-to-end path loss of a microwave Space to Ground system would be around 40% [13].

2.1.2 Laser Technology

The laser, which originally was an acronym for "Light Amplification by Stimulate Emission of Radiation" was invented in the late 1950's. While the credit for inventing the laser has been hotly contested (the Nobel Prize in Physics being awarded to Soviet and American laser scientists in 1964), the first LASER device was demonstrated at Hughes Research Labs in 1960. Prior to that, the MASER (Microwave Amplification by Stimulated Emission of Radiation), which is similar to the laser but in the microwave spectrum – was developed at Bell Labs in 1957. While the device itself is relatively recent, the theory behind lasers lies in the Quantum Theory of Radiation developed by Einstein in 1917.

Light is emitted by electrons moving from a high energy level to a lower energy level. Each atom contains electrons that roam around the nucleus. These electrons occupy distinct energy levels, sometimes referenced as “orbits”. In order to move to a higher energy level, the electron must have a certain amount of energy applied to it. When an electron falls to a lower energy level, energy is released, often in the form of a photon – a unit of light. The external energy applied to the individual atoms can vary widely – it can be electrical energy (the method used in incandescent light bulbs), chemical energy (the striking of a match to create a spark), and even light itself (sunlight reflecting off of everyday objects). In these cases, the electrons are changing energy levels randomly. This is known as spontaneous emission. How lasers differ from everyday light is that their light is generated by *stimulated* emission – the electrons are forced in and out of their energy levels to create coherent light. The main property of coherent light is its existence at one precise wavelength. Lasers therefore produce light at precise wavelengths (usually thought of as one, but sometimes multiple lines are emitted, and can be modified with optics). This means the energy is concentrated in those specific bands.

The lasing operation involves two main parts – the “pump” source and the laser medium. The pump source applies energy to the laser medium, and moves electrons in the medium to different energy levels. Traditionally, xenon or flashlamps have been used as a pump source. While these are still used for high-powered lasers, other pumping methods have been developed. One light source that is stronger than a xenon bulb is another laser (often reliable diode lasers, but high powered lasers can also be used to power very high powered lasers). Diode lasers use electrical current to populate energy levels in p-n junctions. The choice of a pump source is mostly dependent on the kind of laser medium being used, and the required power output.

Developments in laser technology are reflected strongly in the different types of laser mediums available. The three most popular types of laser mediums are gas, solid-state, and diodes. Often when people think of lasers, the image of a red-beamed helium-neon (He-Ne) laser comes to mind. This was the second type of laser developed; the first laser demonstrated was a solid-state laser consisting of a ruby crystal pumped with a flashbulb. Diode lasers were developed when transistor research began, and operate in a much different way than gas or solid state lasers. Other sorts of mediums exists, including dye and organic lasers, but are not used much outside of very specialized research fields.

The two most important laser parameters are wavelength and power. Since lasers emit photons, which are massless, the famous $E=mc^2$ equation does not apply. For photons:

$$E = hf$$

Eq. 1

where $h=6.63\times10^{-34}$ [Js], which is Plank's constant. Remembering that frequency is inversely related to wavelength:

$$f = \frac{c}{\lambda}$$

$$E = \frac{hc}{\lambda}$$

Eq. 2

So, the energy of the light output of the laser is inversely dependent on the wavelength. While that is a decision-making factor in laser design, there are other factors at play. The energy required to generate light at certain wavelengths (for instance, low-wavelength x-rays and gamma rays) is incredibly high, and often does not yield a significant light density. Wavelength is important in other aspects as well. From a SSP point of view, if you are trying to beam power through the Earth's atmosphere, a wavelength that can freely pass through that atmosphere is important. For some military applications, a beam that is invisible to the naked eye but not to night vision (infrared) goggles is desired.

The other important laser design parameter is power. There are two types of "power" typically used when referring to lasers – "peak" power and "average" power. Peak power is typically used with pulsed lasers, and represents the power during one pulse.

$$P_{peak} = \frac{E_{laser}}{t}$$

Eq. 3

Note that in this case, we are measuring the entire energy output from the laser. Taking the equations above:

$$E_{laser} = E_{photon} = \frac{hc}{\lambda} n_{photons}$$

Eq. 4

A more useful measure of total power of the laser is the average power:

$$P_{avg} = P_{peak} * t_{pulse} * RR$$

Eq. 5

Some other design parameters of use are shown above, the pulse length (t_{pulse}) and repetition rate (RR), collectively known as the laser Duty Cycle of a pulsed laser. Pulsed lasers are often a necessity due to heat buildup or due to characteristics of the laser medium (time needed to build a population inversion). The pulse length is not arbitrary, but is depending on the wavelength. The time that a laser can emit light puts a limit on what wavelengths are possible, this is known as the transform limit. To find the theoretical minimum pulse length for a given wavelength:

$$BW_{rel} = \frac{\Delta\lambda}{\lambda}$$

Eq. 6

$$t_{pulse} = \frac{0.441}{BW_{rel} * f}$$

Eq. 7

In the laboratory environment, pulse lengths as low as 6 fs ($6x10^{-15}$ s) have been achieved.

Another important design parameter is beam divergence. Beam divergence is dependent on the optics used and their properties, and is not generally calculated, but it is important to know when designing an entire system. Beam divergence is usually quite low, and measured in terms of mrads (milli-radians). In a space environment however, the distance between the laser source and target will be quite large, and the beam divergence can become a driving parameter. As illustrated in Figure 1, the beam diameter on the target is:

$$d_{beam} = 2l\tan(\phi)$$

Eq. 8

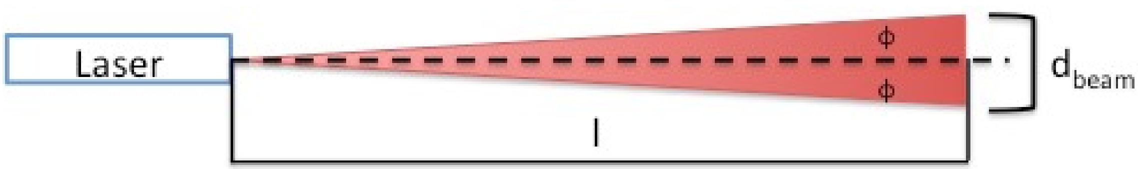


Figure 1: Beam Divergence

In general, the physical mechanisms of lasers are the same, no matter what type they are (arguably with the exception of diode lasers). The pump generates light/energy in the laser medium. That medium, coupled with optics, amplifies the light in the laser cavity. Once a population inversion has been achieved (when enough energy has been put in the system to cause there to be more electrons at higher energy levels than lower ones), a laser is produced. The optics integrated into the laser cavity guide the beam out of the cavity, into the outside world. Once outside the cavity the beam is typically modified further using more optics.

2.1.2.1 Gas Lasers

When it comes to high-powered lasers, gas lasers (specifically CO_2) are the lasers of choice. The gaseous medium is typically held in a vacuum tube, similar to “neon” signs and other gas arc lamps, but with mirrors on the ends of the tube. Like with any cathode tube lamp, light is emitted when current is applied to the cathode ends. In a gas laser, this light is amplified by the repetitive reflections off of the mirrors in the laser cavity, and a laser beam is produced.

