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An Optical Payload for Cubesats

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ABSTRACT

Optical wireless communications provide a promising, high bandwidth alternative to radio communications, where high performance links are desired. For large satellites (say, wet mass>1000kg), laser cross links have been successfully established since 2001 by various space agencies in Europe and Japan. Thus far, the cross-links have been able to achiever data rates in Gbps range for distances greater than 10,000km. Such gains would be monumental improvement for communications in small satellite domain (say, wet mass for Cubesats >10kg), where the typical communications payload users radio antenna that achieve an average data rate of 10kpbps.This paper proposes a promising laser communication system for CubeSat. First, a study of the laser crosslink system of large satellites is provided. Then, the subsystems of the larger satellite laser communications are analyzed for suitability in the CubesSat frame. Each subsystem is further analyzed in terms of functionality, contribution to the weight of the optical payload and power requirements. The parameters of the larger system are then redesigned to meet the size, weight and power constraints of the CubeSat. The new system is simulated for performance and various candidate scenarios are discussed.

INTRODUCTION

The need for high data rate communications soon hit distance and power limits posed by the RF communication. Lasers, with their high directionality and low power requirements, promise to be a better way to implement long distance space communications. With the advent of systems like CubeSat and Inter-Planetary Networking, traditional long range ground-satellite links have to be replaced by inter-satellite links. For very long distances, because of a polynomial relationship between power and distance, multi-hop communication is much more power efficient than long range, direct source to sink communication. Furthermore, Long range RF communication links, because of their weak signal strengths, are susceptible to jamming and thus are prone to DOS (Denial of Service) attacks. Inter-satellite laser communication can provide power efficiency, security and data delivery with CubeSat clusters. In addition, because of their high directionality, laser communications are very robust against jamming and electromagnetic interference. Lastly, with advances in microelectronics some laser modules can fit the size of a match box making them attractive to space and weight constrained space applications, especially CubeSats. This paper proposes a promising laser communication system for CubeSat. First, a study of the laser crosslink system of large satellites is provided. Then, the subsystems of the larger satellite laser communications are analyzed for suitability in the CubesSat frame. Each subsystem is further analyzed in terms of functionality, contribution to the weight of the optical payload and power requirements. The parameters of the larger system are then redesigned to meet the size, weight and power constraints of the CubeSat. The new system is simulated for performance and various candidate scenarios are discussed.

OPTICAL CROSSLINKS FOR LARGE SATELLITES

The world's first Semiconductor Intersatellite Laser Link Experiment (SILEX) was performed by the European Space Agency (ESA) on November 20th, 2001 between the data relay satellite ARTEMIS and the earth observation satellite SPOT-4[1]. Preliminary tests to check the health of the SILEX terminal, were conducted from the ground station wherein two link sessions of 20 minutes each were established before the inter satellite laser link could be established. The ARTEMIS satellite which was deployed to perform North/South station keeping was spiraled out to its GEO orbital position of ⟦21⟧^0 East, a maneuver that lasted from the start of 2002 until February of 2003.By definition of the article, the SPOT-4/ARTEMIS inter-satellite link statistics last conducted consists of 1327 sessions of which 57 failed with an accumulated link duration of 10 days, 18 hours and 30 minutes, while the OGS (Ground Station on earth)/ARTEMIS space to ground link statistics counts 137 sessions of which 25 failed with an accumulated link duration of 2 days, 10 hours and 37minutes.The laser links between the satellites are as shown in figure 2. The SILEX experiment was subsequently followed by the Japanese Space Exploration Agency bidirectional optical link between their Optical Inter-orbit Communication Engineering Test Satellite (OICETS) and ARTEMIS satellites in 2005.

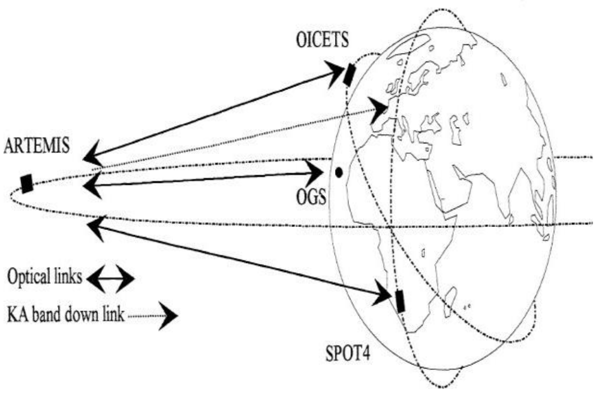

Figure 2: SILEX Inter Satellite Laser Links[1]

The OICETS/ARTEMIS inter-satellite link statistics counts 83 sessions of which 2 failed with accumulated link duration of 14 hours and 21 minutes[1]. In 2006, the German Space Agency launched a laser communication terminal (LCT) on TerraSAR an earth observation satellite[1]. The LCT parameters consist of binary phase shift keying modulation at 1064nm for a data rate of 5.6Gbps at 10000km. The partner terminal for establishment of the optical link was launched on the American NFIRE satellite by NASA in 2007.In 2007, the ESA launched the AlphaSat program where in 80 % of the payload was awarded to Inmarsat Global Ltd to extend the capabilities of its Broad Global Area Network Services which currently consists of a wide

