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# THESIS

**MOBILE CUBESAT COMMAND AND CONTROL GROUND STATION ARCHITECTURE FOR FREE-SPACE OPTICAL COMMUNICATION RECEIVER**

by

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September 2022

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The United States military continues to encourage the need for robust satellite communications in order to successfully execute defense missions. CubeSats are a smaller-scale spacecraft, initially utilized to expand educational opportunities in the field of aerospace and satellite communications. This research explores both existing and potential ground station architecture options for integration of free-space optical communication downlinks from CubeSats. Future experimentation plans will focus on the application of this capability in more diverse environments to include expanded ground architecture opportunities. Systems engineering design and architecture methods are useful in understanding the current hardware and software options and limitations for future expansion opportunities. By considering a comparable planning approach, alternatives for architecture development can be organized to aid in the identification of control factors for sub-system and ground communication interfaces. As a well-established CubeSat communications system, the existing Mobile CubeSat Command and Control (MC3) architecture serves as an excellent candidate for experimental integration and eventual considerations for a planned proof of concept.

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# MOBILE CUBESAT COMMAND AND CONTROL GROUND STATION ARCHITECTURE FOR FREE-SPACE OPTICAL COMMUNICATION RECEIVER

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# ABSTRACT

The United States military continues to encourage the need for robust satellite communications in order to successfully execute defense missions. CubeSats are a smaller-scale spacecraft, initially utilized to expand educational opportunities in the field of aerospace and satellite communications. This research explores both existing and potential ground station architecture options for integration of free-space optical communication downlinks from CubeSats. Future experimentation plans will focus on the application of this capability in more diverse environments to include expanded ground architecture opportunities. Systems engineering design and architecture methods are useful in understanding the current hardware and software options and limitations for future expansion opportunities. By considering a comparable planning approach, alternatives for architecture development can be organized to aid in the identification of control factors for sub-system and ground communication interfaces. As a well-established CubeSat communications system, the existing Mobile CubeSat Command and Control (MC3) architecture serves as an excellent candidate for experimental integration and eventual considerations for a planned proof of concept.

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# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ACF | Advanced Coma-Free |
| AO | Adaptive Optics |
| AoA | Analysis of Alternatives |
| APD | Avalanche Photodiode |
| API | Application Programming Interface |
| ATC | Action Tracking Camera |
| BER | Bit Error Rate |
| BIST | Built-In Self-Test |
| BPF | Bandpass Filter |
| BPSK | Binary Phase Shift Keying |
| CCD | Charge Couple Camera |
| CLICK | CubeSat Infrared Crosslink Mission |
| CONOP | Concept of Operations |
| COTS | Commercial-Off-the-Shelf |
| CSTOL | Coarse Stage Tracking in an Open Loophole |
| DBS | Dichroic Beam Splitter |
| DLR | German Space Agency |
| DSPK | Differential Phase Shift Keying |
| EDFA | Erbium-Doped Fiber Amplifier |
| FCC | Federal Communication Commission |
| FF | Forward Feed (control table) |
| FOV | Field of View |
| FPGA | Field Programmable Gate Array |
| FSM | Fine Steering Mirror |
| FSOC | Free-Space Optical Communication |
| FWHM | Full Width Half Maximum |
| GEO | Geosynchronous Orbit |
| GPS | Global Positioning System |
| HPA | High Powered Amplifier |
| HTV-8 | H-II Transfer Vehicle |

| | |
|---|---|
| ISS | International Space Station |
| JAXA | Japan Aerospace Exploration Agency |
| KSAT | Kongsberg Satellite Services |
| LaCE | Laser Crosslink Experiment |
| LADEE | Lunar Atmosphere and Dust Environment Explorer |
| LCRD | Laser Communications Relay Demonstration |
| LD | Laser Diode |
| LEO | Low Earth Orbit |
| LHCP | Left Hand Circular Polarization |
| LLCD | Lunar Laser Communications Demonstration |
| LLGT | Lunar Lasercom Ground Terminal |
| LNA | Low Noise Amplifier |
| MC3 | Mobile CubeSat Command and Control |
| MDA | Missile Defense Agency |
| MIT | Massachusetts Institute of Technology |
| MLPC | Multi-plane Light Conversion |
| MOC | Mission Operations Center |
| MOCT | Miniature Optical Communications Transmitter |
| MOPA | Master Oscillator Power Amplifier |
| NASA | National Aeronautics and Space Administration |
| NFIRE | Near Field Infrared Experiment |
| NICT | National Institute of Information and Communications Technology |
| NIWC | Naval Information Warfare Command |
| NODE | Nanosatellite Optical Downlink Experiment |
| OCU | Optical Communications Unit |
| OFC | Optical Fiber Communication |
| OGS | Optical Ground Station |
| PAT | Pointing, Acquisition and Tracking |
| PPM | Pulse Position Modulation |
| PPT | Precision, Pointing and Tracking |
| RF | Radio Frequency |
| RHCP | Right Hand Circular Polarization |

| | |
|---|---|
| RTD | Resistance Temperature Detectors |
| SATRN | Satellite Agile Transmit and Receive Network |
| SDL | Space Dynamics Laboratory |
| SDR | Software-Defined Radio |
| SOLISS | Sony Computer Science Laboratory |
| SWaP | Size, Weight, and Power |
| TRL | Technology Readiness Level |
| TSX | TerraSAR-X |
| USRP | Universal Software Radio Peripheral |
| VPN | Virtual Private Network |
| WDM | Wavelength Division Multiplexing |

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# EXECUTIVE SUMMARY

The demand for data communications continues to increase as new technologies emerge and introduce the need for faster and more efficient means for data transfer. Traditional satellite and fiber optic communications methods have provided a gateway to nearly instantaneous global connectivity. However, radio frequency bandwidth availability is becoming quickly saturated, and underground fiber optic systems are expensive and time consuming to build. Free space laser communication offers some potential for eliminating some of these relative limitations and providing much higher data rates but comes with the need for new engineering strategies to mitigate atmospheric interference.

In recent years, smaller-scale satellite systems deployed into low earth orbits have become a progressively popular method for researching and deploying space communication capabilities in a much more cost efficient and expedited manner. An example of this can be observed by the Mobile CubeSat Command and Control (MC3) program hosted by the Naval Postgraduate School. The ground system consists of several operational radio frequency (RF) receiver locations interconnected via a virtual private network and customizable software allowing the advantages of a remote management mission platform.

Laser communications from space to a ground receiver present a potential alternative and next step toward expanded research and development for the MC3 ground station network. Several recent studies and experiments conducted by organizations with similar interests were researched in a detailed literature review to assess the breaking edge state of the art for both interspace and space to ground optical communications using small satellite architectures. The MC3 current system configurations and parameters were evaluated and compared to propose new architecture suggestions based on examination of recent discoveries in the space systems community and new systems in development.

A theoretical ground station architecture concept and recommendations for future research expansion are presented for consideration for further study and reference for the NPS Space Systems Department. A systems engineering outline and high-level

requirements are offered to support a roadmap for pursuing a step-by-step approach to progress the technology readiness level of future design and prototyping efforts. Today, the number of successful missions that have provided proof of concept is limited, and development has been underway for several years in each case. As the feasibility of optical ground station communication becomes apparent, several manufacturers are pursuing the development of commercial hardware products. Some of these products are listed as recommendations but may not be available in the immediate timeframe.

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# I. INTRODUCTION

As communication satellite programs continue to expand, there is an increasing interest in research and development strategies for improving technologies, reducing costs, and assessing the environmental impacts associated with the benefits. During the early development of satellite communications, the purpose of space utilities was primarily related to scientific exploration and pursuing military advantages by expanding traditional communications. Today, effectively every minute of every day, satellite communications are utilized for a wide variety of services and applications that apply to both government mission essential and commercial purposes. Some typical applications are weather monitoring, surveillance, broadcasting, point-to-point communications, and web networking. The ability to use hardware and software components across a wide range of ever-expanding applications has become increasingly beneficial for meeting the Earth's communications-environment needs.

Traditional space communication systems introduce specific challenges associated with mass, power consumption, and maintenance costs. The evolution of satellite technologies has presented opportunities to overcome some of these challenges with the development of smaller form factor satellites known as CubeSats. These developments and the expanding maturation of space systems technologies have expanded the realm of possibilities in the communications technology disciplines. One of these breaking-edge advancements is the ability to connect point-to-point communications between satellites and ground stations via optical laser links. Optical links allow for efficiencies in data transfer speeds, power consumption, and distribution stability. The pursuit of research and design development in optical link communications via laser links could provide signification advantages to the capabilities and efficiencies of communication links between CubeSats and ground stations.

## A. THESIS OBJECTIVE

There is an interest in identifying a ground station architecture that works well for optical laser satellite communications, specifically for small form-factor satellites. This research develops a systems engineering approach and design to explore the potential benefits of interfacing the Naval Postgraduate School's Mobile Command and Control (MC3) ground station architecture and a free-space optical communication (FSOC) ground station concept. MC3 is an existing architecture that has proven to work successfully with CubeSats that utilize radio frequency (RF) communications for mission operations (Minelli et al. 2019). In combination with an analysis of architecture methods, systems engineering design is instrumental in understanding options to incorporate laser link communication for future small satellite missions. This research considers architecture alternatives to aid in identifying control factors for sub-system and ground communication interfaces. The existing MC3 architecture includes several ground station locations across the United States which are continuously utilized for space systems research and development, particularly for communications to and from CubeSats. This makes MC3 an excellent candidate for this evaluation.

Integration of optical communications on small satellite platforms with MC3 ground stations requires further research and experimentation. This research analyzes system interfaces to develop potential design concepts and identify if applicable modifications for MC3 compatibility could be beneficial to future research endeavors. Given the design of the MC3, this research will propose candidate architecture design alternatives that can integrate optical receiver technologies, providing an expanded set of capabilities for Department of Defense (DOD) stakeholders. The research agenda will investigate the use of available resources in the Space Systems Academic Group as well as similar research endeavors performed across the academic community to explore realistic mission design parameters.

## B. METHODOLOGY

This thesis explores published designs and methodologies corresponding to satellite-to-satellite, satellite-to-ground, and RF communications that have been utilized within the CubeSat community. The data collection gained from assessing the current experimental procedures and analysis of results aids in the development of design concepts for further exploration at NPS and the MC3 program. The application of software-based tools increases the chance of better understanding concept parameters for satellite mission planning.

A disciplined and documented approach aims to better understand optical laser link integration into the complete communications loop. The research begins with an analysis of the existing laser link and optical ground station research developments and the current interfacing technologies which support them. The analysis aids in identifying challenges and constraints which may be specific to the unique application proposed. Background research on existing capabilities and similar space systems experiments are utilized to develop several design concepts and recommendations for an optical ground station architecture to support CubeSat communications and interface with the existing MC3 RF infrastructure. This research will then focus on the developmental ideas behind FSOC interfaces, space-to-ground communications, design concepts, and expansion for optical downlink integration with the existing MC3 radio ground station configuration. Finally, this research will study the feasibility of such integration, particularly focusing on considerations for optical tacking mounts and laser modulators.

Identification of MC3 use cases for laser optical ground station links and recommendations for requirements verification of a reliable communications infrastructure are critical factors in this research. The procedure includes investigating the MC3 functional parameters to capture current system configurations, identify interfaces between them, and propose new architectures based on examination of both pre-existing discoveries and new systems in development by investigating the findings from other institutions of interest. This research examines existing features to assess strengths and weaknesses at the possible interface points to describe a combination of RF and laser communication capabilities for small satellites.

## C. EXPECTED BENEFITS

This research has the potential to advance the use of practical satellite applications and improve efficiency and security of small satellite communication links. Successful integration of optical link communications would ultimately benefit MC3 users and DOD stakeholders, given the ubiquity and low-risk posture of RF and high-risk, high payoff potential of orders-of-magnitude improvements in data rates with optical communications. The development of design interface concepts identifies beneficial adaptations in system-to-system design parameters while contributing methods for risk mitigation where applicable. The results and findings of this research drive the development of several new proposed integrated architecture concepts. System design characteristics are outlined as a concept of operations (CONOP) and as the first step to developing a sponsor-ready proposal and test plan for the next level of progression in experimental objectives. Finally, expanding the knowledge base of free-space optical technology utilization for space systems can influence the availability of future mobile and remote communications capabilities.

## D. OVERVIEW

Chapter II, Background and Motivation: This chapter reviews high level satellite and optical communications concepts and provides a historical background overview of the technologies. It provides context for the circumstances which outline the developmental progression and relevance of traditional satellite ground station receivers, CubeSats and optical communications.

Chapter III, Optical Communications in Space: This chapter reviews the various recent research and development projects which focus on laser communications advancements for the benefit of government, private industry, and academic use cases. It highlights the few successful space to ground optical links that have been established in just the last couple of years.

Chapter IV, Design and Systems Engineering Architecture Development: This chapter provides a systems engineering road map for pursuing the various stages and preparation required for technology readiness level progression. It describes the existing MC3 architecture and presents optical ground station components that could serve as alternatives for future research applications at NPS.

Chapter V, Conclusions: This chapter summarizes the outcomes of the research presented in this thesis. It also provides recommendations for additional research that would benefit the progression toward a fully developed proof of concept and prototype.

# II. BACKGROUND AND MOTIVATION

## A. LASER SATELLITE COMMUNICATIONS

Satellite communications systems consist of two primary subsystems: the ground and space segments. Each subsystem contains system-of-system components based on the specific architecture that may be required to achieve the mission requirements. Communications satellites allow for data to be economically transmitted over long distances or broadcast information to multiple receiving locations at once. Most communications satellites function as active repeaters. Once the onboard apparatus receives data, the signal is amplified and then directed to one of several ground stations for retransmission. Amplification is required due to power loss while the signal travels up to the satellite. For a communications satellite to serve its primary purpose of transmitting information from a sender to a receiver, the signal must be transferred to the earth station with specific reliability so that data received can be extracted. A theoretical power budget is validated based on measured transmission power levels throughout the data transport (Gordon and Morgan 1993).

