Exploring Low Beam Divergence Optical Transmission of Raw Digital Signal Using a Stabilized Antenna to Improve Power Efficiency and Data Security for Point-to-Point Link Space Communication in Autonomous LEO Satellites

ABSTRACT

Since the advent of satellite communication using lasers in 1995, humans have been ever seeking to improve the efficiency and data security of optical laser-based communications in space. This paper explores and expands on the idea presented by a group of researchers in Chalmers University in November 2024 regarding a novel method of optical communication utilizing a single high power laser source and a hyper sensitive receiver, replacing the traditional low-power message signal plus high-power carrier configuration. In this paper, we expand on the above idea by replacing the standard semiconductor laser source with a solid-state crystal laser which has a beam divergence several magnitudes lower. While this would allow us to reduce transmitted power required for the source laser due to the decreased beam divergence, it also introduces a new challenge. Namely, maintaining the transmitting antenna at a precise attitude with sufficient angular stability. This was previously not an area of concern as the beam divergence angle was wide enough for slight deviations to not impact the quality of the received signal in any meaningful way. To address this new problem, we have explored the use of a Lyapunov-inspired stabilizing subsystem connected to the transmitting antenna module to accommodate the increased degree of precision in attitude that is now required. The addition of this subsystem enabled us to correct a jitter of up to 100 μrad to within 99% of the beam divergence angle in just 1.5 s. In our research, we simulated the effects of the above stated modifications to the traditional optical communication we use today, and studied their effect on the power consumption at the source, the security of the data through the channel, and the bit error rate during recovery at the receiver. It was found that by implementing these modifications, it was possible to vastly reduce the effect of natural interference, and greatly decrease the viability of artificial interception by malicious actors. While simultaneously reducing the power consumed for transmission at the source by more than 7 folds, from the traditional 5 W to 0.6816 W. Further, we also decreased the noise susceptibility by 40 folds, decreasing the maximum SNR required for error-free recovery from the traditional limit of 10 dB to -6 dB. These huge differences can be majorly attributed to the fact that we are transmitting the data in its raw digital form unlike traditional optical communications, which convert the digital data into analog before transmission. This was not viable earlier owing to limitations in the receiver technology, but is possible today because of recent advancements and research in optical receivers which allow them to be hyper-sensitive to received signals.

Keywords: Optical Communication, Beam Divergence, Interference, Interception, Single Laser Source, Raw Digital Transmission, Lyapunov-Inspired Stability System, Physical Encryption, Hyper-Sensitive Receiver, Power Consumption, Data Security

1. INTRODUCTION

In 1957, Sputnik 1, the first artificial space satellite, and the first to prove the feasibility of space to Earth communication, was launched. Ever since, there have been numerous advancements in communication technology, the most notable being the shift from radio wave communication to the higher frequency and more robust optical communication. Among many factors that make a satellite link a reliable one, is the data security of the channel. Till date, there have been no shortage of researches aimed at increasing the security and minimizing the viability of malicious interception. However, these advancements have almost exclusively been aimed at digital encryption techniques on the transmitting satellite end. There is a gap in the exploration of altering the very physical characteristics of the transmitted signal to achieve the same result. This paper will explore the idea of utilizing physical encryption as an alternative to digital encryption. This shift will not only save computational heavy resources used for modern digital encryption, but will also be a reliable safeguard against the rising threat of the use of quantum computers for interception using brute-force algorithms. The marked increase in the effectiveness of physical encryption can be attributed to the fact that if a third malicious party is unable to even detect the signal, it renders even the most advanced decryption techniques useless. In exploring the possibility of physical encryption in satellite communication, this paper aims to open the door on a completely new level of data security, and explore the advantages that comes with it such as reduced power consumption at the transmitting satellite, and a faster rate of communication.

