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Design Tradeoffs and Challenges of Omnidirectional Optical Antenna for High Speed, Long Range Inter CubeSat Data Communication

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ABSTRACT

Omnidirectional Optical Antennas (OOA) with 360^{o} Field of Regard along with full-duplex laser communication capability can play a remarkable role in achieving sophisticated CubeSat mission that can achieve high speed (≥1Gbps), long distance (≥50km) data communication, data relaying among CubeSats and that possesses formation flying ability. In this paper, we discuss miniature optical antenna design optimization techniques using COTS components to facilitate OOA development. In particular, we present challenges involving design tradeoffs among scanning mirror size, scanning angle, transmit beam width, beam divergence, pointing accuracy requirements and component availability in a SWaP-C limited system. We show that to achieve maximum SNR at long distance, the transmit laser beam diameter to mirror diameter ratio needs to be 0.8-0.9. Moreover, we show that the peak intensity varies and can decrease up to 70% over the mirror scanning range depending on transmitter beam size. Furthermore, we explain the effect of laser peak power, initial beam size and communication distance on Effective Communication Beam Width (ECBW) to maintain SNR≥10dB at 1Gb/s. We show that by choosing the optimum components and parameters an ECBW of ≥50m at 50km distance is achievable. Therefore, the communication link can endure angular disturbance of 50 µrad - 180.5 µrad.

INTRODUCTION

CubeSat technology continues to develop, and more sophisticated missions are being proposed and executed each year. NASA's new mission for small spacecraft technology mandates small, affordable and transformative approaches to enable high-speed data communication and relative navigation without sacrificing performance metrics. In CubeSat system mass, volume, available power, pointing and acquisition accuracy, Signal to Noise Ratio (SNR) are important factors in the design phase. Advanced CubeSats should be able to form a constellation formation, perform formation flying, and provide high-speed omnidirectional (>1Gbps) data communication and data relaying among satellites to transfer remote sensing data as in Fig.1. In particular, high-speed data communication and relaying among CubeSats will introduce new areas of application which were previously unattainable. Designing of a miniature optical transceiver is crucial in achieving omnidirectional communication capabilities.

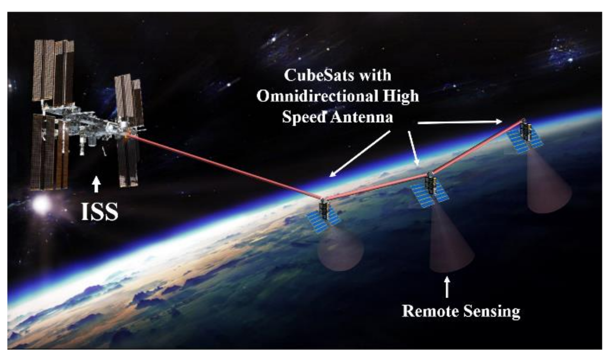

Figure 1. CubeSats with Omnidirectional Antennas in Formation Flying.

Optical aperture diameter plays a vital role in such a transceiver design. A few research have been conducted in recent years on the deployable optics and structure compatible with CubeSats to increase the aperture size and hence to achieve better communication distances[1,2]. We aim to build a multi-aperture Omnidirectional Optical Antenna (OOA) using Commercially of The Shelf (COTS) optics and lasers which can fit in 1U of a 6U CubeSat as shown in Fig 2. Our goal is to use multiple apertures of ≤15mm to achieve a Field of Regard (FOR) of 360 ° and very high Field of View (FOV) without any bulky mechanical rotating parts. Deployable optics is also prohibitive in the multi-aperture system due to the small form factor of the CubeSat and design complexity. In our work, we investigated compact transceiver design techniques based on COTS MEMS-based and dual axis vector-based scanning mirrors considering Size Weight and Power-Cost (SWaP-C) limitation imposed by CubeSat technology.

In this paper, we explain the design techniques for the fabrication of a small, cost-effective optical transmitter to achieve omnidirectional data communication using COTS components. In particular, we discuss the design tradeoffs among scanning mirror size, scanning angle, transmit beam width, beam divergence, pointing accuracy requirements in transmitter design to achieve high SNR(≥10dB) in inter-satellite high speed (≈1Gb/s) optical communication. In the presented design analysis, we have adopted 850nm as operating wavelength to achieve less divergence, as well as the availability of high gain APDs, high power VCSELs and COTS optics. All analysis is scalable to other wavelengths, such as conventional telecom wavelengths near 1550nm with proper component parameters.