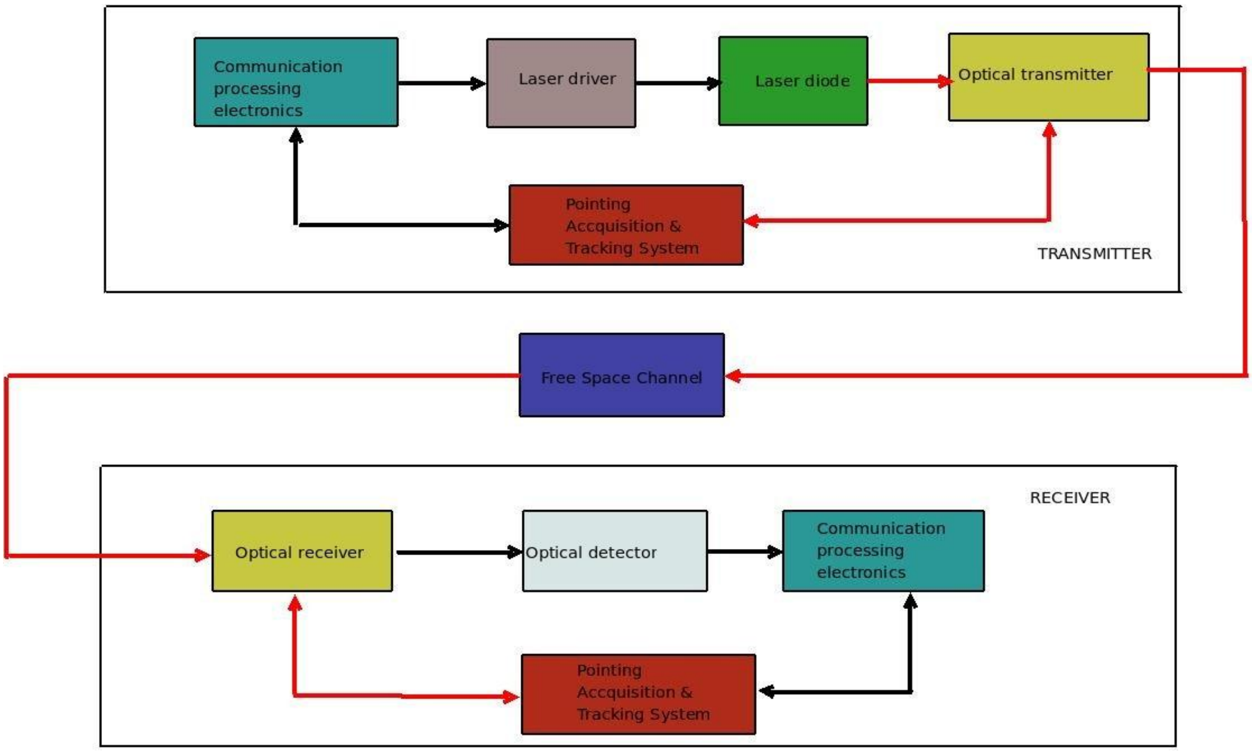

Figure 1: Block Diagram of ISL System

range of high data rate applications to a new line of user terminals for aeronautical, land and maritime markets [1,2]. Optical inter satellite links have thus far been successfully demonstrated on large satellites. While a number of small satellite missions have been flown to perform earth observations tasks, optical inter satellite links have yet to be experimented with**.**

INTER SATELLITE LASER LINK SYSTEM

A block diagram of the Intersatellite Laser Link is shown in figure 1 with in-depth considerations of the block parameters detailed in the following sections. Next, we describe the subsystems of larger satellites laser communication optical payload and analyze the subsystem for small satellites. The subsystems parameters are targeted to meet the 3U CubeSat payload weight constraint of 1.5-2kgs and power constraint of 3-5W.

OPTICAL SOURCE

The optical source consists of the laser along with the modulator. The modulator could be an external or internal modulator. The external modulator modulates the emitted laser light. The internal modulator affects the way the laser emits the light. The common types of laser that have been tested for large satellites and are suitable to establish an ISL are the CO2 gas, Nd: YAG solid state, InGaAsP diode /Nd: YAG power amplifier, GaAlAs diode. Gas lasers are large in size and require kilowatts optical power to turn on[3, 4]. Solid state lasers need to be pumped by another semiconductor laser diode to turn it on and can provide kilowatts of output power and hence are very useful to establish deep space optical links with link distances up to 40,000kms. QCL (Quantum Cascade Laser) is another promising semiconductor infrared laser that is being experimented with and shows potential for future use**.**

Operation: The chosen laser diode is turned on by the bias current .In order to obtain a modulated output; the modulating current is superimposed on the bias current. The output of the laser diode is then passed through a collimator which produces a beam of the desired quality. The design of the laser diode transmitter package must meet the specified volume and weight constraints of the payload.

Choice of Laser Diode: A laser diode is chosen depending on the required output power and wavelength. The average output power is dependent the distance at which the inter satellite links needs to be established and the available drive current. For CubeSats, drive currents values of >10mA and less than 1A for the payloads are available. Such small currents are sufficient to drive the laser to produce optical output powers in the range of 10mW-25mW. Since both CO2 and solid state lasers cannot be used due to their volume, weight and power constraints[6], the only choice of diodes that can meet payload requirements of the Cubesats are the semiconductor laser diodes such as Distributed Feedback laser diode (DFB), Vertical Surface Cavity Emitting Laser diodes (VSCEL) and QCL Some of the common laser diodes and their operating wavelength are tabulated in table 1.

