Free Space Optical Cooperative Communication Enhancement using CubeSat Constellation and Reconfigurable Intelligence Surfaces

CHIH-HSUAN LI, LI-ZHEN HSU, CHUNG-WEI CHENG, CHI-EN TANG

Abstract：

The increasing demand for high-speed data transmission has driven the need to advance optical communication technologies, notably Free-Space Optical (FSO) communication. Traditional RF communication methods are reaching their limits in terms of frequency and speed. FSO, with its attributes of high transmission rates, minimal latency, broad bandwidth, and strong security, is well-suited for applications like high-capacity data transfer, real-time operations, and secure communication. However, FSO faces challenges, particularly its sensitivity to environmental factors like atmospheric conditions, clouds, and weather fluctuations, which can lead to signal attenuation and communication disruptions.

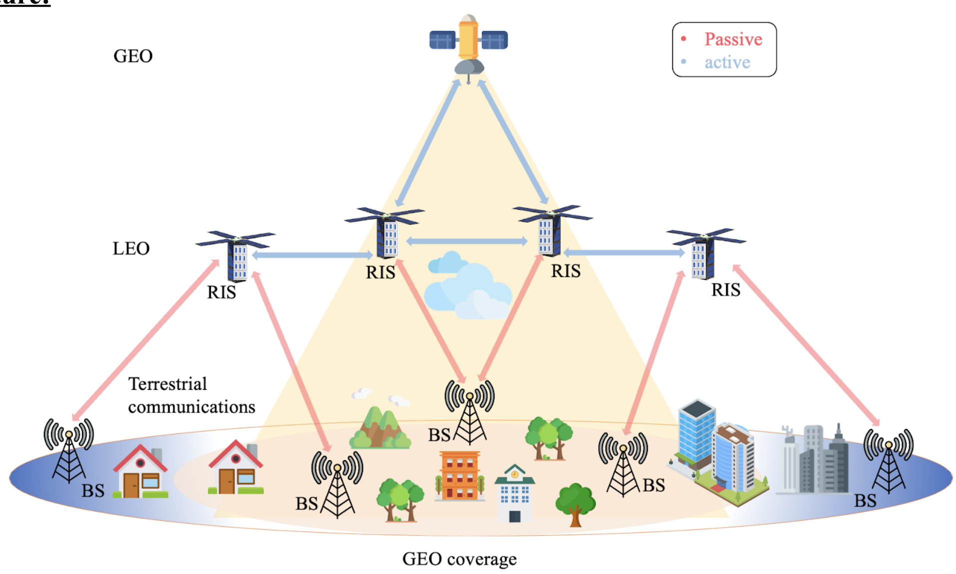
This study focuses on leveraging Low Earth Orbit (LEO) CubeSats as cost-effective and flexible optical communication relays to enhance data transmission from Geostationary Earth Orbit (GEO) satellites. The system integrates Convolutional Neural Networks (CNN) for precise cloud detection and collaborates within the LEO constellation to select optimal relay CubeSats unaffected by cloud interference. Reconfigurable Intelligent Surfaces (RIS) optimize signal pathways, circumventing cloud interference and ensuring robust data transmission to the ground. This approach strengthens data transmission signals from GEO satellites to the Earth's surface, addressing challenges related to long-distance communication and atmospheric interference. It broadens the scope of optical communication applications and extends ground coverage beyond the constraints of GEO satellites.

Keywords: CubeSat, Free-Space Optical communication(FSO), Reconfigurable Intelligence Surfaces (RIS),CNN

1. Mission Overview

The primary objective of this study is to establish a cooperative communication system by utilizing a Low Earth Orbit (LEO) CubeSat constellation equipped with reconfigurable intelligent surfaces (RIS) as relays. Incorporating RIS into the integrated terrestrial/non-terrestrial (INTENT) networks and considering the challenges faced by high-orbit satellites when transmitting data to the Earth's surface via optical communication, which can be hindered by atmospheric cloud cover, we aim to address these issues. To effectively mitigate cloud interference, it is essential to determine the cloud coverage area for each CubeSat within their coverage regions, given the varying density of atmospheric clouds. However, the physical limitations of CubeSats, including communication link restrictions and available power, make data download and processing challenging. To resolve this issue, we introduce an artificial intelligence (AI) system that performs onboard real-time cloud detection in RGB images using edge computing. This eliminates the need to download thumbnails for assessing cloud coverage during operations. Subsequently, we explore two relay mechanisms: the first involves passive transmission, where RIS is installed on CubeSat surfaces to optimize signal capture and passive relay by adjusting their reflective properties. This aims to alter the path of optical communication signals to circumvent clouds, enhancing data transmission signal strength from high-orbit satellites to the Earth's surface, thereby improving long-distance communication latency and overcoming atmospheric interference. The second approach aims to significantly expand communication coverage, incorporating inter-satellite links (ISL), by actively relaying signals between low Earth orbit (LEO) CubeSat constellations after receiving signals from high-orbit satellites.This not only extends the signal coverage range but also ensures the overall communication system's robustness, potentially serving as a backup solution in case of RIS system failure. This study aims to present an innovative cooperative communication system that effectively addresses cloud-related disruptions in optical communication links from high-orbit satellites to the Earth's surface.