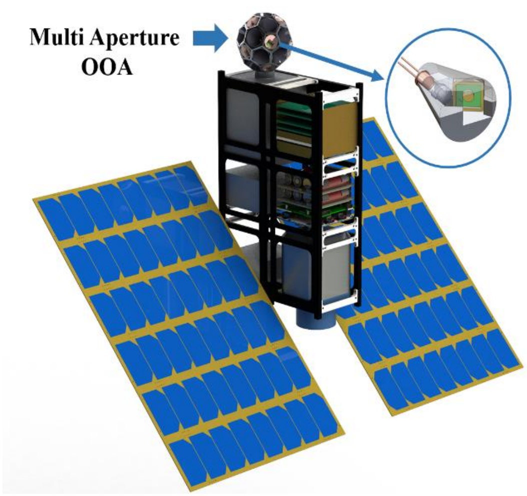

Figure 2. Multi Aperture Omnidirectional Optical Antenna (OOA) to Achieve High Speed Data Communication and Relaying Among CubeSats.

TRANSMIT BEAM SIZE OPTIMIZATION CONSIDERING SCANNING MIRROR SIZE

Scanning capability of a mirror intertwined with its size form factor and driving mechanism. The optical path of the laser beam can support multiple the lager fixed mirror without compromising the performance of the system and hence, the scanning mirror can be a major limiting factor in designing the transmitter. Full divergence angle (θ) of a Gaussian beam in free space is inversely proportional to its initial beam waist (ω_o) and proportional to the wavelength (λ) as in (1)[3]. As a result, the larger the initial beam size the higher the optical antenna gain.

$$\theta = \frac{4\lambda}{2\pi\omega_0} \tag{1}$$

Although incorporating a beam expander after scanning mirror is the easiest way to expand the initial beam, the scanning system loses scanning range due to beam expansion. If M is the beam expander expansion ratio, then the system's scanning range, $\alpha \approx \frac{1}{M}\phi_m$, where ϕ_m is the intrinsic scanning range of the scanning mirror. In many cases, the scanning mirror diameter limits the allowable transmitter aperture where sacrificing scanning range is disadvantageous. Therefore, initial beam size needs to be optimized considering required scanning mirror size. In most of the transmitter design techniques, it is very common to assemble the scanning mirror at 45° with respect to the incident laser beam axis. Under this circumstance, a larger (over-filled) beam exhibit small beam size because of less divergence as seen in Fig. 3.

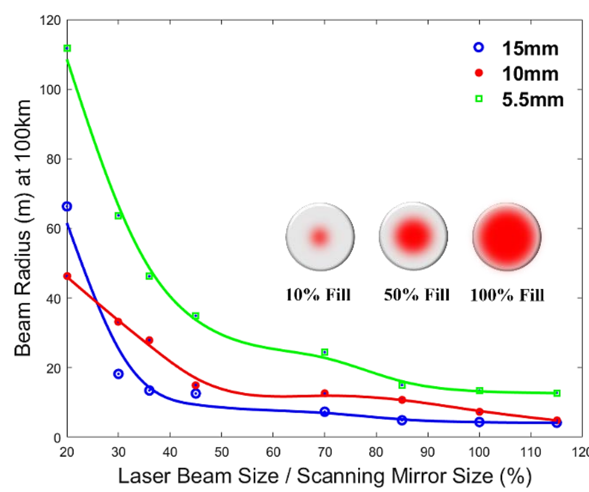

Figure 3. Effect of Initial Beam Size to Scanning Mirror Size Ratio on Far Field Beam Radius. The Solid Lines are Fitted Curve on the Zemax Simulated Data Points Based on COTS Components.

Beam size in Fig. 3 is measured as $1/e^2$ radius at a 100km distance from the transmitter. Three commercially available compact scanning mirrors 15mm, 10mm and 5.5mm) are considered in far field beam size simulation. Most of the mirrors are purchased from Mirrorcle Technologies, Inc[4], and Optotune[5]. Divergence data of all collimators are obtained from the datasheets of commercially available collimators[6–8] and hence, considered the non-ideal effect of actual optics inside collimators. The collimated laser beam can be optimized to under-fill or over-fill the scanning mirror. It is seen from Fig.3 that an overfilled beam (>100%) can cause smaller beam size at far field. An overfilled Gaussian beam can exhibit less divergence and therefore, smaller beam size at the target as shown in Fig 3. However, an overfilling beam experiences higher beam profile distortion and will be discussed in a later section.