Table 1: Operating Wavelengths of Laser Diodes[4, 7]

Type of Laser Diode	Wavelength(nm)
Diode Pumped Nd:YAG (YAG)	1.064-0.503
Indium Gallium Arsenide Phosphide (InGaAsP)	1.3-1.5
Aluminum Gallium Arsenide (AlGaAs)	0.8
Semiconductor Laser diodes	600-1.5

Optical Source Requirements

Beam Quality: The parameter of major interest from the point of view of the optical design is the beam quality which specifies how tightly or how divergent is the beam of the laser diode transmitter package. A good optical link design ensures that the beam divergence is as minimum as possible. This parameter is determined by both the laser source and collimation optics.

Minimizing Wavefront Error: The inherent astigmatism of the laser diode has to be corrected by dedicated means like cylindrical lenses to achieve the specified demanding figure of Wavefront Error (WFE) [5, 7]. Higher order deviation from the laser diode wavefront from the ideal plane wave cannot be compensated. A good correction of aberrations for the collimator itself is required to cope with the specification.

Link Establishment: For a transceiver system, the stability of the beam direction is related to the requirement on co-alignment between the transmitter and received beam in the optical terminal. The alignment cannot be made during communication and hence has to be made before the communication starts. The optical devices that are the part of the system have to maintain a stable alignment of the optical signal for a typical communication period say for 24hrs.

Optical Source Design

Collimator specifications: The optical design consists of determining the specifications of the collimator which include the focal length and numerical aperture based on the beam diameter and the e^2 divergence angle. An example of a collimator assembly is shown in figure 3.The optical design of the collimator is very demanding due to the combination on various requirements such as chromatic aberrations, optical field and wavefront error. For the example collimator assembly shown in figure 4, the first six lenses are used for obtaining the desired beam width and have to be manufactured with thickness +/-0.05mm.Tolerance values for air gaps +/-1um.The collimator lenses should be fully achromatized for the wavelength specified. [5]

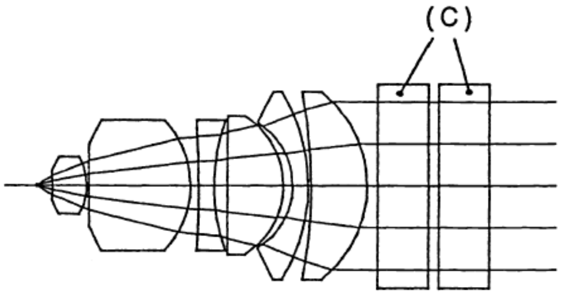

Figure 3: Example System of an Optical Source Collimator[4]

Compensation of aberrations: Aberrations which are produced due to the deviation of the laser source from the principle axis of the collimator have to be compensated by providing for the lateral displacement of the lenses. [4, 5]

Efficiency of the laser diode: If the efficiency of the laser diode drops, the drive current has to be increased, thereby causing an increase in the dissipated heat and the temperature gradient in the heat sink of the laser diode. The change in the temperature gradient causes a lateral displacement of the laser diode beam waist and the displacement has to be compensated by the terminal pointing assembly at the same maintaining the beam quality.

Astigmatism: Laser diode astigmatism has to be corrected by placing a pair of cylindrical plano convex lenses in front or behind the collimator. The lenses have to be rotated to compensate the amount of astigmatism present. In figure 4, the lenses marked as 'c' are used for correcting the astigmatism. [4]

Electrical & Mechanical Requirements

Rise Time: The rise time of the pulse is determined from the data rate to be achieved. For a data rate of 120Mbps, using QPM, a pulse width of 4ns requires a rise time of 1ns. [5, 7]

Frequency Response: The frequency response of a transmitter is a function of the drive current speed and the impedance matching between the laser driver output and the Laser Diode Transmitter Package (LDTP) input. The laser driver output and the LDTP input has to be properly matched as the resistance at laser diode input is smaller than the output of the laser driver. If they are not properly matched, reflections of the driver signal can occur. Also, the inherent inductance of the laser diode package has to be minimized.

Operating temperature: The operating temperature of a laser diode can vary anywhere from 20 degree Celsius-100degree Celsius. The temperature at which the laser meets the power budget requirements must be chosen and maintained.

Optical Source Mechanical Design

The Mechanical design has to take into consideration the following important aspects:

1. Accommodation of the collimator and the cylindrical lenses for correcting astigmatism.
2. Small lens diameters resulting in small dimensions of the housing.
3. Positioning of the laser diode relative to the collimating optics.

The material for the lens should be chosen so as to have a high coefficient of thermal expansion. Each optical component has to have its own mount as they have to be individually centered. A laser diode support is used for mounting the laser diode relative to the collimating optics.

Optical Source Electrical Design

The electrical design needs to take into consideration the following important aspects

Protection against negative current: In order to provide protection against negative current a monitor photo diode (MPD) has to be included in the laser diode package. A Schottky diode needs to be connected in parallel to the laser diode to protect it from negative current surge and a thermistor has to be positioned near the laser diode baseplate in order to measure the temperature of the laser diode with a high accuracy.

Impedance Matching: As high speed modulation is required, the two lines for modulation current and for monitor diode current have been matched to the required impedance. The drive line should have the same impedance as the resistance of the laser diode, which is around 2 Ohm. Since this very low value cannot be realized and a compromise of 10 Ohm has been chosen. The laser driver, which is matched to the 10 Ohm line, has to absorb the reflections induced by the laser diode [5, 7]. The monitor current line has standard 50 Ohm impedance. The above mentioned impedances can change depending on the resistance offered by the different types of diodes.

