Building the New Generation of Communication Technologies for New Space Era

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Abstract: New Space becomes more attractive for many space industries due to its huge potential for commercialization opportunities that involve private companies and driven by new technologies including Earth observation, satellite communication and space services. Due to fast growth of spacecrafts and number of constellations, the data to be stored onboard and latency to get it to the final user are becoming challenging because of radio frequency (RF) communication system limitations.

Optical communication technologies offer significantly higher data rate compared to RF communication systems and optical beams are less susceptible to interferences from other RF signals in congested space environments. In addition, optical systems offer low size, Low Weight and Power consumption (SWaP) that makes them suitable for small satellites and rapid deployment in LEO orbits. However optical technologies come with their own challenges, one such being atmospheric turbulence effects between space to ground stations.

We are developing an optical payload with the new space requirements in terms of SWaP and space environment qualification. In addition to space applications, the payload can be used as an optical transceiver to enable ground to ground optical communication. To address this, we work on the miniaturization of the optics including telescope, PCB boards, space qualified opto-mechanical designs. The payload can operate with data rates up to 1 Gbps and over a link distance of up to 1000 km with an additional objective to reach 1 Tbps in ground-to-ground line of sight applications. It uses the Intensity-Modulation-Direct-Detection (IM-DD) offering flexibilities of transmitter and receiver designs. We also explore the possibility to increase the data rate by using advanced modulation techniques including Quadrature Amplitude Modulation (QAM) and Optical Angular Momentum (OAM). A promising technique in spatial multiplexing is OAM as it presents, in theory, an infinite degree of freedom basis, allowing for the use of extensive symbol sets in optical communication systems.

Regarding the propagation channel, we are carrying out local weather monitoring and analysis to gather the gradient of the weather conditions (wind speed, temperature, relative humidity). The measured data contributes to the building of a UAE local weather database and to predict the optical communication link performance. As a result, the atmospheric conditions data gives relevant information about the possible communication windows with the optimum Fried parameter and Cn2 parameters. The use of neutral networks for turbulence mitigation is one of the solutions we investigate to correct for the residual turbulence effect on the optical link, along with an adaptive optics solution. In this work we introduce the use of Brownian-Bridge and CycleGAN Neural Network architectures to mitigate atmospheric turbulence-induced distortion.

We will present the optical link budget design of space to ground optical communications links. The radiometry of the transmitter and the receiver, along with propagation channel loss will be discussed. Different link scenarios for ground application (few kilometers) and LEO orbit applications (400-600 km) are analyzed where we calculate the link margin from the received power and the receiver sensitivity. To make the model closer to the UAE near-ground weather conditions, we use real data measured in Masdar city during December 2023 where we calculated the Cn2 at different times of the day.

1.Introduction

New Space becomes more attractive for many space industries due to its huge potential for commercialization opportunities that involve private companies and driven by new technologies including Earth observation, satellite communication and space services. Due to fast growth of spacecrafts and number of constellations, the data to be stored onboard and latency to get it to the final user are becoming challenging because of radio frequency (RF) communication system limitations.

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2. Optical payload system overview

1.1. Electronics system

The electronics system consists of mainly three boards. The beacon laser board, communication laser board, sensor board. The beacon laser board consists of 808 nm butterfly laser diode, along with current and temperature control modules. This board is responsible for pointing and alignment. The communication laser board consists of the carrier laser emitting at 1550nm wavelength, along with current and temperature control modules. Lastly, the sensor board which is mainly a photodetector circuit to monitor the incoming signal.

1.2. Mechanical System

FSO transceiver is made of Aluminium alloy 6061 T6. This material is light weight, affordable, space qualified and has low thermal expansion. The overall size is 1U and its weight is around 1 kg. The face of the device has 3 apertures: telescope, beacon camera and collimator aperture. Both the beacon camera and collimator axis must be parallel. The telescope's aperture size is 30.5 mm while the beacon camera and collimator aperture size are 32 mm and 11 mm respectively. The telescope designed based on magnification factor and lenses were selected accordingly. The transceiver's structure comprises three layers illustrated in figure (1). The ground level carries electrical components such as PCBs, power supply and laser diodes. The optical bench lays on the first level, it carries main optical components like the telescope, beacon camera, dichroic mirror and laser collimator. The second level holds the beacon collimator, which ensures collinearity with the beacon camera adding the value of minimizing the mis-potting in bi-directional use cases.