An overfilled beam can be utilized when achieving the smallest beam size is the primary goal. However, the peak irradiance at the receiver side largely depends on the relative size of the laser beam and mirror size (effective aperture size). Due to clipping, scattering and diffraction[9,10] by the mirror limit the power throughput. As a result, the peak irradiance (I_{peak}) and hence, the maximum achievable received power reduces at the receiver as in (2) [11], where P_o, ω are the total power and the beam waist at a certain distance.

$$I_{peak} = \frac{2 * P_o}{\pi * \omega^2} \qquad (2)$$

Received power at the receiver, $P_{rcv} = Irradiance \times A_{rcv}$ where A_{rcv} is the area of the receiver aperture. Therefore, the irradiance is of great importance in data communication to maintain acceptable SNR. In Fig. 4, it is seen that the peak irradiance at a 100km distance for different scanning mirrors as a function of laser beam size to mirror size ratio. The actual peak irradiance deviates from the simplified (2) in long distance as the equation does not consider the interplay between diffraction, scattering and divergence. It can also be observed from Fig.4 that if the collimated laser beam diameter ($1/e^2$) is 80%-90% of the scanning mirror diameter, the receiver will experience the highest irradiance and hence, better SNR.

BEAM IRRADIANCE PROFILE VS MIRROR SCANNING ANGLE

To attain Omni directionality and data relaying among CubeSats, fast and compact scanning mirror is important. Commercially available MEMS mirrors have a small diameter(<5mm), small scanning angle($\pm 5^0$ - $\pm 7^0$) but high scanning frequency(3KHz -1KHz) [12,13] while dual axis mirrors have a relatively larger diameter (≈15mm), wide scanning angle($\pm 16^0$ - $\pm 25^0$) with much lower scanning frequency(<350Hz)[14].

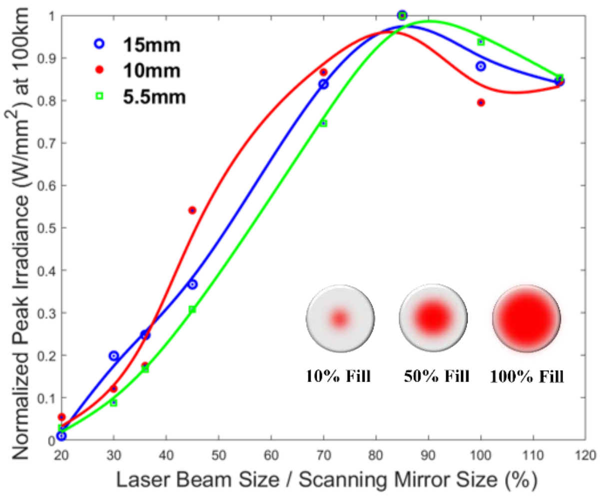

Figure 4. Effect of Initial Beam Size to Scanning Mirror Size Ratio on Far Field Peak Irradiance. The Scanning Mirror is at 45º w.r.t. Laser Beam Axis. The Solid Lines are Fitted Curve on the Zemax Simulated Data Points Based on off-the-shelf Components.

High scanning angle (≥7º) is desirable to achieve omnidirectional transmission due to the small form factor of CubeSat. However, the mirror scanning angle also affects the irradiance profile at the receiver when the beam size and mirror size are comparable. Detail analysis of the far field beam profile due to different scanning angle needs to be performed to optimize the transmitter design for the omnidirectional transmitter of a CubeSat. As a proof of concept, Peak irradiance variation due to different scanning angle of a scanning mirror at a 100km distance for commercially available collimators is shown in Fig. 5. Here we assume that the initial laser power is 1W. The vertical axis is the peak irradiance normalized with respect to the peak irradiance of a 13mm transmitter beam. It can be observed from Fig. 5 that peak irradiance varies noticeably if the laser beam diameter ($1/e^2$) is ≥ 30% of the mirror diameter. For example, peak irradiance can drop ≈10% and ≈70% for a 7mm and 13mm laser beam sequentially at a large scanning angle. Beam clipping phenomenon occurs at the mirror for a Very Large Angle. Therefore, the Signal to Noise Ratio (SNR) can vary based on the mirror's dynamic angular position and hence, transmit beam size needs to be optimized accordingly. The free space optical link should be designed, and the link budget should be calculated considering this dynamic SNR variation due to mirror scanning angle at an instant of communication. In addition to peak irradiance, far field beam profile also changes significantly due to different phenomena at the scanning mirror such as diffraction, scattering, beam clipping etc.