The parameters of a Laser Diode Transmitter Package originally designed for large satellites that meet the volume, weight and power constraint for the small satellites is outlined in the table 2 [5].

Table 2: Optical Source Parameters

Parameter	Range
Clear Aperture	9mm
Wavelength	0.8um-1.064um
Transmittance	95.00\%
Stability of beam direction	5urad
Wavefront Curvature Radius	250m
Wavefront Error	1/20 waves
Spectrum Width under modulation	4nm
Polarization Purity	1/100
Average Output Optical Power	30mW-400mW
Peak Optical power (DC=25%)	Depends on the diode specs
Rise Time in Pulsed Operation Depends on data rate	For 120Mbps, pulse width is 4ns and rise time is 1ns.
Operational Temperature Range.	20-30 degrees
Dimensions	53x50x57mm
Weight	180g

COMMUNICATION ELECTRONICS

The communication processing electronics determine the type of modulation that has to be applied to the laser. Conversely, it controls the modulator which in turn modulates the laser based on the input from the electronics. Data rates achieved with an ISL in geostationary orbit with a separation of 40,000 kilometers are about 360-500Mbits/sec. The common and simplest modulation techniques are On and Off keying (OOK), Q-ary PPM (Quaternary Pulse Position modulation) and Frequency Shift Keying (FSK).

On and Off Keying

Amplitude Shift keying is a form of modulation that represents digital data as variations in the amplitude of a carrier wave. The amplitude of an analog carrier signal varies in accordance with the bit stream, keeping frequency and phase constant. OOK can be considered to be a special case of ASK where in the binary bit '1' is represented by the presence of a carrier and binary '0' is represented by the absence of a carrier signal.
Advantages: The circuitry for OOK is relatively very simple and inexpensive.
Disadvantages: It is very sensitive to atmospheric noise, distortions and propagation conditions. For Laser diodes, binary 1 is represented by a short pulse of light for a specific duration and binary 0 is represented by absence of light for a specific duration. An example of OOK is shown in figure 4.

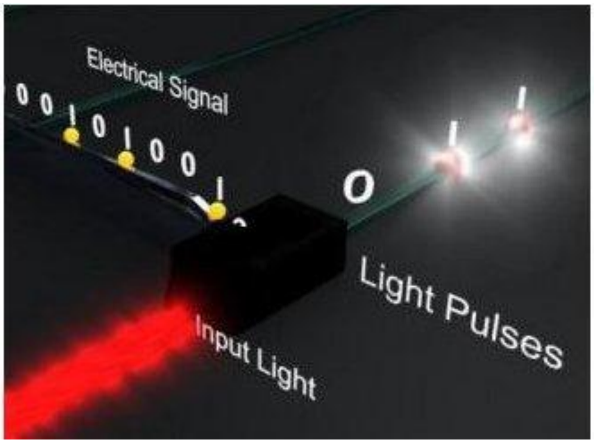

Figure 4: OOK modulation

Pulse Position Modulation

Pulse-position modulation (PPM) is a form of signal modulation in which M message bits are encoded by transmitting a single pulse in one of the 2M possible time-shifts. This is repeated every T seconds, such that the transmitted bit rate is M/T bits per second.
Operation: It is often implemented differentially as differential pulse-position modulation, where by each pulse position is encoded relative to the previous , such that the receiver must only measure the difference in the arrival time of successive pulses. It is possible to limit the propagation of errors to adjacent symbols, so that an error in measuring the differential delay of one pulse will affect only two symbols, instead of affecting all successive measurements.

Advantages: One of the principal advantages of PPM is that it is an M-ary modulation technique that can be implemented non-coherently, such that the receiver does not need to use a phase locked loop (PLL) to track the phase of the carrier. This makes it a suitable candidate for optical communications systems, where coherent phase modulation and detection are difficult and extremely expensive.

Disadvantages: A key difficulty of implementing this technique is that the receiver must be properly synchronized to align the local clock with the beginning of each symbol. Aside from the issues regarding receiver synchronization, the key disadvantage of PPM is that it is inherently sensitive to multi path interference that arises in channels with frequency-selective fading, whereby the receiver's signal contains one or more echoes of each transmitted pulse. Since the information is encoded in the time of arrival (either differentially, or relative to a common clock, the presence of one or more echoes can make it extremely difficult, if not impossible, to accurately determine the correct pulse position corresponding to the transmitted pulse.

Frequency Shift Keying

Frequency-shift keying (FSK) is a modulation scheme in which digital information is transmitted through discrete frequency changes of a carrier wave. The simplest FSK is binary FSK (BFSK). BFSK uses two discrete frequencies to transmit binary (0s and 1s) information. With this scheme, the "1" is called the mark frequency and the "0" is called the space frequency. In Optical communications, a variation of FSK known as M-FSK is used where in 2 or more frequencies are used to binary data.