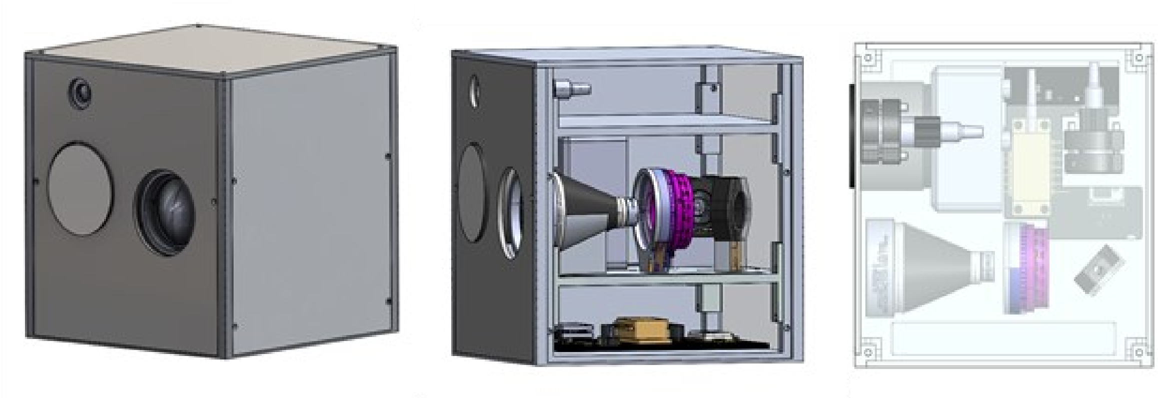


Figure. 1. Structural design of the transceiver displaying the optical layout and other components

1.3. Embedded System Overview

The embedded system controlling all the electronic boards mentioned earlier will require high-speed data processing, including signal processing, video encoding/decoding, and real-time data analysis. Therefore, the selected core of the system is an FPGA board, which surpasses other microcontrollers in parallel processing (multitasking), lower latency, configurable I/O interfacing, and customizability, allowing it to perform the various tasks more efficiently. One of its main functions is supplying and setting the current values for both diode boards, as well as setting and monitoring the temperature. This ensures the constant operation of the Beacon diode and the correct emission of the communication laser diode. Another function is to control the aiming and pointing of both stations, which is achieved using the Hexapod platform and the CMOS image sensor module. The camera feed, which captures the Beacon's constant output beam, is used to move the Hexapod according to the beam's location. Along with the control and management of the photodiode sensor, the system will offer the platform of achieving the optical transmission and receiving successfully.

1.4. Optical System

The optical system in Free Space Optical (FSO) communication faces distinct challenges in both ground and space applications. In ground applications, sensors encounter challenges including precise pointing capabilities, accurate field of view (FOV), noise figure, and environmental conditions such high temperatures and dust which could impact the detection system performance. In space applications various sets are introduced including space radiation, launch vibrations, thermal cycling, and vacuum conditions adding complexities to the system's overall reliability.

The optical system consists of the camera, lenses, and hexapods. Each component will be tested thoroughly to identify any potential challenges. The camera performance will be evaluated based on sensitivity and FOV test to select the most suitable model. The sensitivity test determines the minimum detectable optical signal, while FOV test will determine the angular range visible to the camera which is critical for maintaining long-distance optical links. Additionally, lenses of varying focal lengths will be tested to optimize the FOV. Lastly, space qualification tests will ensure the beacon system is ready for deployment in space, verifying its resilience under harsh conditions.

