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EMERGENT BEHAVIOR ANALYSIS OF MARITIME OVER-THE-HORIZON COMMUNICATION USING LASERS AND SPACE PLATFORM RELAYS

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THESIS

EMERGENT BEHAVIOR ANALYSIS OF MARITIME OVER-THE-HORIZON COMMUNICATION USING LASERS AND SPACE PLATFORM RELAYS

by

Frank Conenna Jr.

September 2022

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13. ABSTRACT (maximum 200 words)

This thesis studied an over-the-horizon (OTH) maritime laser communication concept using free-spac optics (FSO) and space-based relays. This thesis applied a systems engineering analysis approach to stud stakeholder needs, identify requirements, and develop a conceptual design of the FSO concept. Three concept of operations scenarios were developed to illustrate (1) land-to-maritime, (2) maritime-to-land, and (3) maritime-to-maritime communication transmission. The three conceptual FSO communication capability scenarios were modeled using the behavioral modeling tool, Monterey Phoenix (MP). The MP models could be varied to represent nominal, or clear atmospheric conditions, and off-nominal, or poor atmospheric conditions (e.g., precipitation, thermal turbulence, absorption, and scattering). The thesis analyzed expected, unexpected, and emergent behavior using the MP model. The results yielded event traces characterized by transmission time, success data, and behavior expectation data. The MP model analysis produced a pattern of unexpected or emergent behavior that would interfere with successful communication transmission. Laser system failures, ship movement, or operator issues are possible emergent behavior factors. The study results indicated that the FSO OTH communication system could transmit communication quickly and with high data rates, but only during nominal or fair atmospheric conditions.

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EMERGENT BEHAVIOR ANALYSIS OF MARITIME OVER-THE-HORIZON COMMUNICATION USING LASERS AND SPACE PLATFORM RELAYS

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ABSTRACT

This thesis studied an over-the-horizon (OTH) maritime laser communication concept using free-space optics (FSO) and space-based relays. A systems engineering analysis approach was applied to study stakeholder needs, identify requirements, and develop a conceptual design of the FSO concept. Three concept of operations scenarios were developed to illustrate (1) land-to-maritime, (2) maritime-to-land, and (3) maritime-to-maritime communication transmission. The three conceptual FSO communication capability scenarios were modeled using the behavioral modeling tool, Monterey Phoenix (MP). The MP models could be varied to represent nominal, or clear, atmospheric conditions, and off-nominal, or poor, atmospheric conditions (e.g., precipitation, thermal turbulence, absorption, and scattering). The thesis analyzed expected, unexpected, and emergent behavior using the MP model. The results yielded event traces characterized by transmission time, success data, and behavior expectation data. The MP model analysis produced a pattern of unexpected or emergent behavior that would interfere with successful communication transmission. Laser system failures, ship movement, or operator issues are possible emergent behavior factors. The study results indicated that the FSO OTH communication system could transmit communication quickly and with high data rates, but only during nominal or fair atmospheric conditions.

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LIST OF ACRONYMS AND ABBREVIATIONS

AEHF	advanced extremely high frequency
C4I	command, control, communications, computers, and intelligence
CNO	Chief of Naval Operations
CONOPS	concept of operations
CW	continuous wave
DCIO	Deputy Chief Information Officer
DMSP	Defense Meteorological Satellite Program
DOD	Department of Defense
EHF	extremely high frequency
EMS	electromagnetic spectrum
ESA	European Space Agency
FCC	Federal Communications Commission
FSO	free space optics
GEO	geosynchronous equatorial orbit
HEL	high energy laser
HEO	highly elliptical orbit
HF	high frequency
ITU	International Telecommunication Union
LCRD	Laser Communications Relay Demonstration
LEO	low-earth orbit
LOS	line of sight
MEO	medium earth orbit
MP	Monterey Phoenix
NASA	National Aeronautics and Space Administration
NAVWARSYSCOM	Naval Information Warfare Systems Command
NFIRE	Near-Field Infrared Experiment
NOHD	nominal ocular hazard distance
NPS	Naval Postgraduate School
OTH	over the horizon
PEO	program executive office

PMW	program management, warfare
PPE	personal protective equipment
RF	radio frequency
SHF	super high frequency
SoS	system of systems
SYSCOM	United States Navy Systems Command
UHF	ultrahigh frequency
USA	United States Army
USAF	United States Air Force
USMC	United States Marine Corps
USN	United States Navy
USSF	United States Space Force
VHF	very high frequency

EXECUTIVE SUMMARY

Communication is critical in all aspects of military operations. A primary form of maritime communication is the use of radio frequency (RF). Military communication relies heavily on RF in all bands. RF communications are omnidirectional and are subject to interception, jamming, and spoofing. The RF spectrum lacks available frequency bands that the military can use to counter adversarial interception, jamming, and spoofing due to commercial and aviation proliferation of the RF spectrum. These communication challenges are concerns for the United States Navy since over-the-horizon (OTH) communication between ships and shore is necessary for maritime operations. The Navy desires alternative communication solutions that can provide secure and fast OTH transmission with high data bandwidth. Laser communication or free-space optics (FSO) uses highly collimated pulses of light that are modulated to transmit large amounts of data and voice communications.

This thesis studied FSO communication, laser systems, and space-based relay systems to develop a system of systems (SoS) concept for OTH communications by using space-based relays to transmit communications from land- or maritime-based transmitters to land- or maritime-based receivers. The following objectives were established to accomplish this study: (1) to understand the Navy's needs and requirements for secure and reliable communications in the maritime and littoral domains, (2) to study the use of FSO laser devices, space-based relays, and both mobile and stationary terminals for maritime OTH communications, (3) to develop and evaluate a conceptual design and architecture of an OTH maritime communication SoS using FSO laser devices and space-based relays, and (4) to identify and analyze emergent behavior in an FSO OTH Communication SoS.

The first step to accomplish these objectives was to identify stakeholders and conduct a needs analysis. The stakeholders were divided into primary and secondary stakeholders. The needs analysis was conducted by researching existing command, control, communications, computers, and intelligence (C4I) requirements and laser-based system requirements. The needs analysis identified operational, functional, performance, and safety requirements.

The next step in the thesis research was a systems analysis. The requirements were used to develop functional and physical diagrams. Top-level functions were decomposed into lower-level functions and revealed in hierarchy diagrams. The decomposed functions were used to develop physical components in that were decomposed in hierarchy diagrams. A conceptual design for the FSO OTH communication system was developed from the physical and functional diagrams. A traceability analysis was conducted to validate consistency between the conceptual design artifacts and the system requirements. Three concept of operations scenarios were identified based on the conceptual design: (1) land-to-maritime, (2) maritime-to-land, and (3) maritime-to-maritime transmissions. The scenarios included representations of nominal (good) and off-nominal (bad) atmospheric conditions. The scenarios assumed the space-based relays were in geosynchronous orbit (GEO). The nominal scenarios represented one-way transmission from transmitter to receiver in good atmospheric conditions. The off-nominal scenarios introduced poor atmospheric conditions (e.g., precipitation, thermal turbulence, absorption, and scattering).

Next, the three FSO OTH communication scenarios were modeled in a behavioral analysis tool called Monterey Phoenix (MP). The Naval Postgraduate School developed MP. The MP program models system architectures and enables the analysis of emergent behavior. This thesis used MP to model the FSO OTH communication conceptual design and to capture the three operational concept scenarios as three separate MP models. The models gave equal probability to nominal (clear) conditions and off-nominal (precipitation, thermal turbulence, absorption, and scattering) conditions.

The thesis used the MP models to study expected, unexpected, and emergent behavior of the conceptual FSO OTH communication system. The MP model result event traces provided transmission times and several event traces in each model. These event traces were categorized by model as successful and unsuccessful transmissions and expected and unexpected behavior. The results showed that the FSO OTH communication system can provide fast communication with high data rates, but atmospheric conditions need to be good (or clear). There were more unsuccessful transmissions than successful transmissions. Since the atmospheric conditions are equal in probability, there are more opportunities for unsuccessful transmission. Emergent behavior is defined as unexpected behavior produced from the MP models. However, MP does not explain causes for unexpected behavior in the model. This research inferred some possible explanations for the unexpected behavior (or unsuccessful transmissions): laser system failures, ship movement, and operator issues. The results of the model were traced to some of the operational, functional, performance, and safety requirements for verification and validation.

This study provides a foundation for future studies into FSO OTH maritime communication. The results of this thesis' needs analysis, systems analysis, and MP behavioral modeling indicate that the nascent concept of FSO OTH communications shows promise as an alternative means of maritime communication for the Navy. Although the FSO communication has only been tested in short distances, the concept of long distance FSO OTH communications has significant potential to gain an operational advantage in national defense. Current FSO communication deficiencies will be met with technological advancements of lasers and space relays to enable effective and successful FSO communication through the atmosphere in the future.

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I. INTRODUCTION

Technology has evolved to increase our ability to communicate. The advent of long-distance communication emerged from older technologies like the telegram, the facsimile, and the radio. Technology advances have focused on reducing the time for transmitting and receiving communications, increasing the amount of information transmitted, and improving the reliability and security of message delivery. Significant human-made technological innovations have been defined by revolutionary ways to send information. Modern communication capabilities are not only faster and more reliable, but they have also enabled access to the masses (e.g., telephone, the cell phone, and the internet). These platforms have become almost an inseparable part of our daily lives.

Although these indispensable platforms are user friendly, the same platforms are not ubiquitous in military operations and are instead heavily reliant upon radio frequency (RF) transmissions in various frequency ranges like high frequency (HF), very high frequency (VHF), ultrahigh frequency (UHF), super high frequency (SHF), extremely high frequency (EHF), and advanced extremely high frequency (AEHF). Most of these frequency ranges require line of sight (LOS) between the transmitter and receiver, but communication range can be extended by either using a lower frequency like HF or by using a relay system mounted on an aircraft or satellite. Radio frequency transmission is a proven and reliable means for communicating over distances; however, it is prone to jamming and spoofing. Methods have been developed to counter jamming and spoofing including frequency hopping and secure communications through cryptographic keys.

Peer competitor nations and potential adversaries continue to develop new ways to jam, spoof, intercept, and gain access to our military RF communication systems. The RF systems are omnidirectional, and their inherent direction-finding characteristic makes them vulnerable to adversary detection. This makes stealth operations a challenge. Advancements in technology are enabling alternative forms of communication. Laser communication or free space optics (FSO) is a form of communication that is currently resistant to jamming and spoofing and has stealth capabilities. Laser communication is limited to LOS between the transmitter and receiver; however, there are recent developments studying the use of relays to extend beyond LOS. While laser communications have been demonstrated and used in a limited capacity, this study explored the use of space-based relays and mobile terminals to extend laser communications for naval maritime applications.

A. BACKGROUND AND PROBLEM STATEMENT

According to Frederick D. Moorefield, the Deputy Chief Information Officer (DCIO) for the Department of Defense (DOD), “DOD uses spectrum for almost everything wireless, everything from tactical radios that the soldier uses in the field, or in operations, to satellite communications, to radar that we use to track objects and devices” (Lopez 2020). The United States Navy (USN), like the rest of the DOD, uses the RF spectrum for communication. Current shore-to-ship and ship-to-ship maritime communication relies on various RF ranges to communicate or transmit data. This type of communication, although reliable, is susceptible to jamming, spoofing, and interception. The Navy has developed several standard operating procedures (SOPs) to reduce interception and, according to Poisel, is “one of the methods to thwart such tactical operations of an adversary is to deny communication over these nets by conducting electronic countermeasures, in this case, by jamming them. This jamming is accomplished by emitting energy toward the receiver at the same frequencies as the adversary nets whenever there is an attempt to communicate” (Poisel 2011, 3). Mpitziopoulos et al. (2009) articulated that a jamming attack is “the Radio Frequency (RF) signal emitted by the jammer corresponds to the ‘useless’ information received by all sensor nodes. This signal can be white noise or any signal that resembles network traffic.” Many ships practice emission control (EMCON) to reduce jamming and interception. The term EMCON is defined by the Joint Chiefs of Staff DOD dictionary (2021, 74) as a “controlled use of electromagnetic, acoustic, or other emitters to optimize command and control capabilities while minimizing, for operations security, detection by enemy sensors, mutual interference among friendly systems, and/or enemy interference with the ability to execute a military deception plan.” Popa et al. (2018) further elaborated on EMCON that “while the intent is to reduce the adversary’s probability of finding and targeting, therefore increasing blue survivability, this limitation of blue capabilities also hinders friendly forces. With instruments and equipment reconfigured to reduce susceptibility of being attacked, the friendly platform is also unable to fully employ its sensors and weapons systems that are restricted in operation." Although this reduces communication susceptibility and location tracking, it limits critical communication, and therefore mission success.

The DOD is pushing for electromagnetic spectrum (EMS) superiority as outlined in the 2020 DOD *Electromagnetic Spectrum Superiority Strategy*. Although all wireless communication is through the RF spectrum, laser communications using the near infrared spectrum of the EMS can enable the DOD to achieve the goal of EMS superiority. Laser communication offers an alternative medium to transmit information and data that is more covert, avoiding adversarial jamming and interception attempts (Magnuson 2014). Historically, as Martinez (2018) observed, "Free-space optical communication system consists of a line-of-sight technology that transmits a modulated laser beam through the medium for broadband communications, performed from satellite to satellite, from ground to ground, or from satellite to ground, and vice versa." Boroson and Robinson revealed in 2013, "NASA's Lunar Laser Communication Demonstration (LLCD) successfully demonstrated high-rate duplex laser communications between a satellite in lunar orbit, the Lunar Atmosphere and Dust Environment Explorer (LADEE), and multiple ground stations on the Earth." The data transmission of selectable downlink rates ranged from 39 to 622 Mbps (Boroson and Robinson 2014). This demonstration used land-based terminals for transmission. The next step for this technology is to use mobile ship-based terminals for FSO laser communications. Figure 1 illustrates this concept, showing a system of systems (SoS) architecture for maritime laser communications using space-based relays to connect ships with land-based facilities.

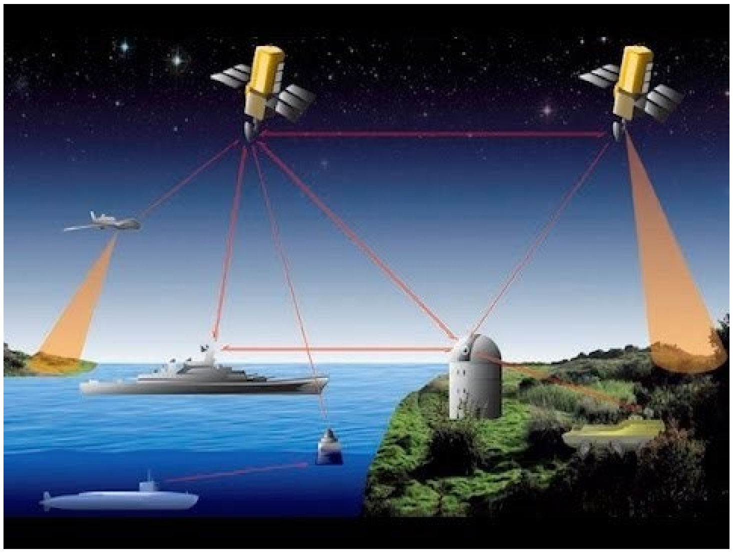


Figure 1. Concept Illustration for Space-Relay Laser Communication in the Maritime Domain. Source: Hensoldt (2016, 14).

This thesis studied this concept as a means of providing a secure OTH communications means for maritime and littoral naval forces. Laser communications require precise point-to-point transmission. This type of transmission is inherently secure. The only way for an adversary to jam laser communication is to obstruct the beam, which is challenging as laser beams are narrowly focused. They are nearly impossible to spoof or intercept. Laser communications are limited to LOS ranges, so this study explored the use of space-based relays. The thesis also explored the challenges involved in implementing both stationary (land-based) and mobile (ship based) communication terminals for the system concept.

B. MOTIVATION FOR THESIS

DOD has outlined a strategy for superiority in the EMS. According to the DOD *Electromagnetic Spectrum Superiority Strategy* (DOD 2020), "The modern EMOE is increasingly congested, contested, and constrained" and "recognizes that the same technology used to enable the maneuverability required in the highly contested near-peer environments can also be used to enhance access in highly regulated peacetime environments." The DOD must find new ways to achieve communication and information dominance. Studying the use of FSO communications in military operational settings is paramount to achieving EMS superiority.

In the next war, the EMS and space domains will play a central role in addition to land, sea, and air battlespaces. These new battlespace domains can be fought against conventional and unconventional forces. Sun Tzu (199, 121) said in the *Art of War*, “Whoever occupies the battleground first and awaits the enemy will be at ease; whoever occupies the battleground afterward and must race to the conflict will be fatigued.” The DOD needs to continue to develop technology that enhance our command and control to arrive first on these new battlefields and await the enemy. Laser FSO communications is a potential critical capability enabler for maintaining U.S. military superiority.