System structure:



2. Mission Objectives

2.1 FSO (Free-Space Optical Communication)

Free-Space Optical Communication (FSO) is a high-speed data transmission method that utilizes optical signals propagating through free space. FSO communication offers advantages such as high data rates, minimal transmission latency, wide bandwidth, and exceptional security, making it suitable for various applications, including high-capacity data transmission, real-time applications, and secure communication. However, FSO communication is highly directional, making it susceptible to signal attenuation when encountering obstacles along the transmission path, such as atmospheric conditions and cloud cover. This research leverages Low Earth Orbit (LEO) satellite constellations equipped with reconfigurable intelligent surfaces (RIS) as relay stations to overcome the constraints of conventional Free-Space Optical (FSO) communication in higher orbit satellite communication links. Additionally, this approach reduces power consumption and extends communication coverage.

2.2 Why RIS (Reconfigurable Intelligent Surface)?

2.2.1 RIS introduction

Reconfigurable Intelligent Surfaces (RIS) are surfaces composed of passive reflective elements, each with the capability to independently adjust the phase of incoming signals. When electromagnetic waves, such as radio frequency or optical signals, pass through the RIS, these elements can precisely alter the phase and amplitude of the signals. This allows the signals reflected by RIS elements to undergo coherent phase summation at the receiver, achieving high matrix gain while also controlling the direction and characteristics of signal propagation. RIS offers several key advantages, including (1) low power consumption, (2) signal enhancement, (3) coverage extension, (4) multipath transmission, (5)full-duplex(FD), and more.

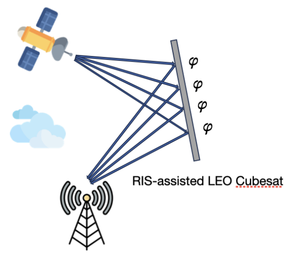


Fig. 1. RIS-assisted Cubesat

2.2.2 RIS on satellite

This research focuses on the mission objective of enhancing signal strength from high-orbit satellites to ground stations in optical communications using Low Earth Orbit (LEO) CubeSats. Given the limited energy capacity of CubeSats due to their small size, and considering that traditional relay methods such as Amplified and Forward (AF) relay and Decoded and Forward (DF) relay require comparatively higher power consumption and complex system designs, Reconfigurable Intelligent Surfaces (RIS) emerge as an efficient and simplified alternative. Additionally, optical communications exhibit high directionality, with a narrow coverage area. RIS offers beamforming capabilities to optimize communication links, providing increased flexibility and extending the coverage range of optical communications to the ground. Therefore, employing RIS on LEO CubeSats holds significant potential for achieving these objectives.

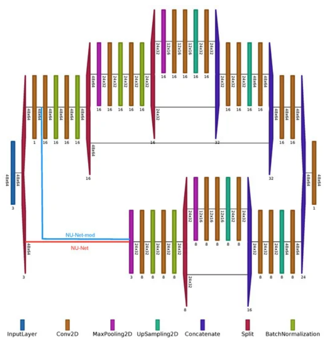


Fig. 2. NU-Net

2.3 Cloud Detection Autonomous System:

In the context of Edge AI, we introduce a module that deploys a pre-trained CNN (convolutional neural network) image segmentation model on a microcontroller for direct cloud layer detection and quantification of cloud coverage on CubeSats. The module can be divided into several components: image processing for cloud detection, the CNN architecture, cloud coverage calculation, and embedded devices suitable for CubeSats. In this section, we will introduce the usage and principles of these elements.

2.3.1 Neural-Network for Cloud Detection （NU-Net）

NU-Net is a convolutional neural network designed for image segmentation. To make the network suitable for microcontrollers, it has been modified from RS-Net into a lightweight version with reduced kernel numbers. It features a multi-stream architecture to optimize color features suppression and the single-band stream focuses on extracting spatial features. Both streams are connected at the end of the network to obtain a segmented and classified image of the same size as the input image, as shown in the diagram.