1.5. Optical Payload Specifications

The following table summarises the main features of the optical payload:

Specifications/Parameter	Value	Comment
Payload size	1U	To fit within either 3U or 6U
Power Consumption	50W max	Full operating mode
Weight	1.5 Kg max	--
Beam Optical Power	250 mW	Continue wavelength
LaserCom Optical Power	1 W	Modulated beam
Communication Data Rate	1 Gbps	Over 1000 km
Link Distance	Up to 1000 km	Covers all the LEO to ground links
Modulation Format	OOK	--
Hosting Platform	Gimbal/Hexapod	Body pointing
Operating Conditions	LEO orbit	Space qualified

1.6. *Link budget design*

This overview of link budget design for Free Space Optics (FSO) communication systems focuses on both ground-to-ground and up/down links, encompassing ground applications (few kilometers) and LEO orbit applications (400-600 km). Key parameters and challenges, such as atmospheric loss, turbulence, and free space loss, are explored for their impact on FSO link performance. The importance of minimizing optical inefficiencies and pointing errors is emphasized, alongside addressing theoretical challenges like atmospheric modeling, beam tracking, and optimizing trade-offs between link distance, data rate, and reliability. Data from the UAE was utilized to test various system specifications, enhancing the robustness and efficiency of FSO communication under diverse conditions.

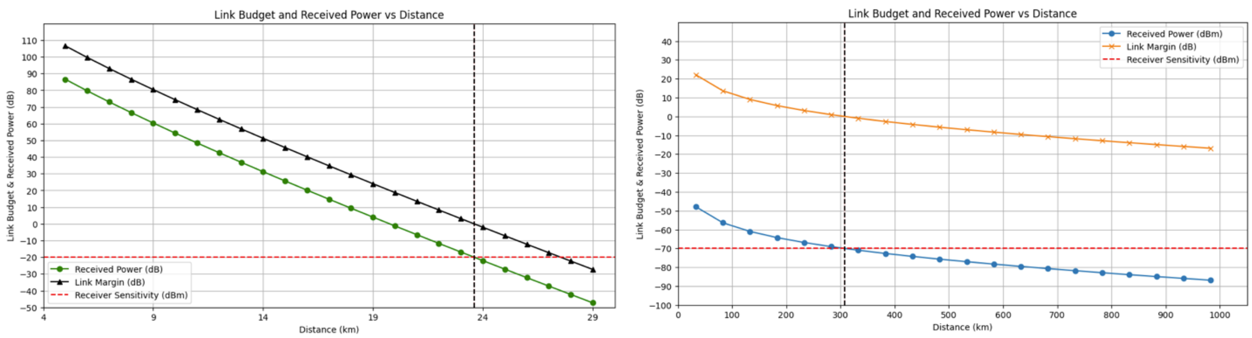


Figure 2. Link margin, Received power vs Distance of G-G & S-G

In ground-to-ground communication, a link can be maintained up to 24 km, beyond which received power falls below the receiver sensitivity threshold, risking link failure. At a fixed distance, increasing transmitted power improves received power and link margin, though benefits diminish beyond certain power levels.

For satellite-to-ground communication, significant path loss occurs over large distances, with reliable communication feasible up to 300 km. It's crucial to consider the rapid decrease in received power with distance and design the system to optimize link budget components, considering atmospheric conditions.

When the parameters such as transmitted power, receiver sensitivity, antenna gain, and beam divergence are improved by 10%, the communication range could be extended up to 900 km. To extend communication ranges and improve system performance, it is essential to enhance transmitted power, improve receiver sensitivity, use larger optics apertures (if the design allows it), and optimize beam divergence.

2. Propagation channel

2.1. *Atmospheric propagation channel*

The Earth's atmosphere is composed of several gases, vapors and chemicals that are attracted by gravity. These elements are concentrated in the lower layers of the atmosphere (up to 20 km). The higher layers of the atmosphere are higher up to 700 km from the surface. For this reason, when ground-satellite Free-Space Optical Communications are considered, the effects of the atmosphere in the optical propagation are relevant. These effects are known as *optical turbulence* [1]. The effects of the optical turbulence includes the beam wavefront variations, beam wandering and scintillation that, in practical effects, it will produce a loss of information in the communication link and difficulties when pointing the satellite from the ground station.

The optical turbulence physics has been widely described using statistics to model the complex thermodynamics of the change of temperature and pressure in the atmosphere that makes the refractive index of the air to change. The models of Kolmogorov, Von Karman and Tatarskii are the most used to describe the optical turbulence [1]. All these models use the structure parameter of the refractive index (C_n^2) to provide a numerical descriptor of the optical turbulence strength. The structure parameter of the refractive index range goes from $C_n^2 = 10^{-16}\ m^{-2/3}$ for weak turbulence, $C_n^2 = 10^{-15}\ m^{-2/3}$ for moderate turbulence, and $C_n^2 = 10^{-13}\ m^{-2/3}$ for strong turbulence.