C. THESIS STATEMENT

Thesis statement: The current primary form of maritime communication relies on RF which has vulnerabilities and exposes users to detection. Naval forces use large distances to mask behind the horizon of an enemy. Any OTH communication enables commanders the ability to command assets from great distances. However, each communication comes at the risk of possible detection. Communication is controlled when the risk of detection exists though EMCON. Laser FSO is a technology that can be leveraged to counter the vulnerabilities due to:

- lack of detection and low emission footprint
- inability to be intercepted without obstruction
- high data rates

This study examined system and architecture concepts for developing a secure and reliable maritime communication system using highly columnated FSO laser devices, ship-based mobile terminals, land-based stationary terminals, and space-based relays for providing OTH communication for naval forces at sea and on land. This thesis addressed the following research objectives:

- to understand the Navy’s needs and requirements for secure and reliable communications in the maritime and littoral domains.

- to study the use of FSO laser devices, space-based relays, and both mobile and stationary terminals for maritime OTH communications.
- to develop and evaluate a conceptual design and architecture of an OTH maritime communication SoS using FSO laser devices and space-based relays.
- to identify and analyze emergent behavior in an FSO OTH Communication SoS

D. RESEARCH METHOD

This thesis applied a systems engineering analysis approach to research the use of ship-based laser communication and space relay systems for enabling OTH maritime communications for the Navy. The study began with a needs analysis to understand naval stakeholder needs and requirements and to explore the current state of research and development in the related technologies. The needs analysis relied primarily on a literature review. Next, the study used a model-based systems engineering (MBSE) approach to develop system, operational, functional, and physical models, or views, of the conceptual system and architecture. The study defined requirements for this conceptual system and used MBSE tools to capture SE artifacts. The study developed a concept of operations (CONOPS) using a behavioral modeling tool called Monterey Phoenix (MP) and modeled the behavior of this conceptual system. The model behavior includes how the laser will interact with atmospheric conditions. The models were evaluated to understand the capabilities, limitations, and emergent behavior of this conceptual system along with the potential benefits of this system for the Navy. Figure 2 illustrates the research method for this thesis.

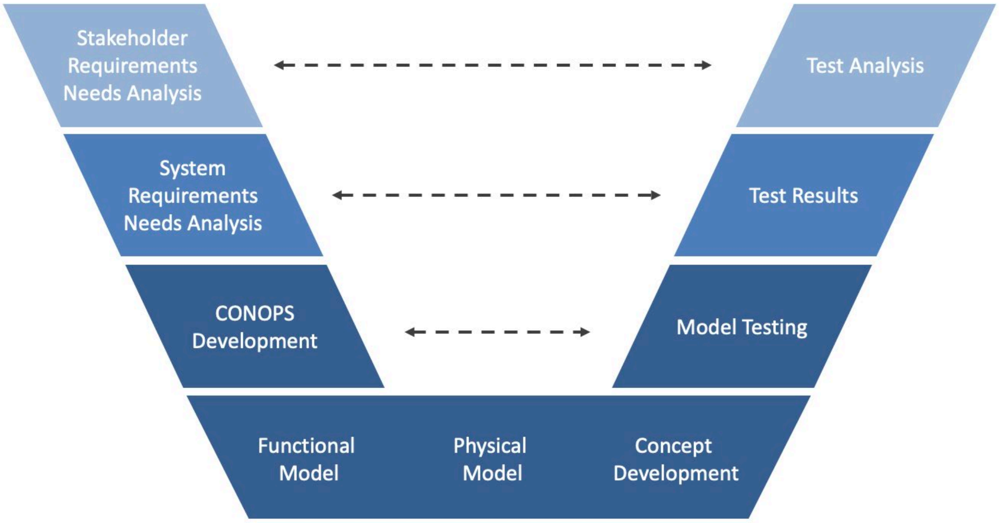


Figure 2. Research Method "Vee" Model. Adapted from Blanchard and Fabrycky (2011, 37).

E. EXPECTED BENEFITS OF THESIS RESEARCH

The potential benefits of implementing an OTH maritime communications using lasers and space-based relays for the Navy are threefold: (1) they enable very rapid transmission of large amounts of data from ship-to-ship, ship-to-shore, and shore-to-ship, and (2) they provide an effective "stealthy" means of communication within the fleet in a communication denied environment as it cannot be jammed, spoofed, or intercepted (3) they provide an alternative communication medium from the congested RF spectrum (Magnuson 2014).

This study supports the potential benefits of this future capability by expanding the Navy's understanding of how the combination of lasers and space-based relays can support OTH maritime communications. The study provides insights into the capabilities and limitations of this technology concept. The study provides systems engineering artifacts including a needs analysis and conceptual design that can be used by the Navy as a foundation for a detailed design and development of this future capability.

F. THESIS ORGANIZATION

This thesis comprises of six chapters: Chapter I Introduction, Chapter II Literature Review, Chapter III Needs Analysis, Chapter IV System Analysis and Conceptual Design, Chapter V Analysis Results, and Chapter VI Conclusion. Chapter I introduced the problem statement, background, motivation, thesis statement, research method, benefits, and thesis organization. Chapter II provides an overview on lasers, laser communication systems, atmospheric laser influences, and satellite communications and tracking. Chapter III conveys the needs analysis for stakeholders and requirements. Chapter IV presents the system analysis, which included a functional model, a physical model, a conceptual design, and three concept of operations scenarios. Chapter V describes the MP methodology and results of MP model testing. Chapter VI examines MP shortfalls and benefits; the results of emergent behavior found in the MP results; and conducts a verification and validation of the MP model to requirements. Chapter VII summarizes the results and findings, provides recommendations, and presents ideas for future research.

II. LITERATURE REVIEW

This study began with a review of related literature to understand research to date and provide a foundation of knowledge pertaining to this study. The literature review included understanding the fundamentals of lasers and laser communications. With the foreknowledge that weather and the environment effects laser beams, the study included a review of atmospheric effects. Finally, the study reviewed literature on the MP modeling tool and its ability to support behavioral modeling. This chapter presents the findings of the literature review.

A. LASER OVERVIEW

Since the first satellite orbited the earth, communication was used to track its location and send signals. Laser technology started in the 1960s and has become more sophisticated. Lasers have been used to send signals, to space such as to satellites or the moon, through uplinks and downlinks. FSOs have been used to crosslink in space where the atmosphere is not significant, but it is limited to LOS and orbit type. Lasers are limited by atmospheric effects, but developments are underway to provide solutions to overcome these challenges.

Laser is an acronym for light amplification by the stimulated emission of radiation. A laser is further defined by Davim (2012, xi) as “a device which uses a quantum mechanical effect, stimulated emission, to generate a coherent beam of light from a lasing medium of controlled purity, size, and shape.” Lasers are classified by power output, wavelength, nominal ocular hazard distance (NOHD), and other hazards. The NOHD is the minimum distance between a laser and the human eye which a laser becomes safe. Table 1 shows wavelengths, power limitations, and a description of the laser for Class I, II, IIIR (sometimes referred in older classification publications as Class IIIa), IIIb, and IV derived from the 2021 Department of Energy classification of light emitting products (21 C.F.R. § 1040).

Table 1. Laser Classification. Source: 21 C.F.R. § 1040 (2021).

Laser Class	Wavelength	Power Limit	General Description
Class I	Less than 0.4 µm	Not limited	Non-hazardous
Class II	0.4 µm - 0.7 µm	1 mW	Hazardous when directly exposed to eyes over time
Class IIIR	0.3025 µm -4.00 µm and greater than 0.7 µm; 0.4 µm - 0.7 µm	5 mW	Hazardous when directly exposed to eyes though an optical instrument
Class IIIb	0.4 µm - 0.7 µm	500 mW	Hazardous when directly exposed to the eyes and skin
Class IV	1.4 µm to 1 mm	Not limited	Hazardous when exposure is directed or scattered to the eyes and skin

The laser device contains several components including a gain medium, two mirrors (one fully reflective, one partially reflective), and an energy source to stimulate the laser. Titterton (2013, 19) expressed that the laser "gain medium contains the laser species that will be excited through an excitation process, known as pumping, to create the population inversion necessary for the stimulated emission." Titterton (2013, 19) explained further "the gain medium used to create the photons can be solid, liquid or gaseous." Broadly listed, laser gain medium is used for laser classification.

Free electron lasers use magnetic fields to interact and stimulate light. Titterton (2013, 118) described "the free electron laser operation as extraction of light (synchrotron radiation) from high-speed electrons passing through a magnetic field with spatially periodic variations in intensity as well as direction." Since the laser wavelength can be modulated, the laser can be adapted for different conditions. Titterton (2013, 118) elaborated on this "option to select an emission wavelength can allow for a very high atmospheric transmission of a high-power beam over a range of climatic or meteorological visibility conditions." This is beneficial when overcoming limitations in a maritime environment.

The types of materials used in a laser will characterize the laser beam output. Laser beam operations can be continuous wave (CW) or pulsed. A CW laser is defined by Titterton (2013, 591) as "a laser with a continuous emission for a period of at least 0.25

second." Pulsed lasers are short in duration and can achieve high power. According to Webb et al. (20013, 1254), "A pulse-modulated beam was used with an increased peak power of up to three times the average power."

Other beam characteristics such as divergence, irradiance, and size are related to the beam's quality. A laser's divergence is defined by Hecht (2019, 54) as "the angular spreading of a laser beam." Divergence affects a laser's spot size since the farther a laser travels, the more a laser beam will have a larger spot size. Irradiance is defined by Titterton (2013, 604) as "power density on a surface" and can be calculated by dividing a laser's terminus power by spot area. Two final beam quality characteristics are Beam Parameter Product (BPP) and Beam Propagation Factor (M^2). The BPP is defined by Hecht (2019, 163) as equaling "half the divergence angle in milliradians times the beam waist radius in millimeters" (2019, 163). Beam waist is also called W_0. He defines M^2 as "the product of π times beam radius at the waist (W_0) times beam divergence (θ) divided by wavelength (λ)."

Laser jitter is a factor when employing lasers. Jitter is a vibration that originates from the laser device. This can be exacerbated from non-land-based laser platforms such as vessels and satellites. Lasers can be characterized by more attributes, but they all measure how effective a laser beam is on an application to a distance or a range.

B. LASER COMMUNICATION SYSTEMS AND CAPABILITIES

Laser communication or FSO, seems like the work of science fiction but this type of technology is common in our daily lives such as bar code scanners, CD players, and fiber optic cable internet. FSO is being developed from long distance communication through high energy lasers (HEL). Programs that have used satellite FSO for communication or have attempted FSO communication in the maritime environment are European Space Agency (ESA) satellite ARTIMIS, NASA Laser Communications Relay Demonstration (LCRD), and the Near-Field Infrared Experiment (NFIRE) and TerraSAR-X. Between 2001 and 2004, Alonso et al. reported that the ESA conducted over 50 successful tests of laser communications at 3,800 km from the Optical ground station located on the Canary Islands to the satellite ARTIMIS (Alonso et al. 2004, 383). On

December 2, 2021, the LCRD was launched into orbit. The LCRD "will transmit data received from missions to two ground stations, located in Table Mountain, California, and Haleakalā, Hawaii" and "will test different cloud coverage scenarios, gathering valuable information about the flexibility of optical communications" (Monaghan 2021). TerraSAR-X and NFIRE were satellites repurposed for FSO testing. Fields et al. (2009, 15) reported "over 20 duplex communication links have been achieved with current acquisition times routinely less than 30 sec, having yielded high quality links up to 650 sec in duration at 5.6 Gbps data rate." These programs have used laser communications to establish uplinks and downlinks on earth to celestial bodies.

The primary benefits to laser communication are high uplink and downlink data rates and available frequencies. RF bands are congested with military and commercial use which is protected by the International Telecommunication Union (ITU) and the Federal Communications Commission (FCC), but laser frequencies do not share the same protections (Neo 2003, 12). An example of high data is NASA's Laser Communications Relay Demonstration (LCRD) can have data rates up to 1.244 Gigabits/sec (Monaghan 2021). FSO communication traveling into space are limited by laser and atmospheric conditions described previously. Aviv (2006, 74) described "the downlink signal suffers very small losses as its beamwidth spreads from the attainable diffraction-limited satellite's optics and goes through essentially a non-atmospheric path, until it reaches about 30 km from the Earth." At 30 km, atmospheric gas becomes denser and interacts with the laser more. Aviv (2006, 74) further described the "losses of the uplink are very large because the beam begins to spread and accumulate distortion the very instant the photons are emitted from the ground-based telescope aperture."

FSO can still uplink and downlink from space despite atmospheric limitations by digitally modulating the laser optics. Bihn (2018, 9) defined digital modulation as "a process of mapping such that the digital data of '1' and '0' or symbols of '1' and '0' that convert it into some aspect of the carrier, the amplitude and phase, and then transmit the carrier, the lightwave." This form of modulation increases the reliability of the laser. Another method to overcome atmospheric limits is by opto-mechanically displacing large water droplets such as fog, a significant factor in the maritime environment, with a shock wave. In 2018, Schimmel et al. (2018, 1338) studied this phenomenon finding that a "high-peak-power laser creates a local cloudless pathway with reduced Mie scattering for the second, modulated, telecom beam that carries information." Atmospheric environment creates long distance FSO limitations, but there are methods to permit FSO communication through some atmospheric factors.

Laser communication architecture is dependent on requirements for the communication system. Performance for the laser subsystem is subject to wavelength, pulse frequency, divergence angle, power, and beam quality. Physical requirements and configuration will depend on tradeoffs of weight and performance. The benefit of FSO, specifically in crosslinks, is the low power and being lightweight. Dmytryszyn et al. (2021, 11) articulated that "the smaller signal power requirement allows for smaller collecting antennae, an advantage seen in a smaller size, weight, and power." Physical configuration for the transmitter and receiver can be either monostatic or bistatic. Titterton (2013, 420) described each system as "a monostatic system, with the transmitter and receiver coincident or bistatic (i.e., with a separation between the receiver and transmitter telescopes)." FSO require safety precautions due to their high energy (Class IIIb and IV). Therefore, laser placement of both transmitter and receiver on ships is a safety concern for ship crews. Gildemeyer et al. (2018, 88) studied the placement of HEL on the USS San Antonio (LPD 17) and found that placing lasers on the ship's fore and aft provided full coverage for laser operation and crew safety. Laser devices must be able to adapt to different types of atmospheric effects on Earth and reliably crosslink with other satellites.

C. ATMOSPHERIC LASER INFLUENCE AND LIMITATIONS

Lasers are limited by the effects of external factors specifically atmospheric factors including absorption, scattering, deflection, reflection, attenuation, turbulence, and thermal blooming. The atmosphere surrounds the Earth with different compositions of gas and humidity. The pressure and temperature of the Earth's atmosphere changes at different altitudes. Figure 3 shows the atmospheric layers and associated layer altitudes. Titterton (2013, 167) discussed laser absorption of molecules in the troposphere "such as ozone, water vapor and carbon dioxide, have vibrational frequencies that correspond to wavelengths from the ultraviolet to the far infrared" and are "mainly a result of the presence of di-atomic and tri-atomic molecules along the propagation path." Different molecules will have different laser absorption effects depending on the wavelength. Figure 4 illustrates common molecules found in the atmosphere and the transmission absorption results in the EMS.

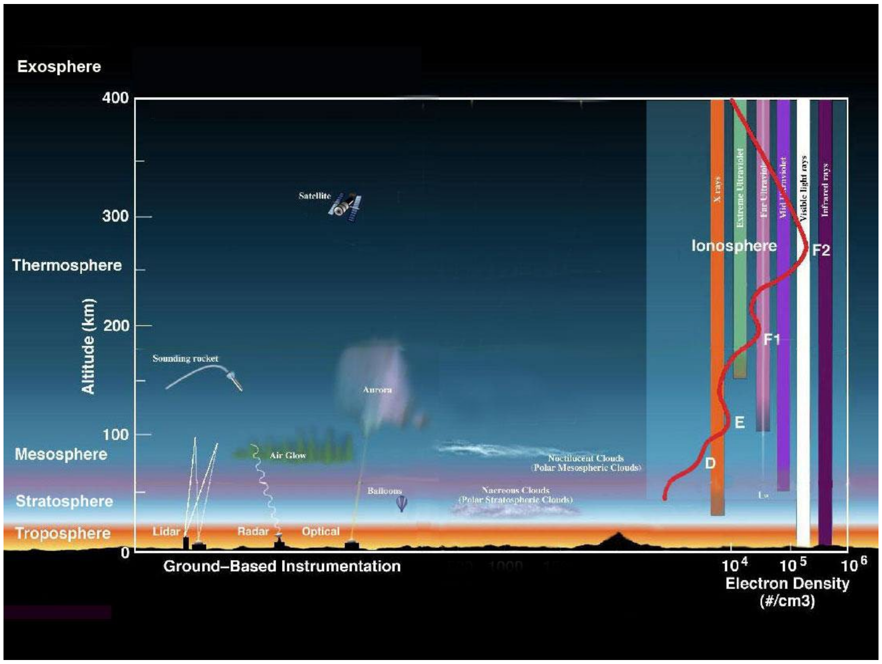


Figure 3. Atmospheric Layers. Source: Zell (2017).