POINTING ACCQUISITION & TRACKING SYSTEM

The Pointing, Acquisition and Tracking subsystem consists in acquiring and tracking the counter terminal incoming laser beam as well as in pointing the transmitter terminal’s outgoing beam with an accuracy which enables data transmission between two satellites. The operations that are needed to be carried out by the subsystem consist of [8,9,10]:

1. Acquisition phase which has to compensate for the initial beam pointing error due to spatial acquisition errors, mainly ephemeris error and spacecraft location prediction errors.
2. Tracking phase wherein once the beam is acquired, it has to track out local angular disturbances transmitted from the host platform and the dynamic elements of the payload with submicroradian accuracy.
3. Pointing phase wherein the terminal's optical head is pointed towards the opposite satellite after compensation for relative platform motions and finite transit time of light.

The strategies required to perform the above three tasks are described below.

Acquisition Strategy:

To establish a link to start communication between two satellites S1 and S2, the satellite S1 must send out a beacon signal. The divergence of the beacon signal is limited to say 700urad.The cone of uncertainty could be limited to 8000urad.The satellite S2 scans the cone of uncertainty till its terminal is illuminated by the laser beam. Once illuminated, it must detect the direction of the incoming light, correcting its Line of Sight, start tracking and emits its communication beam towards the transmitting satellite. Once the satellite S1 receives the communication beam from S2, it stops sending its beacon, starts tracking and corrects its line of sight and sends its communication beam [3, 10]. The two satellites are now in mutual closed loop tracking.

Tracking and Pointing Strategy:

The extremely high pointing accuracy of 1microrad is met by using the incoming light from the counter terminal as a reference to the pointing actuators. The two terminals are thus in a co-operative closed tracking loop during communication. The tracking angle corresponds to where the tracked terminal was when the light was emitted whereas the ideal pointing direction corresponds to where the pointed terminal will be when the light arrives, i.e. the pointing angle must be offset with respect to the tracking reference with the so called point ahead angle (due to relative transverse satellite velocity and the finite velocity of light) [8].

The PAT assembly is shown in figure 5 provides deflection of the incoming and out coming laser beams around two orthogonal axes and thus performs the following operations:

1. In the scanning mode, it sweeps the beacon over a wide angular range.
2. In the acquisition mode it provides a fast deviation angle over a wide range to re center the incoming beam on the tracking sensor as sensed by the acquisition sensor.
3. In the tracking mode it controls of the angular position of the incoming beam as sensed by the tracking sensor with high bandwidth and accuracy.

The design specifications of the PAT assembly detailed as follows.

Positional Accuracy: The distance between the satellites may be several thousands of kilometers. To establish a link between two satellites that is in order to point the laser beam onto the mirror of the other satellite, requires a positional accuracy of 1urad.The device should also be able to move the mirror by +/-

2degrees to provide coarse pointing around the neighboring satellite [9,10].

Bandwidth: The device must have sufficient bandwidth to reject satellite vibrations and disturbances. For small signal disturbances on the order of 0.01 degrees, this bandwidth should be about 200 Hz. Larger disturbances of about 1 degree need to be rejected below 1 Hz [9].

Actuating the mirror: Two types of devices are usually considered for actuation of the beam-steering mirror: voicecoils and piezoelectric actuators. The former offers a potentially large stroke for little power input, but is somewhat limited in bandwidth due to its low force output and consequently low stiffness. Piezoelectric actuators by contrast offer high bandwidth and stiffness, but provide very small position output even at relatively high voltages. The ideal device should combine the benefits of both technologies. While performing all the above described functions the power consumption of the device should be very low [9, 10]

Algorithms: An example acquisition algorithm is shown in figure 6, where the transmitter beam is widened such that it illuminates the receiver from any position within the area of uncertainty .At the beginning of the acquisition process, the receive antenna points at the center of the area of uncertainty Then it starts the spatial search by sequentially scanning the uncertainty area along a spiral track. When the transmitter is found, the receiver switches into tracking mode, where a spatial tracking loop is closed by evaluating the signal from a position sensitive detector and using this information to control the alignment of the optical antenna. The transmitter beam divergence is not reduced during this tracking mode [8].

Design Example: A design example of a PAT system that meets the 3U CubeSat specifications is briefly summarized [9]. It is essentially a configuration of four identical electromagnetic circuits, positioned at 90 degrees from each other around the circumference of a circle as shown in figures fig.5 and fig.7.

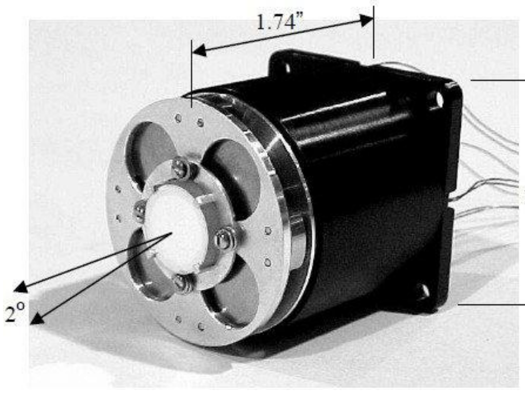

Figure 5: PAT System [9]

Four small permanent magnets are mounted to a moving mirror platform, while four corresponding coils and coil cores reside within a fixed housing. Consequently, most of the components are stationary. Each circuit magnetically pulls on the mirror platform.