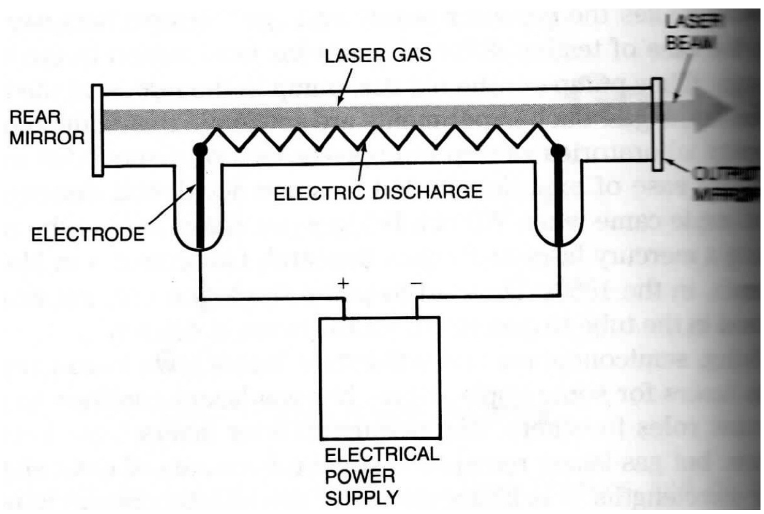


Figure 2: General Gas Laser design [5]

The gas used in gas lasers varies wildly. Like any other laser medium, the choice of laser medium depends on the required wavelength and power output. The most popular gas laser, the helium-neon (He-Ne) laser outputs a primary line at 632.8 nm, which is in the “red” area in the visible spectrum. The He-Ne laser does not provide much gain, however, and can only reach output powers in the milliwatt range. Using CO_2 as a medium gas however, yields much different results. CO_2 emits a variety of wavelengths in the infrared region, at powers up to 45 kW.

In general, gas lasers have an efficiency around 1%. Much of this efficiency loss is due to the pumping method.

2.1.2.2 Solid State Lasers

When most people use the prefix “solid-state”, they often refer to transistor based, semiconductor methods, which in the laser world is not a solid-state laser, but a diode laser. A solid state laser simply refers to the laser medium being a solid. Typically, this material is a glass or semiconductor doped with a specific ion, but can in theory be any material (the first laser ever demonstrated was made of synthetic ruby). Usually this material is formed in a rod or slab, depending on the pumping method (flashbulbs usually use rods, while diode arrays may be more efficient in a slab configuration). As with gas lasers, mirrors are located at the appropriate focal lengths from the rod to resonate and amplify the light inside the laser cavity. Other optical elements, such as rod or slab amplifiers of a slightly different material, may also be used.

One benefit of solid-state lasers is their versatility. Many different pumping methods can be used on a wide variety of materials, scaled up or down to different sizes. Originally, optical pumping was preformed with flash lamps. While this technique is still used often today, especially in high-power scenarios, diode lasers also provide an optimal pumping source. In addition to their small size and inherent efficiency advantage, the coherent light of diode lasers can provide a precise amount of energy, making the laser much more efficient. For instance, GaAs diode laser light (750-900 nm) falls in the peak absorption bands of neodymium (a common solid-state laser dopant), making the energy conversion much more efficient than a flashbulb, which has a wide array of input wavelengths.

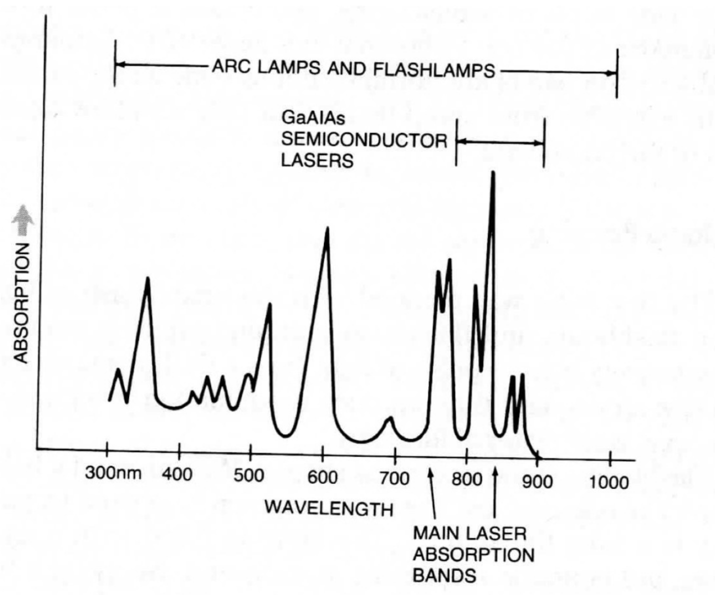


Figure 3: Absorption spectrum of Nd 3+ ion [5]

In terms of numbers, the wall-plug efficiency of a Nd:YAG laser pumped with a flashbulb is in the range of 0.1-1%, while a Nd:YAG laser pumped with laser diodes can have an efficiency around 10%.

Nd:YAG (neodymium doped yttrium aluminum garnet) crystals are a very popular choice, due both to their high efficiency, and due to their ability to produce the 532 nm beam seen in most commercial green laser pointers (though ND:YAG's main spectrum line is 1064 nm, in the IR spectrum). Neodymium doped mediums are also seen as Nd:Glass, Nd:YVO_4, and Nd:YLF, while YAG-based mediums include Yb:YAG, Er:YAG and Cr:YAG [14].

2.2 Spacecraft Technology

2.2.1 CubeSats

One way of reducing overall mission cost is to use platforms previously flown, and those that use off the shelf components. CubeSats are a class of nanosatellite, nominally 100x100x100mm in size, and under 1.3 kg in mass. CubeSats can also be made larger, up to 6U (100x200x300 mm nominal size). These satellites are normally used as university projects and for low-cost development mission. Many companies make components specially designed for, or adaptable for CubeSats, which makes development faster and cheaper.

3 MISSION OVERVIEW

In general, this mission will send two small satellites into LEO, and one satellite will transmit electrical power to the other.

3.1 Launch Vehicle/Orbit

One of the difficulties of small satellite missions is the availability of launch vehicles. Typically, small satellites (especially CubeSats) are launched as secondary payloads. Since the vast majority of launches are in LEO, most CubeSat missions are flown there.

In the past, the following launch vehicles have been used for CubeSat launches:

Launch Vehicle (Company)	Missions	Notes
Falcon 9 (SpaceX)	Planned 2013	In Development
Super Strypi (Aerojet)	EDSN (Q3 2013)	First Flight 2013
Minotaur I (Orbital)	Pharmasat, GeneSat	Further development focused on Antares
Antares (Orbital)	PhoneSat (April 2013)	First launch successful
Dnepr-1 (Yuzhmash)		Former Soviet ICBM, short design lifetime
PSLV (India)	Many Indian/European CubeSats	No US satellites flown

Table 1: CubeSat Launch Vehicles

For a technology demonstration, any orbit can be useful. Due the higher availability, and lower cost of LEO launches, a LEO orbit will be assumed. Due to the size of the Transmission Satellite, a higher orbit (over 400km) would be more useful in terms of mission lifetime than a lower launch, typical of many CubeSat missions.

3.1.1 Launch Assumptions

Based on previous CubeSat missions, and for simplicity, the following orbital conditions (that are identical to the ISS) are assumed:

Launch Vehicle	Falcon 9
Orbit Perigee	402 km
Orbit Apogee	424 km
Inclination	51.6
Drag Coefficient	2.20
Ballistic Coefficient (6U)	20.62

Table 2: Orbital assumptions

Since the 6U CubeSat will have a shorter lifetime due to it's increased drag, the overall mission timeline is based off of the TS operational lifetime.

Orbit lifetime was calculated using the SMAD Design Worksheet, a large Excel spreadsheet encompassing all of the satellite design tools discussed in Spacecraft Mission Analysis and Design, 3rd Ed. by Wertz and Larson. This same worksheet is used to calculate design parameters of most other subsystems for this mission.