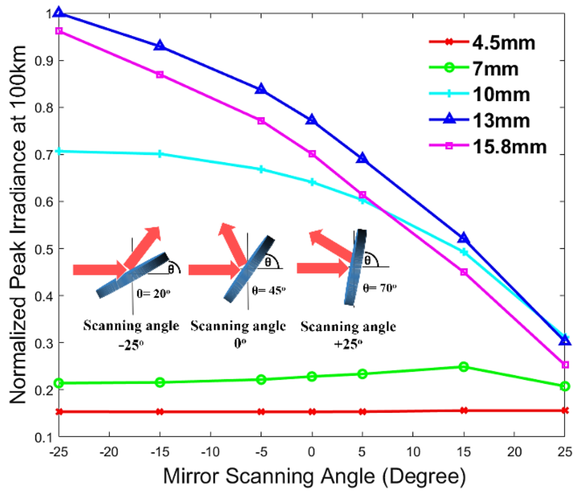

Figure 5. Peak Irradiance Variation Due to Mirror Scanning Angle for Different Initial Transmit Beam Size. 15mm Diameter Scanning Mirror with ±25° Mechanical Scanning Capability is Used in the Simulation Model.

The beam profile at the receiver deviates from the initial beam shape and can be important to optimize if the beam shape needs to be preserved. The beam shape variation in the far field (100km away from the transmitter) for different initial beam size and different scanning angle is shown in Fig.6. The Scanning mirror has the same diameter as mentioned in Fig.5 (15mm). It is seen from Fig. 6 that the irradiance profile distorted from the ideal profile based on relative size of the beam and the mirror as well as mirror scanning angle. A relatively large beam (w.r.t. mirror) manifest high peak irradiance due to low divergence, nevertheless the beam shape distortion is higher for a larger beam as shown in Fig.6. As a result, the transmitter beam size for CubeSat for a given aperture dimension should be optimized considering the interplay between the divergence and the diffraction.

ROBUSTNESS TO HOST CUBESAT VIBRATION AND POSITION UNCERTAINTY.

Transmitter laser beam width needs to be optimized considering the position uncertainty and the imperfect knowledge of the CubeSat orientation. We discussed in the previous section that the peak irradiance and therefore, the received power collected by a finite aperture of the receiver decreases with the scanning angle for a fixed distance as in Fig.5. In this section, we take satellites position uncertainty, pointing accuracy difficulties into account in designing a CubeSat optical transmitter. For the subsequent section, we limit the communication distance up to 50km. The concept can be readily applicable to long-distance communication network considering the transmitter has enough input power to establish error-free data communication.

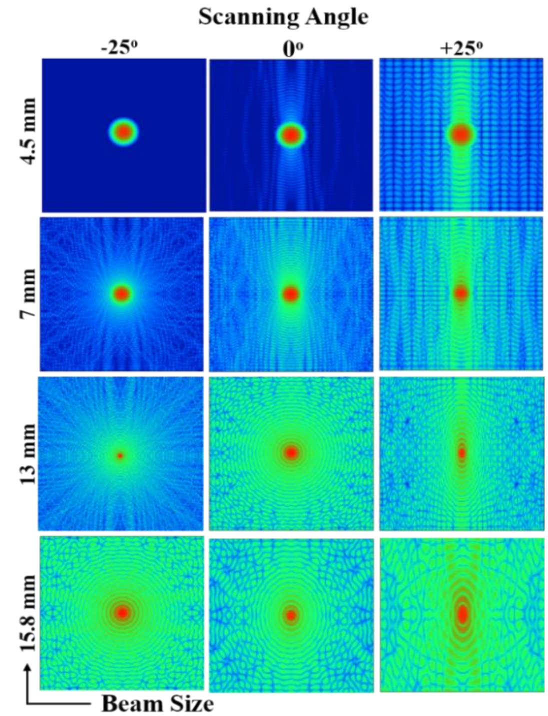

Figure 6. Far Field Beam Profile for Different Initial Transmitter Beam Size and Mirror Scanning Angle.