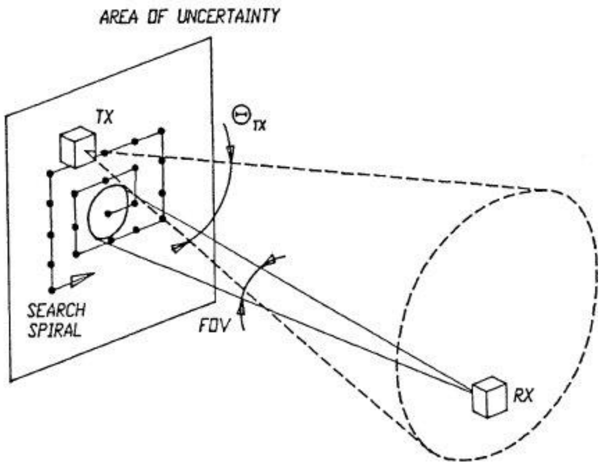

Figure 6: Example Algorithm [8]

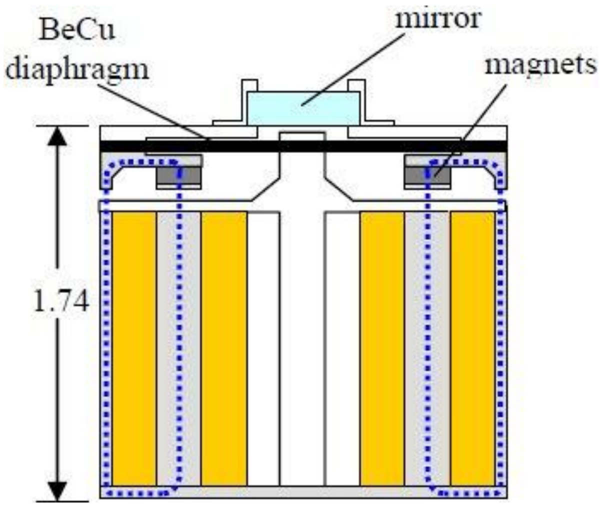

Figure 7: Side View PAT system [9]

However, by increasing positive current in one coil a magnetic field is generated which opposes that of the permanent magnet directly in front of it. Simultaneously increasing negative current in the coil 180 degrees away adds to the magnetic field in that circuit. In this way, a differential force is produced which tilts the mirror platform about its center. Similar operation of the other two coils produces motion along the orthogonal axis, so that the mirror can be positioned anywhere within an optical cone. The platform is mounted on a flexible BeCu diaphragm that provides a linear restoring torque in any direction against which the electromagnetic torque can react, yielding positional control. Also, by varying the total current in all four coils simultaneously, the platform can be positioned linearly along its center line, providing an additional degree of freedom if desired. The parameters of the described PAT system are tabulated in table 3 [9].

Table 3: PAT System Parameters

Parameter	Range
Maximum Deflection range	+/- 35000microradians
Bandwidth	200Hz for disturbances of 0.01 degrees 1Hz for disturbances of 1 degree
Dimension	Less than 3 inches in length, breadth, height and diameter.
Weight	400gms-250gms
Power	1.5 watts in tracking mode 5-16 watts in acquisition mode

OPTICAL TRANSMITTER & RECEIVER

The optical transmitter and receiver consist of a telescope to transmit and receive the optical signal. A considerably large part of the weight of the payload comes from the telescope and the need to minimize this weight is very essential to the design of the system. On studying various telescopes with respect to their contribution to the weight of the payload, the Cassegrain telescope was found to provide the least and hence was finalized as the candidate optical transmitter. The Cassegrain configuration consists of paraboloid concave primary and hyperboloid convex secondary mirrors and is consists of the following specifications [7]**:**

1. f/# varies from f/4 to f/1.5 for the primary mirror where f/# or f-number is called the focal ratio of the focal length to the aperture
2. Diameter of the secondary is 0.2-0.25 of the primary aperture diameter.
3. The telescope is house in a cylindrical tube made of beryllium since it is one of the lightest materials used to make telescope mounts.

Table 4: Transmitter & Receiver Parameters

Parameter	Value
Aperture	10cm
Weight @ 1.85gm/ cm^2	1kg-2.4kg
Primary mirror focal length(f/4) max	40cm
Primary mirror focal length(f/1.5) min	15cm
Secondary mirror diameter	2.5cm
Field of view	½ degree

The parameters of the telescope to be mounted onto cubesat based on the above specifications are tabulated in table 4.

OPTICAL RECEIVER

The function of the optical detector is to convert the incoming optical signal into an electrical signal. Like the optical source, the detectors are also semiconductor devices. Off the shelf receivers include PIN diodes and Avalanche Photo Diodes (APD).The detectors are characterized two main parameters namely quantum efficiency and responsivity at a specific wavelength. Quantum efficiency of a detector is the ability to generate electrons for every incoming photon and responsivity is amount of electric current generated per watt of incident optical power. Detectors operate in a reverse biased mode and hence have high operating voltages in the range of 15-30V.While the PIN diodes have a responsivity in the range of 0.5-0.7A/W and low operating voltages and are used for short link distances the APDs have a responsivity in the range 0f 20-80A/W and higher operating voltages and are used for long link distance. The available detectors and the range of operating wavelengths are tabulated in table 5.