Orbit Dynamics

(All information on this sheet is contained in the block from Cell A1 to Cell R29)

Circular orbit altitude	*425.000*	**Ellipse**	**km**
Semi-major axis		**6791.006**	**km**
Inclination	*51.60*	**51.60**	**deg**
Eccentricity	*0.0016*	**0.0016**	
Perigee altitude	*402.00*	**402.00**	**km**
Apogee altitude		**423.73**	**km**
Repeating ground tracks			
Number of orbits			
Number of days			
Basic Dynamics			
Orbit period		**92.82**	**min**
Orbit revolutions per Earth day		**15.51**	**revs/day**
Orbit energy		**-29.35**	**km^2/sec^2**
Average orbit angular velocity		**1.1282E-03**	**rad/sec**
Average ground velocity		**7.20**	**km/sec**
Satellite velocity (circular)		**N/A**	**km/sec**
Escape velocity (circular)		**N/A**	**km/sec**
Satellite velocity (at perigee)		**7.67**	**km/sec**
Escape velocity (at perigee)		**10.84**	**km/sec**
Satellite velocity (at apogee)		**7.65**	**km/sec**
Escape velocity (at apogee)		**10.83**	**km/sec**

Atmospheric Perturbations				
Drag coefficient	*2.20*		**2.20**	
Ballistic coefficient	*20.62*	*20.62*	**20.62**	**kg/m^2**
Atmospheric scale height			**58.3**	**km**
	Min	**Mean**	**Max**	
Atmospheric density	**7.01E-13**	**2.63E-12**	**7.33E-12**	**kg/m^3**
Change in semi-major axis	**-4.673E+01**	**-1.751E+02**	**-4.888E+02**	**km/yr**
Change in eccentricity	**-1.762E-06**	**-6.546E-06**	**-1.827E-05**	**per day**
Orbit lifetime	**1.480E+00**	**3.951E-01**	**1.416E-01**	**years**
Gravitational Perturbations				
Node precession rate - J2	**-4.969E+00**	**deg/day**		
Node precession rate - Moon	**-1.353E-04**	**deg/day**		
Node precession rate - Sun	**-6.166E-05**	**deg/day**		
Total node precession rate	**-4.969E+00**	**deg/day**		
Node spacing	**-23.59**	**deg/rev**		
Sun synchronous inclination	**97.08**	**deg**		
Perigee rotation rate - J2	**3.717E+00**	**deg/day**		
Perigee rotation rate - Moon	**1.012E-04**	**deg/day**		
Perigee rotation rate - Sun	**4.612E-05**	**deg/day**		
Total perigee rotation rate	**3.717E+00**	**deg/day**		

Figure 4: SMAD Worksheet - Orbital Dynamics

Due to variations in the atmosphere (especially at this relatively low altitude) and other space-weather events, the estimations for orbit lifetime can vary. From the SMAD Worksheet, the mean orbit lifetime is 144 days, though it can be as low as 52 days. To be conservative, 52 days of operational life will be assumed for this mission.

3.2 Satellite Descriptions

3.2.1 Transmitter Satellite

The Transmitter Satellite (TS) is the satellite that gathers solar energy, stores it, and then transmits it to the Receiver Satellite (RS). Since this is a scaled-down demonstration, the power transferred and the size of the satellite are very small, but the technology is the same as it would be for a full size satellite.

3.2.1.1 Solar Power Generation System

The power generation system on the TS is comprised of a large array of photovoltaic cells. The 6U CubeSat form factor can hold up to 56 Spectrolab UTJ solar cells. In the event of increase power needs, deployable solar panels can be added, which can add up to an additional 32 UTJ cells. These panels are designed to both power the

TS’s normal operations, plus charge the storage battery for future transmission.

3.2.1.2 Laser Transmission System

The Laser Transmission System beams the power stored in the TS storage battery packs to the Receiver satellite. This is accomplished by operating the Coherent Matrix 1064 CW laser (see Appendix 2).

3.2.1.3 Laser Pointing System

The Laser pointing system aims the Laser beam itself, aiming it precisely at the target Receiver Satellite. The hardware for this system consists of external optics that can rotate the beam small amounts.

3.2.1.4 Active Attitude Control

As opposed to the Laser Pointing System, the Attitude Control system repositions the TS itself to the proper orientation to aim the laser. This can be thought of as a “coarse” aiming while the Laser Pointing System provides “fine” aiming. Since the satellite is in LEO, stability can be achieved though the use of magnetic torquers. Additional control is achieved with the use of reaction wheels.

3.2.1.5 Space-to-Space Communications

The Space-to-Space Communications system controls the communications between the Transmitter and Receiver satellites. This system creates a handshake that can be use to automatically transfer energy when the satellites are not in ground range. This technology is the same technology demonstrated by the EDSN CubeSat mission, and will use the same hardware.

3.2.1.6 Space-to-Ground Communications

Space-to-Ground Communications are used to send telemetry, health status, and other housekeeping data back to operators on the ground. Ground communications also allow operators to preform software maintenance or potential troubleshooting. The Space to Ground hardware is the same as what is used on many CubeSat missions, such as TechEdSat.

3.2.2 Receiver Satellite

The Receiver Satellite (RS) receives, converts, and stores the energy transmitted from the TS. It also acts as a data collector – in order to verify the power transmission experiment, the RS must be able to record how much energy it has received from the laser.

3.2.2.1 Energy Absorption System

The Energy Absorption system is the receiver of the Laser energy. This GaAs photovoltaic cell array receives the Laser energy much like it would solar energy (except the Laser energy is a known, specific wavelength while the Sun's energy is highly variable). Because the laser beam will be large in diameter when it reaches the RS, a deployable array of photovoltaic cells will be used to gather as much laser energy as possible.

3.2.2.2 Space-to-Space Communications

The Space-to-Space Communications system on the RS is identical to the TS. In the Master/Slave relationship between the two satellites, the receiver plays the role of the "slave". The hardware is the same as the hardware demonstrated on the EDSN mission.

3.2.2.3 Space-to-Ground Communications

The Space-to-Ground Communications system for the Receiver Satellite is identical to the Transmission Satellite, except for slight differences in the frequencies. This helps in reducing interference when the two satellites are close. This is the same hardware that is used on other CubeSat missions, including the TechEdSat mission.

3.2.3 Ground Control Facilities

Since the Space to Ground communications system uses amateur bands, many ground stations already exist. A dedicated HAM radio station will be constructed to download packets from the Stensat radio. In addition, a call will be put out to HAM operators worldwide for packet information. This "crowd sourcing" increases the amount of total data received, while not raising costs.

4 REQUIREMENTS AND SUBSYSTEM DESIGN

4.1 Requirements and Assumptions

In order to design a mission, requirements are needed. The high-level requirements are listed below:

4.1.1 Level 1 Requirements

Number	Name	Requirement	Rationale	Parent
R1-1	Wireless Power	Wireless power shall be transferred from one satellite to another	The technology demonstrated is electrical power transmission.	-

R1-2	CubeSat Platform	The wireless power satellites shall comply to the CubeSat platform	CubeSats provide a low-cost platform ideal for small, technology demonstration missions.	-
R1-3	Wireless Power Safety	Wireless power shall not interfere with other satellites	Ensures the satellites do not damage others	-

4.1.2 Level 2 Requirements

Number	Name	Requirement	Rationale	Parent

R2-1	Dual Satellites	Two satellites shall be launched.	In order to transmit power from one satellite to another, no less than 2 satellites are needed	R1-1
R2-2	Transmitter satellite	One satellite shall transmit energy wirelessly.	One half of the demonstrati on	R1-1
R2-3	Receiver satellite	One satellite shall receive and convert energy transmitted from another satellite.	One half of the demonstrati on	R1-1
R2-4	Transmitter size	The wireless power payload shall fit in a CubeSat platform	Necessary to chose appropriatel y sized technologie s	R1-2

4.2 Transmitter Design

4.2.1 Technology Selection

Choosing the power transfer method is one of the first important decisions of this project. The two different technologies, microwaves and lasers, are different enough that they would yield significantly different satellite designs. Weighing all of the pros and cons of each method, Lasers were chosen as the best design.

Microwave	Lasers
• Operate at 5.8 GHz or 2.8 GHz (less atmospheric absorption) • Difficult to scale down due to size of components • S2G end-to-end efficiency ~40% • At S-band frequencies, relatively weather resistant (S2G) • Receivers are large rectannas with klystron energy converters	• Wavelength = 1030 nm (ErYAG laser) • Can scale up/down (narrow beamwidths possible) • Receivers are solar cells • S2G end to End efficiency ~20% • Weather will interfere with transmission (S2G) • To keep energy levels safe, may need multiple smaller lasers pointing at the same target, rather that one large one (S2G)

Table 3: Properties of Microwave and Laser transmission

4.2.2 Laser Design

The first decision that needs to be made when choosing the laser is what type of laser it should be. Gas, solid-state, and diode laser are all candidates for this selection. The laser choice also depends on the scale of the mission – no matter what laser technology is used; it is difficult to scale the same laser design up or down. Choosing a technology that has the ability to be generally scaled is desirable, knowing that the design will have to change for future missions.