1.1 Background

Traditionally satellite communications relied on Geostationary Earth Orbit (GEO) Satellites. These offered wide coverage for individual satellites but resulted in a high latency and path loss. Scientists began looking at Low Earth Orbit (LEO) Satellites to counter these limitations. It was found that switching from a single GEO to a network of LEOs to cover the same area significantly reduced the latency and path loss, and reduced the cost of operation due to the significantly reduced size, weight, and fuel required to launch a satellite into low earth orbit. [1]

The popularization of Wireless Optical Communication in satellites further boosted the advantages offered by LEO, drastically increasing the capacity due to the increased bandwidth, and reducing the transmission power even further. Additionally, switching to optical from radio communication had the advantage of being almost invulnerable to most of the interference radio signals were experiencing. [2][3]

However, this also came with its own limitations. First, optical communication did get affected by some amount due to atmospheric interference such as rain, fog, and snow. Second and more importantly, the precision required of the transmitting antenna is greatly increased, to be able to focus the transmitted power to the receiver. [3][4]

To mitigate these drawbacks, a few solutions were proposed such as aperture averaging, advanced modulation, adaptive optics, and a variety of diversity schemes. These were effective for the beam divergence of a regular semiconductor laser in LEO and GEO. Further, it was discovered that using the 780-850nm and 1520-1600nm band gaps for transmission provided the best performance due to low attenuation. [4][5]

Now yet another area of research has been opened up by a group of researchers in Caltech in November 2024. They proposed the removal of the modulating carrier wave altogether in the transmitting satellite, bringing down weight, power usage, and cost. They argued that this is made viable by new advancements in the receiver technology allowing them to pick up signals with much lower power than before. [6]

1.2 Research Gap

While there has been significant research in digital encryption techniques, we observed a distinct gap in the use of physical encryption to prevent a potentially malicious third party from even detecting the signal.

1.3 Research Objectives

This paper focuses on the potential of physical encryption, the advantages it affords, its limitations, and possible steps to counter the limitations.

2. MOTIVATION

Traditionally, message signals were modulated using carrier signals to increase their range and offer protection against interference. However, the use of carrier waves increases the power load on the transmitter. This is especially limiting in space applications, where fuel efficiency and mass are the 2 main bottlenecks. To overcome this, and in view of recent developments to receiver sensitivity, this paper proposes a solution where the signal is transmitted without the need for modulation with a carrier wave. This will both increase transmitter robustness by increasing simplicity, and decrease power consumption by eliminating the need for the modulating signal. Amid growing concerns about the environmental impact and the rising cost of fuel, any improvement in the fuel and power efficiency will greatly ease the constraints currently limiting spacecraft launch capabilities. This paper explores the elimination of carrier wave at the transmitting satellite as a means to this end.

3. METHODS AND WORKINGS

This paper aims to evaluate and analyze the effectiveness of optical communication in space without the use of modulation. A Simulink model for the system was built, separately modelling the transmitter and the receiver. The data was randomly generated at the transmitter and passed to the receiver through a channel block which simulated interference and attenuation. Upon receiving the unmodulated data at the receiver, various noise correction techniques were implemented to attempt to recover the original data with minimal bit error. This process was repeated for various transmitter powers to find out the least power required to perfectly recover the original data.

3.1 Overview of Proposed System

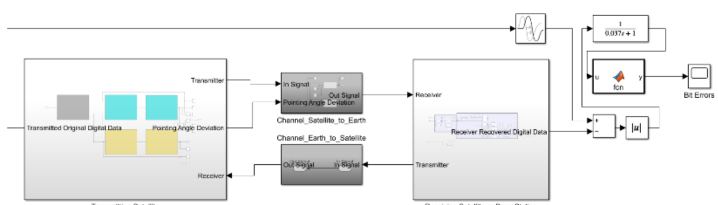

Figure 1. Top level block diagram

The proposed system consists of 2 main blocks, as shown in figure 1. The transmitting satellite and the receiving satellite / base station. In between these 2, acting as the medium, is the channel.

The transmitting satellite consists of 2 subsystem and an On-Board Computer (OBC) connecting these 2 subsystems and acting as the backbone of this block. The 2 submodules work in sync to transmit data, and they are the Lyapunov-Inspired Stability Control Subsystem for attitude stabilization and pointing accuracy, and the Signal Transmission Subsystem, which transmits the signal through the optical transmitting antenna.

The attitude and stability control system controls a reaction wheel directly attached to the antenna. This allows us to adjust the orientation of the antenna without spending unnecessary energy in rotating the entire satellite. This aligns towards one of the primary objectives of this paper, which is to decrease power consumption wherever possible.

The receiving satellite or base station consists of a series of filters and modules to collect and recover the original data from the noisy, attenuated received signal.