The C_n^2 profile for a vertical propagation path as function of the height is modelled through the Hufnagel-Valley model [1]:

$$C_n^2(h) = 0.00594\left(\frac{w}{27}\right)^2 (10^{-5}h)^{10} e^{-h/1000} + 2.7 \times 10^{-16} e^{-h/1500} + Ae^{-h/100} \quad (1)$$

Where, *h* is the height from ground in meters, *w* is the rms windspeed in meters per second and *A* corresponds to the $C_n^2(0)$.

2.2. *Atmospheric Turbulence effect*

To test the effects of optical turbulence in free-space optical communications link and to develop techniques for the mitigation of these effects to enhance the system performance, DERC has implemented emulation technique of optical atmospheric turbulence. The first technique for turbulence emulation is a glass phase mask with a Kolmogorov-generated pattern that represents a propagation length of 100-m and Fried parameter of 2.2 mm. In Figure 1 it is the turbulence phase plate. Figure 2a presents a beam without distortion and Figure 2b presents the same beam under emulated optical turbulence with the phase mask.

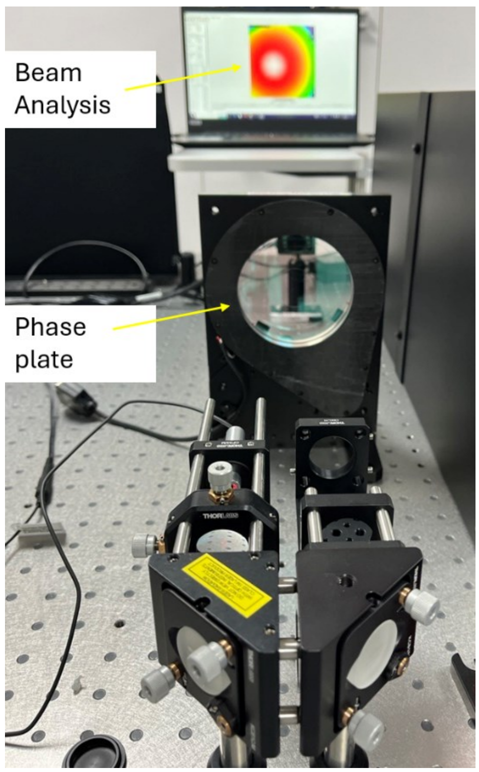
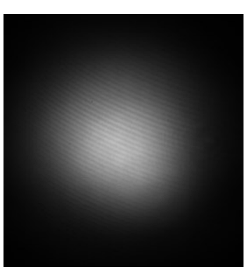
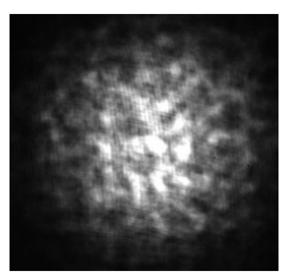


Figure 3. Phase plate mounted in a rotation stage laboratory setup.



a) Beam intensity image without turbulence.



b) Beam intensity image emulating optical turbulence with phase mask.

Figure 4. Laser beam intensity image.

2.3. Atmospheric Turbulence Emulation

At the Directed Energy Research Center, it has been implemented an optical turbulence generator device to emulate a wider variety of optical turbulence strength based on the injection of hot air at variable speed in a chamber [2], [3]. This generator can inject hot air up to 50 ºC with perpendicular windspeed up to 25 km/h. From the experiments performed in laboratory, the turbulence generator can generate optical turbulence with a $C_n^2 \approx 10^{-12} - 10^{-13}$. Figure 3 presents the turbulence generator prototype. Figure 4 presents a laser beam intensity image after going through the turbulence generator.