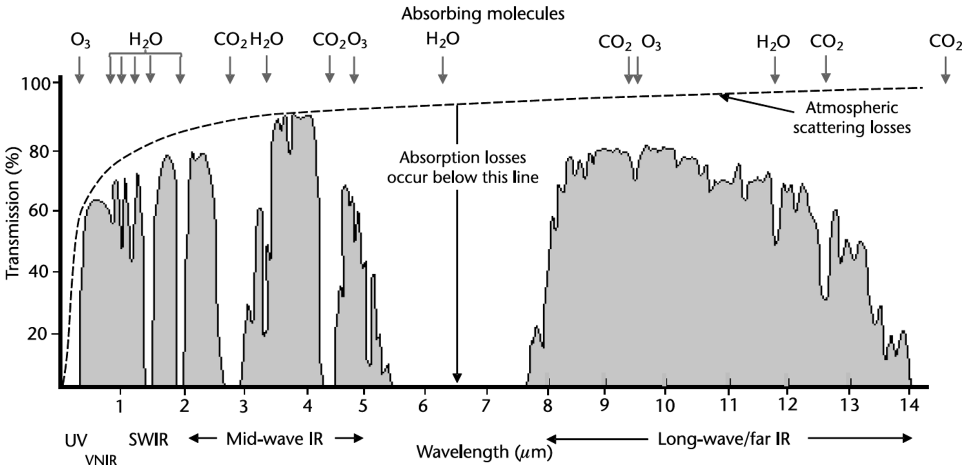


Figure 4. Atmospheric Absorption. Source: Titterton (2019, 168).

Atmospheric particles can scatter laser energy and is defined by Titterton (2013, 167) as "the redistribution of energy by particles in the atmosphere." According to Titterton, there are two scattering mechanisms: Rayleigh and Mie. An example of Rayleigh scattering is how sunlight is scattered and provides a blue sky during the day. This is due to, as Titterton (2013, 168) puts it, "Particles in the atmosphere that are very much smaller than the optical wavelength." He described Mie scattering as being "caused by particles comparable in size with the incident wavelength" (2013, 169). Hecht (2019, 46) explained that "absorption and scattering add together to cause loss or attenuation, the reduction in light power per unit distance as it travels through a material." The attenuation of a laser can result in extinction of a beam. Titterton (2013, 169) described extinction as "a result of the absorption of the photons by the species in the atmosphere and then scattering out of the beam by aerosols and other particles present in this gaseous medium." Extinction leads to a laser being ineffective.

Photonic energy from a laser beam can be affected by modules and particles in the atmosphere, but other factors such as turbulence, wind, and weather also effect lasers. Atmospheric turbulence effects caused by thermal energy in the atmosphere is explained by Titterton (2013, 176) as a "result of fluctuations in the refractive index of the atmosphere within the air mass, along the propagation path followed by an optical beam, typically generated by the convection currents within the air mass" and leads to intensity reduction and increased scintillation." Wind has similar effects as turbulence with a few differences. Wind can cause an increase in aerosol content in maritime environments and flowing wind can mix "with the lower atmosphere in the boundary layer and so reduces the lapse rate and, therefore, also reduces the turbulence created by the thermals" (Titterton 2013, 176). Another type of effect is thermal blooming which is described by Titterton (2013, 186) as a phenomenon that occurs "when high-power beam propagation occurs in the lower atmosphere" from thermal energy absorbing laser energy. Weather effects for lasers include humidity and precipitation such as fog, clouds, rain, and snow. Humidity causes Mie scattering and absorption. Precipitation reduces visibility but the type of precipitation is critical to the scattering effect that it will have to the laser beam. According to Titterton (2013, 173), fog and clouds have large droplets and can cause intense Mie scattering.

Meteorological forecasts and the use of models is vital to ensuring a laser beam is least affected by the atmosphere environment. Various models can be used to predict atmospheric effects such as Lowtran (low-resolution atmospheric transmission) and Modtran (moderate resolution atmospheric transmission). These models can reduce error from laser systems that travel from space orbit to a maritime environment.

D. SATELLITE COMMUNICATIONS AND TRACKING

The first successfully launched satellite to orbit the Earth, Sputnik, was launched in 1957 by the Soviet Union. Sputnik, pictured in Figure 5, had small antennas that emitted radio signals that sounded like a beep. These signals could be heard by anyone with a radio as Harford (2007, 6) pointed out that "for three weeks the world could hear the Sputnik I's beeps before the radio died out, and it orbited more than 1,400 times before burning up in the atmosphere after three months." Since Sputnik, all satellites have sent RF signals back to Earth. Sellers et al. (2015, 538) explained "spacecraft communications primarily use the radio frequency of electromagnetic radiation." Since Sputnik, these RF signals have evolved from beeps to voice and data transmissions.

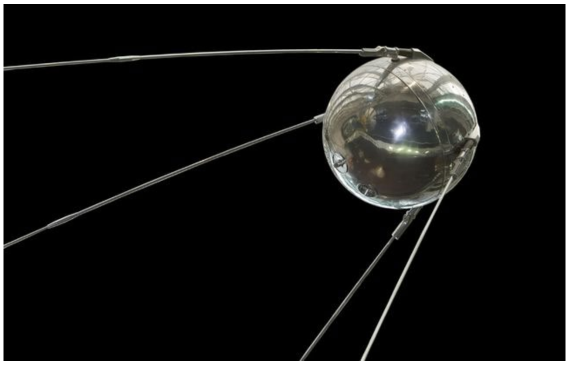


Figure 5. Image of Sputnik. Source: Thiessen (2021).

Satellites are placed into specific orbits around the Earth for the satellite's intended use. Table 2 lists various orbit types and mission for each orbit. All satellites are affected by LOS and different types of orbits attempt to overcome LOS limitations such as inclination and distance from the surface of the Earth. Sellers et al. (2015, 185) defined orbital inclination as "the orientation or tilt of an orbital plane with respect to a fundamental plane: the equator." Certain satellite inclinations can degrade reception at specific latitudes. For example, GEO orbits orbit over the equator, inclination 0°, have a large coverage area but are limited above or below latitudes 65°N or 65°S. Each orbit type is a tradeoff between coverage area and latency time and number of satellites.

Table 2. Orbit Types. Source: Sellers et al. (2015).

Orbit Type	Orbital Altitude	Orbital Period	Inclination	Mission
Low Earth Orbit (LEO)	300km	90–100 minutes	28.5°, 39°, 51°, 57°	Manned spaceflight, reconnaissance, weather, communications
Medium Earth Orbit (MEO)	20,232km	12 hours	55°–65°	Position, Navigation, Timing
Highly Elliptical Orbit (HEO)	7,971km-45,170km	12 hours	63.4° or 116.6°	Communications, Missile Warning, intelligence
Geosynchronous Equatorial Orbit (GEO)	35,780km	24 hours	~0°	Communications, early warning, nuclear detection
Sun-Synchronous Orbit (SSO)	150km-900km	90–100 minutes	95°–105°	Remote sensing, reconnaissance, weather, commercial imagery

Each orbit has advantages and disadvantages. A GEO satellite is fixed in one spot and provide a wide area coverage, but the altitude of GEO satellites causes long transmission times. According to Pelton (2013, 99), "Three satellites in GEO orbit provide essentially global coverage except for the polar regions." Molniya orbits, or HEO orbits, do cover polar regions; however, they have orbital periods of 12 hours and require two HEO satellites to provide continuous coverage over a specific area. Pelton (2013, 104) described HEO orbits coverage as giving a "very long effective 'hang' time especially about high latitude countries such as Russia where this type of orbit was first used." A

MEO orbit is between LEO and GEO orbits and have shorter latency than GEO but require more satellites for coverage.

Satellites in LEO are lower in orbit so RF can travel faster, but they have a shorter orbital period. Consequently, LEO satellite coverage is limited in area and time. A large satellite constellation is required to provide continuous coverage through crosslink communication between LEO satellites. Pelton (2013, 111) stated that LEO satellites "need forty or more satellites to provide total coverage of the globe." Commercially, LEO satellites have been used to provide services like Iridium. SpaceX is developing the Starlink program which will be in LEO. According to Duan and Dinavahi (2021, 3673), "SpaceX has launched nearly 800 satellites. Although it is still at the very initial stage of the entire project, the final Starlink space network will be composed of nearly 12,000 satellites" and "will circle the Earth at an orbit of 500 km to 1200 km overhead." This will provide fast and continuous coverage, through crosslinks between satellites, all over the Earth.

Each orbit type is further limited by environmental factors. For example, MEO satellites orbit above the Van Allen belts and are affected by radiation. As Pelton (2013, 99−100) pointed out "radiation can do damage to satellite electronics and even with spacecraft shielding of the electronics and glass coating on solar cells, the lifetime of the spacecraft will be significantly shortened if it must fly within the Van Allen belts." Satellites that orbit at the highest distances are subject to radiation from the sun, such as solar flares and storms.

Regardless of which orbit satellites are in, they are all composed of various subsystems that interact to ensure the satellite is nominal. Tracking is critical for communication. Aviv (2006, 18) stated that to "attain the proper point-a-head angle between the satellites, as well as in carrying out the necessary acquisition, tracking, and pointing (ATP) processes. This would allow the communication beam to 'lock' on to the receiver satellite for the specified period of communication." The subsystem that deals with communication is called the telemetry, tracking, and control (TT&C) subsystem. Depending on how the subsystem is decomposed, the subsystem can be called by different names. Telemetry is defined by Sellers et al. (2015, 533) as "the payload and spacecraft health and status information that the controller receives on the ground for analysis." Pelton et al. (2013, 1072) defined tracking as "the process of locating and locking onto a satellite from a ground station." There are different methods of tracking but the most common is using Doppler shift. Ippolito (2013, 44) explained "the Doppler shift of the beacon (or the telemetry carrier) is monitored to determine the rate at which the range is changing (the range rate). Angular measurements from one or more earth terminals can be used to determine spacecraft location." Telemetry enables a ground crew to monitor the status of a satellite, and tracking enables a ground crew to know the location of a satellite in its orbital plane.

If a satellite requires changes, the control subsystem enables ground crews to make appropriate adjustments. Pelton et al. (2013, 1077) defined control as "the reception and process of command to allow the continuing operation." Satellites are exposed to extreme environments and are difficult to provide direct intervention when problems occur. The TT&C subsystem enables ground crews to gain perspective of the satellite. The TT&C, as Ippolito (2014, 44) described, consists "of the antenna, command receiver, tracking and telemetry transmitter, and possibly tracking sensors." See Figure 6 for an example decomposition of the TT&C subsystem. The satellite subsystem supports the primary mission of the satellite and is necessary for any type of communication satellite.

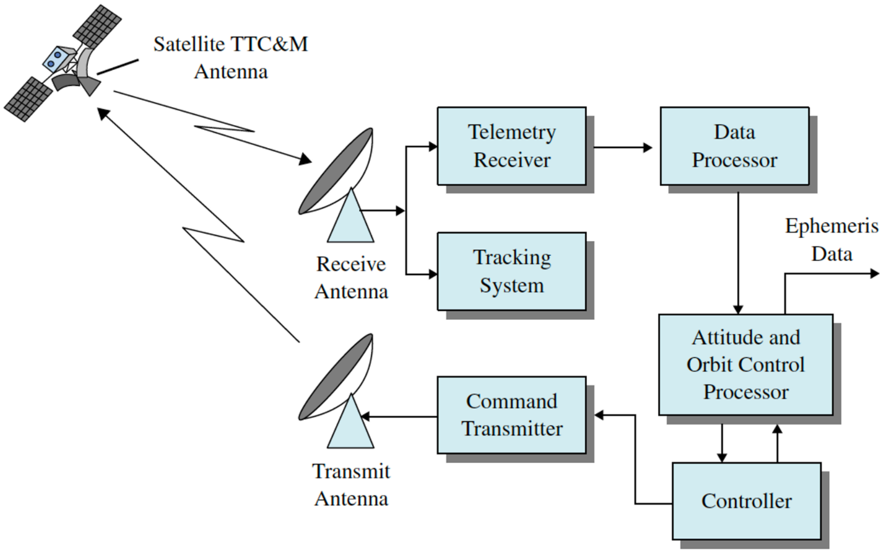


Figure 6. TT&C Subsystem. Source: Ippolito (2013, 43).

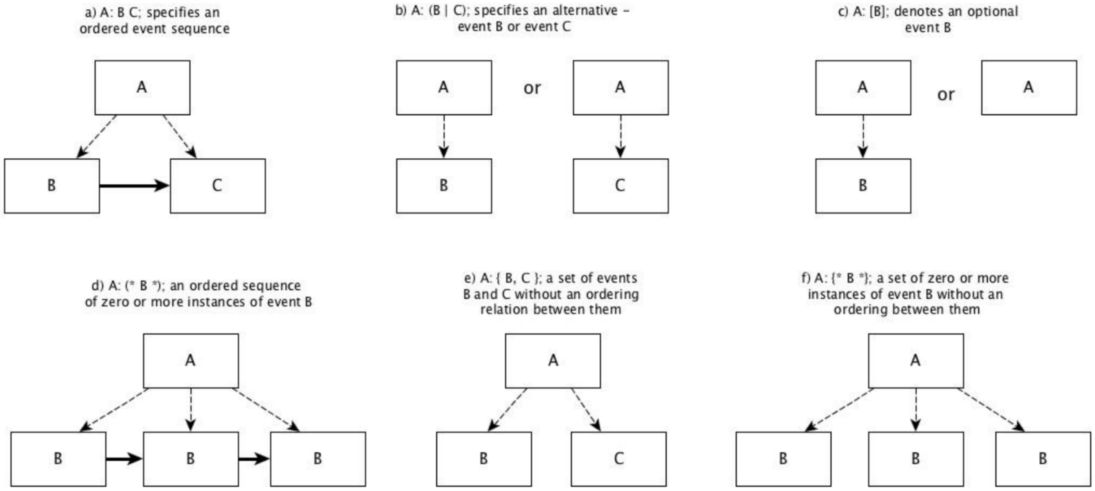
Communication with a satellite is conducted with RF signals and can be completed with simplex, half duplex, or full duplex. Simplex is a type of communication which data flows one way from sender to receiver. A radio in a car is like this: a radio station broadcasts music at a specific frequency and tuning a radio receiver to that frequency enables a user to listen to that radio station's music. Half duplex enables two-way communication, but the sender must transmit to the receiver and the receiver must receive the communication prior to the receiver being able to send communication back. A walkie talkie works this way. Military and civilian aircraft use this type of communication to talk to air traffic controllers. Full duplex permits communication between the sender and receiver at the same time such as on a telephone call. Simplex, half duplex, and full duplex apply to all types of communication including lasers.

E. MONTEREY PHOENIX

This section discusses the MP program. Chapter IV will discuss how MP is used in this thesis. Systems have become more complex and due to the complexity as Auguston et al. (2006, 972) explained "it has become a common practice for engineers to analyze system behaviors from an external point of view using use cases." The MP program models system behaviors and processes though event analysis to identify emergent behavior by characterizing system activities as events.

A schema is a MP program that is decomposed into root events, composite events, and atomic events colored as green, orange, and blue boxes respectively. A schema is defined by Auguston (2020, 6) as "a collection of rules describing behavior of components within the system, external actors, and their interactions." A root event is a high-level function or component in a system's architecture. An MP model needs to have at least one root event defined. A composite event can be used to group multiple atomic events but is not required for an MP model. An atomic event is the sub functions or subcomponents in a system architecture. The colors for each event type identifies the type of function or component that is in presented in an MP model in graph view. These events are organized by MP grammar rules to analyze the possible event interactions that can occur within a system.

Grammar rules provide system event coordination to define an order for system processes. Figure 7 provides six examples of possible event traces where A, B, and C are different events in a schema. In this set of examples, A can either be a root or composite event, and B and C are atomic events. These examples show the grammar syntax required to define event traces with given constraints to produce desired subsequent events.


a) A: B C; specifies an ordered event sequence

b) A: (B | C); specifies an alternative – event B or event C

c) A: [B]; denotes an optional event B

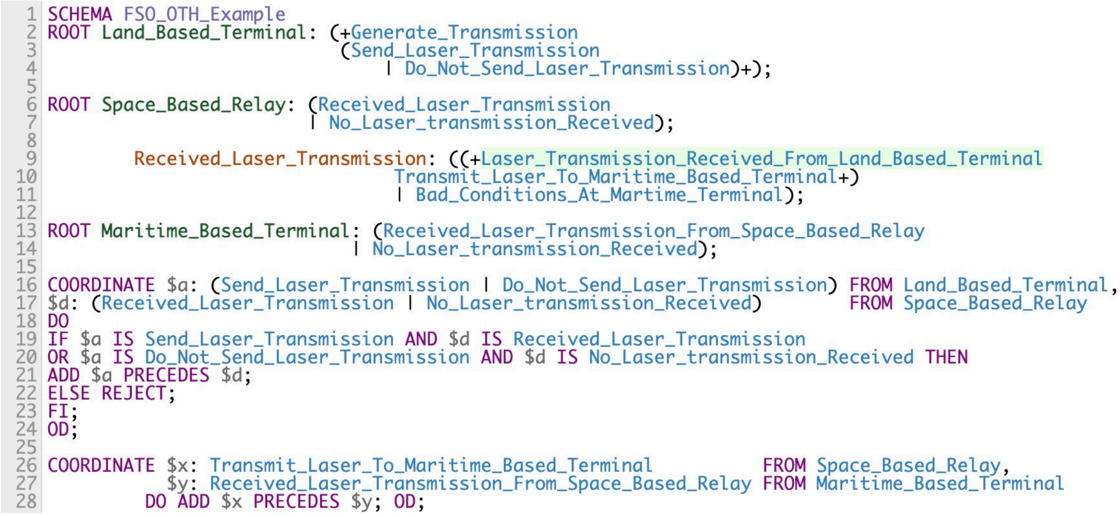
d) A: (* B *); an ordered sequence of zero or more instances of event B

e) A: { B, C }; a set of events B and C without an ordering relation between them

f) A: {* B *}; a set of zero or more instances of event B without an ordering between them

Figure 7. Event Grammar Rules. Source: Auguston (2020, 7).