Both optical and radio signals are part of the electromagnetic spectrum but segmented by frequency and wavelength. Electromagnetic waves can propagate through air, solid materials and the vacuum of space and the efficiency of propagation through various mediums is dictated by the wavelength. Figure 1 shows the scale of frequencies which classifies radio and optical frequencies by wavelength.

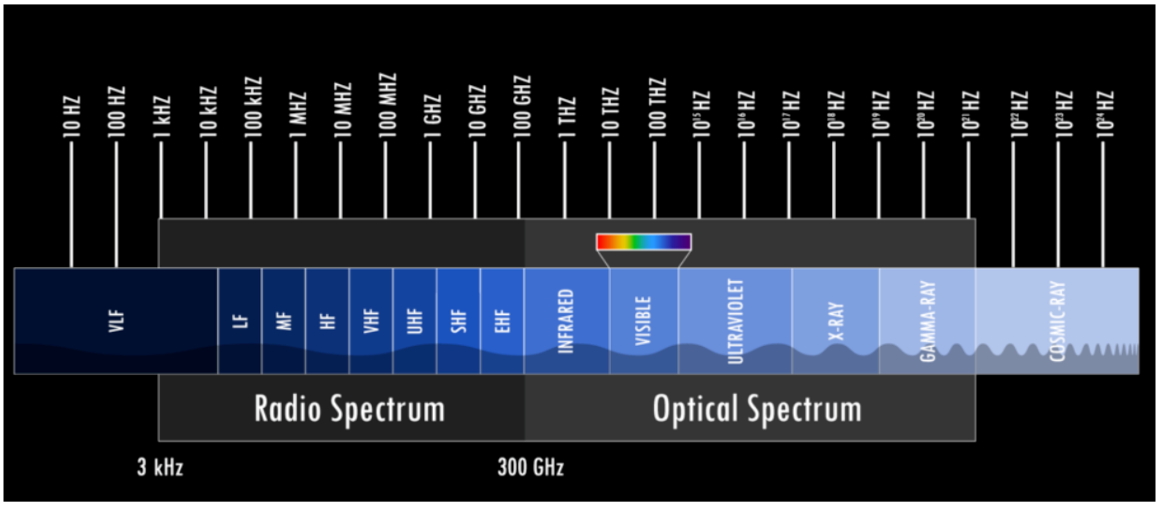


Figure 1. NASA spectrum band designators. Source: Manning (2015).

Higher frequencies allow for larger bandwidth and more data to travel through the channel as long as interference does not disrupt the transmission.

### 1. Link Budget for FSOC

Laser is an acronym used to describe the representation of Light Amplification by Simulated Emission of Radiation in a single wavelength structure via a narrow beam. In many laser optic applications, the typical output of a laser is described as a Gaussian beam (Edmond Optics 2017). The intensity distribution over the direction perpendicular to the axis of propagation graphically resembles a bell-shaped curve. Link budget is a calculation of power gains and losses from the transmission source to the received though a communication medium. In the case of wireless communication, it is the primary means for measuring the performance of a laser linked system and can provide a reasonably accurate estimate of what kind of hardware is required in design development to meet the high-level system requirements. Various factors can affect the outcome of link budget analysis, such as weather conditions, obstructions in the signal path, and multipath reflection from undesired contact surfaces. Both the satellite segment and the earth segment are components of the link budget. Pointing misalignment may cause polarization losses that will, in turn, cause a loss in power. When evaluating the communication exchange, the atmosphere attenuation must be taken into consideration. The received power is calculated by equation (1):

$$P_R = P_T \eta_T \eta_R G_T G_R L_T L_R L_A L_{PG} \tag{1}$$

where $P_R$ is the receiver signal power, $P_T$ is the transmitted power, $\eta_T$ is the transmitter efficiency, $\eta_R$ is the efficiency of the receiver, $G_T$ is the transmitter gain and equal to 16 divided by the square of the transmitting divergence angle in radians (Polishuk and Arnon 2004). $G_R$ is the receiver gain and is calculated by $G_R$=$(D_R\pi/\lambda)^2$ where $D_R$ is the diameter of the receiver telescope for an optical downlink or $G_R = (4\pi\eta A/\lambda^2)$ for a RF ground station,(Gordon and Morgan 1993) $L_T$ is the transmitter pointing loss and is represented by $L_T$=exp(-$G_T{\theta_T}^2$)where $\theta_T$ is the transmitter pointing error, $L_R$ is the receiver pointing loss, (Arnon 2005) $L_A$ is the atmospheric attenuation loss, and $L_{PG}$ is the free space path loss between the satellite and earth station. (Lim et al. 2020) $L_A$ and $L_{PG}$ are obtained by equations (2) and (3).

$$L_A = exp\left(-\frac{\rho}{sin(\theta_E)}\right) exp\,(-\theta_A d_A) \tag{2}$$

$$L_{PG} = (\lambda/4\pi d_{GS})^2 \tag{3}$$

The link margin is the difference between the minimum expected power received and the receiver's sensitivity. The receiver's sensitivity represents the received power at which the receiver will no longer function as desired. The link margin is the amount of power left in oscillation in the attenuation of the link as is given by equation (4).

$$L_M = P_R / P_{req} \tag{4}$$

$P_{req}$ signifies the receiver sensitivity. The link margin calculation $L_M$ should always be positive and above 6 dB, and the total link budget is assessed for the worst-case occurrence.(Liang et al. 2022)

## 2. Optical Fiber Principles Applied to Laser Satellite Communication

Optical fiber is a predominant component of today's networking infrastructure. The most basic configuration of a fiber optic system consists of a transmitter, receiver, and a channel to transport data. Fiber optic cables are made of thin glass strands coated with reflective material and synthetic casing to direct the light at higher wavelengths along the desired path for long distances with a low level of interference. The confined environment allows data to travel at higher speeds. The evolution of optical fiber architectures has resulted in a technological shift in terms of efficiency for information technology communications. However, light propagation over optical fiber does exhibit a flaw related to weakening in wavelength due to absorption and scattering caused by absorption of the encasement. This observation appears to be relatively minimal compared to atmospheric limitations over extensive distances, which presents the first and most challenging limitation for FSOC (Kaushal and Kaddoum 2015).

The theory of FSOC is similar to that of optical fiber communication (OFC). As the advantages of OFC have proven successful in the last two decades, the desire to produce replicated efficiencies in a FSOC environment has become increasingly appealing. The main difference is link exposure to atmospheric turbulence or other forms of interference to the unhoused free-space link. However, the benefits may outweigh the risk when considering optical data transfer for communication between ground nodes and satellite endpoints. The higher carrier frequency increases the volume of communication information that can be transferred within a given period of time. The narrower beam reduces the chances of infiltration, and data encryption technologies are more robust over optical connections, increasing the communication link's security level significantly.

> In RF and microwave communication systems, the allowable bandwidth can be up to 20% of the carrier frequency. In optical communication, even if the bandwidth is taken to be 1% of carrier frequency ($\approx 10^{16}$ Hz), the allowable bandwidth will be 100 THz. This makes the usable bandwidth at an optical frequency in the order of THz which is almost $10^{5}$ times that of a typical RF carrier. (Kaushal and Kaddoum 2015)

Figure 2 shows a comparison of beam divergence as from a distance to Mars. Beam divergence is proportional to the carrier wavelength divided by the aperture diameter

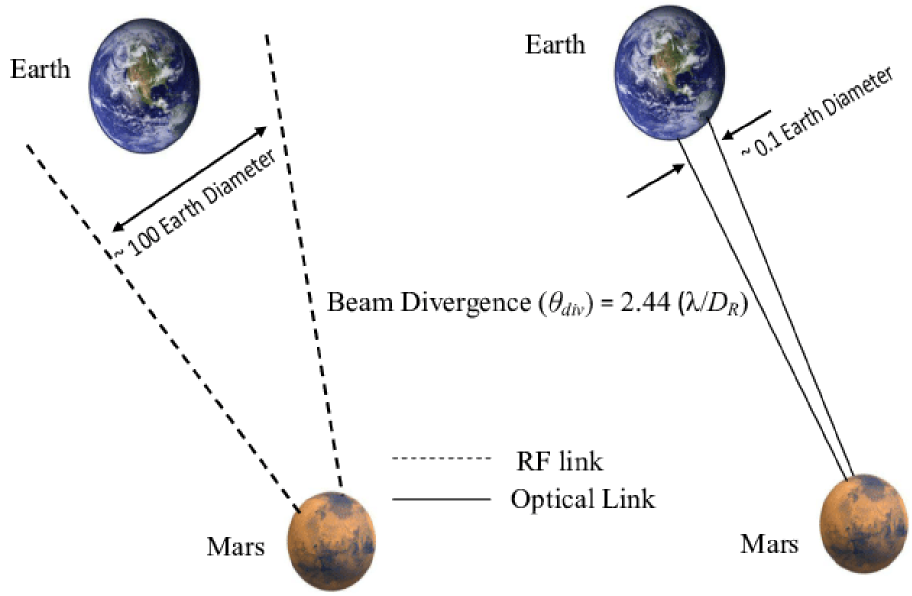


Figure 2. Comparison of optical and RF beam divergence from Mars to Earth. Source: Kaushal and Kaddoum (2015).

While propagating through the atmosphere, optical signals are affected by various forms of atmospheric turbulence. FSOC is pursued as it offers a higher data rate, but it presents challenges that require the ability to mitigate atmospheric interferences and beam misalignment errors. Figure 3 shows an overview of the basic principle of the Gaussian beam and beam divergence. Beam divergence is the angular measurement of the beam diameter fluctuation as the light propagates over distance from the aperture. The Rayleigh length $Z_R$ is the distance from the beam waist $w_0$ to the location of the path where the beam cross section has doubled. For a Gaussian beam, the minimum divergence can be defined as $\theta_0$ as shown is equation (5).

$$\theta_0 = \frac{\lambda}{\pi * \omega_0} \tag{5}$$

The optimal aiming performance is achieved when the divergence calculation is close to $\theta_0$ (R. Paschotta 2008).

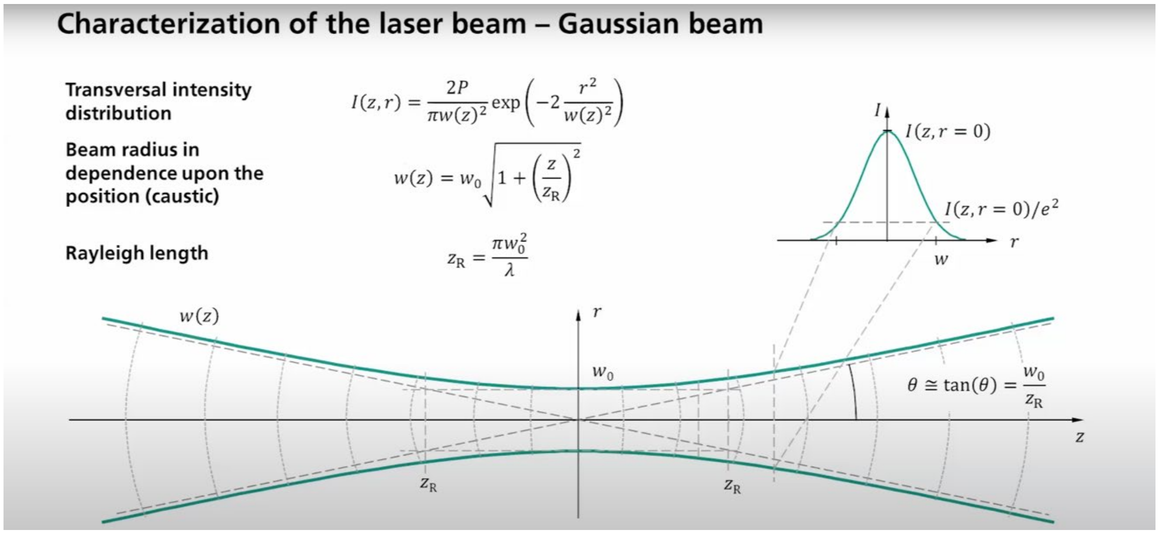


Figure 3. Schematic of Gaussian beam and beam divergence parameters. Source: Schneiter, Rätzel, and Braun (2018).

During laser light transmission, absorption and scattering occur by particles the light comes into contact with during the signal path. The number of photons effected in the beam can be predicted by the probability that a collision will occur (Puent 2017). Information received from the beam can be unitized to adjust the receiver system to apply calculated corrections to optimize the data collection.

## B. CUBESAT HISTORY AND OPTICAL AMBITIONS

CubeSats were first introduced to the scientific community in 1999 as a collaborative effort between professor Jordi Puig-Suari at California Polytechnic University and professor Bob Twiggs at Stanford University's Space Systems Development Laboratory (NASA CubeSat Launch Initiative 2017). The original purpose for the development of CubeSats was to explore a more cost-efficient and accessible alternative to conventional satellites that would require less time and less complexity to ensure increased capabilities for more recurrent launches for space systems research and development. A CubeSat is a satellite class that is identified by a standard size and form factor. According to the CubeSat Design Specification, released in February 2022, a CubeSat design can range in sizes from 1U to 12U. A single U is defined by a 10cm cube weighing up to 2kg. Due to the low weight, the rocket requires less fuel to propel them into orbit. In many circumstances, they can even piggyback into space onboard heavier payloads.

The United States military continues to encourage the need for robust satellite communications to execute defense missions successfully. CubeSats are smaller-scale spacecraft initially utilized to expand educational opportunities in the field of aerospace engineering and satellite communications. Modeling and simulation engineering tools have been increasingly applied to both learning and professional environments for CubeSat development and have contributed to improvements in experimental results. There is a need for an increase in knowledge and technological expansion in management and integration engineering related to the understanding of system interfaces for improving small form factor satellite communications.