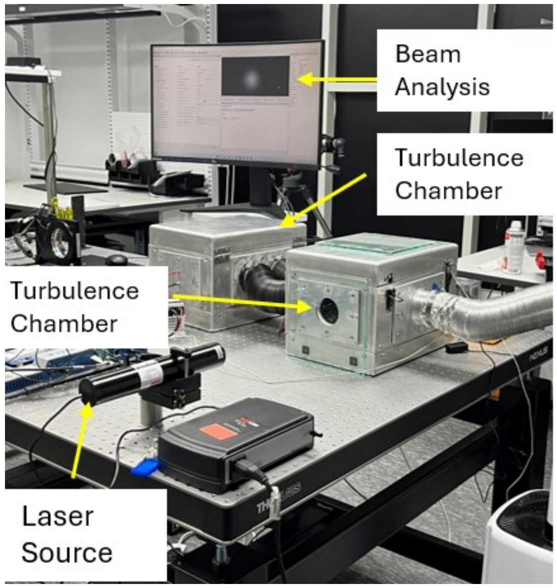


Figure 5. Laser beam turbulence emulation experimental setup using turbulence chamber.

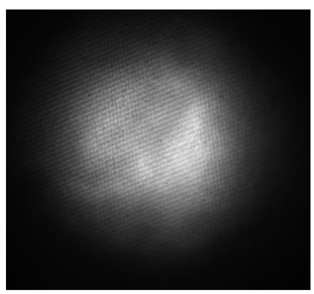


Figure 6. Laser beam intensity image after crossing the turbulence generator in the laboratory.

3. Turbulence mitigation solutions

3.1. Adaptive Optics for Optical Communication

Adaptive optics (AO) was first conceptualized in the 1950s by American astronomer Horace W. Babcock[4], who proposed the idea to correct for the blurring effects of Earth's atmosphere on astronomical images. However, the technology required to implement AO was not yet available, and it wasn't until the late 1980s and 1990s that significant advancements were made. Early developments were driven by military and aerospace application, primarily for improving accuracy of laser-based communication. In the 1990s, AO systems began to be successfully implemented in ground-based astronomical telescopes, such as those at the Keck Observatory [5] in Hawaii, allowing to produce diffracted-limited images with large aperture telescopes.

AO systems are essential to improving telescope performance in FSOC systems by compensating for atmospheric distortions. A wavefront sensor (WFS), like a Shack-Hartmann Wavefront Sensor (SHWFS) for example, measure the wavefront aberrations of the downlink laser beam, which are then corrected in real-time by a Deformable Mirror (DM). The DM dynamically adjusts its optical surface to cancel out the distortions. To ensure image stability, AO systems often include a Fast-Steering Mirror (FSM), which compensates for minor jitter caused by atmospheric turbulence, keeping the image stable and improving the AO corrections. The encoded laser beam is then focused on a fiber and transmitted to the receiver.

The main benefit of optical communication is the capability to transfer high data rates. This implies that receivers have to use a single-mode fiber to transfer signal to the detection system. In ground-based laser communications systems, AO is used to keep the beam focused on an optical fiber, ensuring maximum signal transfer. It is essential to maximize the coupling efficiency of the laser beam into the fiber and this requires an Adaptive Optics to minimize the aberrations, maximize the signal transmitted to the transceivers, and consequently improve the receive data rate and reduce data losses. For instance, AO helps to improve the signal quality injected into single-mode fibers, which typically have a core diameter of around 10 µm. It has been demonstrated that the integration of adaptive optics into ground-to-ground, ground-to-space, and space-to-ground communication links leads to a significant reduction in communication error rates, improving system performance by several orders of magnitude[6].

In addition to improving beam stability, AO systems must operate at very high correction rates (often in the range of 1kHz or higher) to track rapid changes in atmospheric conditions. By optimizing the beam shape and minimizing distortions, adaptive optics allows laser communication systems to achieve higher data transfer rates and more reliable transmission over long distances, even in challenging atmospheric environments. This makes AO indispensable for both ground-to-space and space-to-space laser communication applications, where precision and signal quality are paramount.