Additionally, there are grammar rules that define precedence so one event does not occur before another event. Figures 8 and 9 provide an example of an MP code and graphic derived from the code used for this thesis. Running the code in Figure 8 on scope 1 will generate three event traces. A scope is one complete execution of the MP code with the maximum iterations that the code can produce within the constraints of the coordination functions. Figure 9 shows the first of the three even traces which includes three root events (green), one composite event (orange), and multiple atomic events (blue).



```
 1 SCHEMA FSO_OTH_Example
 2 ROOT Land_Based_Terminal: (+Generate_Transmission
 3                            (Send_Laser_Transmission
 4                                | Do_Not_Send_Laser_Transmission)+);
 5
 6 ROOT Space_Based_Relay: (Received_Laser_Transmission
 7                         | No_Laser_transmission_Received);
 8
 9         Received_Laser_Transmission: ((+Laser_Transmission_Received_From_Land_Based_Terminal
10                                 Transmit_Laser_To_Maritime_Based_Terminal+)
11                                 | Bad_Conditions_At_Martime_Terminal);
12
13 ROOT Maritime_Based_Terminal: (Received_Laser_Transmission_From_Space_Based_Relay
14                             | No_Laser_transmission_Received);
15
16 COORDINATE $a: (Send_Laser_Transmission | Do_Not_Send_Laser_Transmission) FROM Land_Based_Terminal,
17 $d: (Received_Laser_Transmission | No_Laser_transmission_Received)        FROM Space_Based_Relay
18 DO
19 IF $a IS Send_Laser_Transmission AND $d IS Received_Laser_Transmission
20 OR $a IS Do_Not_Send_Laser_Transmission AND $d IS No_Laser_transmission_Received THEN
21 ADD $a PRECEDES $d;
22 ELSE REJECT;
23 FI;
24 OD;
25
26 COORDINATE $x: Transmit_Laser_To_Maritime_Based_Terminal          FROM Space_Based_Relay,
27            $y: Received_Laser_Transmission_From_Space_Based_Relay FROM Maritime_Based_Terminal
28          DO ADD $x PRECEDES $y; OD;
```

Figure 8. Example of MP in Code View

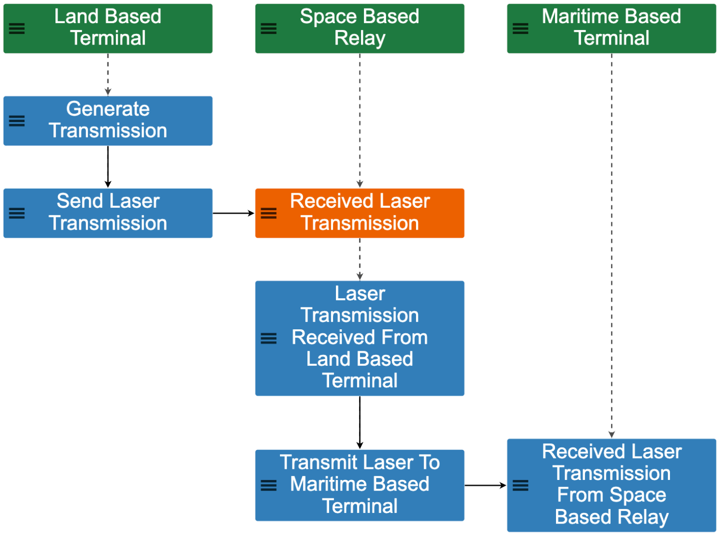


Figure 9. Example of MP in Graph View Scope 1 Event Trace 1

Different MP grammar rules used in Figure 8 include COORDINATE, FROM, DO, OD, ADD, IF, IS, AND, ELSE, FI, THEN, and REJECT. COORDINATE, used in line 15 and 26, is used to set a precedes event which two events interact one after the other. Line 26 defines $x as Transmit_Laser_To_Maritime_Based_Terminal, which comes from the root event Space_Based_Relay, which is derived from the grammar rule FROM. The

DO OD in line 28 opens and closes the loop that the coordinate rule establishes and the ADD rule specifies additional relationship events to the events specified in the coordinate function. The PRECEDES rule in line 28 specifies that event $x will occur before event $y, which is defined in line 27. The grammar rules IF, THEN, AND, IS, ELSE, and REJECT statements are used in MP to set up conditions for events using linear algebra. Each root, composition, and coordinate function must be closed with a semicolon. If the grammar rules are not set correctly, then errors will appear. If the coordinate and precede rules are too restrictive or if the events do not match appropriately in the code, then the program will not generate event traces. The rules described are not inclusive to all the grammar rules in MP but only the ones that were used in the example code. This code was only run for one scope or one iteration. MP is limited to five scopes due to the small scope hypothesis.

The Small Scope Hypothesis is a way to find issues that are found in large and complex systems. The Small Scope Hypothesis is articulated by Jackson (2020, 15) as "most flaws in models can be illustrated by small instances, since they arise from some shape being handled incorrectly, and whether the shape belongs to a large or small instance makes no difference." If there are faults in complex systems, then emergent behavior will be revealed in small iteration numbers.

The MP program solves problems in many different applications including, inter alia, software, engineering, and business. Additionally, MP is used for model verification and validation to ensure that that model is meeting requirements such as functional requirements. Verification is defined by Giammarco and Giles (2018, 432–433) as "performing tests to ensure the system continues to meet the requirements and specifications as the system develops" and validation "confirms the model generates outputs that accurately reflect the model's purpose." Any MP modeling can be based on mission narratives and can model how a system is intended to operate. The MP syntax enables all possible events to occur to identify unexpected behaviors or events in a system.

F. SUMMARY

Using FSO from Earth to orbit has several difficulties, predominately atmospheric effects and orbit selection and tracking. This chapter covered lasers and atmospheric limitations on lasers; laser communications capabilities; satellite orbits, satellite communication, tracking satellites; and Monterey Phoenix. The information described in this chapter provides a general overview of these concepts for thesis application.

III. NEEDS ANALYSIS

This chapter discusses the needs analysis for the FSO OTH system. The needs analysis was developed by researching existing command, control, communications, computers, and intelligence (C4I) requirements and laser-based system requirements. Additionally, the FSO OTH CONOPS was referenced. This chapter is composed of three sections: the stakeholder analysis, the requirements analysis, and a summary. The stakeholder analysis categorizes the stakeholders as either primary or secondary and describes several needs with descriptions for each stakeholder. The requirements analysis is comprised of operational, functional, performance, and safety requirements.

A. STAKEHOLDER ANALYSIS

Primary stakeholders include the USN program executive offices (PEO) within the USN systems commands (SYSCOM), geographic combatant commanders, the Chief of Naval Operations (CNO), engineers, and the warfighter. Within SYSCOM, the primary SYSCOM stakeholder is the Naval Information Warfare Systems Command (NAVWARSYSCOM) PEO C4I program management, warfare (PMW) offices specifically PMW 146, PMW 170, and PMW 760. These PMWs oversee the communication satellite program, GPS and communication program, and ship communication integration respectively. Secondary stakeholders include the Defense Meteorological Satellite Program (DMSP), NASA, the other branches: U.S. Army (USA), U.S. Marine Corps (USMC), U.S. Air Force (USAF), and the U.S. Space Force (USSF). Table 3 details a stakeholder analysis by identifying the primary and secondary stakeholders and needs. The table combines the primary and secondary stakeholders, but the table is split with the top portion identifying the primary stakeholders and associated needs and the bottom portion with the secondary stakeholders and associated needs. There are several needs to each stakeholder that describe requirements and expectations for each stakeholder.

Table 3. Stakeholder Analysis

Primary Stakeholder	Needs Description
PMW 146	- Develop or repurpose satellites for use as laser communication relays - Design and develop laser relay satellite constellation that supports the FSO OTH Communication System - Provide FSO Communication satellite tracking and telemetry data capability
PMW 170	- Develop laser relays for communication - Develop laser transmitters for atmospheric FSO communication - Develop laser receivers for atmospheric FSO communication
PMW 760	- Integrate laser communications on existing and future ships - Test laser communications integration to ship equipment - Provide upgrades to hardware and software to operate with the FSO OTH Communication System
CNO	- Direct FSO OTH Communication System program that can close kill chains for the local unit - Maintain resilient communication architecture (Gilday 2021, 8)
Engineers	- Develop laser transmitters for the FSO OTH Communication System - Develop laser receivers for the FSO OTH Communication System - Integrate laser hardware and software - Integrate FSO laser communication equipment to ship equipment
Warfighter/user	- Use FSO OTH System - Maintain high level of proficiency - Train dedicated individuals on the maintenance and operations of the FSO OTH Communication system
Geographic Component Commands	- Train and maintain units in laser communications - Ensure units maintain training programs - Ensure proficiency rates for operational use of the FSO OTH Communication system is greater than 95%
Secondary Stakeholder	**Needs Description**
USMC/USCG/USA/ USAF	- Validate joint maritime interoperability - Use FSO OTH Communication System - Maintain high level of proficiency - Train dedicated individuals on the maintenance and operations of the FSO OTH Communication System
USSF/NASA	- Track and monitor orbiting satellites

	- Launch additional satellites - Provide telemetry data to stakeholders
DMSP	- Provide terminal weather information to stakeholders

B. REQUIREMENTS ANALYSIS

The requirement analysis section provides high-level requirements for the FSO OTH System. The requirements lists were developed from researching existing C4I systems and examining potential gaps in the kill chain to align with stakeholder requirements. The requirements section is further broken down into four subsections: operational requirements, functional requirements, performance requirements, and safety requirements.

The operational requirements that Table 4 provides are general purpose statements that describe high-level system expectations. Kossiakoff et al. (2011, 145) defined operational requirements as “operational requirements will describe and communicate the end state of the world after the system is deployed and operated.” Table 4 comprises of a list of operational requirements and associated descriptions of each requirement. The operational requirements include capability, maintainability, repairability, survivability, availability, and reliability which enable the system to perform.

Table 4. Operational Requirements

Operational Requirements	Description
FSO OTH Capability	The FSO OTH Communication System shall be able to achieve fast, precise, and reliable over-the-horizon communication using highly columnized lasers in lieu of RF signals via space-based relays with high data rates.
Maintainability	The FSO OTH Communication System shall be able to be maintained by military personnel with minimal civilian specialist intervention required with existing equipment on naval ships.
Repairability	The FSO OTH Communication System shall be able to be repaired by military personnel using training and existing tools and materials.

Operational Requirements	Description
Survivability	The FSO OTH Communication System shall be able to survive in maritime environments with high precipitation in extreme temperatures of -40 to 140 degrees Fahrenheit. High precipitation will limit laser communication but should not damage equipment.
Availability/Reliability	The FSO OTH Communication System shall have an availability of over 99% for users in environments that permit lasers usage.

The functional requirements are derived from operational requirements and CONOPs. These requirements can also be called system action requirements. The functional requirements describe what the system needs to do to its operational task and accomplish the mission. Table 5 decomposes the FSO OTH communication system into three primary subsystem components and correlates a functional requirement with an associated description for each component.

Table 5. Functional Requirements

Subsystem Component	Description
Maritime-based Mobile Terminal	- The maritime-based mobile terminal shall send laser communication data - The maritime-based mobile terminal shall receive laser communication data - The maritime-based mobile terminal shall amplify laser energy - The maritime-based mobile terminal shall interpret laser communication signals to an interface for user - The maritime-based mobile terminal shall process laser signal - The maritime-based mobile terminal shall record laser signal - The maritime-based mobile terminal shall be able to send laser communication data to other maritime-based mobile terminals
Space-based relay	- The space-based relay shall be able to receive laser communication data - The space-based relay shall be able to crosstalk with other space-based relays

Subsystem Component	Description
	- The space-based relay shall be able to amplify laser signals - The space-based relay shall send laser energy to other space-based relays - The space-based relay shall send laser energy to maritime-based terminals - The space-based relay shall send laser energy to land-based terminals - The space-based relay shall send position information to users - The space-based relay shall send position data of other satellites to users
Land-based Terminal	- The land-based mobile terminal shall send laser communication data - The land-based mobile terminal shall receive laser communication data - The land-based mobile terminal shall amplify laser energy - The land-based mobile terminal shall interpret laser communication signals to an interface for user - The land-based mobile terminal shall process laser signal - The land-based mobile terminal shall record laser signal

Performance requirements describe the metrics that the system requires. Kossiakoff et al. (2011, 145) defined performance requirements as “how well the system should perform its requirements and affect its environment.” The performance requirement thresholds are listed and described in Table 7.

Table 6. Performance Requirements

Performance Requirements	Description
FSO OTH Communication System	- FSO OTH Communication System interface shall be intuitive to the user for operation - FSO OTH Communication System shall be integrated with existing and future ship C4I systems - FSO OTH Communication System shall be able to use alternative land-based terminals that can send communication to primary receiver due to inclement weather
Reliability	- FSO OTH Communication System shall have secure communication capabilities - FSO OTH Communication Systems shall be able be consistently available for the user - FSO OTH Communication System shall integrate with DMSP for communication rerouting to land-based terminals autonomously
Training	- System shall require minimal training for users - FSO OTH Communication System maintenance and repair training shall be provided
Environmental	- Maritime-based terminals shall have corrosion control measures to counter corrosion in the maritime environment

High-powered lasers can cause bodily harm. Safety requirements are necessary to prevent injury and damage to equipment. Although the energy required to produce a FSO communication link is less than 1000 kW, personnel should use caution when operating near laser transceiver and receiver equipment. Table 8 list general requirements and descriptions for safety.

Table 7. Safety Requirements

Safety Requirements	Description
Personal protective equipment (PPE)	- Personnel working on (i.e., performing maintenance) or near laser receiver or transmitter shall properly wear eye and skin PPE when laser is in operation
Training	- Personnel working on (i.e., performing maintenance) or near laser receiver or transmitter shall have training on laser safety

C. SUMMARY

This chapter presented the needs analysis for future primary and secondary stakeholders of an OTH maritime laser communication capability. The chapter described the requirements for this capability in the form of operational, functional, performance, and safety requirements. The operational requirements captured high-level system requirements. The functional requirements captured essential tasks that the system will need to perform for mission success. The performance requirements contain metrics for the system's effectiveness and the safety requirements provide safety metrics for users and equipment.

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IV. SYSTEM ANALYSIS

This chapter presents the results of the study's system analysis. The analysis included the development of a functional model based on the system requirements developed in the needs analysis; the development of a physical model that identifies major components of the system and subsystems; a traceability analysis that ensured the physical and functional models are consistent; and the development of a concept of operations.

The functional models are decomposed from the high-level function of the system and are organized by the system components. The functional models are matched to physical models to demonstrate that form follows function. Scenarios will be described in the concept of operations as mission narratives. These scenarios will be modeled in MP to analyze emergent behavior from scenarios. The conceptual design and emergent behavior analysis will support development of OTH FSO communication as the technology becomes more established.

A. SYSTEM DESCRIPTION

The FSO OTH Communication System is a SoS that integrates several land-based terminals, maritime-based terminals, space-based relays, and support crews using lasers or FSO as the medium for communication to quickly and reliably send large amounts of data over significant distances with a low probability of intercept. Conceptually, the FSO OTH system will be composed of subcomponents: land-based terminals, maritime-based terminals, space-based relays, and support teams. These subcomponents will have requirements to accomplish the mission. The land-based teams are personnel that ensure terminals are operational and monitor weather and intervene, when required, for automation conflicts so that communication continues to flow. The maritime-based terminals are installed on forward-deployed naval ships. The space-based relays are required to be operational in orbit.

B. FUNCTIONAL MODEL

Functions are the tasks or activities (in MP they are labeled as events) that the system shall perform for successful operation. These functions are derived from the requirements to operate the system. Figure 10 is a high-level model of the system functions. The primary function of the system is to provide FSO OTH communication. The functional architecture then decomposes the primary system function into four main subfunctions. These subfunctions are to provide space-based relay; provide laser transmitter and provide laser receiver; and provide support which will be the teams on the land-based terminals to monitor the maritime-based terminals, the land-based terminals, and the space-based terminals. Each of these subfunctions is further decomposed into their respective models.

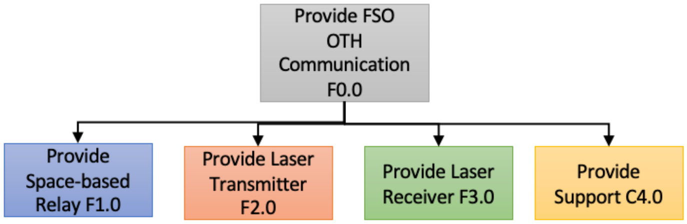

Figure 10. High-Level Functional FSO OTH Communication Model

The subfunction provide space-based relay is decomposed into four subfunctions: provide communication, provide tracking data, provide propulsion, and provide power. Figure 11 illustrates the hierarchy of the subfunctions of the space-based relay. The hierarchy is decomposed down to three layers within the provide communication subfunction while the other subfunctions are decomposed to two layers.