At a fixed scanning angle, due to the Gaussian beam profile, the meaningful high speed data communication is possible if the receiver falls into small region of the beam where the beam irradiance is high enough to maintain desired SNR (such as ≥10dB without forward error correction, or >4dB with forward error correction) as in (3)[15]. I_p, σ, R, P_{rcv} are signal current at APD, total noise current, photodiode responsivity and the received power by the receiver optics.

$$I_p^{\ 2} \geq SNR_{required} \times \sigma^2 \text{, where } I_p = R \times P_{rcv} \qquad (3)$$

Let us introduce two figures of merits, Effective Communication Beam Region (ECBR) and Effective Communication Beam Width (ECBW). The Effective Communication Beam Region (ECBR) is the approximate circular area in a 2D space of the beam at far field within which the data communication can maintain a desired SNR e.g. ≥10dB. The ECBW is the diameter of ECBR. In free space optical communication link, the ECBW is more informative than beam size as it is directly related to SNR and data rate of the communication link. As long as the receiving CubeSat is in ECBR, the communication link is functional maintaining the desired SNR. For example, for a receiver at 50km distance, the ECBR is shown for different initial beam size in Fig. 7**.** It is seen from Fig. 7 that for an average transmitter power of 1W, the ECBW for 13mm, 10mm, 7mm, and 4.5mm are 6m, 6.8m, 7.5m and 8.75m respectively. It is seen that transmitter beam size and ECBW maintain an inverse relationship.

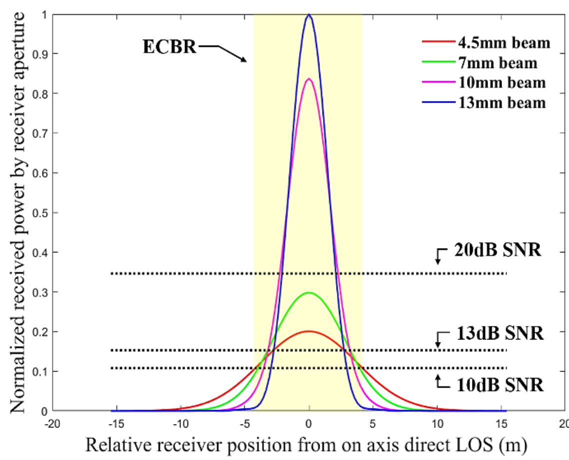

Figure 7. Effective Communication Beam Region (ECBR) for a 1W Laser at the Receiver Due to Different Initial Transmitter Beam Size.

Fig.8 shows the ECBW at a 50km distance for different initial power. The effect of transmitter beam size on ECBW is more prominent if the laser peak power is increased (a commonly adopted technique[16]) to achieve long distance communication as shown in Fig. 8

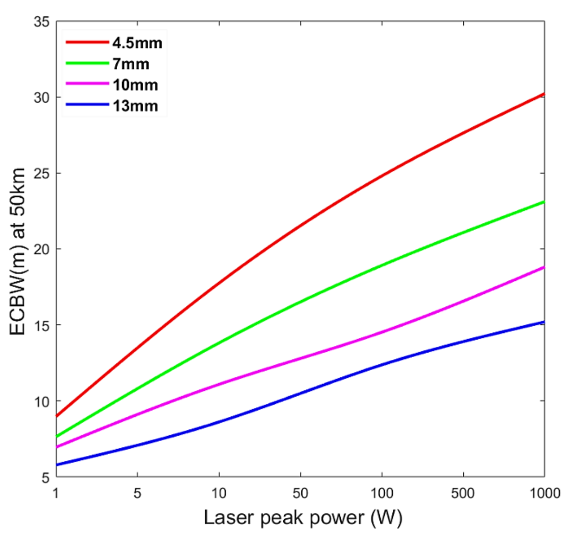

Figure 8. Effect of Laser Peak Power on Effective Communication Beam Width (ECBW) at 50km.

It is obvious that for very high peak power laser(≈1kW), the ECBW for a 4.5mm transmitted beam is ≈30m, which is almost twice than that of a 13mm transmitted beam that produces ECBW of ≈15m. ECBW also depends on the communication distance as shown in Fig.9. In short distance communication (<10km), ECBW for all transmit beam size are almost identical to each other (in the range of 2m-4m) for any transmitted beam size due to the negligible effect of divergence. In the mid-distance communication (10km-40km) a medium size beam shows higher ECBW as beam divergence is still less dominant. However, the effect of initial beam size is pronounced in long-distance communication (>40km). We can see an exponential increase of ECBW for a 4.5mm beam and hence a significant improvement in ECBW.