3.1.1. AO for Space-to-Ground Link

When it comes to space-to-ground optical communication, one can chose to use receive apertures smaller than the Fried's parameter, a measure of the atmospheric turbulence strength. The Fried's parameter, also called Fried's coherence length by Tyson[7], is described as "the maximum allowable diameter of a collector before atmospheric distortion seriously limits performance". If a receive telescope has a diameter smaller than the Fried's parameter, then its performance is limited by the telescope diffraction. If the diameter is larger, then the atmospheric turbulence is the limiting factor. At first hand, smaller apertures look an attractive and cost-effective solution for LEO satellites as they can provide higher power to ground and do not require large apertures. The problem using apertures smaller than the Fried's parameter is the high intensity fluctuations due to beam wandering and scintillations. These fluctuations are increased for smaller aperture due to their difficulty to be compensated by aperture averaging[8]. It is then more efficient to use larger ground aperture, but this requires an Adaptive Optics system to compensate for atmospheric turbulence.

3.1.2. AO for Ground-to-Space Link

The main challenges of Low-Earth Orbits are to track accurately high-speed satellites travelling at altitudes below 2,000 km and to transmit an uplink laser beam with minimized atmospheric turbulence. An effective method for establishing and maintaining a stable link is to transmit a slowly divergent uplink laser beam from the ground terminal. The divergent beam increases the chances of signal detection at the satellite receiver, allowing the link to close more efficiently. This approach is particularly useful for LEO satellites, where the relative motion between the satellite and ground station is rapid and where a typical pass duration is between 5 and 15 minutes. Since LEO satellites move at very high speeds, typically around 7.5 km/s or 0.5 deg/s, there is a noticeable delay between when the ground station transmits the signal and when the satellite is in position to receive it. To overcome this, the ground-based transmitter must aim the laser beam at the predicted future location of the satellite, rather than its current position. This point-ahead angle ensures that the transmitted beam reaches the satellite's receiver even with the high velocity of LEO satellites. The angle is carefully calculated based on the satellite's predicted trajectory and speed, which requires precise orbital data and accurate timing.

To improve uplink communication efficiency, AO systems can use the downlink (satellite-to-ground) signal to measure atmospheric distortion and then pre-compensate the uplink laser beam to correct for these effects. However, the AO system's effectiveness is constrained by the isoplanatic angle -a measure of how much of the atmospheric turbulence is similar between the uplink and downlink paths- meaning that the turbulence correction might not fully compensate for the atmospheric effects due to the limited overlap between the uplink and downlink paths. Recent advancements in pre-compensation techniques[9] aim to address these challenges by refining the measurement and correction processes. These methods optimize the uplink beam based on real-time atmospheric data, improving the overall stability and efficiency of the laser communication link. This is particularly beneficial for LEO satellites, where the short communication windows demand highly efficient ATP systems to maintain a reliable link despite atmospheric disturbances.

3.1.3. AO Capability at DERC

The Directed Energy Research Center (DERC) is advancing both traditional and innovative adaptive optics (AO) systems. In conventional AO setups, the atmospheric distortions are measured using a Shack-Hartmann wavefront sensor (SHWFS), and corrections are applied via a deformable mirror (DM). The systems at DERC are designed to operate with beam diameters ranging from 2.2 mm to 50 mm. In addition to traditional AO methods, DERC is also developing machine learning-based AO techniques. These novel approaches address the challenges of remotely measuring wavefront errors without the need for a physical wavefront sensor, which is particularly advantageous in ground-to-ground communication systems. By leveraging machine learning, the DERC is paving the way for more efficient and resilient wavefront correction strategies in complex environments. Beyond optical systems, DERC is also focused on the development and testing of control systems that support these advanced techniques, enabling the real-time retrieval of distorted wavefronts and closing the feedback loop on the deformable mirror.

The DERC has initiated comprehensive atmospheric monitoring efforts to gather statistical data on local atmospheric turbulence conditions in the UAE. These measurements include key turbulence parameters such as the refractive index structure constant (C_n^2), Fried's parameter (r_o), the Greenwood frequency, and the scintillation index, alongside meteorological data such as ground temperature, pressure, humidity, and wind speed. This data is critical for optimizing and refining AO systems under local conditions, ensuring reliable performance in the region's unique atmospheric environment.