CubeSats have become an integral component of space technologies research and development. The small size and cost savings provided have proved to be quite beneficial in many ways over the last 20 years. However, some challenges remain consistent in CubeSat design. They are typically launched in Low Earth Orbit (LEO), and the significant increase in the number of launches due to the unit's popularity has become a major reason for concern regarding space debris. Their small size and low costs result in increased sensitivity to radiation. This causes the unit to degrade much faster than its larger and more expensive counterparts. In 2019 the U.S. Government Orbital Debris Mitigation Standard Practices released an update to the standard to recognize some of the challenges and define guidelines and safety concerns for small satellite missions. The Federal Communication Commission (FCC) also began enacting new rules in April of 2020, which would place increased restrictions due to concerns about space debris (Ostrom and Opiela 2021). In addition, the FCC has introduced stricter regulations for obtaining licenses for allocated communication space on the RF band as a result of overcrowding and concerns related to interference risks (Federal Communications Commission 2022).

Seeking to conduct research in alternative solutions such as FSOC ground stations can help to alleviate some of these concerns in the small satellite research and development community. As RF band licenses become more difficult to obtain, free space communications can provide a new boundary without such limiting restrictions.

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# III. OPTICAL COMMUNICATIONS IN SPACE

## A. SPACE TO SPACE LASER COMMUNICATION

Inter-satellite crosslinks in space are not subject to the adverse atmosphere and therefore can be utilized to increase the efficiency of the communication network architecture. Several satellite constellations intended for global telecommunications are currently under development. The concepts and design developments of small satellite constellation missions focus extensively on the need for satellite-to-satellite links as a mitigation strategy for reducing the amount of data loss by atmospheric interference. A consistent challenge for inter-satellite crosslink implementation is the cost for the space network's required quantity of transceivers capable of multi-Gbps links over ranges up to 6000km with a 7–10 year lifetime and resistance to radiation damage (Hemmati 2021).

### 1. NFIRE to TerraSAR

Beginning in 2007, a Missile Defense Agency (MDA) satellite and a German commercial SAR satellite conducted testing with a laser communications payload engineered by Tesat-Spacecom. Two laser communications terminals were mounted on TerraSAR-X (TSX) and Near Field Infrared Experiment (NFIRE) space vehicles. NFIRE was launched on April 24, 2007, to 495Km altitude at a 48-degree inclination, followed by the TSX launched into sun-synchronous orbit on June 15, 2007. On February 21, 2008, the first inter-satellite laser communication links were documented at a range of 4900 and 3800 Km (Fields et al. 2009). The European Data Relay System (EDRS) series of satellites use these FSOC payloads for relaying data from satellite sensor instruments in LEO and GEO orbit. Data gathered at LEO is sent to a GEO satellite and sent to the Earth over a Ka-band link (Hemmati 2021).

Figure 4 shows the laser communications terminal developed by the German Space Agency (DLR) and implemented on the experimental NFIRE satellite (Gregory 2012). The unit is based on homodyne binary phase shift keying (BPSK) modulation. For homodyne detection, the frequency of the local oscillator is altered to match the frequency of the received signal (Hemmati 2021). Phase Shift Keying is a digital modulation technique by which the carrier signal phase is changed by fluctuating the sine and cosine inputs at 0° and 180°.

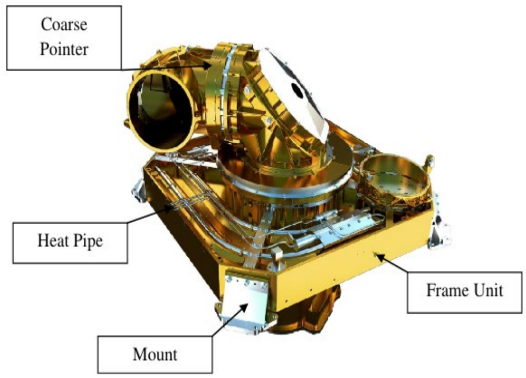


Figure 4. DLR laser communication terminal. Source: Gregory (2012).

To establish a point-to-point communications link between two terminals in space, the payloads cycle through a pointing, acquisition, and tracking (PAT) sequence in the order shown in Figure 5. During pointing, the transmit and receive terminals are aligned using the trajectory of each end on an open loop (Hemmati 2021). A search algorithm ensures reduced uncertainty in alignment accuracy. Acquisition is performed using "point ahead" calculations without the use of a beacon. Once the terminals are aligned, the light received is used as a tracking guide between the terminals in a closed loop. Then, a frequency sensor begins adjusting the local oscillator frequency to lock the phase of the signal at which point tracking is homodyne and communication begins (Hemmati 2021).

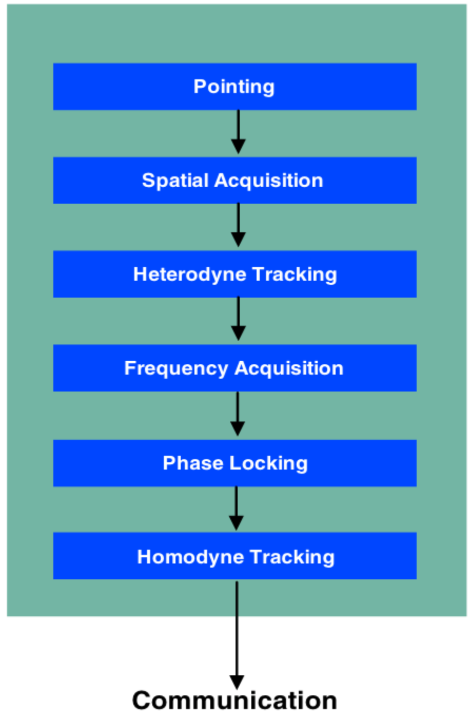


Figure 5. DLR laser communications terminal PAT sequence. Source: Gregory (2012).

### 2. The Laser Crosslink Experiment

For the United States Navy and DOD, transitioning to more advanced forms of space communications is crucial to keeping up with today's fast-paced communications environment. Advancing laser communication options for CubeSat architectures can provide a much greater return on investment for applicable missions. The Laser Crosslink Experiment (LaCE) engineering team at the Naval Information Warfare Command (NIWC) Pacific is actively dedicated to pursuing further experimentation on optical links for CubeSats. A research and development engineering team is working on proposals for experimentation with Laser CubeSat communications. The LaCE program currently consists of two or more 6U CubeSats and a single, standalone test ground station, which has not been linked for coverage expansion. The experiment will aim to connect the two satellites in a "peer-to-peer" optical laser network connection and communicate to the ground station using radio frequency (RF). The LaCE design integrates various sub-systems for handling commands, telemetry, power, control, payloads, and ground station communication. Currently, the mission seeks primarily to demonstrate an optical laser communication crosslink capability on a small scale.

The LaCE project will focus on applying this capability in more diverse environments to include expanded ground architectures. An architecture for communication from satellite to ground via laser is still developing for the LaCE experiment. However, this is a topic of high interest and an area for exploration in this research effort. The current proof of concept establishes a satellite-to-satellite optical communications link, which can then be linked to a single ground station location via radio frequency signals. The LaCE engineering team conducted an initial ground station trade study and analysis of alternatives (AoA). The study proposed a comparison between the NRL Blossom Point, KRATOS Quantum, and MC3 ground station architectures. The results concluded that the MC3 build would be the most viable option. Based on the similarities of the study, the findings of this thesis research have the potential to aid in the progression of the LaCE program objectives.

## B. FREE-SPACE OPTICAL COMMUNICATIONS DOWNLINK

### 1. Lunar Laser Communications Demonstration

In 2013, MIT Lincoln Laboratory conducted an experiment called the Lunar Laser Communications Demonstration (LLCD) mission. The project was in collaboration with NASA and demonstrated a laser communications downlink at 622 Mbps and uplink at a rate of 20 Mbps between Earth and the Lunar Atmosphere and Dust Environment Explorer (LADEE) satellite in orbit around the Moon. The Lunar Lasercom Ground Terminal (LLGT), located at White Sands Missile Range in New Mexico, was the primary ground station.

The LLGT includes an array of eight telescopes contained in clamshell dome and a converted 40ft shipping container, shown in Figure 6. The LLCD was conducted over a five-week period and collected data from 55 passes when there was a clear line of sight from the Earth station to the target satellite. The established links occurred at elevation angles between 4° and 75°. The average link duration was 16.3 minutes with the longest clocking in at 29.1 minutes and the shortest at 0.3 minutes on a day when there was extensive cloud coverage. In addition to weather constraints, the results indicated that link durations were also limited by the power available on the spacecraft and the temperature at the ground station terminal.

Figure 6. LLCD ground terminal. Source: Lincoln Laboratory, MIT (2022).

### 2. Laser Communications Relay Demonstration

NASA is currently researching several projects to achieve advancements in this territory. The Laser Communication Relay Demonstration (LCRD) is an experimental program being conducted by NASA and aims to provide a demonstration of laser link connectivity from satellites in geosynchronous (GEO) orbit to two ground stations located in Table Mountain, California and Haleakala, Hawaii. The primary goal of the research and development for LCRD is to demonstrate effective laser communications between Earth ground stations and various satellites in low earth orbits (LEO) (Moores and Wilson 2013).

Figure 7 shows a block diagram of the LCRD mission:

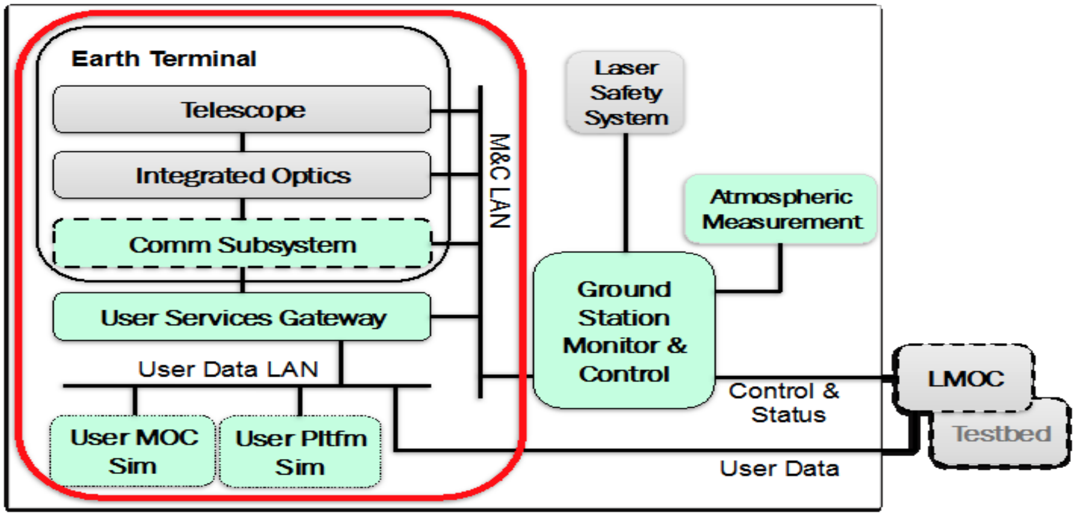


Figure 7. NASA LCRD ground station configuration block diagram. Source: Moores and Wilson (2013).

The subsystems labeled in green represent components that are duplicated at each ground station, while the subsystems labeled in grey depict the items that are developed independently depending on the ground station location (Moores and Wilson 2013).

The first LCRD payload was launched in December 2021 into GEO onboard the DOD STPSat-6 space vehicle. The technology demonstration requirements for this mission are the following:

- Demonstrating optical relay communication architectures
- Demonstrating simultaneous and bidirectional direct optical communication services between LEO and GEO
- Demonstrating pulse position modulation (PPM) services up to 311 Mbps
- Demonstrating differential phase shift keying modulation services up to 1.244 Gbps
- Measuring and characterizing the system performance through the life of the demonstration. (Edwards et al. 2022)

The LCRD mission will inform future space FSOC capabilities and advancements. LCRD will provide a minimum of two years of continuous high data rate demonstrations to explore further developments to meet the growing requirements for higher data rates from systems with lower power and mass requirements that continue to meet and exceed the information security standards.

### 3. Small Optical Link for International Space Station

Sony Computer Science Laboratory (Sony CSL), Japan Aerospace Exploration Agency (JAXA), the National Institute of Information and Communications Technology (NICT), and Kongsberg Satellite Services (KSAT) have been participating in a collaborative effort to develop, produce and test a small form factor FSOC system capable of establishing data links to and from the International Space Station (ISS). The laser communications terminal was launched on September 25, 2019 via the H-II Transfer Vehicle (HTV-8) (Iwamoto et al. 2021) and arrived at the ISS three days later. On March 11, 2020 the team successfully demonstrated data optical communication through 100Mbps with NICT's optical ground station located in Tokyo, Japan (Komatsu et al. 2020).

The LEO is ideal for small satellite experimentation because of lower launch costs, power requirements, and decreased latency. However, the shorter distance between the spacecraft and the earth means that the window of opportunity to connect the optical link is shorter. OGSs are limited to approximately 10 minutes of continuous communication per pass under clear weather conditions. This implies that optical payloads need to be able to communicate with multiple OGSs to avoid the risk of connection failures. In September 2021, a second test was pursued to establish a downlink from the ISS to a KSAT OGS in Nemea, Greece. The communication link for the second OGS was accomplished and proved that the SOLISS is capable of connecting with multiple ground stations at different locations on the globe (Yamazoe, Henniger, and Iwamoto 2022).

The SOLISS onboard terminal system leverages a technology developed by Sony Group in the 1970s. Optical disk drives control a micro-objective lens with an actuator to process information from the reflective light on the disk's surface. Optical disk systems must be capable of correcting errors that scratches or fingerprints may cause.