2.3.2 Cloud Coverage Calculation

The cloud coverage was calculated from the NU-Net segmentation result by evaluating the ratio of the cloud pixels and the total number of pixels of the image:

$$Cloud\ Coverage = \frac{Number\ of\ Predicted\ Cloud\ Pixels}{Total\ Number\ of\ Pixels}$$

This equation was implemented as follows：

$$Cloud\ Coverage = \frac{\sum_{i=1}^{a}\sum_{i=1}^{b} p_{i,j}}{(a)(b)}$$

where a and b are the width and height of the image, respectively, and p the value of pixels that can be 0 or 1 as a result of the classification. In this way, the cloud coverage went from 0.0 when the image was fully clear to 1.0 when it was fully cloudy.

2.3.3 Cloud Detection System on Embedded Device (ESP32)

Using Edge Impulse, we've converted the trained model into TensorFlow Lite format for implementation on a microcontroller (MCU). The system utilizes an ESP32-CAM TinyML device running the NU-Net model. This module receives images, detects cloud layers in satellite images, and calculates cloud coverage based on the model's image output.

The main CPU is responsible for sending images to the MCU and receiving cloud coverage values. To operate independently from the host, the MCU is programmed using UART communication protocol at 115,200 bps.

3. Mission architecture

3.1 Structure: 6U (20x10x34.1 cm)

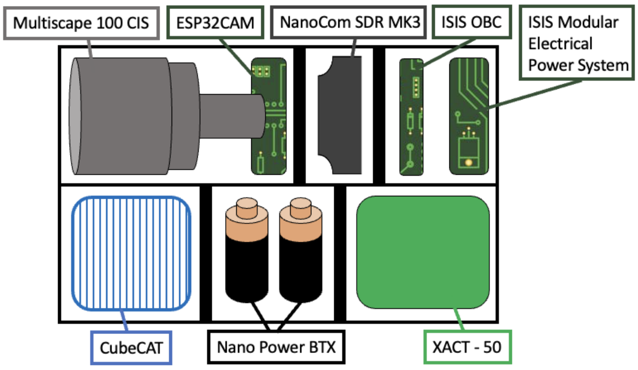


Fig. 3. Cubesat structure

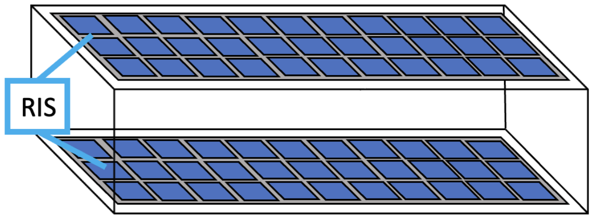


Fig. 4. Lateral view of the structure

3.2 Payload:

3.2.1 CubeCAT

CubeCAT is a compact, high-performance laser communication terminal for use in CubeSats.

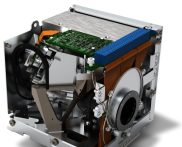


Fig. 5. CubeCat
https://www.aac-clyde.space/what-we-do/space-products-components/communications/cubecat

Size	**96*96*96mm (~1U)**
Mass	**< 1330g**
Power	**15W**
Data Rate	**1Gbps**
Fine Point Assembly	**±0.5°**
Wavelength	**1545nm**

Table 1. Specifications of CubeCAT

3.2.2 RIS (Riconfigurable Intelligent Surface):

Requirement Standards:

Size	**< 20*34cm**
Mass	**<5kg**
Dimension of RIS Elements	**1cm*1cm**
Numbers of RIS Elements	**approximate 540**
Passive or Active	**Passive**
Operating Frequency	**3GHz**
Method	**Reflect**

Table 2. Specification of RIS

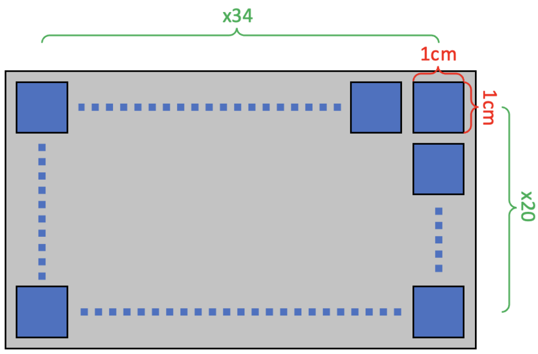


Fig. 6. RIS elements

3.2.3 Multiscape 100 CIS:

Size	**98*98*176mm**	**Aperture**	**95mm**
Mass	**1200g**	**Full Field of View**	**2.22° (across-track) 1.66° (along-track)**
Power	**20~30W**		
Focal Length	**580mm ±1mm**	**Ground Sampling Dist (GSD)**	**4.75m (at 500 km height)**