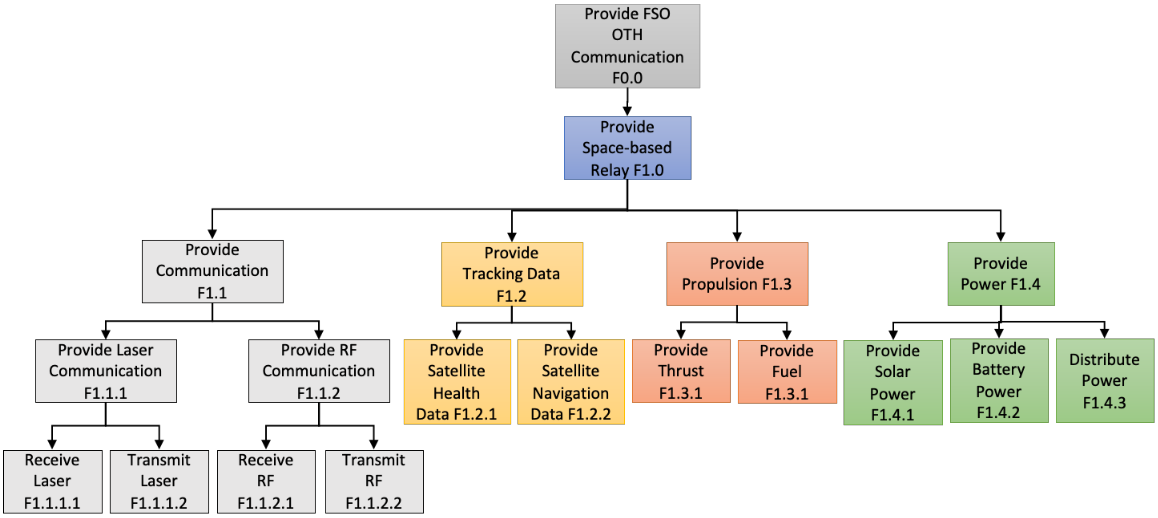

Figure 11. Satellite Relay Functional Model

The subfunction provide laser transmitter is decomposed in Figure 12 with four main subcomponents: provide laser, provide interface, provide laser tracker, and provide power. The model is decomposed to three layers in the provide laser subfunction. The provide laser subfunction includes the five subfunctions and further decomposes provide reflective mirrors into provide highly reflective mirrors and provide partially reflective mirrors.

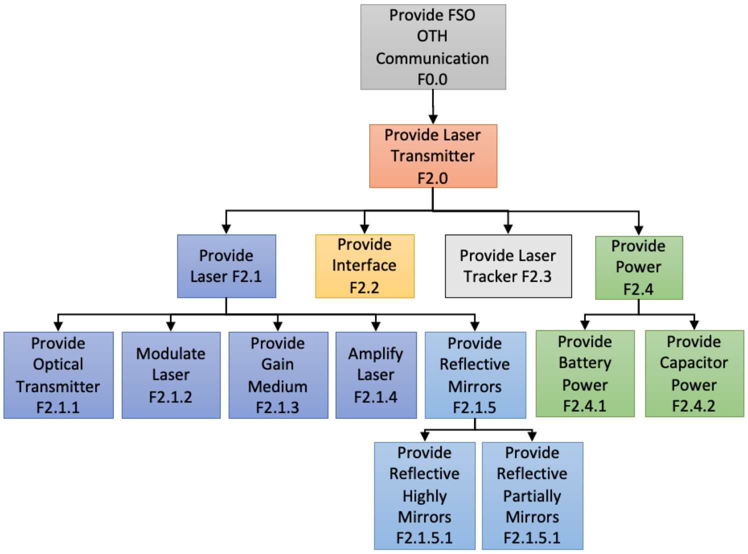

Figure 12. Laser Transmitter Functional Model

The third main subfunction is provide laser receiver which is decomposed in Figure 13 down to one level of functions: to provide optical transmitter, amplify received laser, provide data interface, demodulate laser, and receive and convert signal.

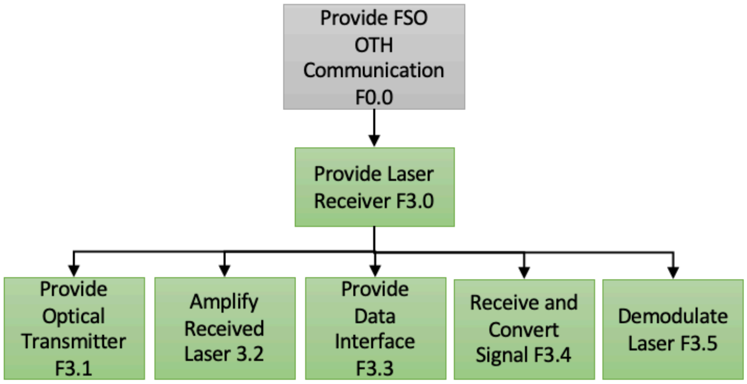

Figure 13. Laser Receiver Functional Model

The last subfunction is to provide support which is decomposed in Figure 14 to three layers. The subfunctions of provide support are what the land-based personnel will ensure: to provide land-based support, provide weather sources, and provide asset tracking. Asset tracking is decomposed to track ship and track satellite.

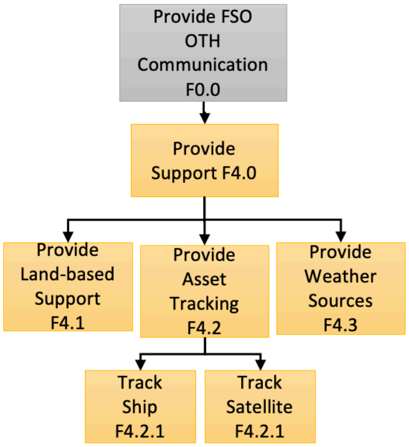

Figure 14. Support Functional Model

C. PHYSICAL MODEL

The FSO OTH Communication System involves three main subsystems with an additional support system that interact with the internal boundaries of each main system. Each of the main components of the FSO OTH Communication System are decomposed with physical models. Figure 15 shows the high-level physical model of the FSO OTH Communication System comprising the space-based relay, support, and the maritime-based and land-based laser transmitter and receiver.

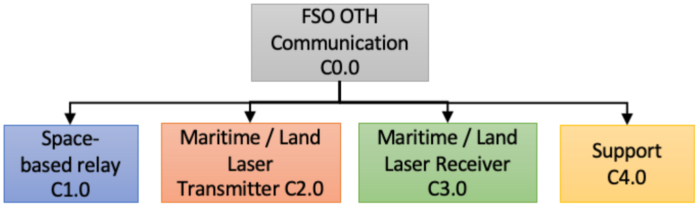

Figure 15. High-Level FSO OTH Communication System Physical Diagram

The space-based relay is decomposed in Figure 16 based on the functional model shown in Figure 11. This model conceptualizes the form derived from the function. The four subfunctions of the space-based relay are the communication subsystem, the TT&C subsystem, the propulsion subsystem, and the electrical subsystem. The communication subsystem is decomposed into the laser communication subsystem and radio frequency communication subsystem. Although the primary mission of the FSO OTH communication system is laser communications, RF communication is required as a backup to the laser communication in situations of laser communication failure and as a method to provide satellite health and navigation and control capabilities for the satellite. Each communication subsystem is comprised of a receiver and a transmitter. The TT&C subsystem is decomposed into the satellite health information and navigation system. The propulsion subsystem is comprised of the thrusters to move the satellite, as required to stay in orbit or to move to another orbit, and the storage fuel tanks. The electrical subsystem is based on the satellite's energy capabilities from solar panels and storing the collected power in a battery. When power is required, the electrical distribution provides power to the subsystems that need it.

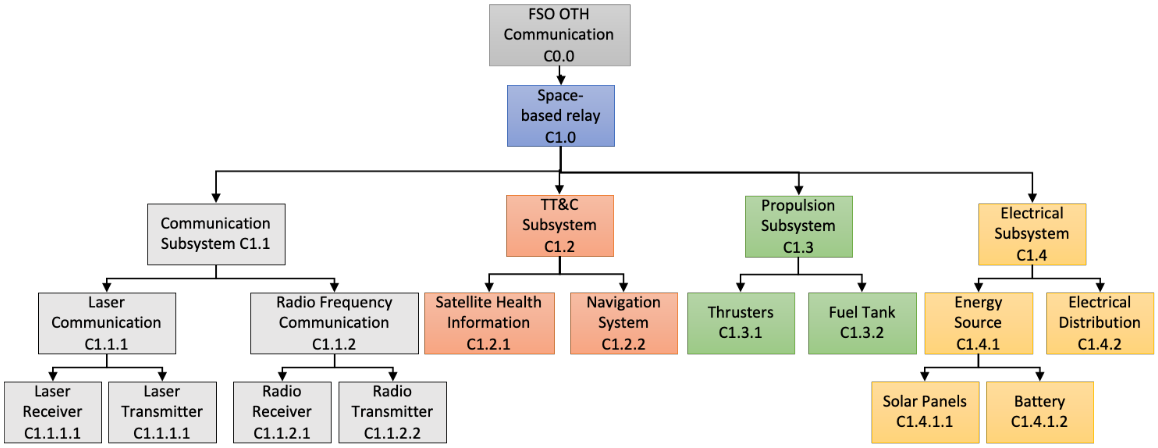

Figure 16. Laser Communication Satellite Physical Diagram

The laser transmitter for both maritime-based and land-based terminals is decomposed in Figure 17 and is derived from the functional model in Figure 12. The laser transmitter is decomposed into four subsystems: the laser, data interface, tracker, and power source. The laser is comprised of five components including the optical transmitter, the modulator, the gain medium, the amplifier, and the mirror. The laser function requires a highly reflective mirror and a partially reflective mirror which is decomposed into the layer below mirror. The power source, a battery and capacitor, is what gives the laser transmitter the energy required to complete the function of the laser.

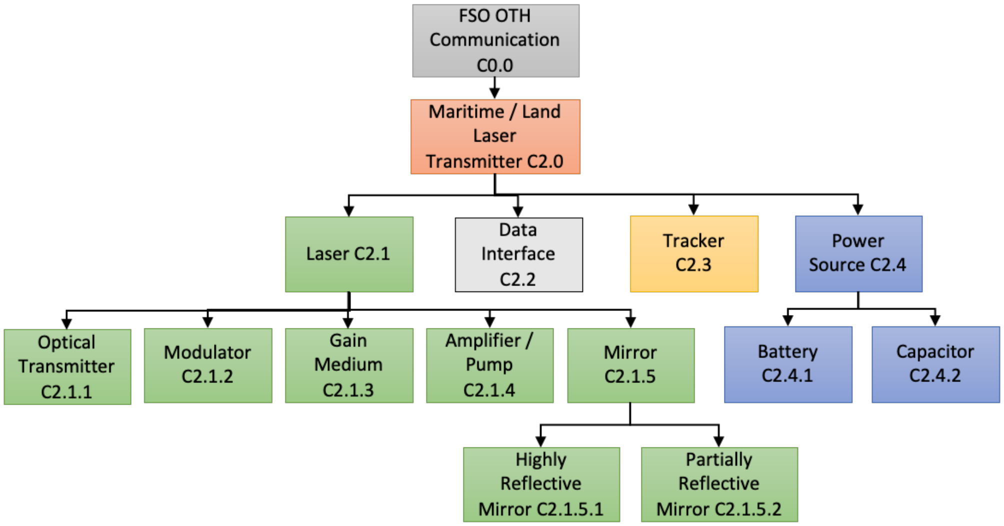

Figure 17. Laser Transmitter Physical Diagram

The laser receiver for both the maritime-based and land-based receiver is decomposed in Figure 18 from the functional model in Figure 13. The laser receiver comprises five components: the optical receiver, the amplifier, the data interface, the demodulator, and the signal receiver and converter.

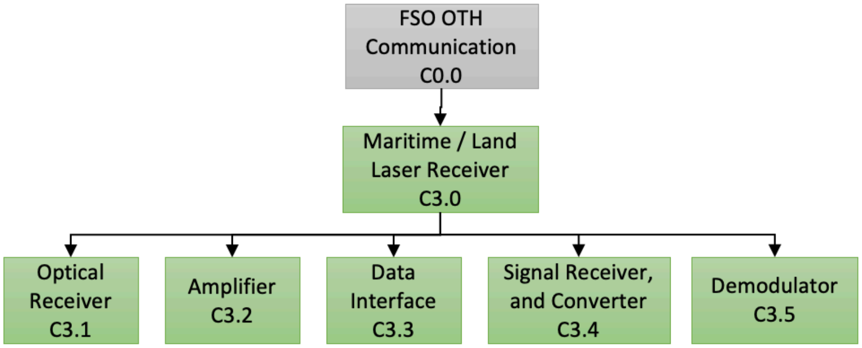

Figure 18. Laser Receiver Physical Diagram

The support physical model is decomposed in Figure 19 from the functional model in Figure 14. The support model comprises personnel teams that will support operations of the FSO OTH Communication System. The support teams that will track assets, provide weather from weather sources, and work as ground station personnel. Asset tracking is decomposed into ship tracking and satellite tracking.

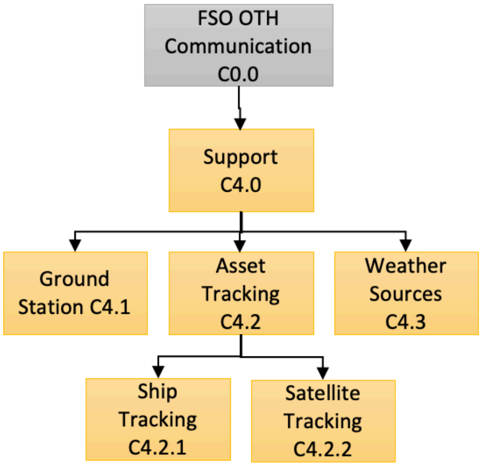

Figure 19. Support Physical Diagram

The context block diagram in Figure 20 shows the transmitter, satellite (space-based), and receiver for a one-way transmission. The location of the transmitter and receiver is not specified, regardless of whether it is a maritime-based or land-based terminal. The diagram shows that the weather and possible adversaries may cause obstructions to the system, and that gathering weather data and satellite orbital tracking data will be needed to operate the system. The functional subsystem that supports the weather data and satellite orbital tracking will be from the support teams in the land-based terminals. The dashed-line boxes represent the internal boundaries in each subsystem.

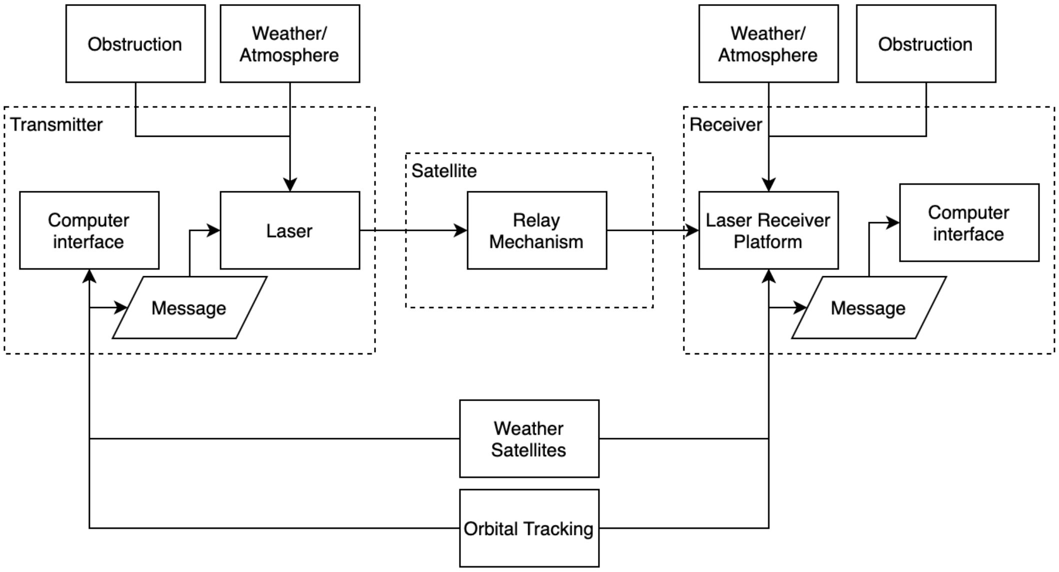

Figure 20. System Context Diagram

D. TRACEABILITY

The physical models are traced back to the functional models in Table 8 to display how the physical model components are traced to show that form follows function. Each function performs the physical form matched in each row.