The channel in between acts as the medium which simulates the attenuation and interference of the signal.

3.2 Channel

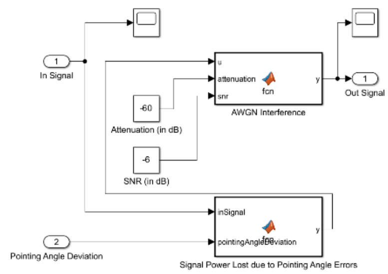

Figure 2. Channel block diagram

The channel is simulated for a controlled value of attenuation and SNR, as shown above in figure 2. For our scenario, we have found that the type of noise in channel which predominantly affects space to Earth communication is Additive White Gaussian Noise (AWGN). Hence, we have only considered this type of noise for simplicity, and the effects of other types of noise are considered negligible for our purpose.

3.3 Transmitting Satellite: Overview

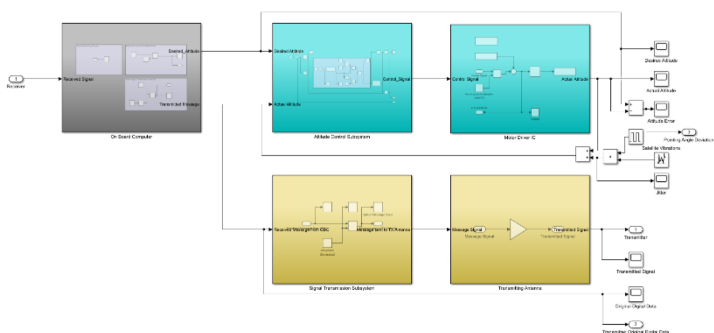

Figure 3. Transmitting satellite block diagram

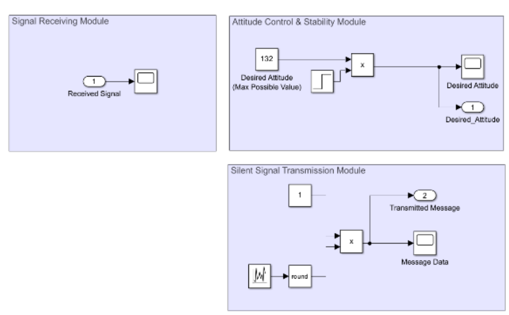

Figure 4. On-board computer (OBC) block diagram

The transmitting satellite consists of multiple subsystems, but in our paper, we are going to focus on two. The signal transmission subsystem, and the attitude control subsystem. Both the subsystems are connected by the On-Board Computer (OBC), which monitors and controls both the subsystems and is responsible for maintaining synchronicity within this block.

This is shown in figure 3, where the OBC (shown in figure 4) connects to both the attitude control and signal transmission subsystems. The attitude control subsystem consists of the main logic, which is the Lyapunov-inspired algorithm, and the motor driver IC, which acts as the actuator executing this algorithm. The signal transmission subsystem too is a dual-part system like above, the main logic for primitive modulation of the signal, and the transmitting antenna which transmits this modulated signal.

3.4 Transmitting Satellite: Signal Transmission Subsystem

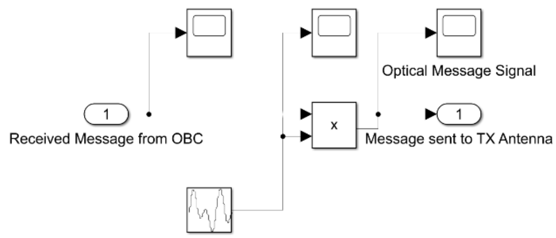

Figure 5. Signal transmission subsystem block diagram

This is the signal transmission subsystem. As shown in figure 5, the system is markedly less complex than traditional optical communication systems, opting for a single wavelength of transmission instead of the conventional dual or triple. We have directly coded the data in a high frequency message signal, removing the need for an additional carrier wave. The modulation technique is deliberately kept as primitive as possible while maintaining as much of the traditional systems range and reach. It performs a simple multiplicative modulation of the binary digital data and the analog high-frequency message signal. This modulated data is then passed to the transmitting antenna for transmission.