Gas/CO_2	Solid State	Semiconductor/Diode
√ High-power √ Some have high wall-plug efficiencies (>10%) ⊗ Limited wavelengths available ⊗ Cathode tubes are fragile, require maintenance ⊗ Large structure required	√ Many available wavelengths √ Can be small in size √ Variable power √ Can be very efficient (10% commercially, 30+% in lab) ⊗ May need a substantial cooling system	√ Very efficient √ Very small √ Do not require optical pumping ⊗ Low power ⊗ Large arrays would be extremely expensive

Table 4: Tradeoffs of different laser technologies

A solid-state laser was chosen, due to its high efficiency and compact size. While many SSP studies have focused on gas lasers, solid-state lasers can still fulfill large-scale missions when they are used in arrays (in fact, some studies favor the idea of multiple small lasers over singular large, high-powered lasers).

The second step in the laser design process is choosing the laser medium. One of the most popular solid-state laser mediums is Nd:YAG, which refers to a YAG (yttrium aluminum garnet) crystal, doped with neodymium. The Nd^{3+} ion is the active particle during the laser action. This material is used for all sorts of lasers ranging from green laser pointers to high-powered spectroscopy experiments. It's main emission line is at 1064 nm, in the IR band. Lasers in this frequency range have been proposed for use in Space to Ground missions.

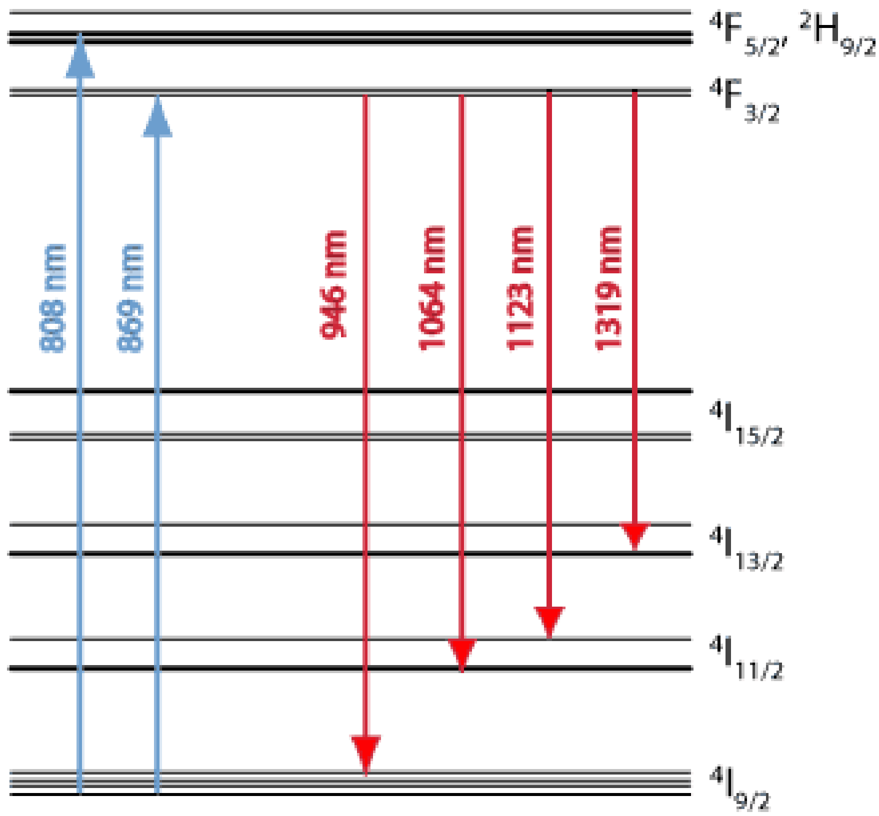


Figure 5: Energy level diagram of a Nd:YAG crystal[14]

The next major design parameter is the pumping method of the laser. There are three possible ways to pump a solid-state laser in space: optical pumping directly from the Sun, optical pumping with a flashlamp, or diode pumping. Like flashlamp pumping, “solar pumping” takes the Sun’s light energy and directly uses that to pump the laser. This has a large efficiency advantage, but also requires the satellite to be in sunlight while it is transmitting. While this makes sense for S2G applications, it is impractical for S2S.

Solar Pumped	Optically Pumped	Diode Pumped
• Solar radiation focused through a heated black body tube to directly pump the gaseous lasent (CO2 or CO). • Black body tube much more efficient than just shining the light on the lasent. • Wider selection of wavelengths • Difficult to scale down • Energy is not stored – Laser can only transmit while the Sun is pumping the laser.	• Flashlamp used to stimulate emission • Larger internal area needed for lamp housing • Lamps burn out and need maintenance • Can provide high powered pulses • Energy can be stored, and lasing can be started at any time.	• Semiconducter medium • Readily available – typically used for consumer electronics and medical devices. • Diode itself is very small in size • Can be used to pump a solid-state laser for higher efficiencies • Energy can be stored, and lasing can be started at any time.

Table 5: Properties of different pumping methods.

4.2.2.1 Off-The-Shelf Laser Solutions

For a small-scale technology demonstration, off-the-shelf components are attractive. Instead of spending development time on designing a custom laser for this purpose, modifying an off-the-shelf laser may mean lower cost and shorter development time. Appendix 1 shows a table of potential laser candidates.

4.2.2.2 Off-The-Shelf Laser Trades

In order to select a laser to use, a trade study must be constructed.

	Gigashot	Matrix	Surelight	Minilite	Powerlite	Indi	Big Sky	Centurion	Impex
Pump Type	2	-1	-2	-3	0	1	-4	3	4
Power	-1	1	3	-2	4	0	2	-3	-4
Divergence	1	-3	2	-4	4	3	0	-1	-2
Diameter	0	3	-1	2	-3	-2	-4	1	4
Size	-3	1	-1	2	-4	-2	0	3	4
Thermal	-4	2	-3	0	-2	1	-1	3	4
Power Req	0	-1	-4	1	-2	-3	2	3	4
TOTAL	-5	2	-6	-4	-3	-2	-5	9	14

Table 6: Off-the-shelf laser selection matrix

The biggest limiting factor for this project is size and power requirements. Many of the high-powered lasers (most of which are designed for lab-use) have large housings, power supplies, and water-cooling systems. While these features are tolerable, and sometimes desired on land, these systems will not fit in a small satellite. This means a less powerful but small laser must be used.

This trade table shows the Impex and Centurion lasers as “best options”. Upon further analysis, neither of these lasers provide enough power to run a decent experiment. The third best option, the Matrix laser from Coherent Inc., was chosen for use in this mission design (see Appendix 2 for the Matrix data sheet).

4.2.3 Laser Link Analysis

There are two main aspects to the link design of a laser power transmission system: the actually power transferred by the laser, and the amount of that energy that is gathered by the receiver satellite.

4.2.3.1 Laser Power Transmitted

Most off-the-shelf lasers provide the user with their pulse energy, pulse length, and the repetition rate. In order to find the power output of the laser, we must first find the Peak Power

$$P_{peak} = \frac{E_{pulse}}{t_{pulse}}$$

Eq. 9

Which is then used to find the Average (or Nominal) power:

$$P_{avg} = P_{peak} \times DC = P_{peak} t_{pulse} R_{rep}$$

Eq. 10

Once the transmission time (t_{trans}) is known, the total energy transmitted can be calculated:

$$E_{out} = P_{avg} t_{trans}$$

Eq. 11

4.2.3.2 Laser Power Received

The total amount of power received depends on the transmitting laser, the size of the receiving panel array, and the efficiency of those panels.

The laser divergence is the conical angle the laser beam has between the source and the target. This angle is very small (on the order of tenths of degrees), but when beamed over large distances, these small angles can result is beam diameters much larger than the source diameter.