In this consideration, FSOC systems share some commonalities in technological requirements, as fine pointing and error correction are vital parameters for design. Figure 8 shows an overview of the SOLISS system Optical Communications Unit (OCU) and control system.

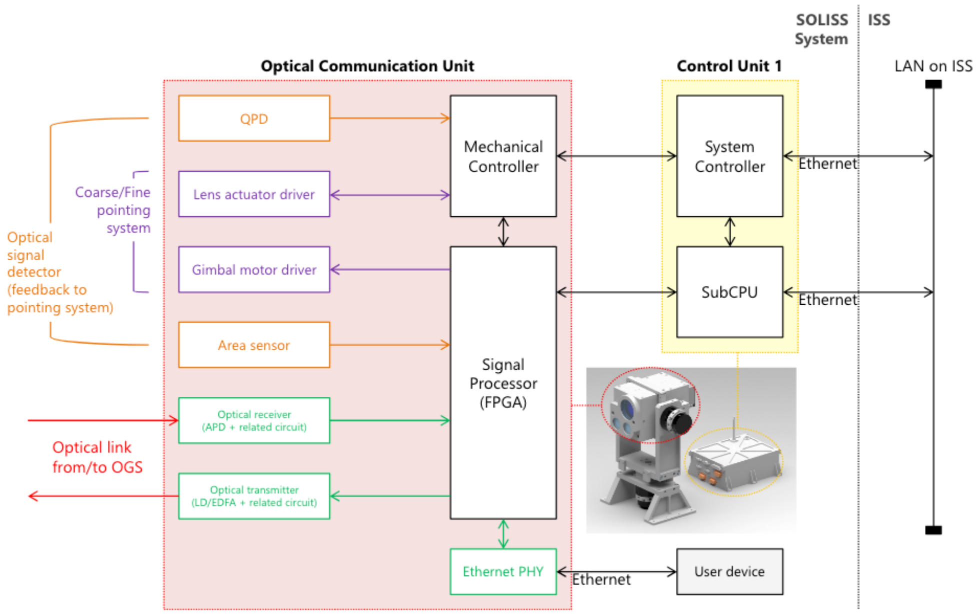


Figure 8. Overview of SOLISS OCU and onboard control system.
Source: Yamazoe, Henniger, and Iwamoto (2022).

The OCU consists of a Mechanical Controller and Field Programmable Gate Array (FPGA). The System Controller and SubCPU are used to send commands to the ISS to obtain telemetry data such as time, position, altitude, and velocity (Yamazoe, Henniger, and Iwamoto 2022). This information is used to synchronize time and predict the ISS orbit. The SubCPU organizes the data into a forward feed (FF) control table, which is passed on to the Signal Processor which controls the gimbal direction based on the telemetry provided in the FF table. The Mechanical Controller searches for the signal and moves the gimbal into position to align the center of the area sensor with the laser beam. The quadrant photodetector and area sensor are then used to control the gimbal and adjust the lens actuator so that the light can be returned in the opposite direction. The Signal Processor also converts the data received from the SubCPU into an electrical signal so that it can be sent to the ground station via a Laser Diode (LD) and Erbium- Doped Fiber Amplifier (EDFA) (Yamazoe, Henniger, and Iwamoto 2022).

The SOLISS OGS at the NICT campus in Koganei, Tokyo receives the laser link by an optical telescope with a diameter of 1.5m, precision of 1 arc per second, and a maximum angular rate of 9 degrees per second. Table 1 shows the link budget for both directions for the first ISS to OGS link. The communication distance was designed for a maximum of 1000km. SOLISS returned a positive margin at max distance (Iwamoto et al. 2021). However, it is important to note that the weather conditions were mostly clear during the 22-day experiment and cloud coverage returned less optimal results for successful data transport. Table 2 includes the daily log details.

Table 1. SOLISS link budget for Japan OGS experiment.
Source: Iwamoto et al. (2021).

| | SOLISS -> OGS | OGS -> SOLISS | |
|---|---|---|---|
| Tx Power | 24.0 | 40.0 | dBm |
| Tx Optical loss | -1.7 | -3.4 | dB |
| Tx antenna gain | 86.4 | 99.0 | dB |
| Pointing Loss | -1.0 | -1.0 | dB |
| Aberration loss | -0.1 | -0.5 | dB |
| EIRP | 107.6 | 134.2 | dB |
| Space loss (1000km) | -258.2 | -258.2 | dB |
| Atmospheric transmission | -9.4 | -9.4 | dB |
| | | | |
| OGS antenna gain | 129.7 | 94.4 | dB |
| Optical loss | -3.4 | -0.5 | dB |
| Receiving Power | -33.7 | -39.4 | dBm |
| Sensor required Power | -40.0 | -40.0 | dBm |
| | | | |
| System margin | 6.3 | 0.6 | dB |

Table 2. Daily weather conditions results. Source: Iwamoto et al. (2021).

| Operation # | date (UTC +9) | sky condition | OGS -> SOLISS | SOLISS -> OGS |
|---|---|---|---|---|
| 1 | 10/26/2019 | clear | OK | OK |
| 2 | 11/12/2019 | clear | OK | OK |
| 3 | 11/21/2019 | partially cloudy | OK | OK |
| 4 | 11/30/2019 | clear | OK | OK |
| 5 | 12/4/2019 | partially cloudy | OK | OK |
| 6 | 12/12/2019 | clear | OK | OK |
| 7 | 12/26/2019 | cloudy | - | - |
| 8 | 1/8/2020 | foggy | OK | - |
| 9 | 1/10/2020 | partially cloudy | OK | OK |
| 10 | 1/20/2020 | clear | - | - |
| 11 | 1/21/2020 | clear | OK | OK |
| 12 | 1/24/2020 | partially cloudy | OK | OK |
| 13 | 2/4/2020 | partially cloudy | OK | OK |
| 14 | 2/5/2020 | clear | OK | OK |
| 15 | 2/27/2020 | clear | OK | OK |
| 16 | 2/29/2020 | partially cloudy | OK | OK |
| 17 | 3/4/2020 | cloudy | - | - |
| 18 | 3/5/2020 | clear | OK | OK |
| 19 | 3/8/2020 | partially cloudy | OK | OK |
| 20 | 3/11/2020 | clear | OK | OK |
| 21 | 3/26/2020 | cloudy | OK | OK |
| 22 | 5/26/2020 | clear | - | - |

An overview of the SOLISS OGS operated by KSAT is shown in Figure 9. In this configuration, a Beacon assembly is mounted in parallel to the optical axis of the telescope. The receiving telescope's direction is driven by the Mount Controller and Gimbal based on the telemetry data received from the ISS (Yamazoe, Henniger, and Iwamoto 2022).

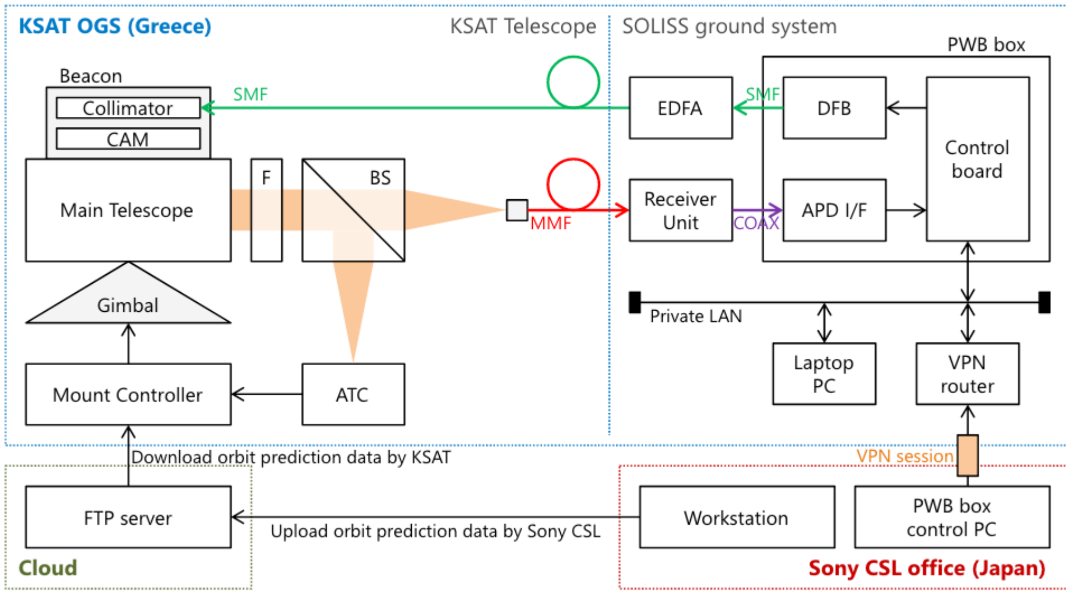


Figure 9. Overview of SOLISS OGS in Neama, Greece.
Source: Yamazoe, Henniger, and Iwamoto (2022).

Once the data signal passes through the telescope, it is passed through a light filter and continues into the beam splitter. The beam is split into two paths, one directed to the multimode fiber medium and the other to the acquisition and tracking camera (ATC). The ATC functions to ensure pointing accuracy feedback to the Mount Controller, while the receiver unit passes the data through an avalanche photodiode (APD) to convert the light into electricity before it proceeds to the control board. The control board delivers analytical data to the control box and relays distributed feedback over single mode fiber to be amplified and sent back to the Beacon Collimator to maintain tracking and pointing control (Yamazoe, Henniger, and Iwamoto 2022).

### 4. Click Mission

The Massachusetts Institute of Technology (MIT), NASA Ames Research Center, and the University of Florida are participating in a joint project to develop the CubeSat Infrared Crosslink Mission (CLICK) experiment, which was developed as an expansion to MIT's Nanosatellite Optical Downlink Experiment (NODE). The NODE project focused on the design and development of a Miniature Optical Communications Transmitter

(MOCT). The CLICK mission will demonstrate new technologies aimed toward low SWaP laser communication both to/from a portable ground station and between satellites. The project is broken down into two main objectives:

1. CLICK A: Establish an optical downlink with a data rate of ≥ 10Mbps from a small 3-unit satellite from an altitude of 400 kilometers.
2. CLICK B/C: Demonstrate sending and receiving optical communication crosslink between two small satellites in LEO. The goal is to establish the crosslink at distances between 25 and 580 kilometers apart at data rates ≥ 20 Mbps. (Hall 2019)

The CLICK-A mission integrates the MOCT pointing, acquisition, and tracking (PAT) system. The KSATLite ground station network was selected as the primary site to establish RF communication. Commands from the KSATLite ground station will exchange telemetry and mission data with the CubeSat and return output to the mission operations center (MOC) located at MIT's testing facility. The MOC will perform operational tests to confirm functionality of the payload subsystem and conduct passes with the ground station (Serra et al. 2021).

The optical downlink practice is administered through numerous stages. Before the beginning of each pass, the payload control sequence adjusts and points the spacecraft mounted aperture toward the OGS. (Serra et al. 2021). Parameters of this laser and the payload transmitter are 1150 nm wavelength, 200mW of power, with a beam divergence of 1.3 mrad full width at half maximum intensity (FWHM). Meanwhile, the ground station operates in coarse stage tracking in an open-loop (CSTOL) setting. Ephemeris data created by the onboard GPS receiver provides more accurate tracking of the spacecraft (Serra et al. 2021). A high level overview of the CLICK-A mission concept of operations is shown in Figure 10.

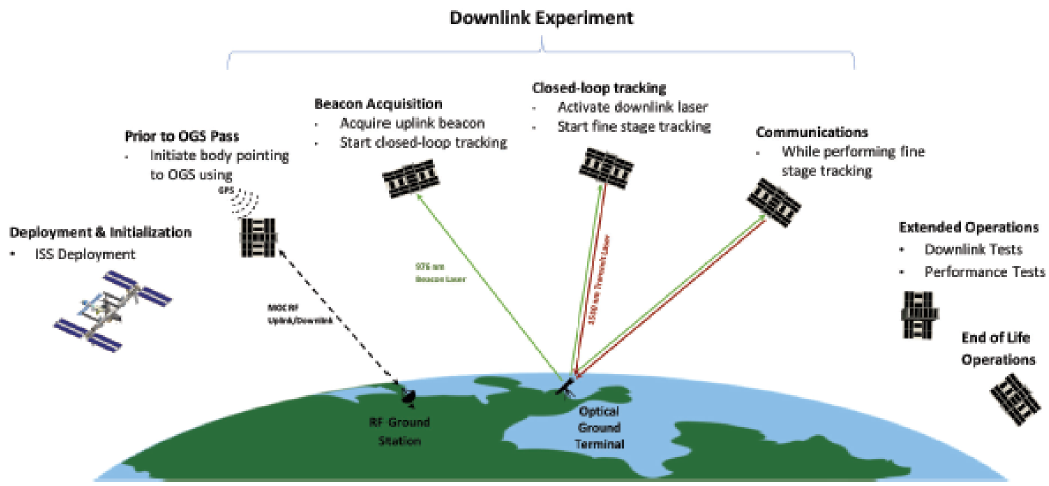


Figure 10. CLICK-A mission concept of operations.
Source: Serra et al. (2021).

The CLICK-A optimal encasement of the payload is approximately 96mm x 96mm x 138mm, and weighs of around 1.17 kilograms. The top section of the payload holds the PAT system, while the remaining housing space is occupied by optoelectronics. A camera for beacon tracking, a Matrix Vision mvBlueFOX, a Schneider Xenoplan lens, and a fine steering mirror (FSM) are included as part of the optical bench and used to conduct beam steering. The broadcast laser at 1550nm and the calibration laser at 980nm are coupled via wavelength division multiplexing (WDM) (Serra et al. 2021). The laser beams are correlated and directed toward the steering mirror. The steering mirror carries out fine directing by guiding the beam of light to the dichroic light beam splitter (DBS). The transfer laser is returned in the new path direction then continues the path by means of the spacecraft aperture and the calibration laser is guided utilizing the lens setup and the camera's focal selection (Serra et al. 2021).