Table 5: Operating Wavelengths of Optical Detectors

Material	Wavelength(nm)
Silicon	190-1100
Germanium	400-1700
Indium gallium Arsenide	800-2600
Lead II sulphide	<1000-3500

ANALYSIS OF THE PROPOSED OPTICAL PAYLOAD

The weight, volume and EPS requirements of the proposed payload are summarized below. While the contribution to the weight of the payload optical source, PAT and detector is very minimal, a large of the weight comes from the transmitter/receiver telescopes. Therefore careful consideration of the materials to manufacture telescopes should be carried out carefully. The PAT system consumes the maximum amount of power and in the case of the detector, voltages in the range of 15-30V are hard to generated given the very low power generation of 3W by the CubeSat. Hence though the system successfully meets the volume and weight specifications and can be compactly packed inside the CubeSat, it doesn't satisfy the power requirements. However, a viable alternative to deploy the payload would be on nanosatellites as this system would not only meet the volume and weight constraints of the nanosatellites but also the power requirements.

Table 6: Optical Payload Parameters Summary

Subsystem	%Weight	Volume	EPS Requirements
Source	9	53x50x57mm	10-50mA
PAT	20	L=4.35cm H=3.95cm	1.5W-15W
Tx/Rx	50	L=15cm,H=10 cm	No power consumption
Detector	Negligible	Negligible	15V-30V

OPTICAL LINK BUDGET EQUATIONS

In this section we outline the equations with simulations performed in matlab and simulink to describe the optical payload and spell the corresponding parameters for the small satellite scenario.

Link budget equation

$$P_r = P_t G_t L_t L_R G_r L_r \quad (1)$$

The terms in the equation are detailed in the following sections.

Transmitter Power

The transmit source power is a direct entry into the optical link equation. It is the measured signal power at the output of the laser. Usually, the transmit power is specified in watts, if the designer is consistent the average power can be used and specified in milliwatts. In case the laser is hermetically sealed, the power coming out of the hermetic seal needs to be considered. The power at the output of the laser is given by

$$P_t(f) = H_T(f).I_d(f) \quad (2)$$

$$H_T(f) = H_T(0).H_T^*(f) \quad (3)$$

Multimode Fabry Perot Laser

The transfer function of a multimode fabry perot laser is expressed as [11, 12]**:**

$$H_T = \left(\frac{h.c}{\lambda.q}\right).\eta_{int}.\eta_{ext}.\left[\frac{I_d - I_{th}}{I_d}\right] \quad (4)$$

$$\eta_{ext} = \frac{ln\left[\frac{1}{R_l}\right]}{\gamma.l + ln\left[\frac{1}{R_l}\right]} \quad (5)$$

$$\eta_{int} = \frac{\tau_{nr}}{\tau_{nr} + \tau_r} \quad (6)$$

$$H_T^*(f) = \frac{f_o^2}{f_o^2 - 4.\pi^2.f^2 + j\beta 2\pi f} \quad (7)$$

$$f_o^2 = \frac{(I_o - I_{th})}{\tau_{sp}\tau_{ph}I_{th}} \quad (10)$$

$$\beta = \frac{I_o}{\tau_{sp}I_{th}} \quad (9)$$

Quantum Cascade Laser

The Quantum Cascade laser and Distributed Feedback Lasers are modeled using the following rate equations [11, 12].

Table 7: Parameters of the Equations

Parameter	Description
I_d	Injected Current
I_{th}	Threshold Current
R_l	Mirror Reflectivity
γ	Loss Coefficient
l	Cavity Longitudinal dimension (m)
I_o	Polarization Current (A)
τ_{sp}	Carrier Recombination Lifetime (s)

β	Damping Frequency (Hz)
f_o	Resonant Frequency

$$\frac{dN}{dt} = \frac{I}{q.V_{act}} - g_o(N - N_o)(1 - \varepsilon.S) - \frac{N}{\tau_n} + \frac{N_e}{\tau_n} \quad (10)$$

$$\frac{dS}{dt} = \gamma g_o(N - N_o)(1 - \varepsilon.S)S + \frac{\gamma\beta N}{\tau_n} - \frac{S}{\tau_p} \quad (11)$$

$$\frac{S}{P_f} = \frac{\gamma\tau_p\lambda_o}{V_{act}\eta hc} = \upsilon \quad (12)$$

Table 8: Parameters of Rate Equations

Parameter	Description
N	Active region carrier density
q	Electron charge
V_{act}	Active region volume
g_o	Gain Coefficient
N_o	Optical transparency density
ε	Fenonmenological gain saturation term
S	Photon Density
τ_n	Carrier lifetime
N_e	Equilibrium carrier density
γ	Optical Confinement Factor
β	Spontaneous emission coupling factor
τ_p	Photon lifetime
λ_o	Lasing wavelength
η	Differential quantum efficiency per facet
h	Plank's constant
c	Velocity of Light

Transmitter Gain

The gain of the transmitting antenna is given by

$$G_t = \frac{4\pi A}{\lambda} \quad (13)$$

where

$$A = \frac{a^2\pi}{4} \quad (14)$$

where a =aperture of the transmitting antenna.

Transmitter Loss

Transmitter loss is a measured loss that is caused by aberrations due to imperfection in the manufacturing process and mechanical stresses on the optics result in a non-perfect optical wavefront. Each optical surface that the ray traverses causes an optical loss that is multiplicative. This multiplicative loss causes a degradation of the transmit power. In our analysis, this loss is considered to be negligible.

Free Space Loss

$$L_R = \frac{\lambda}{4\pi R^2} \quad (15)$$

where

R = Distance over which the link has to be established.