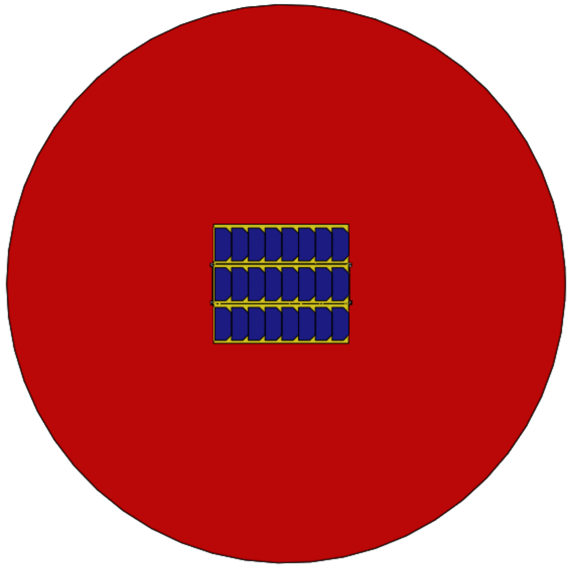


Figure 6: Scale representation of the Matrix laser beam 500m from the source, compared to the RS target array

The diameter of the beam at the target (d_{target}) is found using classic trigonometric relations (disregarding the source diameter, which is very small compared to the target diameter):

$$d_{target} = 2l\tan(\vartheta)$$

Eq. 12

Once the beam diameter at the target is known, it can be compared against the area of the target itself. Not only is this important for energy gathering information, but can also affect the laser pointing requirements. For a CubeSat, the available target area is relatively small, and the target area will be quite large in comparison. For this situation, pointing becomes less important than total array area. The area efficiency is the percentage of energy transmitted that is absorbed in the solar array.

$$eff_{area} = \frac{A_{target}}{A_{beam}} \times 100$$

Eq. 13

Once the area efficiency is known, the total amount of energy absorbed by the target array can be calculated:

$$E_{absorbed} = E_{out} \times eff_{area}$$

Eq. 14

4.2.3.3 Link Analysis Results

In order to make the link analysis of multiple laser systems more efficient, the preceding equations were processed in an Excel spreadsheet. Taking data from the Matrix laser data sheet, the Execl program shows that assuming the satellites are 500m apart, the RS will receive 0.629 W from the TS.

	A	B	C	D	E	F	G	H
1	**Laser Link Design**							
2	**Inputs**			**Assumptions**			**Output**	
3	Pulse Energy (J)	0.04		Seperation (m)	500		Peak Power (W)	5000000
4	Pulse Length (sec)	0.000000008		Beam Quality	TEM00		Avg Power (W)	4
5	Rep. Rate (Hz)	100		Transmission Time (s)	300		Energy Out (J)	1200
6	Nominal Power (W)						Diameter - Target (m)	3.50027211
7	Divergance (deg)	0.4011					Beam Area (m^2)	9.6177453
8	Target Area (m^2)	0.3					Efficiancy - Area (%)	3.1
9							Power Absorbed (W)	0.124
10							Energy absorbed (J)	37.2
11								

Figure 7: Laser Link Design spreadsheet (for the Centurion laser)

4.3 Solar Array and Power Subsystem Design

The TS and RS satellites have different roles, and therefore different power requirements. The TS satellite uses much more power than the RS, and the RS itself is a very low power device. The TS must generate its own operating power, plus the extra power it stores for transmission. The RS gathers power from two sources – the Sun and the TS.

4.3.1 TS Solar Array

The design aspects of the TS Solar Array are calculated with an Excel-based calculator, as shown:

Return to Navigator

Power Subsystem - Solar Array Sizing

(All information on this sheet is contained in the block from Cell A1 to Cell I26)

Required spacecraft power - sunlight	30.0	30.0	W
Required spacecraft power - eclipse	5.0	5.0	W
Orbit period		92.8	min
Maximum eclipse time		36.1	min
Mission duration		1.000	yrs
Solar flux		1367.0	W/m^2
Worst-case Sun incidence angle		23.50	deg
Transmission efficiency - sunlight		80.0%	
Transmission efficiency - eclipse		60.0%	
Ideal solar cell efficiency	28.0%	28.0%	
Inherent degradation		77.0%	
Solar cell degradation per year	0.50%	0.50%	
Lifetime degradation		99.5%	
Solar array power density		25.0	W/kg
Spacecraft dry mass			kg
Percent of spacecraft dry mass for wiring		4.0%	
Percent of spacecraft power for wiring		5.0%	

Total required solar power		42.8	W
Controlled spacecraft power		42.8	W
Converted spacecraft power		42.8	W
Ideal solar cell performance		382.8	W/m^2
BOL power capability		270.3	W/m^2
EOL power capability		268.9	W/m^2
Required solar array area		0.16	m^2

Solar Array Mass & Power Budgets

	Mass (kg)	Power (W)
Solar Arrays		
Deployed	1.7	
Cylindrical, body-mounted	5.4	
Omnidirectional, body-mounted	6.8	
Power Control Unit	0.9	
Regulator/Converters	1.1	8.6
Wiring	0.0	2.1

Figure 8: Solar Array Sizing for TS using the SMAD Calculator

For these calculations, it is assumed that Spectrolab UTJ cells are used. These are triple-junction solar cells (triple junction referring to three different structure types, $GaInP_2$, GaAs, and Ge). Triple junction cells use different layers of photovoltaic cell material to maximize energy absorption for multiple wavelengths. These photovoltaic cells are often used on small satellites and have substantial flight heritage. They are also a proper size to fit on a CubeSat frame. For technical details, see Appendix 3.

The required solar array area from these calculations is 1,600 cm^2, which is 50 UTJ cells. 50 UTJ cells will fit on a 6U CubeSat, though deployable solar panels could be added.

4.3.2 RS Solar and Target Array

The solar array design for the RS is trivial compared to the TS. The key difference is the use of the “target” cells used to receive the laser energy. Due to the coherent nature of the laser light, triple junction cells are not particularly useful. A photovoltaic cell designed for use in the IR band is best for the target cells. For 1064 nm, a single layer InGaAs or Ge cell would be ideal. In order to get a large “target” for the beam, two 3U-sized deployable panels are used, to increase the target area to 900 cm^2.

Due to the size of the target array, there remain three 3U faces and two 1U faces left for solar cell placement. As with the calculations for the TS, the RS solar array area was calculated with the aid of the SMAD Calculator. The required solar panel area is 500 cm^2, which is easily achievable with a 3U CubeSat (even with one face devoted to laser optimized cells).

4.3.3 RS Battery Charging

The key to any power budget is the ability to recharge batteries enough to fulfill the mission. In the case of the RS, the main experiment is to see if the batteries can be recharged enough by the laser to be worthwhile.

The battery used for the RS is the LI-2S1P-2200 battery by Rose Electronics, modified for satellite use (see Appendix 4). Modified versions of this battery have been flown on previous CubeSat missions. This battery has a capacity of 2,200 mAh. To ensure that the battery stays in good condition, it is good practice to not drain the battery to more than 65% depth of discharge. This brings the useful battery capacity to 1,430 mAh.

To figure out the Charging rate of the battery, the following equation is used:

$$Q_{battery} = R_{crg} I_{crg}$$

Eq. 15

Where $Q_{battery}$ is the battery capacity (in mAh), R_{crg} is the charging rate (in hours), and I_{crg} is the charge current. If the RS solar array is directly connected to the batteries for charging (and no other charging source is present), the charge current is the current coming from the solar array. This can be found by:

$$P_{absorbed} = I_{crg} V_{batt}$$

Eq. 16

Where $P_{absorbed}$ is the power coming from the target array, and V_{batt} is the charging voltage of the battery. Rearranging Eq. 15 and 16, and taking charging efficiency into account, an equation for the charging time is:

$$R_{crg} = \frac{V_{batt} Q_{battery}}{P_{absorbed}} \times eff_{crg}$$

Eq. 17

Note that for partial battery charging (which may be appropriate in some circumstances), any suitable value of Q may be used.