The Raspberry Pi-based CPU board is the primary control unit of the payload. It provides interfaces with the CubeSat platform to deliver commands and provide data management. A separate microcontroller is used to make it possible for the Raspberry Pi to be reprogrammable in orbit. The program for the pointing sequence and sends commands to the beacon camera for the feedback driven adjustment (Serra et al. 2021). A

FPGA controls and manages the transmitter laser, similar to the SOLISS architecture. The Xilinx Spartan 6 FPGA is situated on an isolated board configured for sensing and communicating with the daughterboard. The primary function of the daughterboard is to provide a user interface for the indicators from the FPGA to a variety of additional elements. The daughterboard sub-system contains the fast-steering mirror, photodiodes, resistance temperature detectors. transmitter seed laser and calibration laser (Serra et al. 2021).

A master oscillator power amplifier (MOPA) design is used for the seed laser, while the EDFA performs the optical amplification. Control commands from the FPGA, along with the thermoelectric cooler, are applied to the transmitter optical sub-assembly to induce an indication of a particular wavelength which is thus guided by means of optical fiber. Wavelengths inside the passband are mirrored back into the circulator then pointed to the EDFA. The EDFA provides amplification to the signal and guides it to a collimator for alignment (Serra et al. 2021).

Photodiodes are utilized to determine the power at numerous positions to enable a closed loop and regulate the transmitter (Serra et al. 2021). A PIN photodiode is semiconductor with an intrinsic layer between the N and P regions. The PIN structure produced a fast response and high frequency for photon detection (D. R. Paschotta 2022). The FPGA uses projection and the laser diode temperature data to adjust the transmitter wavelength and confirm the output signal (Serra et al. 2021). Figure 11 shows the CLICK-A payload system architecture components.

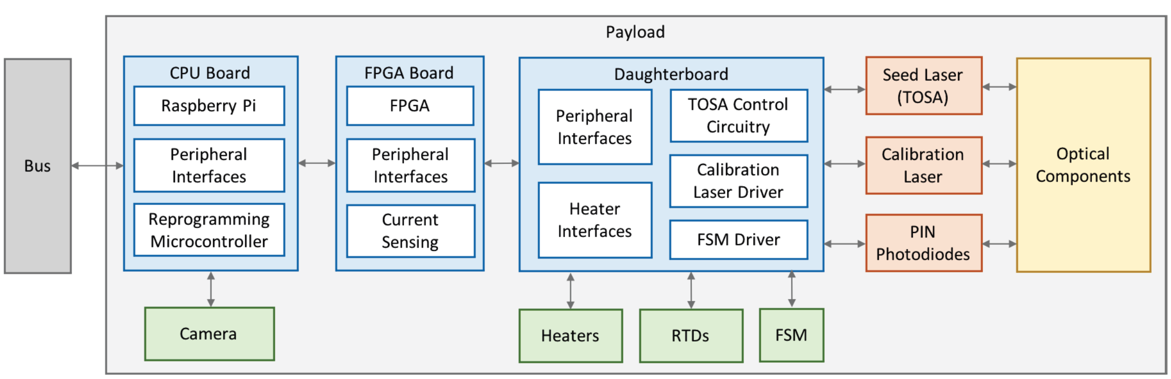


Figure 11. CLICK-A payload system architecture. Source: Serra et al. (2021).

# IV. DESIGN AND SYSTEMS ENGINEERING ARCHITECTURE DEVELOPMENT

## A. MOBILE CUBESAT COMMAND AND CONTROL

### 1. MC3 Program and Network

The MC3 program is a Unites States DOD-led research and development effort to consolidate the interests of several institutions and organizations seeking to achieve common goals related to small satellite integrations. The program began by designing an architecture for transmitting and receiving to CubeSats using UHF frequencies and standard small satellite protocols for Low Earth Orbit (LEO) in 2012. The utilization of commercial-off-the-shelf components allowed for engineering flexibility, cost savings, and general design enhancements to build among research participants. By 2022 the program has evolved to include nine active ground stations across the U.S. and expanded to include S-band and X-band channels. The addition of Satellite Agile Transmit and Receive Network (SATRN) software, developed by the Space Dynamics Laboratory (SDL), enhanced the ground station network capability by implementing an adjustable platform specific to small satellite missions and operations. More recently, the MC3 team has been progressing to incorporate larger scale capabilities by integrating components that expand to X-band frequencies which allow for higher data rates to the existing ground station systems.

The MC3 network consists of multiple ground stations located across the United States:

- Naval Information Warfare Center Pacific - Pearl City, Hawaii
- Naval Postgraduate School - Monterey, California
- Space Dynamics Laboratory - Logan, Utah
- University of New Mexico - Albuquerque, New Mexico
- Air Force Institute of Technology - Dayton, Ohio

- United States Coast Guard Academy - New London, Connecticut
- University of Alaska Fairbanks - Fairbanks, Alaska
- Malabar Transmitter Annex - Melbourne, Florida
- Army Space and Missile Defense Command – Redstone Arsenal, Alabama

The following new locations are currently under development:

- United States Naval Academy - Annapolis, Maryland
- NASA Johnson Space Center - Houston, Texas

SATRN provides users with the ability to connect by virtual private network (VPN) allowing the flexibility of remotely managed services and missions. The software can be hosted on Amazon Web Services and GovCloud and the VPN connectivity integrates operations in the cloud for scaling, resiliency, and improved cybersecurity. Not all MC3 ground stations have the same equipment.

#### *a. Antenna Systems and RF Link Control*

At the NPS MC3 ground station, there are two antennas. Initially the ground station was designed to communicate via UHF only. A Yagi antenna was included in the original architecture design to meet that criterion. As the system progressed, a 3-meter S-band dish was incorporated for further experimentation and development. Both antennas were strategically installed on the roof of Spanagel Hall to minimize signal obstruction and ensure the most direct path for connection to the MC3 Small Satellite Lab and MC3 control room. Figure 12 shows the antenna location and setup at NPS in Monterey, CA.

Figure 12. UHF Yagi and S-Band 3m dish dome. Source: NPS (2022).

#### *b. Downlink*

Once the RF signal is received through the antenna feed, it passes through the diplexer to the receiver path that is dependent on the orthogonal polarization, right hand (RHCP) and left-hand circular polarization (LHCP) of the wave. To compensate for power loss that occurs during the downlink, the signal passes through a bandpass filter (BPF) that allows only the signals from the desired frequency range. A low noise amplifier (LNA) then amplifies the signal to a level sufficient for detection by the radio hardware. The signal is then routed to a transfer relay switch. Relay switches are used to select the RF signal path corresponding to the desired polarization. The signal is then filtered and amplified again before being routed to a four-way splitter. The splitter allows multiple devices to simultaneously receive and monitor the signal. Multiple radios and spectrum analyzers are typically used with these splitters. One of the outputs from the four-way splitter feeds into the USRP-2922 SDR tunable transceiver. Figure 13 shows the RF ground station configuration and data flow.

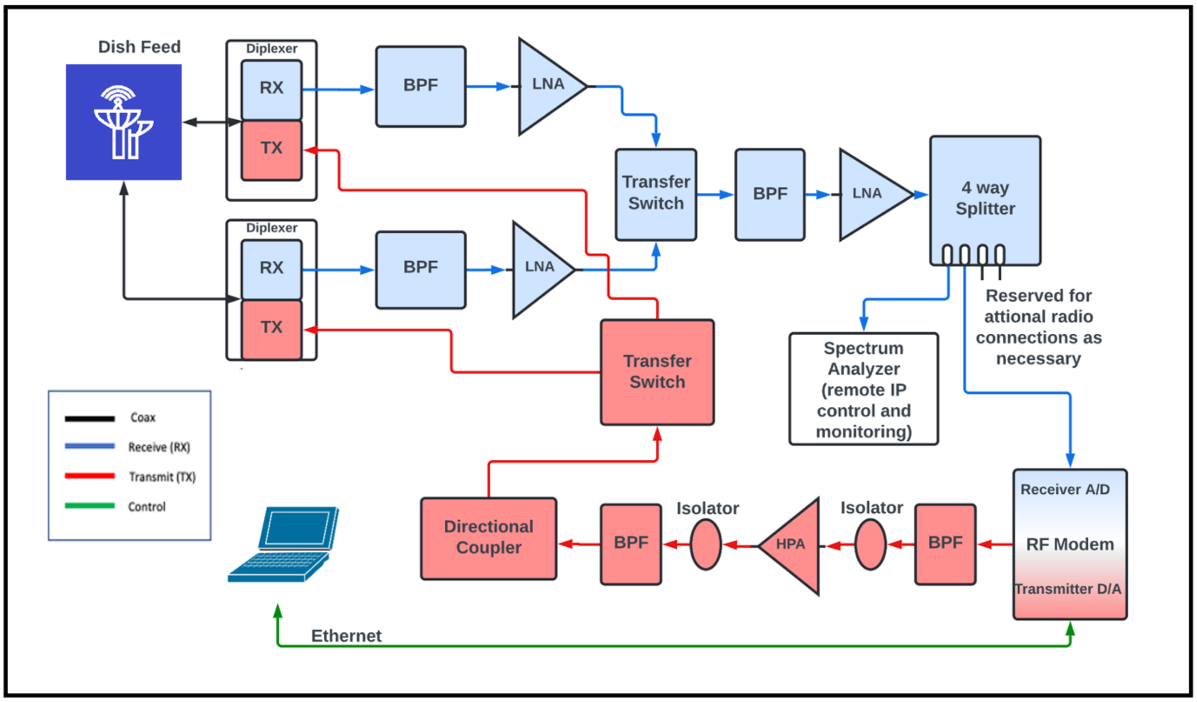


Figure 13. NPS RF ground station configuration diagram

#### c. *Software-defined Radio (SDR)*

MC3 ground stations use a commercial software defined radio (SDR) solution called Universal Software Radio Peripheral (USRP) 2922, produced by National Instruments. The USRP 2922 transceiver has an open-source programming interface and is cost efficient with a wide frequency range. The unit features a small form factor, real time processing, and is easy to install and configure, making it highly deployable. The FPGA on the internal card provides signal filtering and bidirectional rate conversion between digital and analog.(Welch and Shearman 2012) SDRs allow for increased flexibility in the research and development environment because they are reprogrammable and require less hardware than traditional radios. A MC3 laptop controls the required bandwidths for testing by sending control commands to the RF transceiver (SDR).

### *d. Uplink*

The RF modem converts the transmit signal from digital to analog and sends it to a BPA and isolator pair to a High-Powered Amplifier (HPA). The HPA boosts the transmission power so that it can be consolidated at the directional coupler and sent through the diplexer, out of the antennas and toward the direction of the target satellite. The transfer switch determines the path and the polarization of the uplink signal.

### *e. SATRN*

Automation is a vital component of the MC3 development and allows ground stations to be controlled in real-time and remotely. One of the significant developments in this effort is the software component called Satellite Agile Transmit and Receive Network (SATRN). SATRN is a customizable platform to increase accessibility and verify the interoperability of radio networks. Further expansion came with the introduction of S-band and X-band communication to increase throughput. The MC3 network has a great foundation in academic research and there are many factors to be explored. Expanding the capabilities to include optical communications is the logical next step for the MC3 network.

Since SATRN is specifically designed for small satellites, it is a well-suited match for integration with experimental studies related to laser communication systems on CubeSats. SATRN is flexible and easily integrated with customized command and control configurations via TCP/IP, which has been demonstrated but has not been tested for optical links. The software provides a centralized server-based environment that allows for simulation and management of missions via packaged web-based interfaces that control ground sites, hardware devices, and an end-user client control system. The client control GUI provides an organized platform for setting up system parameters and configurations based on the specific components of a particular design. The Application Programming Interface (API) is customized to preset the specific set of commands required for the desired outcomes (Ground System Architectures Workshop 2021).

The SATRN system drives the peripherals of the ground station control and communications system. In the RF configurations, the software is designed to point a satellite dish to a pre-computed position of a satellite and configures the SDRs to modulate and demodulate signals to and from the target satellite. Likewise, this software can be modified to point a telescope and configure an optical modem to provide communications from a satellite to the ground station via an optical link. Currently, this is an open loop tracking process for RF links. In the case of laser communication, the limited field of view requires a more precise tracking system. Accurate position tracking for the satellite requires some method of location feedback which can be accomplished by introducing algorithms that are able to adjust the pointing position based on adaptive optics or beacon sensor input in addition to the predicted position calculation produced from the known predictable parameters such and time and spacecraft azimuth/elevation.

A receive optical path must maintain a sufficient field of view (FOV) for accurate pointing of the system, and wavefront quality must be optimized for sufficient link power levels. A point ahead angle can also account for some error correction. For LEO systems ≤12 μrad is typical but may be slightly increased depending on the distance and speed of the target. Requirements for alignment tolerances on a specific design may calculated by observing the wavefront error and incorporating into the closed-loop calculation for making adjustments to the desired alignment. The following three categories are used to describe misalignment types:

1. axial misalignment (defocus)
2. lateral misalignment
3. tilt misalignment

> In defocus, the optical axes of primary and secondary mirrors remain aligned, while the mirror separation changes. In the lateral misalignment, optical axes are no longer overlapped, while the mirror separation remains fixed. The latter will take the form of a tilt or a decenter of the secondary mirror axis relative to the primary mirror axis.(Hemmati 2021).