3.5 Transmitting Satellite: Lyapunov-Inspired Attitude Control and Stability Subsystem

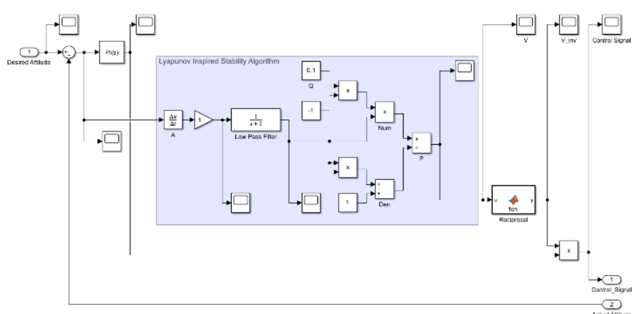

Figure 6a. Attitude control subsystem block diagram – Lyapunov-inspired stability algorithm

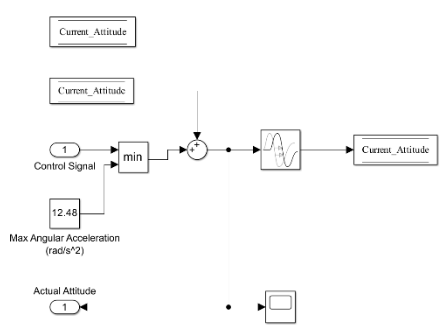

Figure 6b. Attitude control subsystem block diagram – motor driver IC

However, as discussed earlier this method of signal transmission comes with a new set of problems. Since we are not using a carrier wave to increase the signal's range, for the signal to still be detectable at the receiver, we need to drastically decrease the beam divergence to focus as much of the transmitted power at the intended receiving station. Reducing the beam divergence comes with its own advantages and limitations. Because the signal is now low power but intensely concentrated, there is a small area where the signal power is highly concentrated, and the signal power rapidly falls to undetectable levels with as less as a few meters outwards from the center of the target. This offers the advantage of making the signal practically impossible to detect outside the intended target, preventing any malicious third party from even intercepting the message. This characteristic will be referred to as 'physical encryption' throughout this paper. However, it also means that the pointing accuracy and precision of the antenna must be unprecedented, as even slight miscalculations or deviations will mean that the receiver itself will fall out of the coverage area and will not be able to detect the transmitted signal.

To address this, we have designed a reaction wheel for the antenna to control and stabilize its attitude and orientation. This reaction wheel was modelled using a Lyapunov-inspired algorithm, as shown in figure 6a. This ensures the antenna has enough pointing stability to feasibly set up the communication link.

The output from this algorithm is fed into the motor driver IC, as shown in figure 6b. This motor IC directly controls the motor's angular velocity based on this value. Constraints for maximum allowed angular acceleration is in-built into the model to simulate real motors. In our case, we have assumed a maximum angular acceleration of 24.96 rad s^{-2} to simulate a Maxon EC 10 (PN 351007) BLDC servo motor with a reaction wheel load of 0.5kg and radius 0.05m. Assuming an ideal 100% of the motor's energy is transferred to the CubeSat, we calculate that the maximum angular acceleration of a 1kg antenna is 12.48 rad s^{-2}. It is important to note that this is an estimate because it is not possible to completely calculate this coefficient without knowledge of the antenna's exact weight distribution and the position of the reaction wheel module with respect to the antenna. Also, this value can similarly be modified to simulate any other motor.

The motor driver then collects the actual attitude of the motor from the motor's hall sensor, and feeds this data back to the Lyapunov-inspired algorithm. Thereby completing the feedback loop, and creating a real-time rapid and accurate attitude control system.

3.6 Receiving Satellite: Overview and Signal Recovery Subsystem

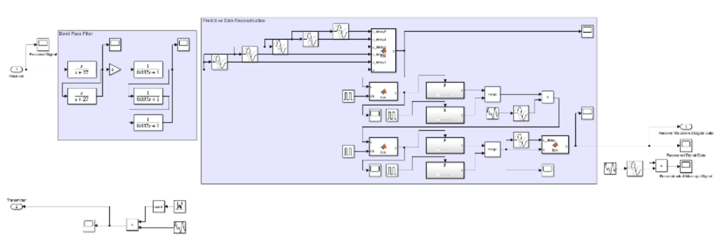

Figure 7. Receiving satellite block diagram

Figure 7 shows the receiving station or satellite. This picks up the noisy and attenuated message signal and uses a combination of data recovery algorithms to recover the original data. This is achieved through a 2-step process. First, the received signal passes through a band pass filter to remove additive white gaussian noise. Second, the output from the filter passes through a custom designed data prediction algorithm to detect and correct burst errors.