Table 3. Specification of Multiscape 100 CIS

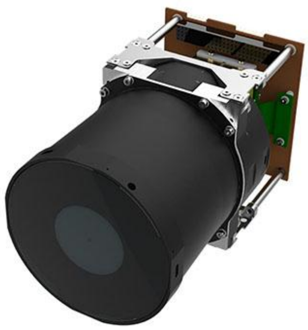


Fig. 7. Multiscape 100 CIS
https://simera-sense.com/products/multiscape100-cis/

4. Orbit Description

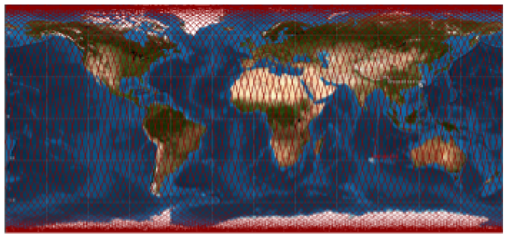


Fig. 8. CubeSat track map

Taking reference from existing LEO satellite constellation launch programs and the current state of rocket launch services, we plan to launch a constellation of cubesat into Sun-Synchronous Orbit (SSO). This orbital configuration will enable the satellites to maintain a stable and highly continuous communication position. Each individual satellite will have a larger coverage area, making it advantageous for stable and global communication.

To achieve this, the plan is to position the satellite constellation in LEO at altitude of 550 kilometers with an orbital inclination set at 98 degrees. The service coverage area will be designed to provide global coverage, similar to the satellite service network offered by Starlink. The constellation is estimated to consist of around 12,000 satellites.

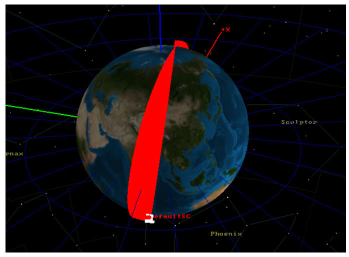


Fig. 9. CubeSat orbit

5. Discussion and Summary

Designing a constellation composed of low Earth orbit cubic satellites, utilizing the advantages of RIS (Reconfigurable Intelligent Surface) technology with its low power consumption, simplicity, and high-speed optical communication, along with a cloud detection system to mitigate the impact of clouds on optical communication. These three payloads are combined to effectively enhance signal strength, reduce signal latency, improve signal transmission between GEO (Geostationary Earth Orbit) satellites and ground stations, and expand the communication coverage area of GEO satellites. This constellation aims to become a highly efficient low Earth orbit relay cubesat constellation.

6. References

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[6]Article modification by ChatGPT, a computer program developed by OpenAI.

▲7. Appendices

Subsystems	Units	Mass	Volume	Power	Voltage	Operating(°C)
Structure	6U CUBESAT STRUCTURE	682g	20*10*34.1cm	N/A	N/A	N/A
EPS	Blue Canyon 6U Solar Array	289g	1.9~2.5mm(thickness)	46~118w	17 or 34.1w	
	ISIS Modular Electrical Power System	417g	90*96*57mm	45whr	8~16V	-40~70
ADCS	Blue Canyon Technologies XACT with gps	1360g	100*100*75mm(0.75u)		12V	-20~60
C&DH	ISIS On board computer	100g	96*90*12.4mm	0.4w	3.3V	-25~65
TCS	ALUMINUM HEAT SINKS	3g	21*25*3.5mm	N/A	N/A	
SDR	NanoCom SDR MK3	272g	95*95*23.85mm		12-32V	-40~50
COMM	Hircom CubeSat UHF tranceiver	85g	95*90*15mm	0.63w	3.3V	-35~80
	ISIS UHF Antenna for 6U	90g	98*98*6.6mm	2.3w	4V	-20~80
	ISIS S-Band High Rate Transmitter	120g	98*93*14.52mm	13w	7~20V	-40~70
	ISIS S-Band Patch Antenna	50g	80*80*5mm	N/A	N/A	-20~50
ISL	CubeCAT	850g	90*95*95mm(1U)	25w		
Cloud detect system	Multiscape 100 CIS	1200g	98 x 98 x 176 mm	5.8w	5V	-10~50
	ESP32CAM	10g	27x40.5x4.5 mm	N/A	5V	-20~70
Total			~5.17U			

▲Table 4. Satellite operational mode

State	Phoenix	Safe	Charging	Standby	Science	TT&C
EPS	ON					
ADAS	OFF	ON				
C&DH	ON					
RIS	OFF				N/A	ON
S-band	OFF				ON	N/A
UHF(Tx)	Beacon					
UHF(Rx)	ON					
ISL	OFF			AS REQ	OFF	
TCS	AS REQ					

◀Table 5. Subsystems budget