The receiver sensitivity parameter identifies the optical receive power required to achieve the desired output performance, which can be measured by observing Bit Error Rate (BER) and the laser beam divergence angle (Hemmati 2021). The BER defines the number of errors received over the total number of bits transmitted. For optimal optical receiver performance, the BER should range from $10^{-9}$ to $10^{-12}$. If the receiver sensitivity is high, a signal with a smaller beam diameter can be received. For example, APDs are more sensitive than PIN photodiodes. Opting for an APD in the design could result in higher data rate performance. The quantum limit is the minimum optical energy required to maintain a desired BER for the receiver application (Engineering Funda 2019).

Temperature variations can result in "local strains in the mirror material proportional to $\alpha \Delta T$, where $\alpha$ is the linear coefficient of thermal expansion. A temperature change across the entire optical assembly can cause the mirror focal length (f) which can be adjusted by $\Delta f = f \times \alpha \times \Delta T$" (Hemmati 2021). Based on the specific architecture, alignment and error gauging calculations can be used to develop built-in algorithms for customizing the SATRN environment to achieve the pointing control necessary for the OGS. Figure 14 shows an overview of the SATRN bent-pipe communications interfaces.

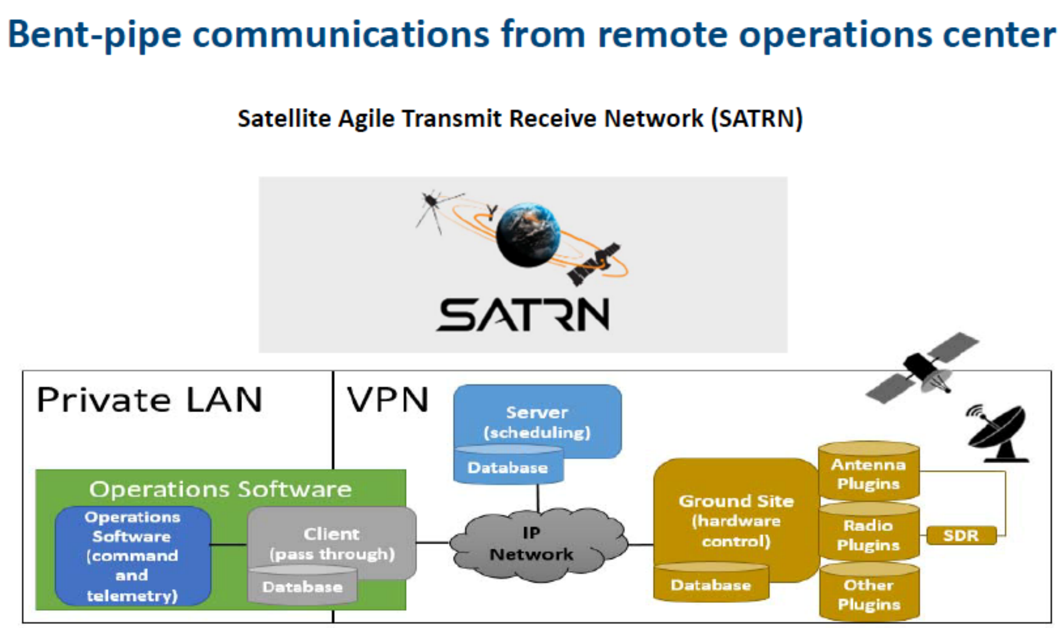


Figure 14. SATRN server overview. Source: Minelli et al. (n.d.).

There are many advantages to optical communications; however, free space communication via a laser beam poses specific challenges, the most apparent being the ability to navigate atmospheric turbulence that causes disruption in the link. Free-space optical communications use photons to transmit encoded digital data. On the downlink, a telescope is used to collect photons and focus them into a detector. The detector converts light into electrical signals which are used to retrieve information embedded in the laser beam. A dedicated tracking and pointing system with sensors are also required for ensuring the link can be properly aimed to the target terminal. Some of the experimental ground stations in testing use mirrors and control software to supplement uncertainty due to the smaller receiving area and atmospheric interference.

Atmospheric turbulence causes the signal to suffer from beam wandering, scattering, and defocus and may prevent the beam from being properly focused on the detector. Mitigating these effects is a critical aspect of the design of an optical ground station architecture. One method that is proving effective in other optical ground station configurations is the use of adaptive optics to measure photon distortion and program corrections with the aid of deformable mirrors. Demultiplexing and recombining the signal allows for a much more deployable optical ground station system. This concept is further explained in the next section of this chapter.

## B. A SYSTEMS ENGINEERING APPROACH FOR GROUND STATION DESIGN

The systems engineering process is considered in the development of the OGS capability interface architecture for integration with the MC3 program. Figure 15 shows the systems engineering process and connecting elements for system design and product development.

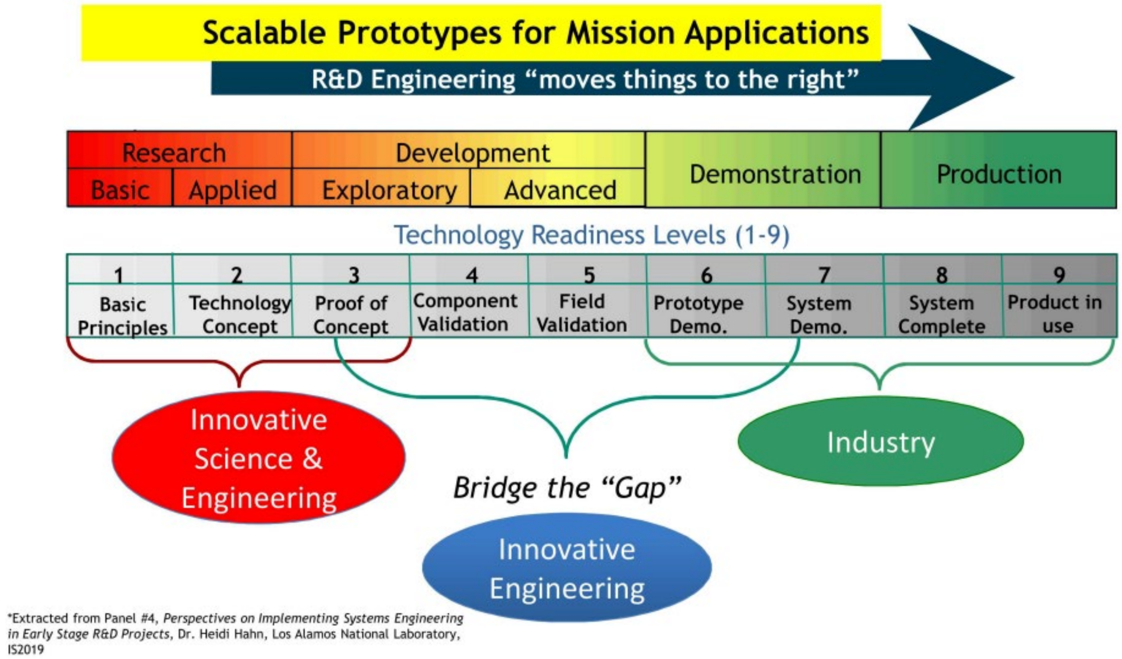


Figure 15. System engineering design process for R&D.
Source: Hodges (2019).

### 1. Requirements

Evaluating the basic principles and developing a concept are the first steps in the technology readiness process. From a systems engineering perspective, establishing requirements contributes to an important aspect of defining what sort of principles need to be obtained. This thesis focuses on research for the ground segment subsystem for optical downlink communications feasibility for the MC3 program at NPS. The basic principles and technology concept level of requirements are captured as the following:

- Identify basic characteristics of the RF ground station system
- Identify desired characteristics of the OGS system concept
- Identify technology readiness level constraints for each subsystem component
- Develop baseline assumptions for the technology concepts

- Identify constraints and design drivers

### 2. Technology Readiness Level

Technology Readiness Level (TRL) is a system used by the DOD and NASA to determine the specific developmental phase of a technology. The TRL scale is defined by numerical values in succession from 1 to 9 which quantify the maturity of the technology as it relates to the TRL scale as it relates to the early stages of the systems engineering process. Table 3 provides the descriptive detail of progression that would be practical for the R&D evolution for the proposed system (Tzinis 2021).

Table 3. Technology readiness level for MC3 optical ground station integration. Adapted from Tzinis (2021).

| Level | Description | Acquisition Phase |
|---|---|---|
| 1 | Basic principles reported | Concept |
| 2 | Technology concept and application framed and documented | Concept |
| 3 | Experimental or analytical proof of concept | Concept |
| 4 | Benchtop validation of components and interconnectivity in MC3 laboratory environment | Proof of concept |
| 5 | Component validation in relevant environment. | Proof of concept |
| 6 | System and subsystem prototype demonstration. Point-to-Point communication over an established distance on Earth | Prototype Evaluation |
| 7 | System prototype demonstration in a space environment | Technology Transfer |
| 8 | Actual system completed test space to ground downlink demonstration | Demonstration Evaluation |
| 9 | Successful mission operations | Mission qualified |

## C. OPTICAL GROUND STATION ARCHITECTURE

Though still limited in number, a typical OGS consists of a telescope, controllable mount or gimbal, acquisition sensor, fine tracking system, beacon, and receiver.

### 1. Atmospheric Effects and OGS Location

To optimize the likelihood of successful downlink, the OGS site location is an important factor to consider. A location at a higher altitude with low humidity and low presence of cloud coverage is most ideal. Figure 16 shows a map of the United States annual cloud coverage and markers for MC3 ground station locations. Based on this overlay, the Albuquerque and Monterey sites would be the primary locations to begin testing integration. In research, Albuquerque shows the least amount of cloud coverage and higher elevation geographically and therefore is the ideal location for experimentation. However, the Monterey location provides more accessible resources, for example a developmental test bench and being the home of the MC3 technology development. These conveniences and cost considerations may outweigh the environmental benefits of opting for the New Mexico location.

It is also relevant to consider visibility of CubeSats from the elevation angle available from the site location. For Geostationary orbit, a closer distance to the equator will minimize the zenith angle and reduce the amount of atmosphere the laser beam needs to travel through (Hemmati 2021). The lower on the horizon the satellite appears when viewed from the ground station, the more atmosphere the optical link must cross through, increasing the disturbances due to atmospheric effects. Location of the receiving system affects the number of passes observable within a given window of time as well as the amount of time per pass the CubeSat will be detectable given the specific limitations of the telescope. A satellite in LEO increases the window of communication opportunity and decreases the chances of atmospheric interference and therefore is preferred for OGS experimentation.

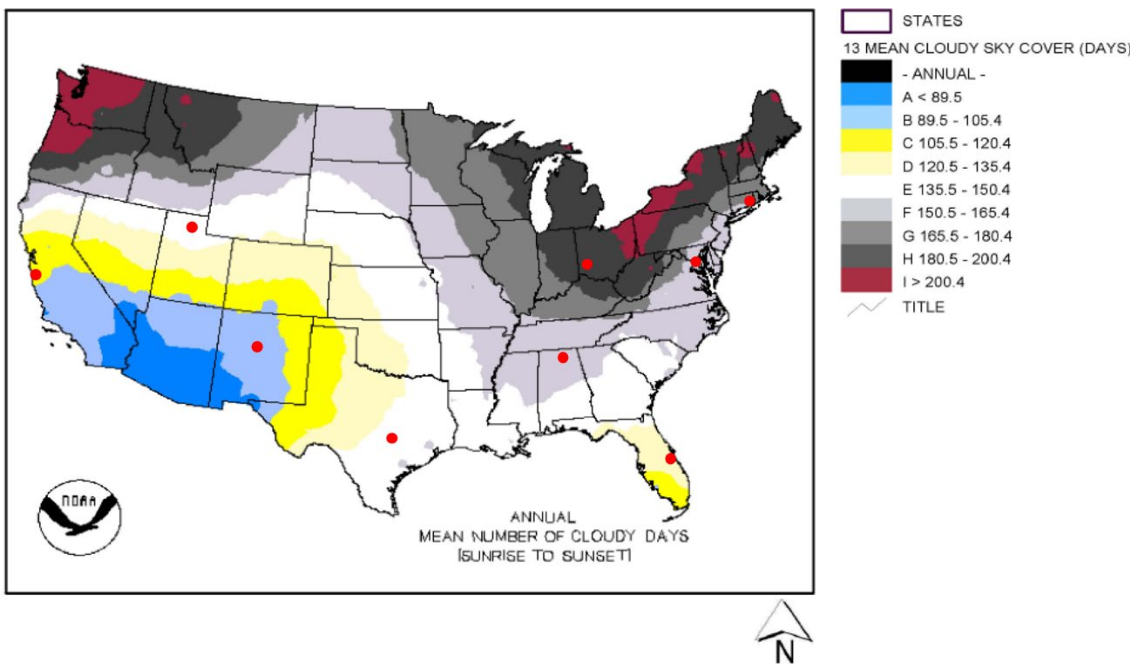


Figure 16. Map of U.S. annual cloud coverage and MC3 ground stations. Adapted from El Dorado Weather (2022).

Laser beam propagation through atmospheric turbulence causes fluctuation of the signal irradiance, known as scintillation. The scintillation index $\sigma_I^2$ is used to identify the normalized variance of the intensity fluctuations. Equation 5 is the mathematical representation of the scintillation index where I is the signal irradiance.

$$\sigma_I^2 = \frac{< I^2 >}{< I >^2} - 1 \tag{5}$$

A high scintillation index results in an increased probability of inconsistency in the received power (Alam et al. 2022).

### 2. Telescope

Of the most notable requirements for an OGS terminal is the need for a method of receiving the light source transmitted from the satellite. A telescope is a feasible replacement for capturing laser beam signals in place of radio antennas. The principal objective is to collect as many photons as possible while maintaining good image resolution. The Meade LX600 telescope is an optical system with a mirror mount and focusing system. A similar but slightly older model (LX200GPS) has undergone proof of concept testing at NPS for experimental tracking of the ISS (Anderson 2019).