Using these equations, the estimated charge time of these batteries, being charged solely by the laser, is 16.8 hours. This seems like a long time, but as a supplemental source of power (not being used to fully recharge batteries), this may be sufficient.

4.4 Pointing

4.4.1 Pointing of the TS

The TS requires the highest amount of attitude control between the two satellites. Two systems are at work with the TS, the Attitude and Control system of the satellite, and the precision aiming of the laser.

4.4.1.1 TS Attitude Control

The TS itself needs to be able to point the barrel of the laser at the target RS. This means the TS needs be able to rotate on all 3 axes. Initial stabilization can be achieved with the use of magnetic torquers. For pointing maneuvers, reaction wheels on each axis are used. There are a few COTS, or semi-custom solutions for CubeSat scale ADCS suites. Maryland Aerospace sells complete solutions that occupy a 1U volume, while Surry Satellite Technology also sells reaction wheels and position sensors for custom solutions.

4.4.1.2 TS Laser Pointing

Once the TS is facing the right direction to begin transmission, slight beam adjustments are made using a rotating mirror in the beam path. This mirror is mounted to a servo that can rotate it +/- 30°, which can be used to finely point the laser beam.

4.5 Communications

The Space to Ground communications for both satellites leverages flight heritage from previously flown nanosatellites, including TechEdSat. Since the Space to Ground communications is one way, and small in size (only consisting of health status and other housekeeping data), the Stensat radio beacon can be used. This radio has been flown on many other CubeSats successfully, including TechEdSat. The Stensat radio (see data sheet in Appendix 5) operates on the Ameteur UHF band, meaning any HAM operator with the proper equipment can downlink data from the beacon. This is helpful for two reasons: amateur band frequencies do not require allocation from the FCC (just a HAM license), and data can be sourced (for free) from operators around the world.

4.6 Command and Data Handling

AAC Microtek’s nanoRTU and OBCLite handle the on-board computing of both the TS and RS. This is the same processor suite used on TechEdSat. Since the RS’s main duty is to preform ADCS maneuvers and report back to the ground, a small, low-power processer can be used. The OBCLite is the main computer, while the nanoRTU is a “safe mode” computer, used as a watchdog and for system life support.

4.7 Structures and Thermal

Many COTS structures for CubeSats exist, from companies such as Pumpkin Inc, ISIS and Clydespace. The 1U skeletonized structure from

Pumpkin was used on TechEdSat and Phonesat (among others). Using these structures saves on design time and cost. For the RS, which mostly consists of different PCBs that can be arranged in a “stack-up” configuration, a 3U Pumpkin structure will work well. For the 6U TS, which houses a laser payload that is quite large, a standard off-the-shelf solution is hard to find. In this case, a custom designed frame will be constructed to specially hold the large payload, and form the 6U form factor.

Using a laser on the ground can cause a lot of thermal issues. Most large lab lasers have extensive cooling systems. The Matrix laser is air-cooled (as opposed to water cooled). Much care must be taken to ensure thermal stability of the laser during flight. Since there will not be room for active cooling, passive cooling techniques (thermal coatings, heat pipes, etc) must be utilized.

4.7.1 TS Structure

The TS is designed to be a 6U CubeSat. About 4U of total internal area is reserved for the laser and it’s associated components (optics, thermal control, etc.). The remaining 2U is reserved for the computer and power regulation (1U) and attitude control components (1U). Due to the recent development of the 6U form factor, no COTS designs for the 6U structure currently exist. A new structure will be designed, using parts from previous, smaller CubeSat form factor designs.

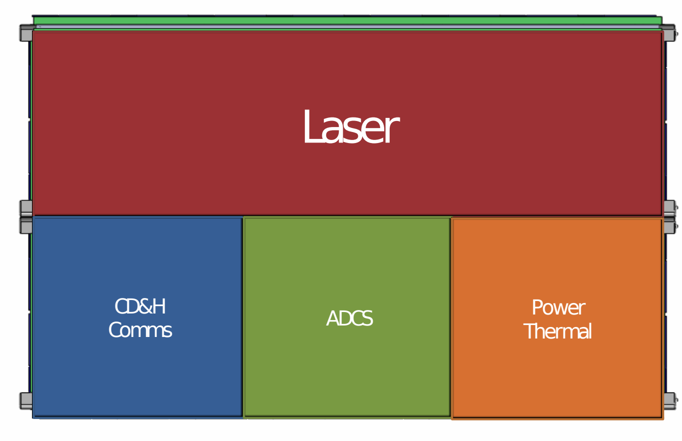


Figure 9: TS Subsystem Volume Allocation

4.7.2 RS Structure

The RS is designed to be a 3U CubeSat. Since much of the internal components come from TechEdSat (a 1U CubeSat), there will be some empty space that can be allocated for additional batteries and power system needs. Of note is the particular “target panel” of solar cells designed for the IR laser radiation, which are separate from the regular solar cells. For simplicity and cost reasons, a COTS structure from Pumpkin Inc. is utilized for the RS.

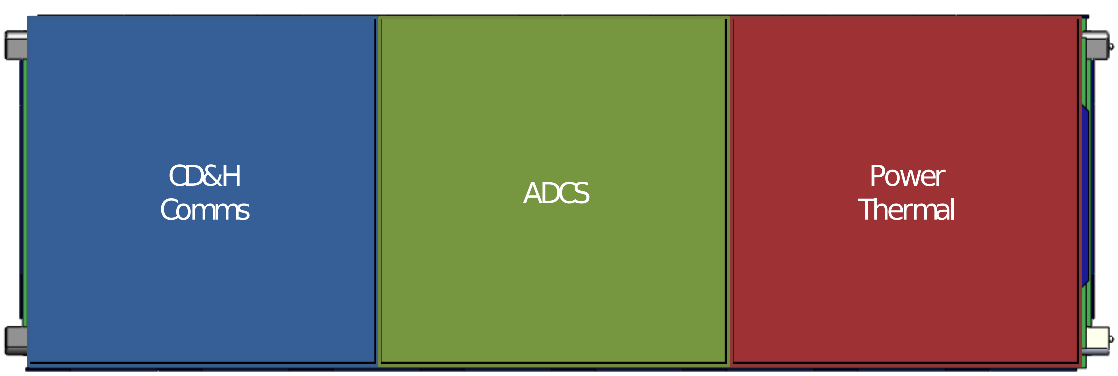


Figure 10: RS Subsystem Volume Allocation

5 MISSION SNAPSHOT

5.1 Mission Timeline

The post-launch mission timeline has three phases. Phase 1 is immediately after launch, where the satellite automatically deploys from the Launch Vehicle, and begins it’s start-up and boot up sequences. The ground also uses this time to establish a communications link with the spacecraft, and verify that it is working correctly. Estimates of the satellite’s positions are given by NORAD, but this data can be sparse, and this process may take between 14 to 30 days.

Phase 2 is when normal operations occur. The satellites communicate with each other, and preform power transfer operations. This process will last as long as the satellites are within range. Due to orbital decay (and differences in decay rate), this window may only be open for a few days after check-out.

Phase 3 occurs when no more power transfer operations can be preformed. The satellites are decommissioned, but will continue to send out heath data over the beacon until they deorbit.

Figure 11: Post-Launch Mission Timeline

5.2 Satellite Specifications

Transmitter Satellite	
Mass	8 kg
Size	6U, 100x200x300 mm
Payload	Coherent Matrix Laser
Power	Laser off – 10W, Laser on, >100W.

Communications	Stensat Beacon, UHF (420-450 MHz)
ADCS	MAI400 ADCS suite (3x magnetorquers, 3x reaction wheels)
CD&H	AAC Mictorek OBCLite (TechEdSat bus), nanoRTU (watchdog)

Table 7: Transmitter Satellite synopsis

Receiver Satellite	
Mass	4 kg
Size	3U, 100x100x300 mm
Payload	Deployable Target Array
Power	7-10 W (nominal and transmitting), Laser Target = 768 cm^2, Solar Array = 896 cm^2
Communications	Stensat Beacon, UHF (420-450 MHz)
ADCS	MAI400 ADCS suite (3x magnetorquers, 3x reaction wheels)

CD&H	AAC Microtec OBCLite (TechEdSat bus), nanoRTU (watchdog)

Table 8: Receiver Satellite synopsis

5.3 End-to-End Laser efficiency

One of the benchmark values for wireless power in general is end to end efficiency. Adding all the inefficiencies for each subsystem, the end-to-end efficiency can be calculated.