The band pass filter consists of a 2nd order high pass filter in series with a 3rd order low pass filter. The frequency pass band of this filter is between 429.7183THz and 430.1485THz. This removes most of the additive white gaussian noise, and we are left with all signals of wavelength close to 430nm, which is the wavelength of the message signal.

Now that we have cleaned the signal to an extent, it is passed on to the custom data prediction algorithm. This is required because although most of the data has been recovered, burst errors might still exist and these need to be corrected. The output of this 2nd step of the signal recovery process gives us the cleanly recovered original data.

3.7 Proposed Hardware

Component or Parameter	Specification
Transmitting Laser	Nd:YAG Solid Crystal Laser
Beam Divergence of Transmitting Laser	< 0.5 mrad
Motor for Reaction Wheel	Maxon EC 10 (PN 351007)
Dimensions and Mass of Each Reaction Wheel	radius = 0.05 m, mass = 0.5 kg
Mass of Antenna Module	1 kg
Maximum Angular Acceleration of Antenna Module	12.48 rad s^{-2}
Height of Orbit	600 km (Low Earth Orbit)
Area on Earth Covered by an Individual Satellite	5000 m^2
Beam Area when it Lands on Earth	50 m^2
Message Signal Frequency	430 THz (red light, visible spectrum)
AWGN Power for a 10K Cryogenically Cooled Receiver and a Pass Band of 0.4302THz	59.3676 pW
Signal Power Required at Receiver for SNR of -6dB	1.4912 pW
Attenuation for a 430THz Wave over 600km and Transmitter Beam Divergence of 0.5mrad	116.6 dB
Transmission Power at Satellite Required to Overcome Noise and Attenuation	0.6816 W
PID Values of the ACS Subsystem	$a_P = 0.05$, $a_I = 0.0001$, $a_D = 0$
Antenna's Reaction Wheel's Range of Motion	132.1082°; 3.78 steradians

Table 1. Proposed Hardware Components and System Parameters

4. Results and Discussion

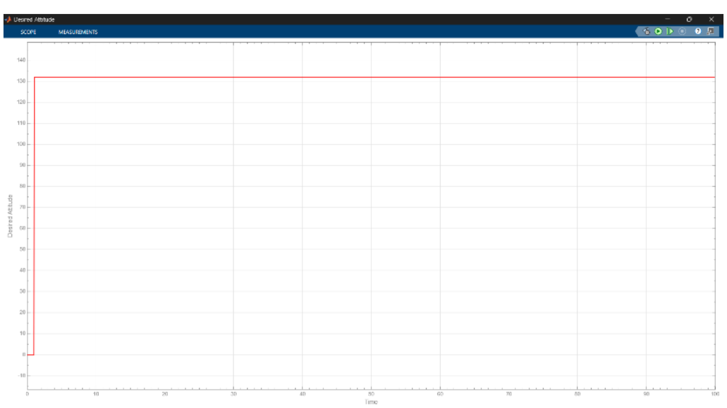

Figure 8a. Desired attitude sent by OBC to attitude and stability control subsystem

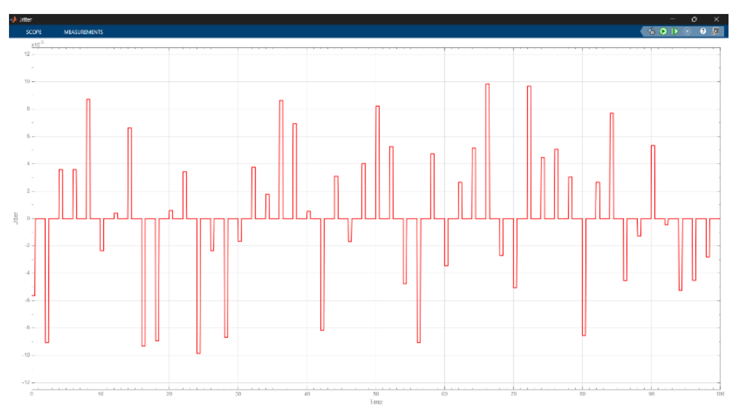

Figure 8b. Artificial jitter introduced to simulate satellite vibrations (zoomed in to a scale of 10-5 rad)