Table 8. Function and Form Traceability Table

Function ID	Function	Physical ID	Physical Form
F0.0	Provide FSO OTH Communications	C0.0	FSO OTH Communication System
F1.0	Provide Space-based Relay	C1.0	Space-based Relay
F1.1	Provide Communication	C1.1	Communication Subsystem
F1.1.1	Provide Laser Communication	C1.1.1	Laser Communication
F1.1.1.1	Receive Laser	C1.1.1.1	Laser Receiver
F1.1.1.2	Transmit Laser	C1.1.1.2	Laser Transmitter
F1.1.2	Provide RF Communication	C1.1.2	RF Communication
F1.1.2.1	Receive RF	C1.1.2.1	Radio Receiver
F1.1.2.2	Transmit RF	C1.1.2.2	Radio Transmitter

Function ID	Function	Physical ID	Physical Form
F1.2	Provide Tracking Data	C1.2	TT&C Subsystem
F1.2.1	Provide Satellite Health Data	C1.2.1	Satellite Health Information
F1.2.2	Provide Satellite Navigation Data	C1.2.2	Navigation System
F1.3	Provide Propulsion	C1.3	Propulsion Subsystem
F1.3.1	Provide Thrust	C1.3.1	Thrusters
F1.3.2	Provide Fuel	C1.3.2	Fuel Tank
F1.4	Provide Power	C1.4	Electrical Subsystem
F1.4.1	Provide Solar Power	C1.4.1.1	Solar Panels
F1.4.2	Provide Battery Power	C1.4.1.2	Battery
F1.4.3	Distribute Power	C1.4.2	Electrical Distribution
F2.0	Provide Laser Transmitter	C2.0	Maritime/Land Laser Transmitter
F2.1	Provide Laser	C2.1	Laser
F2.1.1	Provide Optical Transmitter	C2.1.1	Optical Transmitter
F2.1.2	Modulate Laser	C2.1.2	Modulator
F2.1.3	Provide Gain Medium	C2.1.3	Gain Medium
F2.1.4	Amplify Laser	C2.1.4	Amplifier / Pump
F2.1.5	Provide Reflective Mirrors	C2.1.5	Mirror
F2.1.5.1	Provide Highly Reflective Mirror	C2.1.5.1	Highly Reflective Mirror
F2.1.5.2	Provide Partially Reflective Mirror	C2.1.5.2	Partially Reflective Mirror
F2.2	Provide Interface	C2.2	Data Interface
F2.3	Provide Laser Tracker	C2.3	Tracker
F2.4	Provide Power	C2.4	Power Source
F2.4.1	Provide Battery Power	C2.4.1	Battery
F2.4.2	Provide Capacitor Power	C2.4.2	Capacitor
F3.0	Provide Laser Receiver	C3.0	Maritime / Land Laser Receiver
F3.1	Provide Optical Transmitter	C3.1	Optical Receiver
F3.2	Amplify Received Laser	C3.2	Amplifier
F3.3	Provide Data Interface	C3.3	Data Interface
F3.4	Receive and Convert Signal	C3.4	Signal Receiver and Converter
F3.5	Demodulate Laser	C3.5	Demodulator
F4.0	Provide Support	C4.0	Support
F4.1	Provide Land-based Support	C4.1	Ground Station
F4.2	Provide Asset Tracking	C4.2	Asset Tracking
F4.2.1	Track Ship	C4.2.1	Ship Tracking

Function ID	Function	Physical ID	Physical Form
F4.2.2	Track Satellite	C4.2.2	Satellite Tracking
F4.3	Provide Weather Sources	C4.3	Weather Sources

E. CONCEPT OF OPERATIONS

This section provides mission narratives for scenario events that will likely occur in the FSO OTH communication system. These scenarios annotate singular transmissions from a transmit terminal to a receive terminal. They are then subclassified as nominal conditions and off-nominal conditions.

Nominal conditions are defined as ideal conditions for FSO laser communications. These conditions require good weather (e.g., no precipitation, scattering conditions, nor turbulence). Users will be able to send and receive data using interfaces that integrate into existing communication equipment and not as standalone interfaces using either voice or data communication. Assumptions for nominal conditions are good weather and user proficiency. There are no conditions that would self-constrain communications and GEO satellites are used as space-based relays unless noted otherwise. Scenarios in the nominal cases include:

- land-based terminal to a maritime-based terminal
- maritime-based terminal to a land-based terminal
- maritime-based terminal to another maritime-based terminal

An example of a nominal scenario is a land-based terminal to a maritime-based terminal mission narrative, as follows. A user at land-based terminal generates message to send to maritime-based terminal. User at land-based terminal sends message. Message is modulated to laser. Laser is amplified and sent through optical transmitter. Laser travels through atmosphere to space-based relay. Laser is received by space-based laser receiver. Space-based relay points to maritime-based terminal. Laser received by space-based laser is modulated and amplified then sent though optical transmitter. Laser travels though atmosphere to maritime-based receiver. Maritime-based receiver receives laser. Laser is demodulated and converted into data. Data is provided to interface for receiving user.

Figure 21 illustrates the scenario described with major subcomponents to demonstrate the path of the FSO transmission.

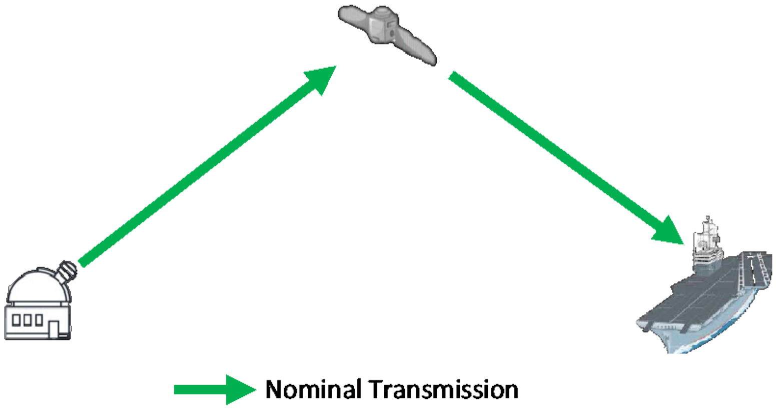

Figure 21. Nominal Land-based Terminal to Maritime-based Terminal Transmission

A second example of a nominal scenario is a maritime-based terminal to a land-based terminal mission narrative is as follows. User at maritime-based terminal generates message to send to land-based terminal. User at maritime-based terminal sends message. Message is modulated to laser. Laser is amplified and sent through optical transmitter. Laser travels through atmosphere to space-based relay. Laser is received by space-based laser receiver. Space-based relay points to land-based terminal. Laser received by space-based laser is modulated and amplified then sent though optical transmitter. Laser travels though atmosphere to land-based receiver. Land-based receiver receives laser. Laser is demodulated and converted into data. Data is provided to interface for receiving user. A depiction of this scenario is in Figure 22 with the major subcomponents and transmission path.

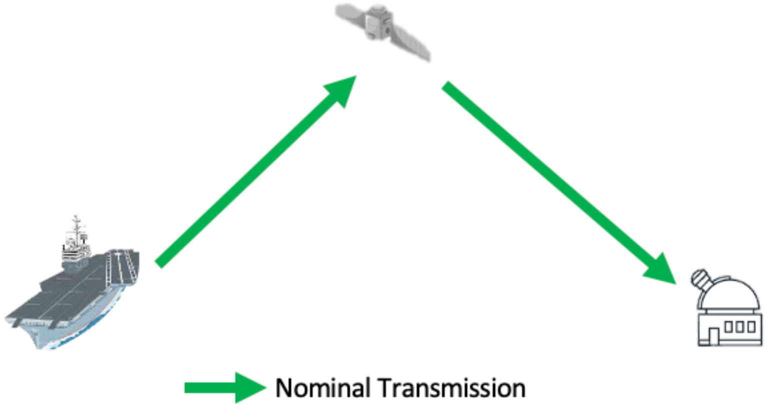

Figure 22. Nominal Maritime-based Terminal to Land-based Terminal Transmission

The third example of a nominal scenario is a maritime-based terminal to a maritime-based terminal mission narrative is as follows. User at maritime-based terminal generates message to send to maritime-based terminal. User at maritime-based terminal sends message. Message is modulated to laser. Laser is amplified and sent through optical transmitter. Laser travels through atmosphere to space-based relay. Laser is received by space-based laser receiver. Space-based relay points to maritime-based terminal. Laser received by space-based laser is modulated and amplified then sent though optical transmitter. Laser travels though atmosphere to maritime-based receiver. Maritime-based receiver receives laser. Laser is demodulated and converted into data. Data is provided to interface for receiving user. This third nominal scenario transmission path is portrayed pictorially with major FSO system subcomponents in Figure 23.

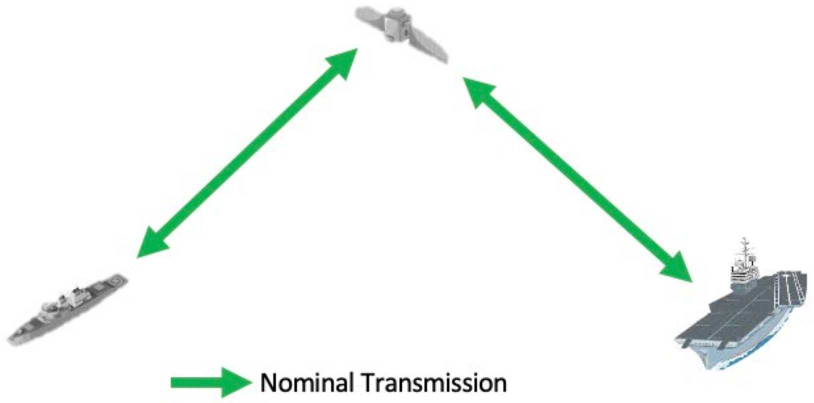

Figure 23. Nominal Maritime-based Terminal to Maritime-based Terminal Transmission

Off-nominal scenarios cover incidences where a condition has occurred that will need the system to perform in a way that is different from normal. Off-nominal scenarios include factors such as weather, scattering, absorption, and thermal turbulence. Additional possible off-nominal scenarios include obstructions or unavailable satellites. An example of an off-nominal scenario with bad weather as the limited factor will require additional terminals and space-based relays to make the transmission successful.

An off-nominal example based on the nominal scenario of a land-based terminal to a maritime-based terminal mission narrative with weather as the condition is described as follows. A user at land-based terminal receives weather from weather source to make the determination to use alternative land-based terminal. Weather is not favorable for laser transmission at originating land-based terminal. User at land-based terminal generates message to send to maritime-based terminal. User at land-based terminal sends message to alternate land-based terminal using fiber cable with weather conditions appropriate for laser transmission. Message is modulated to laser. Laser is amplified and sent through optical transmitter. Laser travels through atmosphere to space-based relay. Laser is received by space-based laser receiver. Space-based relay points to maritime-based terminal. Laser received by space-based laser is modulated and amplified then sent though optical transmitter. Laser travels though atmosphere to maritime-based receiver. Maritime-based receiver receives laser. Laser is demodulated and converted into data. Data is provided to interface for receiving user.

F. SUMMARY

This chapter presented the system analysis of the FSO OTH communication system, which is a SoS that comprises laser receivers, transmitters, and relays and the associated component platforms, (e.g., the maritime-based terminals, the land-based terminals, and the space-based relay) to use FSO to communicate OTH. The chapter included the results of the stakeholder analysis and the system analyses that produced functional models and physical models. The chapter described the traceability analysis that validated the consistency between the physical model and the functional model. Finally, the chapter contained a description of three operational scenarios that are the basis for the MP modeling that will be described in the next chapter.

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V. MONTEREY PHOENIX BEHAVIOR MODEL ANALYSIS

This chapter presents the MP behavior model and presents data from the models. The next step in the thesis research after systems analysis was the development of a model of the system using the MP framework. Three MP models were developed: one for each of the operational scenarios presented in the last chapter: (1) land-based to maritime-based, (2) maritime-based to land-based, and (3) maritime-based to maritime-based. This chapter begins with an overview of the MP methodology that was applied in this thesis research. The following three sections contain descriptions and event traces of the three operational scenarios as they were modeled in MP.

A. MP METHODOLOGY

Three different models of MP were developed to demonstrate three different one-direction transmissions from a land-based terminal to maritime-based terminal, a maritime-based terminal to a land-based terminal, and a maritime-based terminal to a maritime-based terminal. Off-nominal scenarios were accounted for as events within the model. These events are labeled in the MP code as bad weather and can be either precipitation, thermal turbulence, absorption, or scattering. These events are assumed in this code to occur at the same probability as nominal events or clear weather conditions. The coordinate functions set the precedence for specific events. There are coordinate functions in each scenario so that when there are off-nominal conditions, the system can interact appropriately with those conditions.

The models use statistics for internet speeds on page loading times which are "10.3 seconds on desktop and 27.3 seconds on mobile" to factor times for interfaces (Dean 2019). The satellite was assumed to be in a GEO orbit and at least three operable satellites were evenly spaced in orbit for maximum coverage. Satellite transmission time was calculated based on distance of the transmitter to the receiver, which is represented in the time delay equation

$$Time\ Delay = \frac{2R}{c}$$

where c is the speed of light, $3x10^8$m/s, and R equals the distance for a GEO satellite, which directly overhead is 35,780km. Total time for a signal to go from Earth to the GEO satellites and back would be 0.24s (or 0.12s one-way). The distance between the three satellites would be approximately 59620km. A one-way crosslink between two satellites would take approximately 0.2s. These times were incorporated into the MP models.

B. LAND-BASED TERMINAL TO MARITIME-BASED TERMINAL MP MODEL

This section will present the land-based terminal to maritime-based terminal results in ten different categories. Each category will be described and will be provided with an example event trace in graph view. A table will be provided at the end of the section to summarize the results. After the table, a diagram will illustrate all the possible transmission paths.

The land-based terminal to maritime-based terminal in scope 1 generated 74 traces. The nominal example, displayed in Figure 24, is expected behavior, and was generated in scope 1 trace 1 and had a total time of 73.06s. Trace 1 is the first category. In this example, the transmitting environment was clear, and the receiving environment was clear. The user generated the transmission and sent the laser transmission. The space-based relay received the laser transmission, labeled in an orange box as a composite event. The space-based relay transmitted the laser communication transmission to the maritime-based terminal and the information was displayed on an interface. There was no need to transmit to another satellite or to another terminal, as the information was received by the intended recipient.

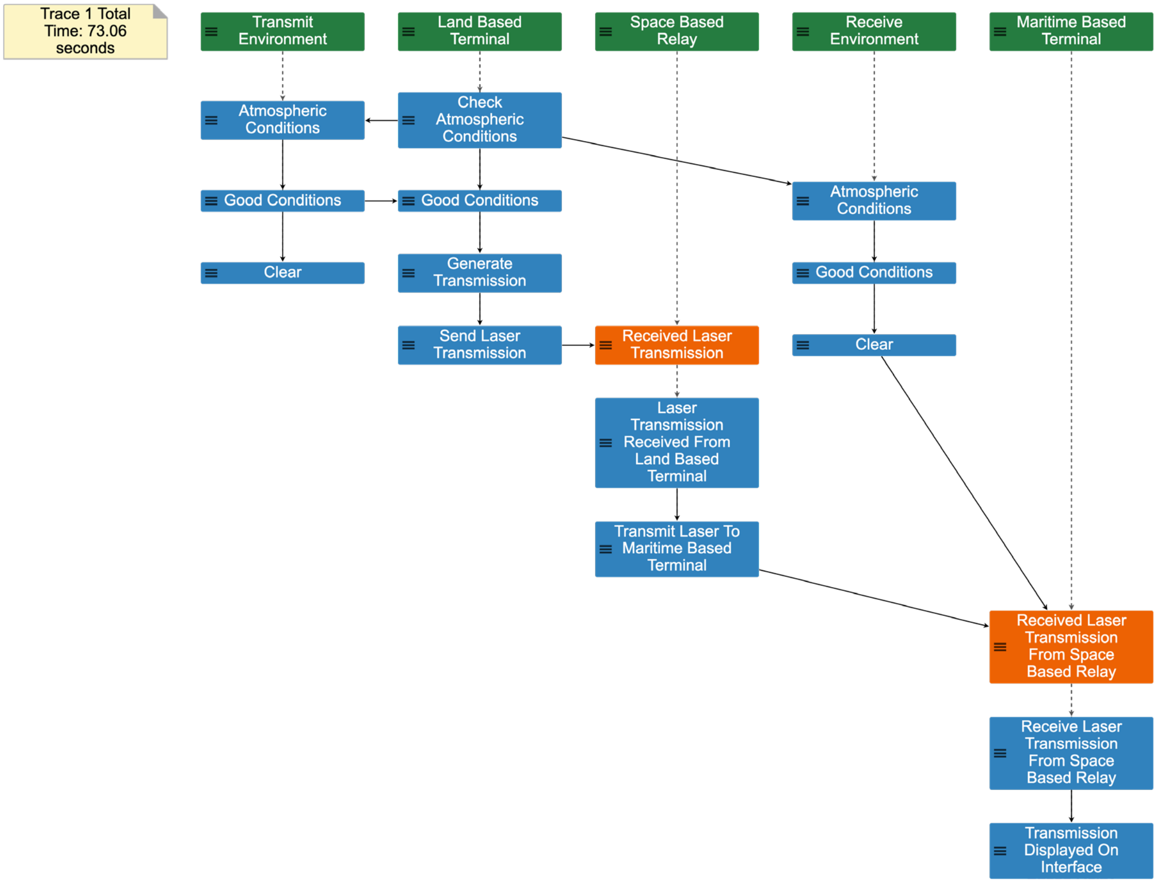


Figure 24. Nominal FSO OTH Communication from a Land-based Terminal to a Maritime-based Terminal

The other traces in the model are categorized into nine different end results (shown in Figures 22–30). The second category is good conditions at both the transmit environment and the receive environment, but the message was not received (Trace 2) shown in Figure 25. Trace 2 is an example of an unexpected behavior since the conditions at both the receive environment and the transmit environment were good, but the transmission was not successful.