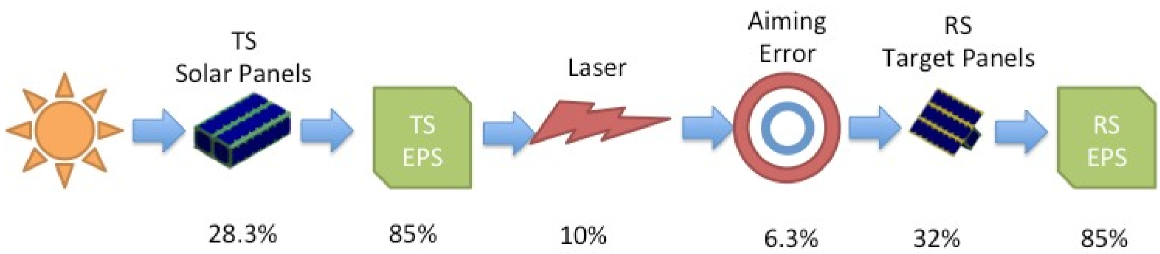


Figure 12: End-to-End Efficiency

The end-to-end efficiency of the entire satellite system is 0.042%

6 FUTURE WORK

While this mission concept is a good starting point, there is still much work to be done to fly a wireless power demo mission. If funding is secured, hardware should be procured to test these concepts on the ground. The laser transmission itself can be tested and characterized. Test data would be very valuable to the COTS Laser Decision Matrix. The efficient of the transmission can be measured, along with the power consumption, and many beam properties.

Other ground testing that can be preformed is ADCS performance. While systems have been developed, no 6U CubeSat has been launched (ECAM Sat, due to launch in 2013-14, does not use active attitude control). The large masses combined with precise pointing requirements may require substantial ADCS development.

Thermal characterization is another topic that needs more attention. The benefit of using a COTS laser is it has it's own thermal system built in. While it may not be perfect for this application, modifications can be made. There is still a large amount of heat generated, and further study into this issue, and possible mitigations, is needed.

One of the glaring faults of this demonstration is the very low efficiency. Much of this comes from the beam divergence, and the relatively small size of the receiving array. Further development in deployable arrays will help with the target area issue. Developments in laser optics, or developing a laser just for this purpose, can also help with beam divergence and laser efficiency.

7 References

1 Anma, K., Kimura, T., Tsukahara, A., Fuse, Y., & Numura, K. (2009). Space Solar Power System and Wireless Power Transmission Technology. *60th International Astronautical Congress*, *8*, pp. 6084-6088. Daejeon, Republic of Korea.

2 Barnett, R. E., Liu, J., & Lazar, S. (2009). A RF to DC Voltage Conversion Model for Multi-Stage Rectifiers in UHF RFID Transponders. *Journal of Solid State Circuits , 44* (2), 354-370.

3 Fowles, G.R. (1989). Introduction to Modern Optics. Dover Publications. New York, New York.

4 Glaser, P. (1973). *Patent No. 3,781,647.* USA.

5 Hecht, J. (1993). Understanding Laser - An Entry-Level Guide. IEEE Press, New York, New York.

6 Jono, T., Takayama, Y., Ohinata, K., Kura, N., Koyama, Y., Arai, K., et al. (2006). Demonstrations of ARTEMIS-OICETS Inter-Satellite Laser Communications. *24th AIAA International Communications Satellite Systems Conference.* San Diego: AIAA.

7 Landis, G. A. (1992). Space Power by Ground-Based Laser Illumination. *AIAA 23rd Plasmadynamics & Lasers Conference.* Nashville: AIAA.

8 Mankins, J. C. (2008). Space-Based Solar Power: Architectural and Systems Considerations. *6th International Energy Conversion Engineering Conference.* Cleveland: AIAA.

9 Moore, C. L. (2001). Gossamer Spacecraft Technology for Space Power Systems. *Aerospace Conferene. 7*, pp. 3585-3589. Big Sky, MT: IEEE.

10 Nagatomo, M. (1996). An Approach to Develop Space Solar Power as a New Energy System for Developing Countires. *Solar Energy , 56* (1), 111-118.

11 NASA. (2012). *International Space Station*. Retrieved Dec 1, 2012, from NASA - Facts and Figures: http://www.nasa.gov/mission_pages/station/main/onthestation/facts_and_figures.html

[12] Nasen, R. (1995). Sun Power: The Global Solution for the Coming Energy Crisis. Ocean PR.
[13] National Research Council. (2001). Laying the Foundation for Space Solar Power: An Assessment of NASA's Space Solar Power Investment. Washington DC: National Academy Press.
[14] Paschotta, R. (2012). *Article on YAG lasers - Enclycopedia of Laser Physics and Technology*. Retrieved Jan 10, 2013 from The Enclycopedia of Laser Physics and Technology: http://www.rp-photonics.com/yag_lasers.html
[15] Purvinskis, R., Giggenbach, D., Henninger, H., Perlot, N., & David, F. (2003). Multiple Wavelength Free-Space Laser Communications. *Society of Photo-Optical Instrumentation Engineers* .
[16] Sabella, A., Piper, J. A., & Mildren, R. P. (2011). Efficient conversion of a 1.064 um Nd:YAG laser to the eye-safe region using a diamond Raman laser. *Optical Society of America , 19* (23).
[17] Saito, Y., Fujita, T., & Mori, M. (2006). Summary of Studies on Space Solar Power Systems of Japan Aerospace Exploration Agency (JAXA). *57th International Astronautical Congress.* Valencia, Spain: AIAA.
[18] Suzuke, H., Fujita, T., Kisara, K., & Sasaki, S. (2009). Technology Demonstration and Elemental Technology Development of Laser Based Space Solar Power System. *60th International Astronautical Congress*, *8*, pp. 6148-6152. Daejeon, Republic of Korea.
[19] Taussig, R., Bruzzone, C., Nelson, L., Quimby, D., & Christiansen, W. (1979). Solar-Pumped Lasers for Space Power Transmission. *AIAA Terrestrial Energy Systems Conference.* Orlando: AIAA.
[20] Whitesides, L. H. (2008, September 8). Researchers Beam 'Space' Solar Power in Hawaii. *Wired Magazine* .

APPENDIX 1 – COTS Laser Options

Mfg	Model	Name	Type	Wavelength	Energy	Rep. Rate	Average Power	Pulse Width	Beam Diameter	Beam Divergence	Power Req.	Water Cooled?	Physical Size
NG/CEO Lasers	GS-320-QUI	Gigashot	DPSS	1064	320 mJ	110 Hz		9 ns	6.5 mm	.6 mrad		Y	40 x 18 x 7 in
Coherent	MATRIX 1064-10-CW	Matrix	DPSS	1064			10w		680 um	2.7 mrad	90 VAC, 750 VA	N	
Continuum	SL-III-10	Surelight	DPSS	1064	850 mJ	10 Hz		4-6 ns	9.5 mm	.5 mrad	280 V, 10A	Y	25 x 7 x 7.5
Continuum	ML-II	Minilite	Lamp SS	1064	50 mJ	10 Hz		5-7 ns	3 mm	3 mrad		Y	10.5 x 6.75 x 2.5
Continuum	DLS 2J	Powerlite	DPSS	1064	3500 mJ	10 Hz		4-8 ns	12 mm	.45 mrad	240 VAC	Y	42 x 18 x 12
Newport	INDI 40-20	Indi	DPSS	1064	420 mJ	20 Hz		6-9 ns	10 mm	.5 mrad	260 VAC	N	25.5 x 13 x 21
Lambda Photo	CFR 800	Big Sky	Lamp SS	1064	800 mJ	20 Hz		9 ns	12 mm	1.5 mrad		Y	
Lambda Photo	Brilliant B	Quantel	Lamp SS	1064	850 mJ	10 Hz		6 ns	9 mm	.5 mrad		Y	