3.2. Spatial Mode Multiplexing and Turbulence Mitigation

As the demand for high-speed communication links continues to grow, the need to increase their capacity becomes more critical. In this context, we investigate the use of Orbital Angular Momentum (OAM) of light, which provides an orthonormal basis for encoding information through its topological charge. This approach enables advanced communication schemes, such as modulation, multiplexing, and multicasting, to achieve higher data rates [10, 11]. However, atmospheric turbulence poses a significant challenge, leading to distortion and crosstalk. To mitigate these effects, machine learning techniques have emerged as a promising solution for accurate classification and correction of atmospheric disturbances [12, 13].

We implemented a BB-DDPM Neural Network architecture for image-to-image translation task. The architecture translates from turbulence distorted interference images (domain A) to clean interference images (domain B). The architecture allows to mitigate atmospheric turbulence effects from distorted interference images. One of the ways to encode information in OAM modes is in the number of topological charge, which at receiver site could be represented as a classification task. For the identification, we use the interference between topological charges of equal magnitude, but opposite in sign. This leads to a petal structure interference having a number of petals twice the topological charge. The dataset for the BB-DDPM training was generated by experiment and simulation. We compare our results with a ResNet-18 only neural network. Our results shown in Figure 7, demonstrate BB-DDPM's capability in enhancement of decoding number of topological charges of OAM modes by efficiently mitigating weak and medium turbulence-induced distortion on spatial structure of the modes.

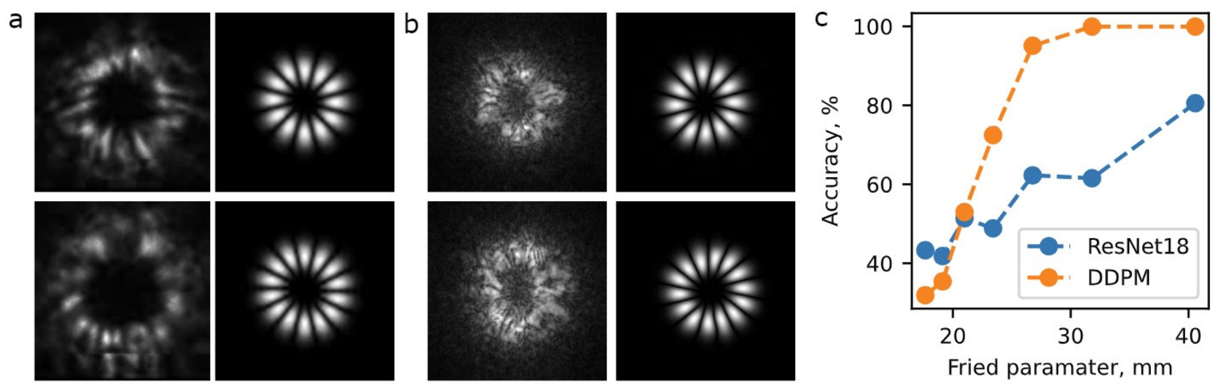


Figure 7. (a) Experimental interference pattern of turbulence distorted OAM beams (r_o = 1.1 mm) before and after mitigation using BB-DDPM. (b) Simulated interference pattern of turbulence distorted OAM beams (r_o = 23.4 mm) before and after mitigation using BB-DDPM. (c) Accuracy of classification on test dataset for ResnNet-18 and BB-DDPM assisted ResNet-18 for different level of atmospheric turbulence, where Fried parameter is a measure of strength of turbulence effect with propagation.

4. Conclusion

This paper covers the optical payload design and the main building block. To reduce the cost of the payload, it's critical to reduce the weight, the power consumption and the size that means a compact system considering both optics, optoelectronics and electronics board all together. The mechanical design to accommodation enough space for the parts appears to be challenging to maintain the optical specification (optical paths, telescope length, optics apertures). The space environment is harsh and can impact the payload performance such as the heat generated by the electronics, the optics mounting, thermal cycling and the vibration. In addition, the atmospheric propagation to establish optical downlink is distorted by the random changes on the reflective index that adds fading to the received power along with mis-pointing.

The status of the DERC's 1 U optical payload is under laboratory tests where we test the poiting algorithm to maintain the optical beam line of sight, electronics boards to generate optical modulated beam and the FPGA embedded system design to control the whole payload and manage the interface with the optical bus. We aim put this system in orbit by Q4/2025 to test downlinks beam acquisition.

5. References

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