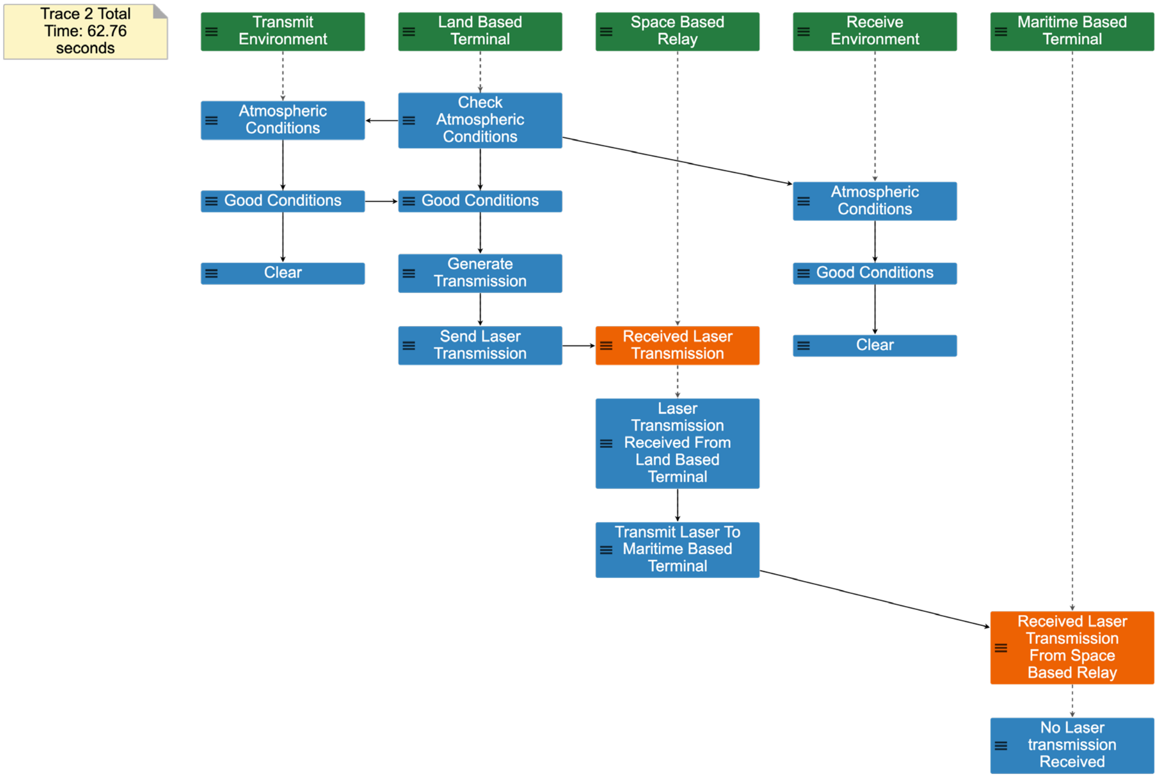


Figure 25. Land-based Terminal to Maritime-based Terminal, Unsuccessful Transmission in Good Conditions

The third category is good transmit environment conditions but bad receive environment conditions (thermal turbulence), therefore crosslink to an alternative space-based relay was required for successful transmission (Traces 3, 5, 7, and 9). Trace 5 is illustrated in Figure 26 and is an example of expected behavior.

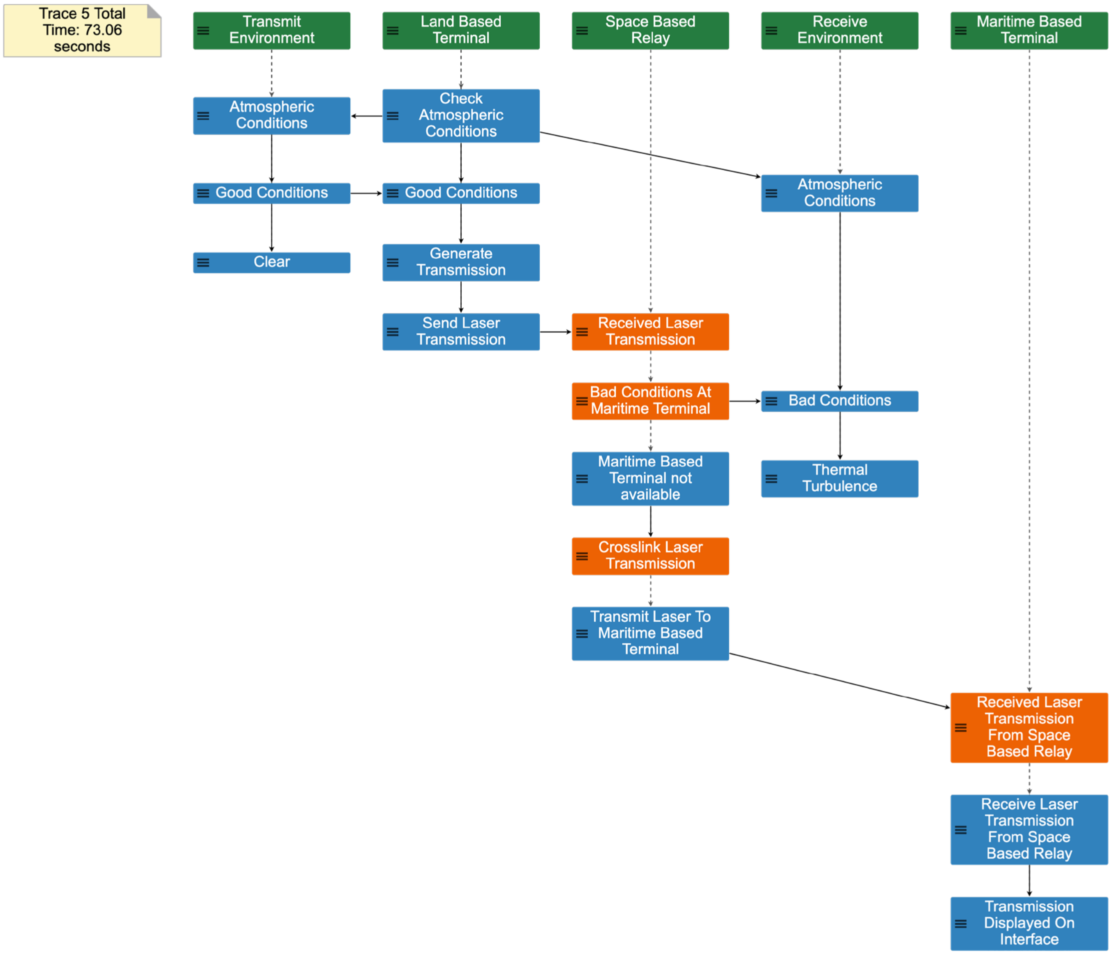


Figure 26. Land-based Terminal to Maritime-based Terminal, Successful Transmission with Crosslink

The fourth category, seen in Figure 27 with Trace 10, is good transmit environment conditions but bad receive environment conditions (scattering), therefore crosslink to an alternative space-based relay was required but the transmission was unsuccessful (Traces 4, 6, 8, 10–14). This is unexpected behavior.

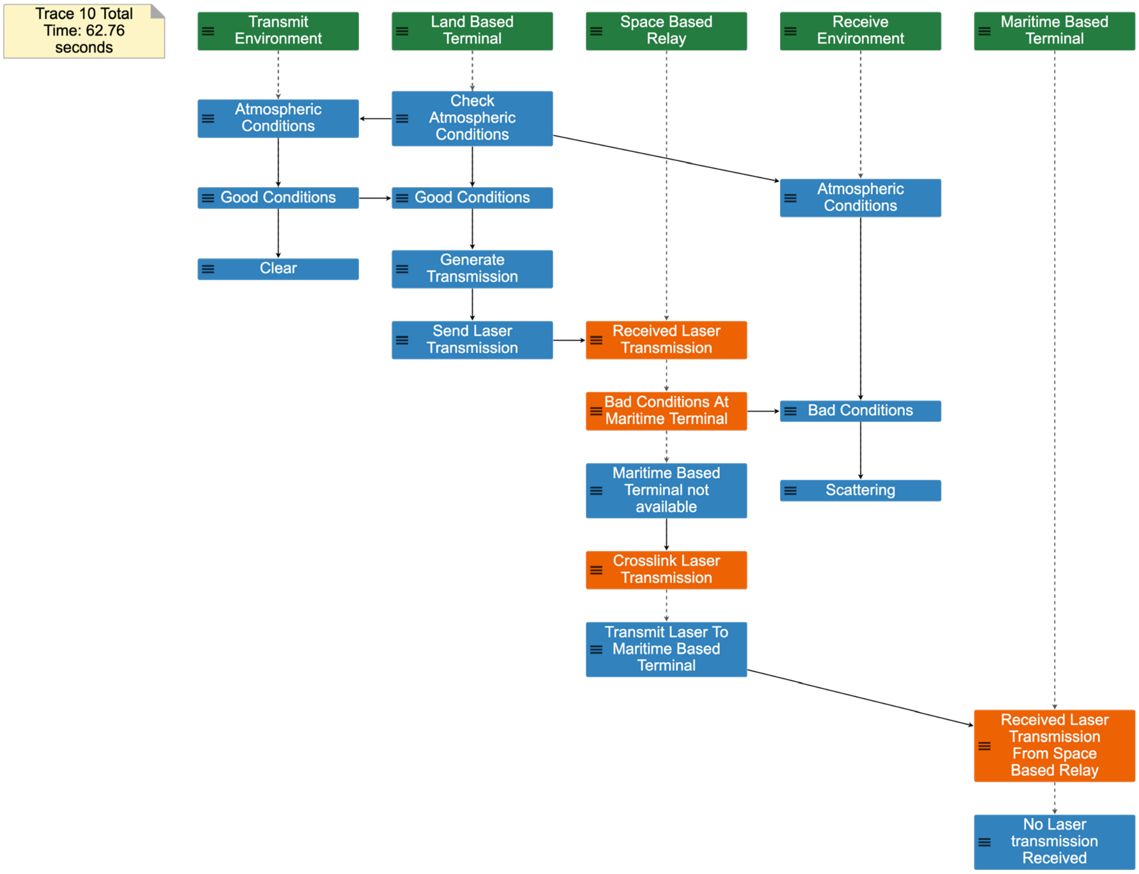


Figure 27. Land-based Terminal to Maritime-based Terminal, Unsuccessful Transmission with Crosslink

The fifth category is bad transmit environment but good receive environment, so the message was sent to another land-based terminal for transmission (Traces 15, 30, 45, and 60). This category is an example of expected behavior and is demonstrated with precipitation as the bad condition in Figure 28 from Trace 15.

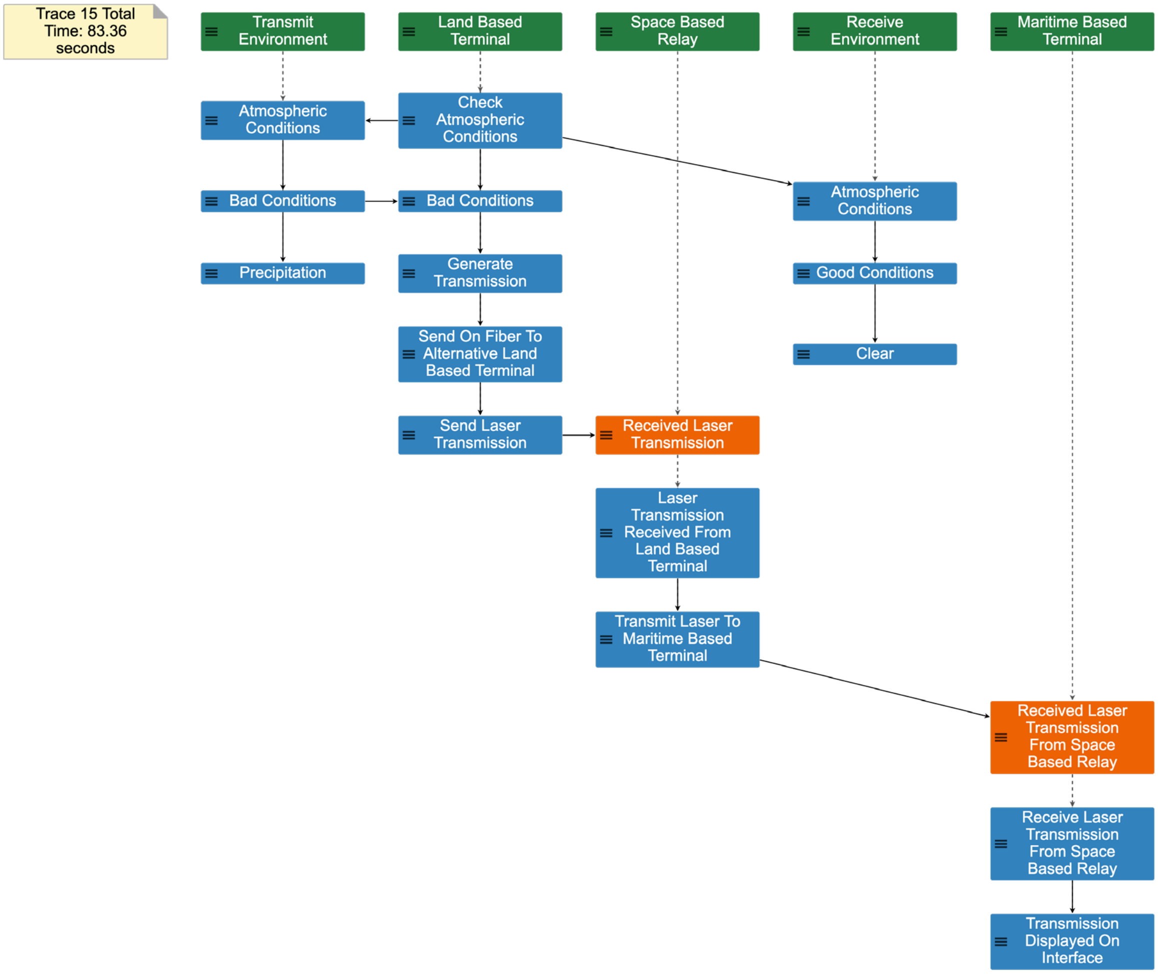


Figure 28. Land-based Terminal to Maritime-based Terminal, Successful Transmission from Alternative Land-based Terminal

The sixth category is bad transmit environment but good receive environment, so the message was sent to another land-based terminal, but transmission is unsuccessful (Traces 16, 31, 46, and 61). This is an example of unexpected behavior and Figure 29 exhibits this with Trace 61, which had a bad condition of scattering.

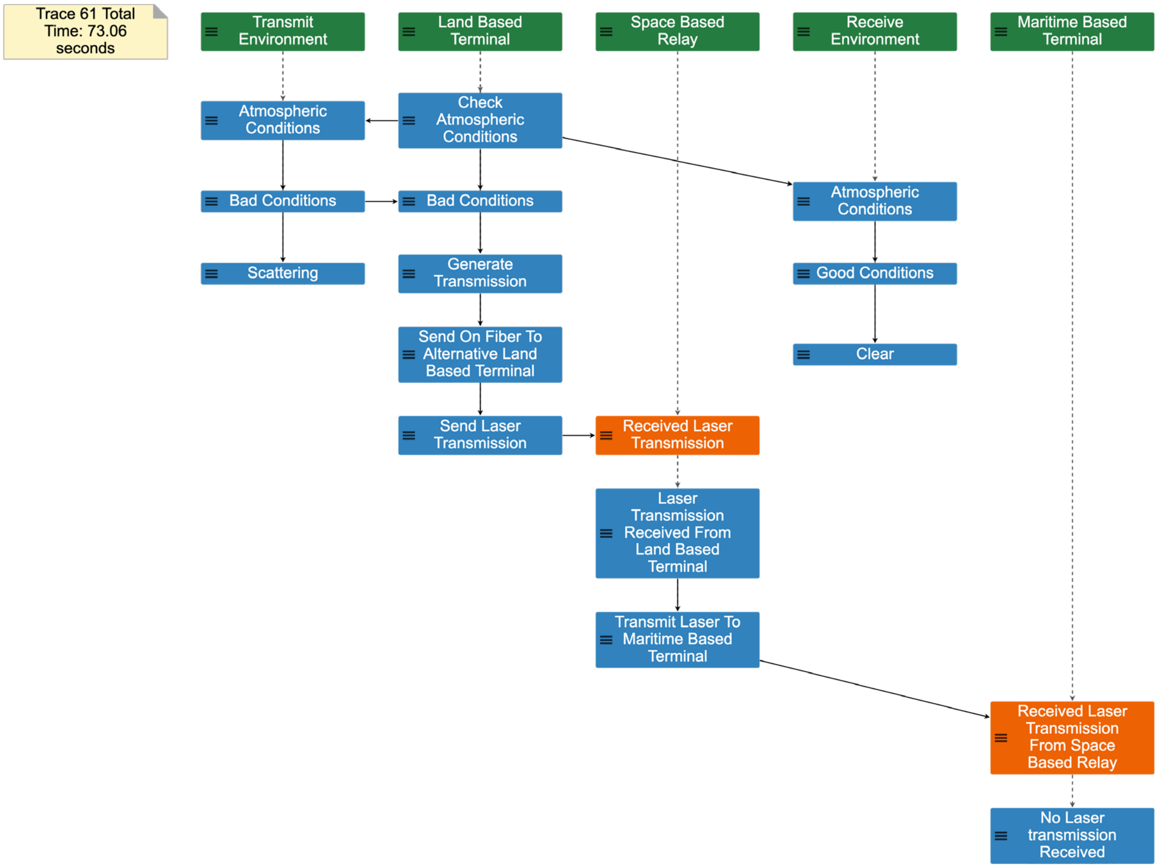


Figure 29. Land-based Terminal to Maritime-based Terminal, Unsuccessful Transmission from Alternative Land-based Terminal

The seventh category is bad transmit environment and bad receive environment. The message had to be sent to another land-based terminal for transmission and bad receive environment, so the message was crosslinked to another space-based relay to a receiving maritime-based terminal successfully (Traces 17, 19, 21, 23, 32, 34, 36, 38, 47, 49, 51, 53, 62, 64, 66, and 68). Figure 30 shows Trace 21 and is an example of expected behavior.