ECBR and ECBW can be utilized to quantify the immunity of the communication link from random angular disturbance caused by satellite vibration, steering mirror pointing inaccuracy, receiver position uncertainty after the initial pointing and acquisition is achieved. Fig.10 shows the CubeSat tolerance for angular disturbance for different initial laser beam size. It is seen that for a long-distance communication (>40km), a transmitter with small (4.5mm) beam size on a 15mm steering mirror shows more robustness to random CubeSat vibration and relaxes pointing and tracking challenges. For a high peak power laser, this effect is more noteworthy. At 50km, 13mm, 10mm, and 4mm beam permit angular disturbance of 82.4μrad, 114.5 μrad, and 180.5 μrad respectively for a 10W peak power Laser.

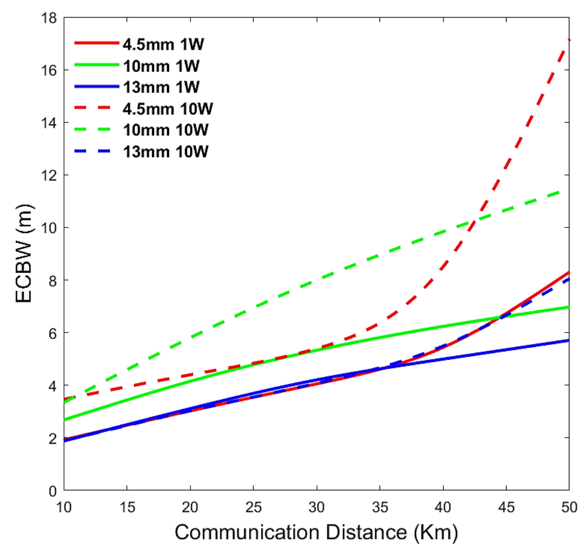

Figure 9. ECBW at Different Communication Distance for Different Initial Laser Power and Laser Beam Size.

Transmitter beam size processes the tradeoff between maximum achievable received power, host satellite vibration and pointing precision requirement for a given distance. Therefore it is imperative to optimize the transmitter beam size of an omnidirectional optical antenna considering the challenges and complexities related to pointing acquisition and tracking [17,18] originated from host spacecraft disturbance, the disturbance of the remote node and tracking sensor noises.

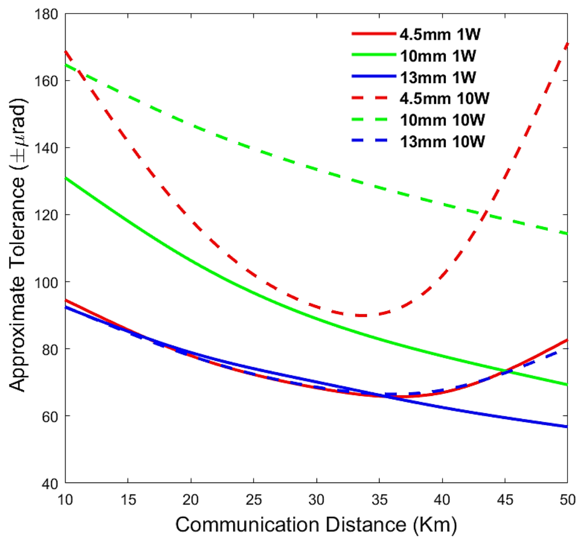

Figure 10. Angular Disturbance Tolerance due to Random CubeSat Vibration, Position and Tracking Inaccuracies.

CONCLUSION

We demonstrated compact transmitter design techniques considering design variables such as initial beam size, scanning mirror trade-offs, pointing accuracy requirement and random vibration of CubeSats to pave the way to achieve multi-aperture Omnidirectional Optical Antenna. We showed that the transmitter beam size needs to be optimized considering the space-power limitations, component availability as well as the interplay between the beam divergence and scattering. Moreover, we have introduced the concept of ECBR and ECBW in designing optical link along with their effect on link SNR and the satellite's angular disturbance tolerance. To achieve the optimum performance, a designer should consider all abovementioned variables and converge to a design technique to attain the desired performance goals.

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