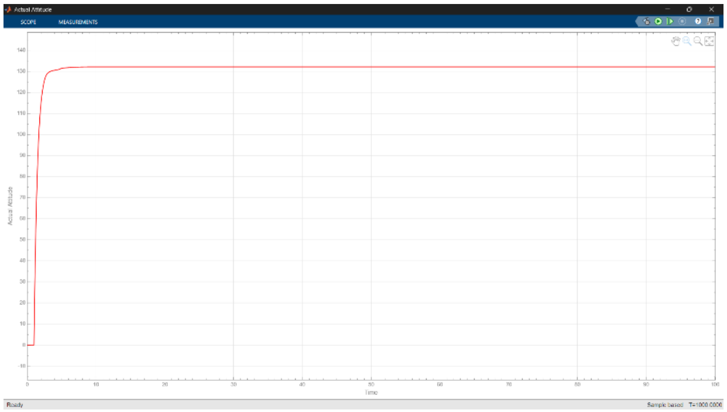

Figure 8c. Actual attitude of satellite's antenna

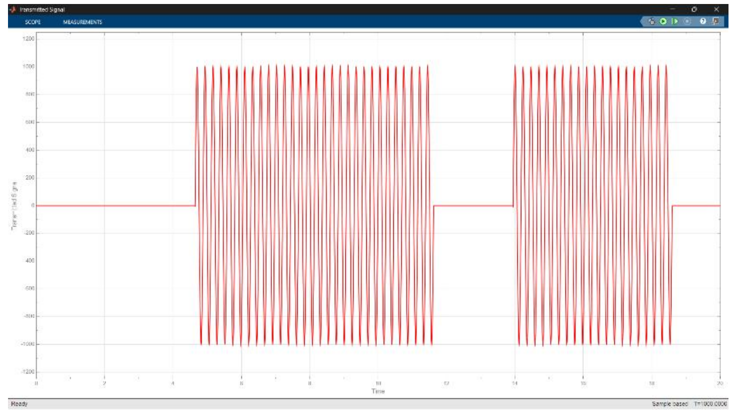

Figure 8f. Modulated data transmitted by satellite's antenna

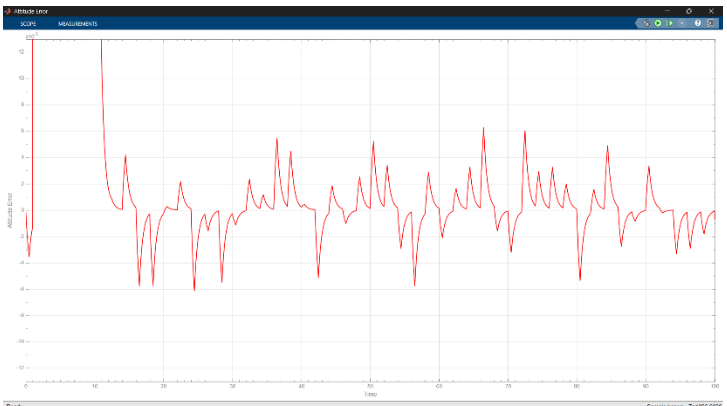

Figure 8d. Attitude error after jitter correction efforts (zoomed in to a scale of 10-5 rad)