Aperture is one of the key elements of the telescope for the successful detection of a satellite. The amount of light that can reach the focal plane is limited by the aperture size. Assessment of performance can be conducted by considering the diameter of the light reflecting surface. A larger aperture diameter allows the telescope to receive more light resulting in higher quality image detection when tracking objects in space.

The LX600 is a computerized telescope that has an aperture of 356 mm, a focal length of 2845mm and a focal ratio of f/8. The unit includes a computerized mount system, StarLock automatic guider and AutoStar II systems which allow for precision tracking. Meade's Advanced Coma-Free (ACF) optical system is designed so that light passes through a two-sided lens for aspheric correction. The light then passes to a spherical mirror and then to a second hyperbolic mirror. The hyperbolic mirror multiplies the focal length of the spherical mirror which results in a focus at the focal plane (Meade Instruments 2019). Figure 17 shows a schematic of the LX600 telescope's internal optical system.

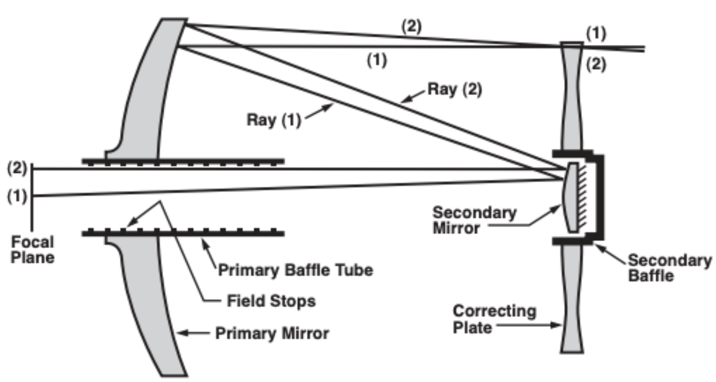


Figure 17. LX600 telescope. Source: Meade Instruments (2019).

### 3. Camera

NPS graduate Laura G. Anderson performed an experimental assessment with test equipment at the NPS ground station in Monterey, CA. Based on her findings, she provided a comparison of commercial-off-the-shelf (COTS) astronomy cameras that would appropriately match the LX600 focal length and optical tube. The comparison considered FOV, detector chip size, and pixel size. Of the six cameras in the lineup, the Starlight Express TRIUS PRO 35 was specified as a recommendation for future exploration due to its large chip, appropriate pixel size, and affordability. This thesis builds on the proof of concept and recommendations provided in her Master's thesis, "Satellite Tracking with Telescope and Software" (Anderson 2019).

The TRIUS Pro 35 is a charge-couple camera, meaning it is a solid-state electrical device and is capable of converting light into an electrical signal. It features a large format high-resolution Kodak KA11002 CCD sensor ensuring a pixel array of 4032 x 2688, 9$\mu$m pixel size and a USB hub for downloading full resolution images to a computer and connecting to other peripherals or accessories, such as a filter wheel or guide camera.

### 4. Precision Pointing and Tracking

Satellites in LEO have a circular orbit at a height range of 250–2000km from Earth. The orbital period is dependent on altitude and ranges from 90 to 120 minutes (ScienceDirect 2018). CubeSats become more difficult to detect when the distance between the terminals is larger. Establishing optical link communication relies heavily on the ability to reduce initial pointing errors. Figure 18 shows a breakdown of error contribution factors that result in the increase of pointing errors.

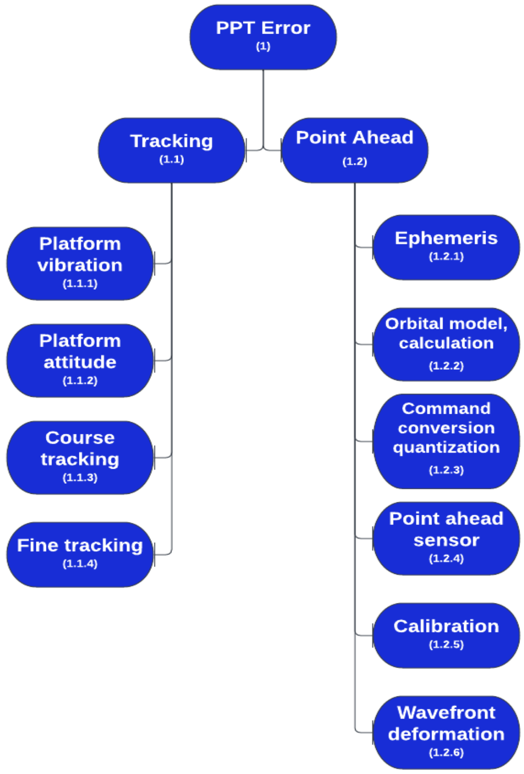


Figure 18. Pointing error structure

From Near Earth Laser Communications, "The problem of lasercom beam pointing can in general be decomposed into (1) optical line-of sight stabilization and (2) providing the appropriate pointing reference to the receiver location" (Hemmati 2021). For these reasons it is recommended to include a high bandwidth control loop with a sensor to correct platform stability and a beacon from the OGS location, through the atmospheric channel, to the satellite terminal to communicate and coordinate relative positioning. Position information is provided via Global Positioning System (GPS) exchange for each terminal. The relative velocity input is used to calculate the orbital trajectory based on ephemeris data. The point ahead angle is 2 times the velocity divided by the speed of light or $2v/c$ (Hemmati 2021). A wide FOV sensor that covers all possible angles uses the information received from the beacon light, calculate the angles of opportunity, and performs a scan.

During previous experimentation at NPS, it was concluded that the computerized mounting system that is included with the LX600 telescope kit is not ideal for tracking and not compatible with MC3's custom control software. A potential hardware alternative is the Paramount Taurus 400 manufactured by Software Bisque (Anderson 2019). Figure 19 shows the LX600 telescope with key features as described by the manufacturer.


Figure 19. Paramount Taurus robotic telescope mount. Source: Bisque (2020).

### 5. Adaptive Optics

An adaptive optics (AO) system is included in the proposed architecture to correct wavefront distortion for downlink beams being captured by the system. An AO system reduces the angular area being observed by the communications detector. As a result, a larger amount of the power received will be directed into the detector, therefore improving the performance of the system. In addition, filtering the undesired light results in an improved signal to noise ratio. Figure 20 is a schematic of a typical adaptive optics configuration. A deformable mirror is used to correct distortion of the incoming wavefront and direct it to the beam splitter. A fraction of the corrected signal is then directed to the wavefront sensor while the remaining signal proceeds to into the CCD camera lens to produce a high-resolution image. The wavefront sensor measures aberrations in the optical wavefront and feeds that data to the control system to adjust the wavefront corrector which unlimitedly improves the quality of the optical signal that is being captured by the CCD.

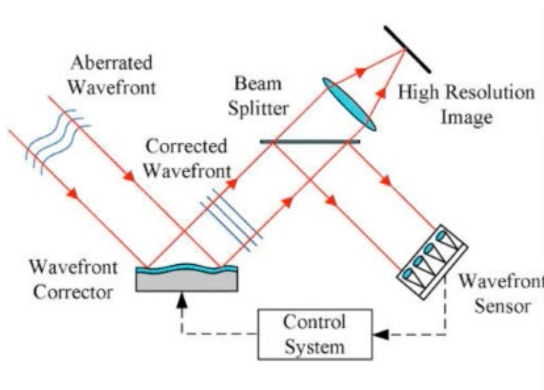


Figure 20. Standard adaptive optics. Source: Allioux (2020).

A Shack-Hartmann wave front sensor is a hardware component commonly used to measure attenuated laser beam light in an optical telescope. The sensor works by using an array of small lenses called lenslets to direct the light to a focused spot. The geometry of the displacement of the focused sport and the focal length of the lenslet are used to calculate the appropriate shape to compensate the wavefront using control software. The sensor can collect information about both the beam intensity and the wavefront. Figure 21 shows a diagram of the Shack-Hartmann sensor.

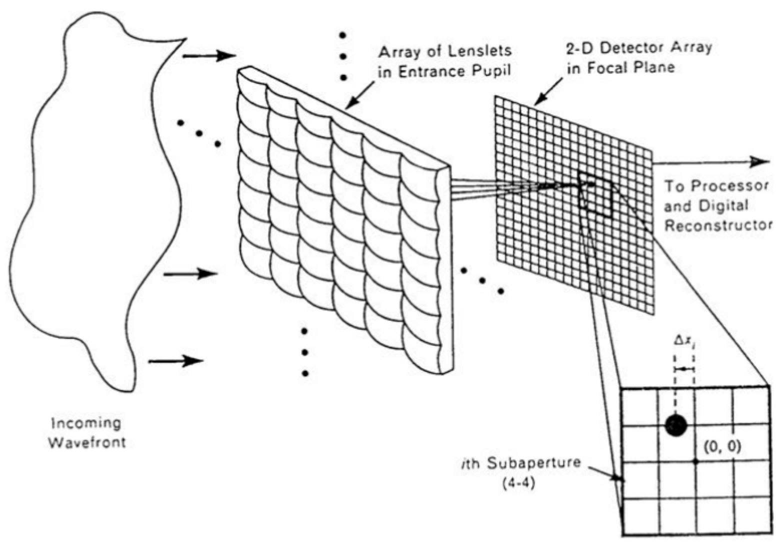


Figure 21. Shack-Hartmann wave front sensor. Source: Puent (2017).

Based on the application, the number of actuators in a mirror array are available for an AO configuration. For compensation of distortion for a long-range, high-speed data link, more advanced deformable mirror systems are recommended but are more expensive. Thorlabs both stock and custom AO kits. One kit that could be considered for experimental consideration is the AOK5 AO kit with MEMS Deformable Mirror and 880 Hz Wavefront Sensor shown in Figure 22. This kit includes a Boston Micromachines MEMS Multi DM deformable mirror and 140 actuators in a 12 x 12 array. A configuration consisting of similar specifications is described in Adaptive Optics and ESA's Optical Ground Station publication (Sodnik et al. 2009).

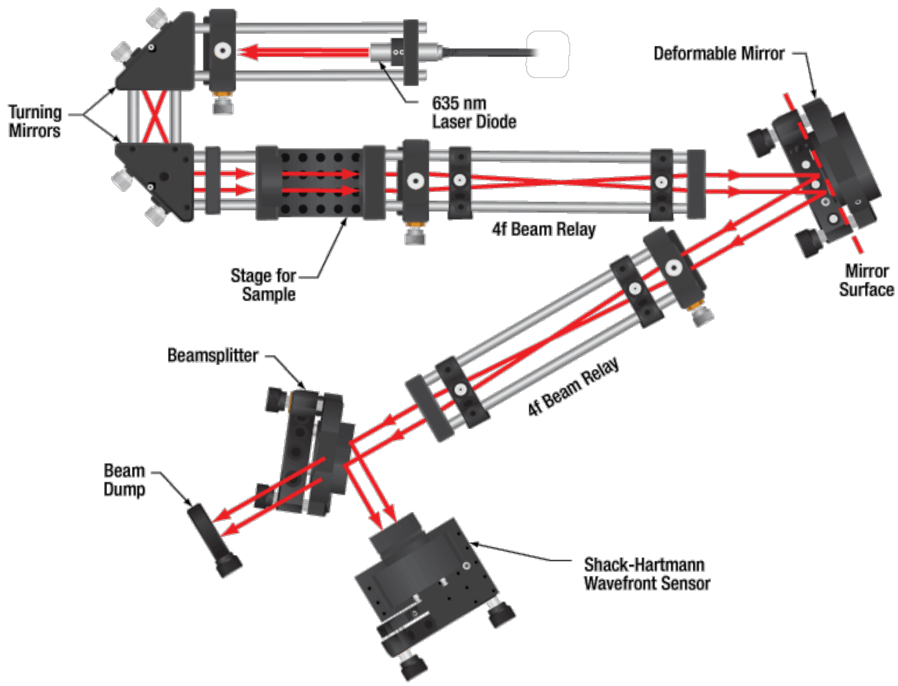


Figure 22. AOK5 AO kit configuration. Source: THORLABS (2022).

### 6. WORK Microwave Optical Ground Station

WORK Microwave is a developer and manufacturer for satellite communications technologies and products. In 2021, the AR-80 OPT Optical Multi-Mission Receiver and FSOD1 Free Space Optical Detector were released. The systems follow the CCSDS 142.0-B-1 standard and support receiving and processing of optical signals from space to Earth up to 3 Gbps.

The AR-80, shown in Figure 23, is a powerful demodulator which supports a wide range of frame formats and data types. It provides the ability to monitor and control signal reception for LEO downlinks. It has a built in FPGA and software base architecture (WORK Microwave 2022a). The FPGA allows for flexible implementation for integration with MC3.

Figure 23. A Series AR-80 satellite demodulator.
Source: WORK Microwave (2021).

The FSOD1, shown in Figure 24, is a fiber coupled optical detector that includes a highly receptive APD. The amplified limited output provides efficient keying signal performance. Network access can be obtained by standard SNMP and HTTP making it a convenient option for the MC3 remote management environment (WORK Microwave 2021).

Figure 24. FSOD1 Free Space Optical Detector.
Source: WORK Microwave (2022).

The company is continuing to develop new and improved technology and is currently working on the development of the DOG-1 multi-mission optical modem. The DOG-1 will be the first unit in a complete line of products for optical link systems for satcom applications. From the WORK Microwave data sheet, the new unit provides, “both native network operation as well as data streaming over IP. Built-in protocol stacks support an increasing number of space data formats as well as streaming of transparent baseband data and synchronized symbols for user-defined processing and integration into virtualized infrastructures" (WORK Microwave 2022c). The release date for the DOG-1 has not yet been recognized, it has potential to be a useful COTS component for the MC3 optical downlink integration efforts.

From the Work Microwave website a list of key features for the DOG-1 are provided (WORK Microwave 2022b).