Receiver Gain

The gain of the receiving antenna is given by

$$G_t = \frac{4\pi A}{\lambda} \quad (16)$$

where,

$$A = \frac{a^2\pi}{4} \quad (17)$$

where a =aperture of the receiving antenna.

Receiver Loss

The loss at the receiver is similar to the loss that occurs at the transmitter but arises from the optical elements at the receiving terminal. In our analysis, this loss is considered to be negligible.

Optical Link Budget Parameters

The parameters for the equations are determined from the ISL systems as detailed in the previous sections and are tabulated in table 9.

Table 9: Optical Link Budget Parameters

Parameter	Value
Aperture	10 (cm)
P_t	-20 (dBW)
Laser Diode Drive Current	10-20 (mA)
λ	1550 (nm)

L_R	Variable
L_t	0 (dB)
Data Rate	120 (Mbps)
Bit Error Rate	0

Radio Frequency Link Budget Parameters

The radio frequency link budget parameters tabulated in table 10 from ref 15 for comparison. These experimental parameters are chosen due the frequency of operation being not as far away from the terahertz range when compared to the existing frequency specifications of 430MHz for the cubesat. The link distances are calculated using the standard RF link budget equations [15].

Table 10: RF Link Budget Parameters

Parameter	Value
G_t	10.36 (dB)
P_t	-32.26 (dBW)
Frequency	5.85 (GHz)
L_R	Variable
Polarization Loss	-0.3 (dB)
System Noise	135 (Kelvin)
Data Rate	1200 (bps)
G_r	10.36
E_b / N_o	9.6 (dB)
Bit Error Rate	10E-5

RESULTS

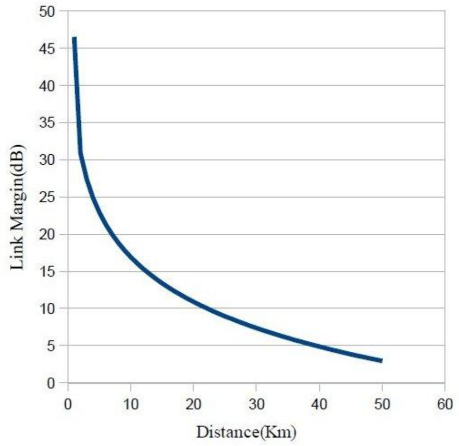

Figure 8: RF Link Distance

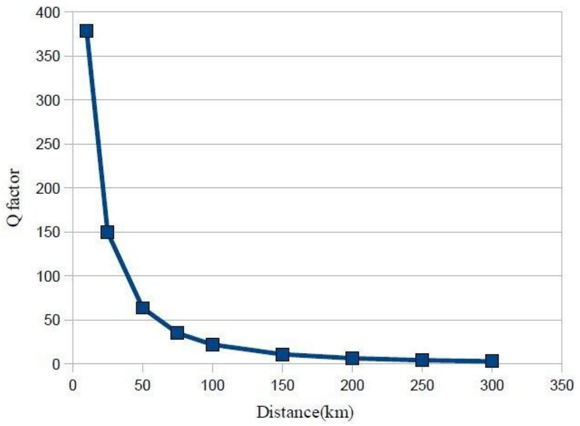

Figure 9: Q factor vs. Link Distance

In figure 8 the link margin vs. the inter satellite link distance are plotted. The figure shows as the distance between the satellites increases the link margin to achieve a bit error rate of 1E-6 decreases. Since a signal to noise ratio of 3dB has to be maintained to ensure that the BER does not drop below the specified value, the maximum achievable distance for the specified parameters is 50km.In figure 9 the Q factor vs. the inter satellite link distance and in figure 10 the received signal power vs. inter satellite link distance is plotted.

The Q factor is a measure of the signal to noise ratio of a binary optical signal. For Q factor values greater than 10 and distances less than 200km, the BER is almost 0

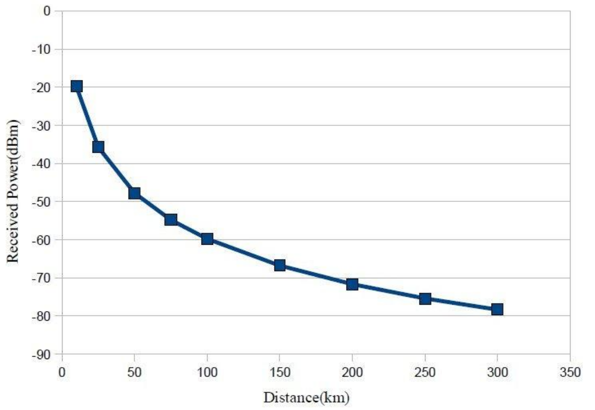

Figure 10: Received Power vs. Distance

thus meeting specifications. But for distances greater than 200km where the Q factor is less than 6, the BER can vary from 1E-9 to 1E-2.The scenario considered here is a highly optimistic scenario as the The results have thus quantified the maximum achievable inter satellite optical links distances for small satellites for parameters of the subsystems described above and for the specified BER.

CONCLUSION

A study of the laser crosslink system of large satellites provided and the subsystems of the large satellite laser communications terminal were analyzed for suitability in the CubesSat frame. Each subsystem was further analyzed in terms of functionality, contribution to the weight of the optical payload and power requirements. The parameters of the larger system were then redesigned to meet the size, weight and power constraints of the CubeSat and it was seen that the optical payload would be much more suitable for small satellites with a wet mass greater than that of the CubeSat.

CONCLUSION

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