Lambda Photo	Centurion GRM	Centurtion	DPSS	1064	45 mJ	1-100 Hz	7 ns	3 mm	1.5 mrad	N	2.5 x 8.5 x 5

Appendix 2 – Coherent Matrix Data Sheet

COHERENT®

MATRIX 1064 CW

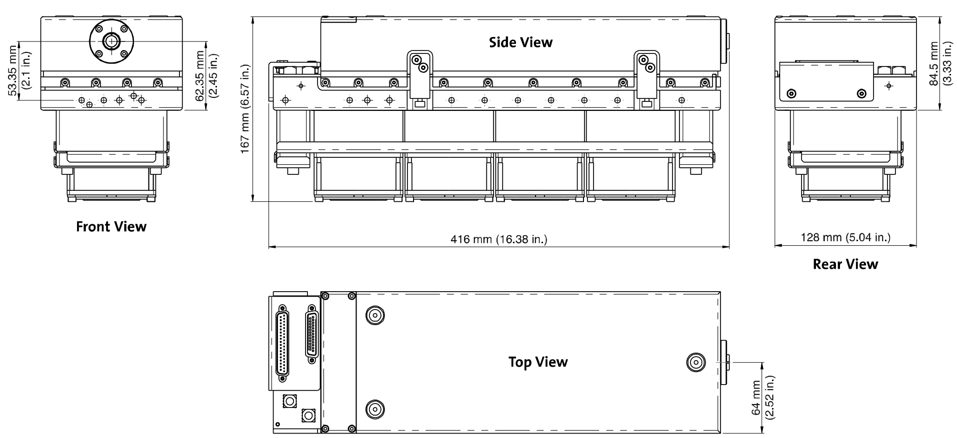
Solid-State, Continuous-Wave Lasers

Features

- Superior optical performance
- PermAlign™ solder-bonded optics technology for permanent optimal alignment and ultra-robustness
- AAA™ (Aluminum-free Active Area) pump diodes for unmatched lifetime
- Robot-assisted, clean room built and hermetically sealed
- Compact, air-cooled design for easy OEM integration (water-cooling optional)
- Best reliability, lifetime and unit-to-unit consistency

Mechanical Specifications

Laser Head



Superior Reliability & Performance

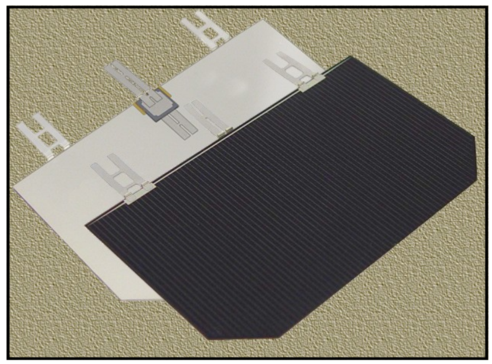
Appendix 3 – Spectrolab UTJ Photovoltaic Cell Data Sheet

Spectrolab
Photovoltaic Products
www.spectrolab.com

28.3% Ultra Triple Junction (UTJ) Solar Cells

Features

- High efficiency n/p design (28°C, AM0)
  -BOL: 28.3% min. average efficiency @ maximum power (28.0% @ load voltage)
  -EOL: 24.3% min. average efficiency @ maximum power, 1 MeV 1E15 e/cm²
- Heritage bypass diode protection
- 140 µm Ge wafer thickness



Product Description

Substrate	Germanium
Solar Cell Structure	$GaInP_2/GaAs/Ge$
Method of GaAs Growth	Metal Organic Vapor Phase Epitaxy
Device Design	Monolithic, two terminal triple junction. n/p $GaInP_2$, GaAs, and Ge solar cells interconnected with two tunnel junctions
Sizes	Up To 32 cm^2
Assembly Method	Multiple techniques including soldering, welding, thermocompression, or ultrasonic wire bonding
Note: Other Variations Are Available Upon Request	

Heritage

- More than 2000 kW of multi-junction cells **delivered**
- More than 675 kW of multi-junction arrays ***on orbit***
- 1 MW annual capacity - cells, panels & arrays
- On orbit performance for multi-junction solar cells validated to ± 1.5% of ground test results

Intellectual Property

This product is protected by the following patents:
- 6,380,601
- 6,150,603
- 6,255,580

ISO9001:2000 REGISTERED
AS9100 REGISTERED

SPECTROLAB
A BOEING COMPANY

Spectrolab Inc. 12500 Gladstone Avenue, Sylmar, California 91342 USA • Phone: 818.365.4611 • Fax: 818.361.5102

Appendix 4 – Rose Battery Data Sheet

ROSE

Technical Specifications

Rose Batteries Standard Lithium Ion Battery 7.4 V, 2200 mAh

Product Name	Rose Standard Lithium Ion Battery 7.4 V, 2200 mAh
Part Number	LI-2S1P-2200
Description	7.4 V, 2.2 Ah lithium ion battery with a safety unit.
Operating Temperature	Operating temperature range (charge): 0° to 45° C
	Operating temperature range (discharge): -10° to 60° C
	Storage temperature range: -20° to +35° Celsius
Operating Humidity	45% - 85% under all conditions
Voltage	Minimum open circuit voltage on shipment: 7.4 V
	Minimum voltage on discharge: 6.0 V
	Maximum voltage on charge: 8.2 V
Current	Maximum charge current: 2.2 A
	Maximum discharge current: 2.2 A

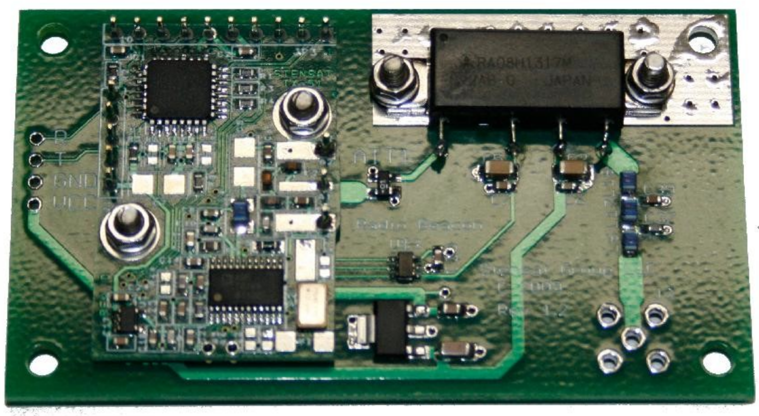
See Rose Applications Engineering for further information

Safety Unit	Nominal over-voltage cutoff: 8.6 V
	Nominal under-voltage cutoff: 4.6 V
	Nominal over-current cutoff: 3.5 A
Date Code Labeling	Battery packs are labeled with the date of assembly.
Storage	Batteries may be stored under the conditions of section 2 for a maximum of six months from the date of pack assembly.

Appendix 5 – Stensat Beacon Data Sheet

Stensat Radio Beacon

Stensat Group LLC



Introduction

The Stensat radio beacon is a small FM transmitter capable of generating AX.25 Unnumbered Information (UI) packets at 1200 bps AFSK and 9600 bps FSK. The 9600 bps FSK signal is compatible with G3RUH modulation. Power level is adjustable from 0 to 3 watts operating on a single 5 to 12 volt supply.

Specifications

Item	Value
Bands available	2m, 70cm
RF Output Power	0 to 3 Watt programmable
Operating voltage (Vdd)	5.0 to 12.0 volts
Operating Current	650 to 2000 ma when transmitting 40 ma when idle
Serial Interface rate	38.4Kbaud UART 8 bit, no parity, one stop bit
Dimensions	1.75 x 3.10" x 1.00" / 44.45mm x 78.74mm
Mass	approx. 50g
Digital Input signal specifications	High signal > 0.7*Vdd Low signal < 0.3*Vdd, 10 uA
Digital Output signal specifications	High signal > 2.0 volts Low signal < 0.4 volts, 3 ma sink