- Multi-mission support
- Hard-decision and soft-decision decoding
- Optical On-Off Keying (O3K)
- High-Photon-Efficiency (HPE) future upgradable extension
- CCSDS 141.0-B-x support
- CCSDS 142.0-B-x support
- O3K symbol rate up to 10 Gsps
- Internal storage for at least 2 LEO passes at maximum bandwidth
- Customizable processing infrastructure for easy integration into large communication systems
- Flexible software architecture for easy extension and future virtualization of functionality
- 3-year warranty

### 7. Optical Digital Converter

Celestia Satellite Test and Simulation BV (C-STS), shown in Figure 25, is a company in The Netherlands which is dedicated to developing ground-based communications solutions for satellite simulations, testing, communications, and data processing. Their Optical Digital Converter is specifically designed for handling the output of FSOC modules and can receive data rates up to 10 Gbps. It is ideal for an experimental FSOC ground station as it provides electrical data extraction, protocol handling, and status annotation. It also supports both copper and fiber connections, making it flexible for interfacing with test bed components. Furthermore, the unit can be customized for forward corrections decoding, protocol handling, and deciphering tailored to the specific needs of a program or research project.


Figure 25. C-STS optical digital converter. Source: Celestia STS (2022).

### 8. Optical Ground Station Concept

Figure 26 shows the basic components and data flow concepts for an optical ground station configuration. The optical signal enters the telescope and is passed through an adaptive optics (AO) system. The data signal is split by the beam splitter (BS) and a portion of the signal is fed into the CCD camera for data relay to the control system. The rest of the signal is sent to the demodulator and optical to fiber interface which converts the signal into digital data and sends it out via fiber interface. An avalanche photodiode (APD) converts the light into electrical current to be sent through the control system loop and adjust the telescope mount.

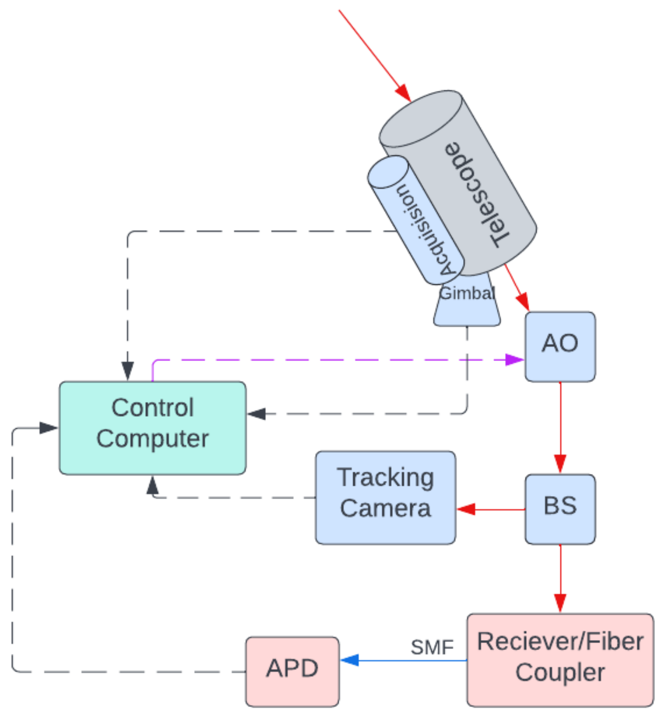


Figure 26. OGS concept diagram

## 9. MC3 Optical Ground Station Integration

Optimizing the potential of CubeSats requires a robust ground system architecture to support their various uses. The MC3 ground station architecture was specifically designed to utilize both commercial- off-the-shelf (COTS) materials and customizable software to expand the utilization of CubeSats. The MC3 network is designed to support the benefits and the cost-effective capabilities, which can be explored with small satellite architectures.

Laser communication is particularly well suited for CubeSat experimentation due to the large number of small satellites being deployed. RF communications require a license to operate on the RF spectrum. The accessibility that has been introduced by the development of CubeSats has caused an increase in demand for channel space, and the Federal Communication Commission (FCC) has started to place new restrictions and regulations for small satellite programs. However, at this time, the laser communication spectrum does not require licensed band space allocation because the narrower beam presents a low risk of interference (Riesing, Yoon, and Cahoy 2017). Figure 27 shows a block diagram of the sub-system interface components that would contribute to the expansion of the current NPS RF ground station to include experimentation for optical communications downlink:

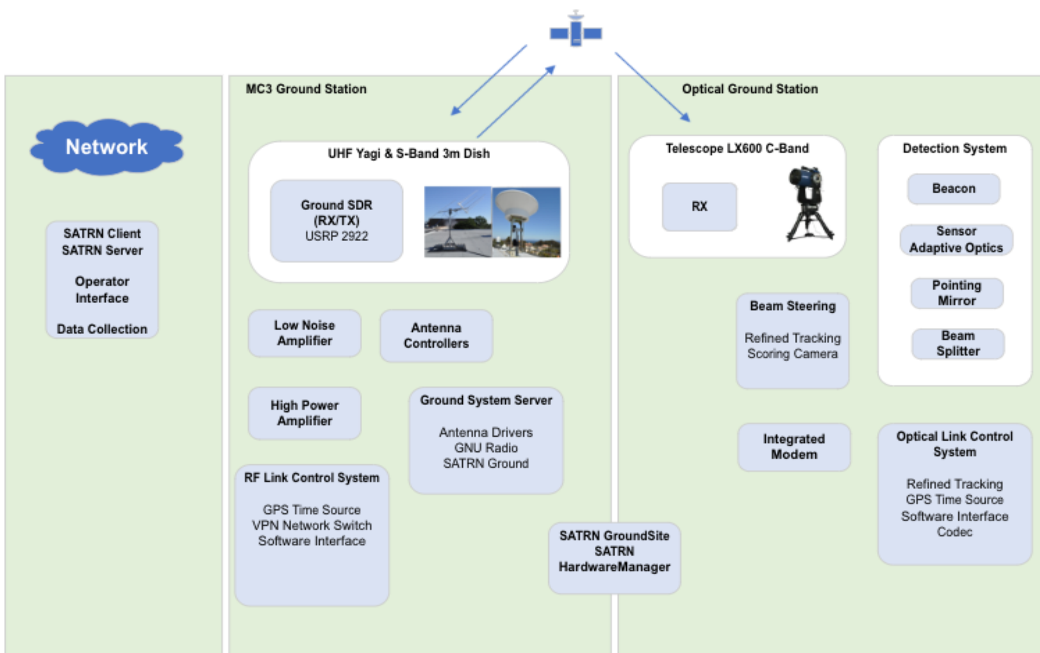


Figure 27. MC3 ground station integration components

Optical ground station integration with the MC3 system requires a high-performance telescope capable of CubeSat detection. The telescope mount must be capable of maneuvering fast enough to accommodate a 10 to 15 minute window of opportunity to communicate with the passing satellite. In addition, a detection system provides additional tracking equipment required for ensuring the appropriate feedback to adjust the pointing mechanism as needed for the smaller beamwidth. Adaptive optics paired with fast-steering mirrors to complement the detection system and ensure the increased level of precision required for small satellite tracking. An optical modem is integrated in place of or in addition to the RF modems currently in use. The recommendation presented is to utilize a modem that interfaces with an optical adaptor and converts the laser signal into a fiber link for ease of integration with ground-based communications systems.

The major overlapping component is the SATRN hardware manager and control system. Each OGS component will need to be added or supplemented into the control system interface to monitor and obtain data from the experimental architecture. The hardware components commercially available are often provided with their own software tools, which may be used in addition or integrated with or replaced by the SATRN capability depending on the specific application. The SATRN client may also be modified to include end user functional interfaces for the integrated ground system and related laser compatible components. A software interface compatibility study will be required to assess the potential options for making the necessary adjustments for full control and integration. Further study in this area, along with other recommendations for continuation, are outlined in the next chapter of this thesis.

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# V. CONCLUSIONS

With the ongoing evolution of these technologies, advancements in space communication hardware and automation tools have made design applications more efficient, accessible, and affordable. It is now easier than ever to consolidate, automate and distribute design parameters in pursuit of prototype development. Software tools can be tailored specifically for an architecture and used to conduct analysis, testing and evaluation of system performance and functionality. A systems engineering approach can be utilized to better understand complex system interfaces. Systems engineering models can help identify potential problems that can be traced back to the source. Engineers and researchers have determined that CubeSat experimentation can introduce substantial cost and accessibility benefits for space technology maturation. However, there are certain constraints when it comes to delivering more significant amounts of data due to size and power limitations. Some of these limitations could be overcome by exploring options to improve ground station capabilities for optical laser communications. Some expansion opportunities are provided for further consideration and future research opportunities.

## A. OPTICAL COMPONENTS AND SATRN

Further research is required to assess the control interface options for integrating the optical communications peripheral devices into the custom SATRN software platform. A more detailed analysis of the telescope, mount and modulation component software can address custom programming to include control modules for the optical ground components to be added to the MC3 configuration.

## B. MC3 OGS COVERAGE

One of the main challenges for transitioning from a traditional RF ground system to an optical ground system is the ability to establish a stable connection when cloud cover is present. For this reason, selecting a test site that allows the maximum opportunity to demonstrate a successful link is important. In the future, a possible solution to mitigate these limitations imposed due to weather interference is to implement site multiplicity across a network consisting of multiple geographically diverse receiving locations. If a single location drops its connection due to weather, another OGS location can supplement the loss, thus ensuring network availability.

## C. MULTI-PLANE LIGHT CONVERSION

While traditional adaptive optics has been the primary solution for handling phase distortion, the scientific community continues to search for improvements to contribute to the feasibility of optical communications on a large-scale deployment. Multi-Plane Light Conversion (MPLC) is a technique that utilizes of a series of phase masks separated by a free-space propagation acting as a Fourier transform (Zhang et al. 2020). This allows the conversion of N orthogonal spatial input modes to coincide with any set of N orthogonal output modes (Billaud 2022). This method permits selective multiplexing of the receiver input in the absence of AO correction (Allioux 2020). Tilba-Atmo developed by Cailabs is a COTS product and mechanically passive component that uses MPLC technology and is a more cost efficient and accessible alternative. However, at the time of this research, implementation examples are limited and as the initial proof concept still appears to be relatively new. Figure 28 shows the MPLC unit and phase plate concept.

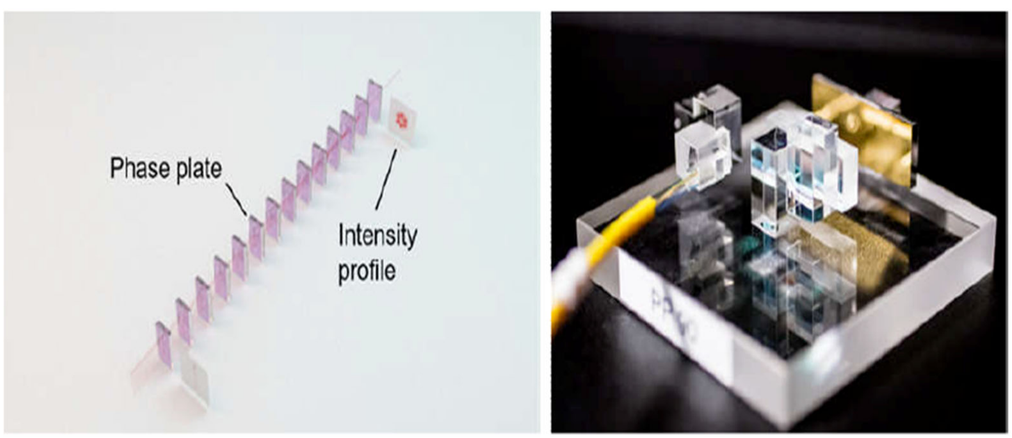


Figure 28. MPLC unit and principle. Adapted from Allioux (2020).

Future experimentation could be pursued at NPS to perform data analysis on a MPLC solution in place of or in parallel to an AO beam correction system. A similar experiment was conducted at a DLR OGS location in Weilheim, Germany. Figure 29 is a photo of the test bed setup.

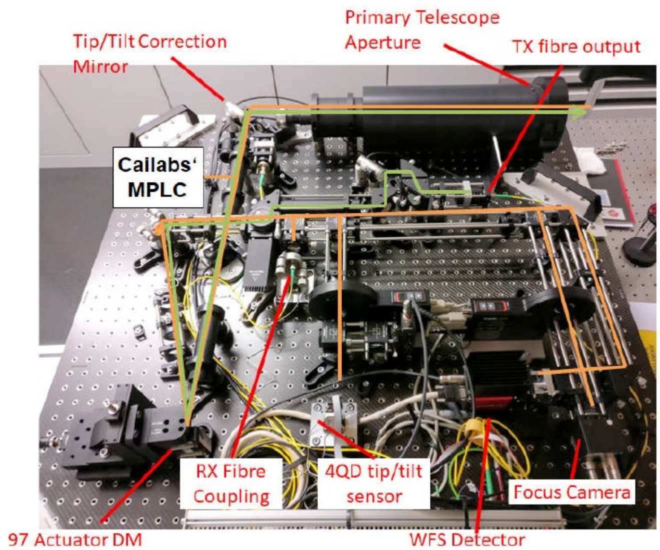


Figure 29. OGS terminal with AO and Cailabs' MPLC solution installed in parallel. Source: Allioux (2020).

The experiment compared fluctuations by capturing data metrics capturing the scintillation ratio and Fried parameter after coupling. The results concluded that performance was similar in both systems under normal conditions. However, the MPLC solution performed slightly better when the signal experienced stronger turbulence (Allioux 2020). Further research is required to determine if the Tilba Atmos MPLC alternative would be desirable for MC3 OGS implementation.

Overall, the research presented, and work carried out in this thesis emphasize the benefits and trade-offs associated with the design of an optical ground station architecture. The background research, methodology, and recommendations provided may serve as a considerate foundation for future ground segment research and development at NPS.

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