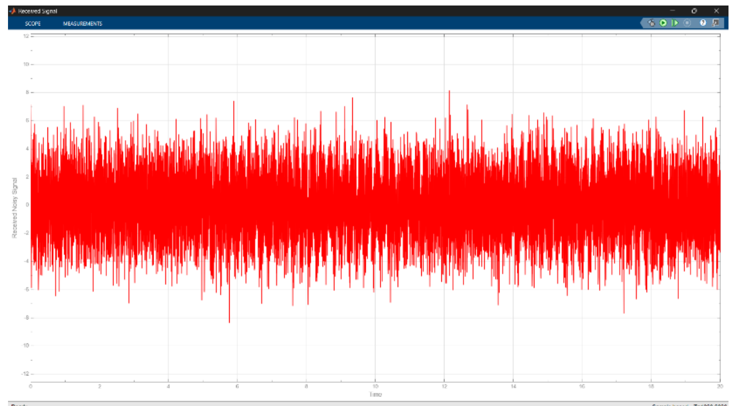

Figure 8g. Noisy signal received by receiving station on Earth for SNR of -6 dB

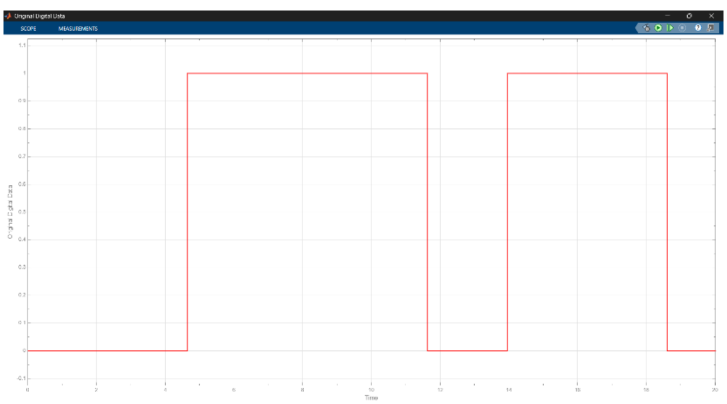

Figure 8e. Digital data to be transmitted sent from OBC to signal transmission subsystem

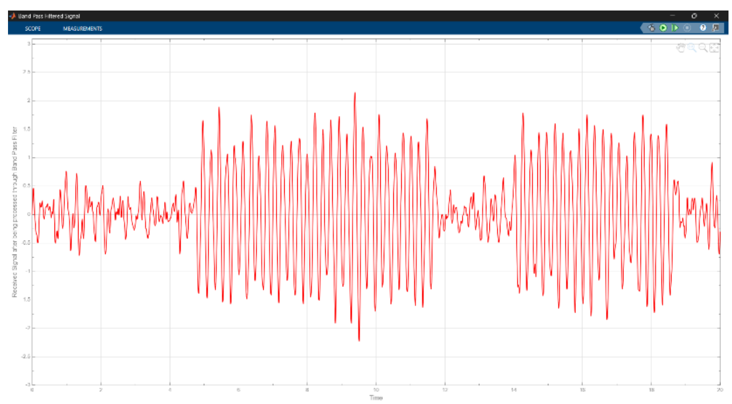

Figure 8h. Partially recovered received signal after passing through band-pass filter

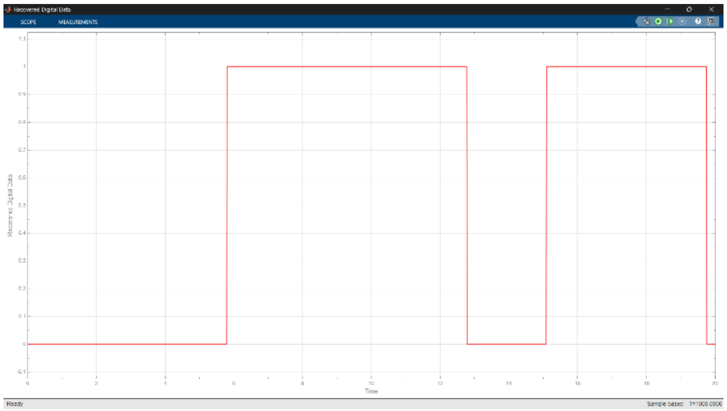

Figure 8i. Completely recovered received signal after passing through custom predictive reconstruction algorithms

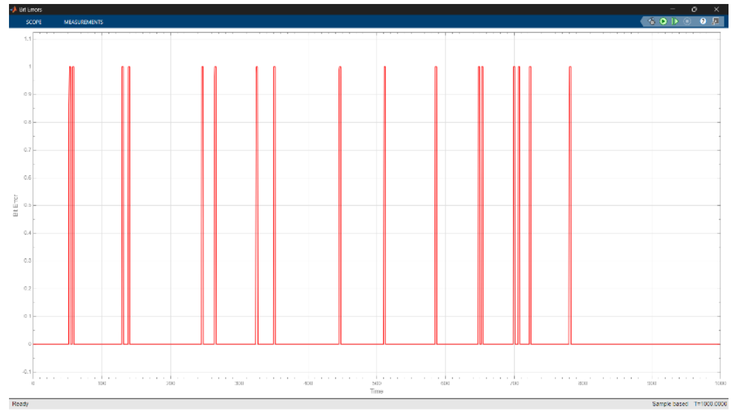

Figure 8j. Graph of number of bit errors over 430 total transmitted bits for SNR of -6 dB

The reconstructed digital data was observed for 430 symbols over 1 picosecond for various SNR values. The complete transmission and recovery process has been shown for an SNR of -6 dB in figures 8a through 8j. Using our designed system, we observed the following relation with SNR and bit error rate (BER) as shown below in table 2.

SNR	**Accuracy of Recovered Data**	**Bit Error Rate (BER)**
-2dB	99.77%	0.23%
-3dB	99.30%	0.70%
-4dB	98.37%	1.63%
-5dB	97.44%	2.56%
-6dB	96.05%	3.95%
-7dB	93.95%	6.05%

Table 2. SNR vs BER

Now for the attitude control and stability subsystem, after reaching the initial orientation, we have artificially simulated satellite vibrations as impulse changes to the pointing angle by a random arbitrary. We observed how the system corrects these isolated jitters and recorded 1.5 s for the system to correct jitters of an amplitude up to 100 µrad, to within 50 µrad (1% of beam divergence angle) of the desired pointing angle. Finally, when the system was simulated under the exposure of constant and continuous jitter, the stability subsystem was consistently able to maintain a pointing angle accuracy of 0.5 mrad to the desired attitude, which is within 10% of the beam divergence angle. Only resulting in occasional overshoots in isolated bursts of a maximum of 0.1 ms.

6. CONCLUSION AND FUTURE SCOPE

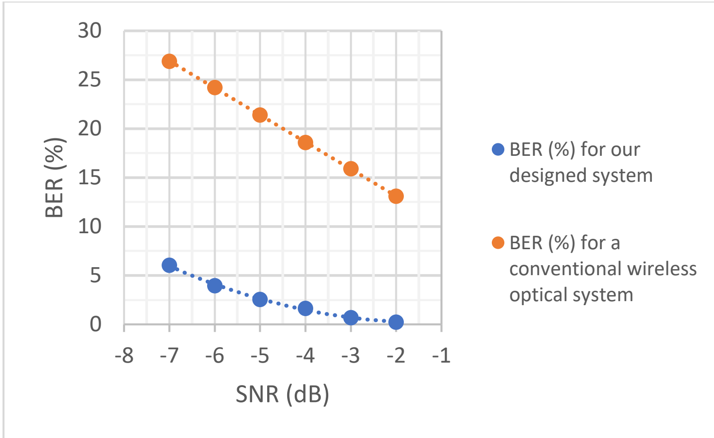

Figure 9. SNR vs BER

As we saw earlier, we have achieved a less than 1% BER for an SNR of -3 dB, and less than 5% BER for an SNR of -6 dB. If we plan to take this further, we can employ forward error connection techniques such as Reed-Solomon coding, which will allow us to detect and recover a perfect message signal for up to 16 errors for each 255-symbol block. This means that if we assume the signal recovered by our system will be passed to a Reed-Solomon code RS(255,223), we can perfectly recover the original data from a signal as noisy as one with an SNR of -6 dB. Combining our system with forward error correction techniques, we can achieve a theoretical maximum symbol rate of 37.6 Tb s^{-1}, however in reality we are limited by transmitter technology. We have plotted this data as a graph alongside values for a traditional wireless optical communication system in figure 9. We see that our designed system outperforms a conventional wireless optical communication system by a steep margin, allowing us to transmit data at a much lower SNR than conventionally possible, thereby saving significant power needed for transmission at the satellite.

And owing to the attitude control and stability subsystem working parallelly to maintain stable pointing accuracy for the antenna, the signal communication subsystem can work smoothly without interruptions from internal vibrations and external forces. These 2 subsystems working hand-in-glove achieve this paper's goal of decreasing power consumption and increasing data security, by opting for a raw digital data transmission system using an ultra-low beam divergence antenna.

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