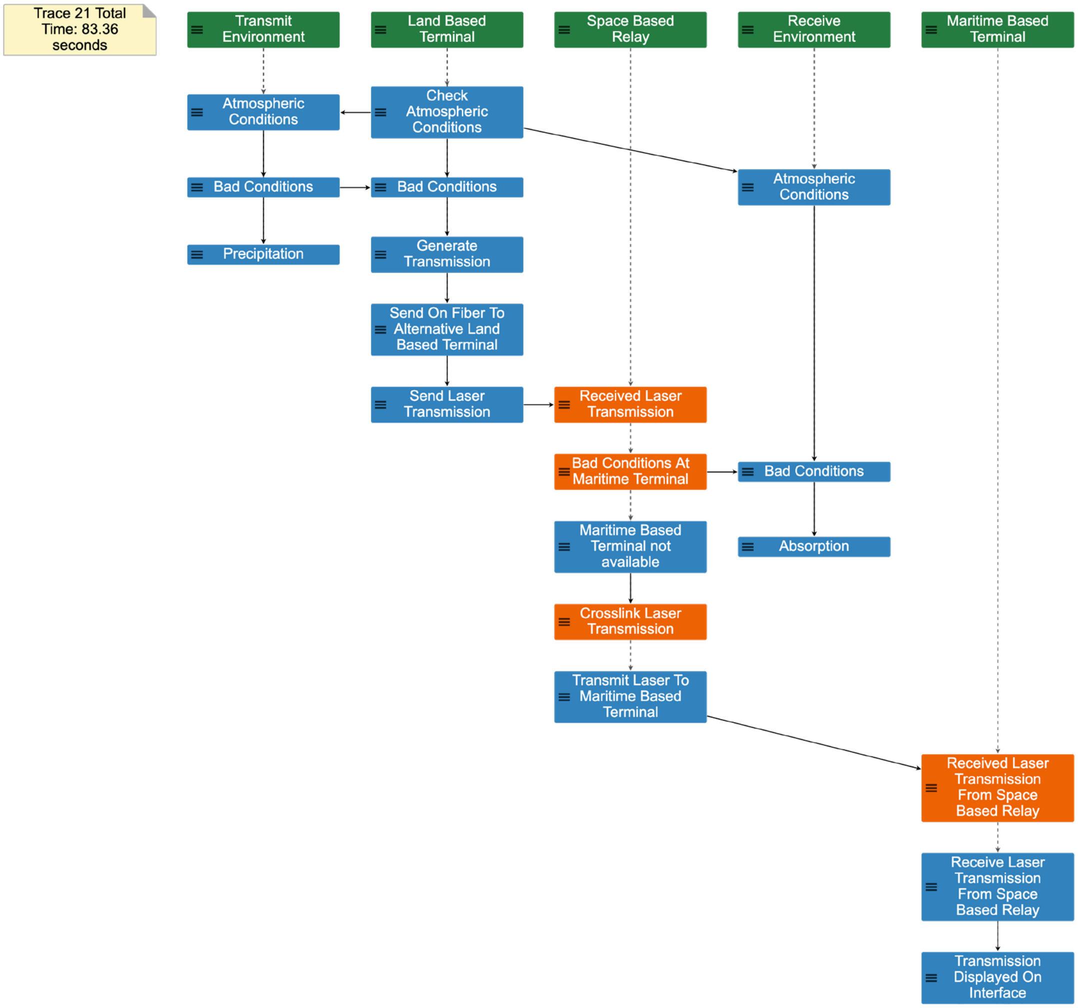


Figure 30. Land-based Terminal to Maritime-based Terminal, Successful Transmission from Alternative Land-based Terminal with Crosslink

The eighth category is an unsuccessful transmission in bad transmit environment and bad receive environment. The message had to be sent to another land-based terminal for transmission and bad receive environment, so the message was crosslinked to another space-based relay to receiving maritime-based terminal (Traces 18, 20, 22, 24, 33, 35, 37, 39, 48, 49, 50, 52, 54, 63, 65, 67, and 69). This is an unexpected behavior and is presented in Figure 31 with Trace 50.

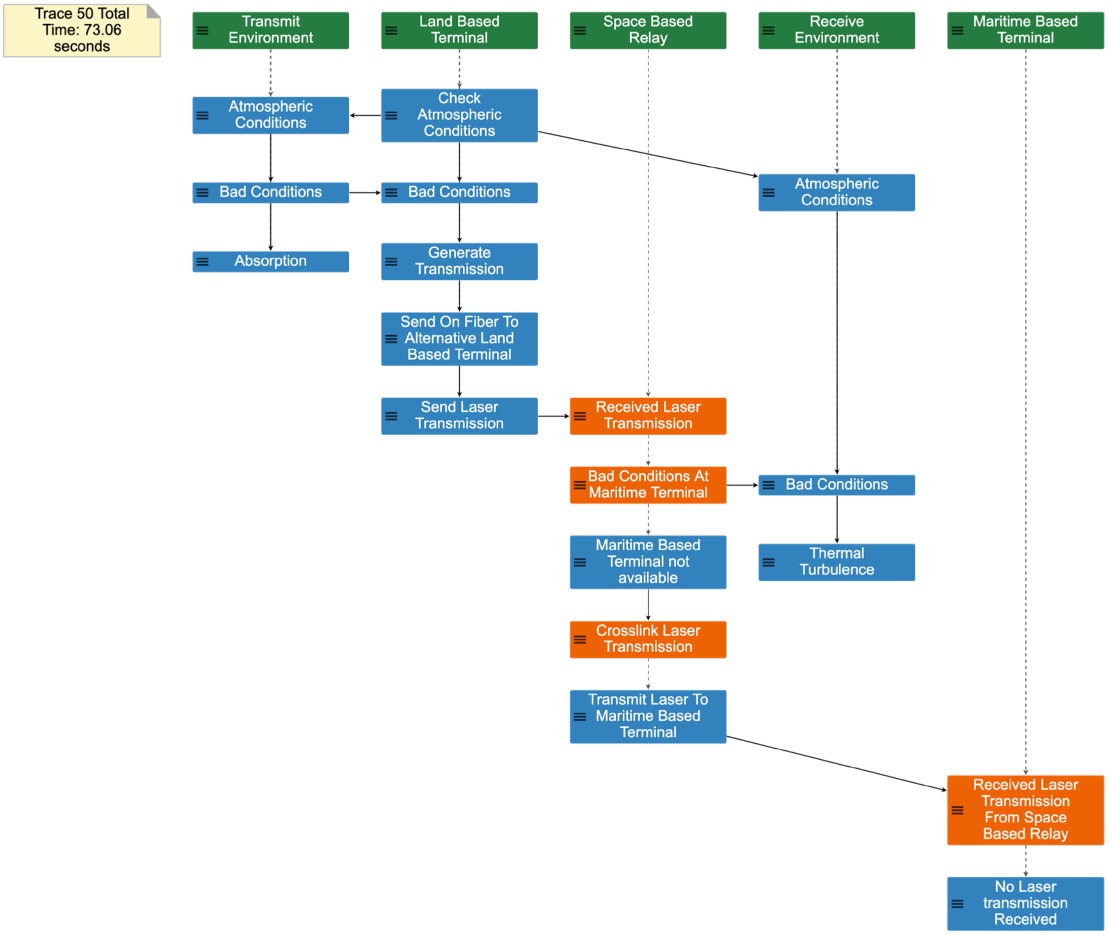


Figure 31. Land-based Terminal to Maritime-based Terminal, Unsuccessful Transmission from Alternative Land-based Terminal with Crosslink

The ninth category, Figure 32 with trace 56, is bad receive environment and bad receive environment, so the message had to be sent to another land-based terminal for transmission and was crosslinked to another space-based relay to receiving maritime-based terminal but was not received (traces 25–28, 40–43, 55–58, and 70–73). This category is expected behavior.

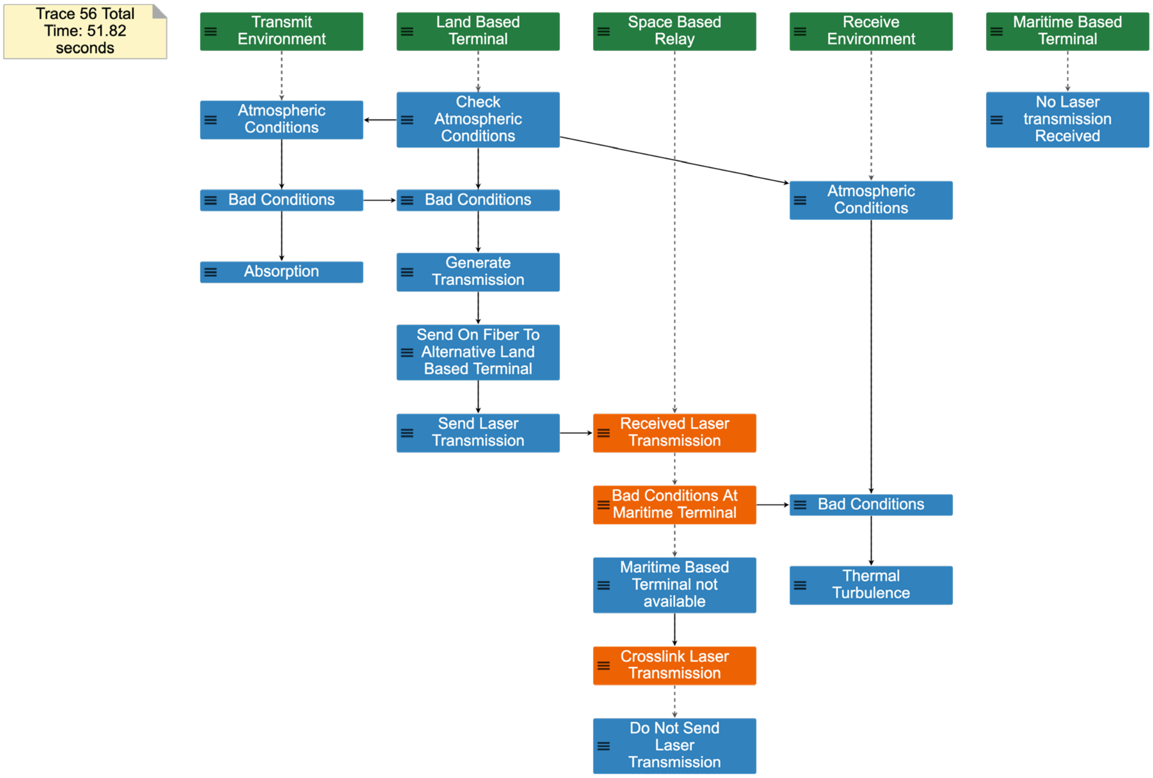


Figure 32. Land-based Terminal to Maritime-based Terminal, Unsuccessful Transmission from Alternative Land-based Terminal with Crosslink Unsuccessful

The tenth category is bad transmit environment and the message was not sent (traces 29, 44, 59, and 74). The ninth category is displayed in Figure 33 with trace 74 and is expected behavior.

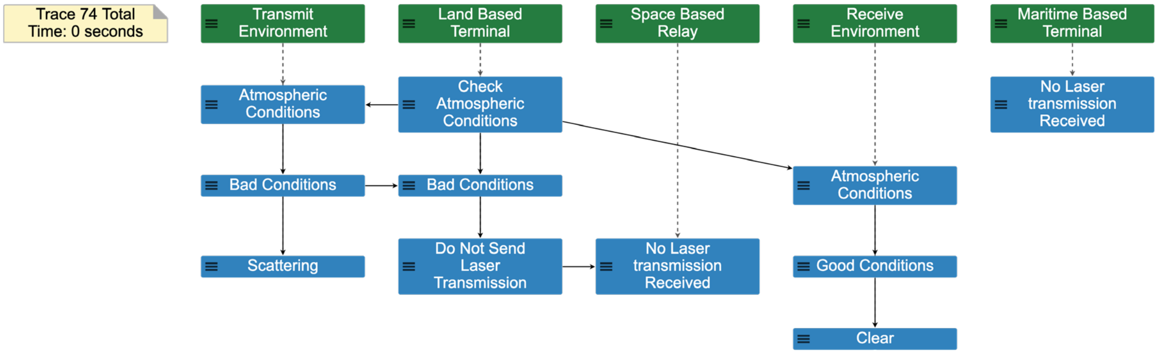


Figure 33. Land-based Terminal to Maritime-based Terminal, Unsent Transmission with Bad Conditions at Transmit Environment

A summary of the traces in the Land-based Terminal to Maritime-based Terminal by category, trace number and identification of the trace behavior as expected or unexpected is in Table 9.

Table 9. Land-based Terminal to Maritime-based Terminal Scenario Categories

Category Number	Category Description	Transmission	Trace Number(s)	Behavior Type
1	Good conditions at both the transmit environment and the receive environment	Successful	1	Expected
2	Good conditions at both the transmit environment and the receive environment	Unsuccessful	2	Unexpected
3	Good transmit environment condition, bad receive environment conditions with crosslink to an alternative space-based relay	Successful	3, 5, 7, and 9	Expected
4	Good transmit environment condition, bad receive environment conditions with crosslink to an alternative space-based relay	Unsuccessful	4, 6, 8, and 10–14	Unexpected
5	Bad transmit environment, good receive environment. Message was sent to another land-based terminal	Successful	15, 30, 45, and 60	Expected
6	Bad transmit environment, good receive environment. Message was sent to another land-based terminal	Unsuccessful	16, 31, 46, and 61	Unexpected
7	Bad transmit environment, bad receive environment. Message had to be sent to another land-based terminal for transmission. Message was crosslinked to another space-based relay to receiving maritime-based terminal	Successful	17, 19, 21, 23, 32, 34, 36, 38, 47, 49, 51, 53, 62, 64, 66, and 68	Expected
8	Bad transmit environment, bad receive environment. Message had to be sent to	Unsuccessful	18, 20, 22, 24, 33, 35, 37, 39, 48,	Unexpected

Category Number	Category Description	Transmission	Trace Number(s)	Behavior Type
	another land-based terminal for transmission. Message was crosslinked to another space-based relay to receiving maritime-based terminal		50, 52, 54, 63, 65, 67, and 69	
9	Bad receive environment, bad receive environment. Message sent to another land-based terminal for transmission and crosslinked to another space-based relay to receiving maritime-based terminal	Unsuccessful	25–28, 40–43, 55–58, and 70–73	Expected
10	Bad transmit environment conditions. Message was not sent	Unsuccessful	29, 44, 59, and 74	Unexpected

Figure 34 illustrates the land-based terminal to maritime-based terminal different scenarios. The arrows, green for a nominal scenario and red for the different alternative off-nominal scenarios, depict the direction of the transmission, solid lines depict FSO laser transmission, and dashed lines depict fiber transmission.

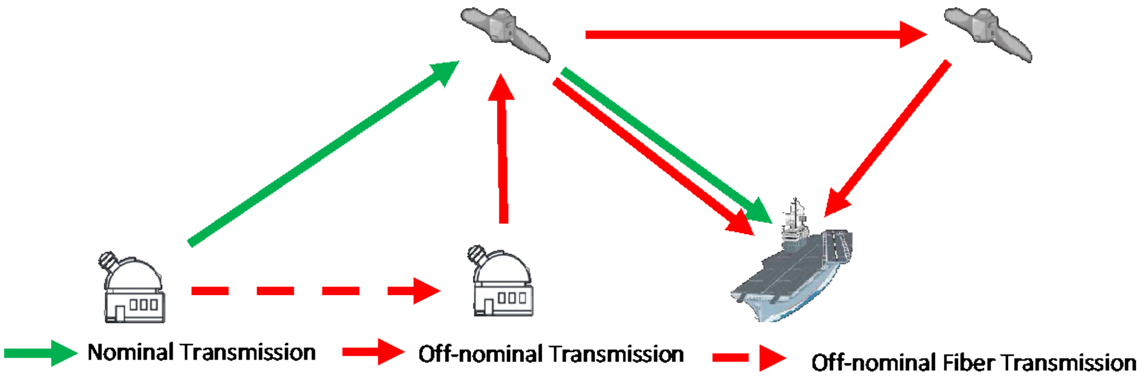


Figure 34. Land-based Terminal to Maritime-based Terminal Possible Transmission Concept

C. MARITIME-BASED TERMINAL TO LAND-BASED TERMINAL MP MODEL

This section will present the maritime-based terminal to land-based terminal results in four different categories. Each category will be described and will be provided with an example event trace in graph view. A table will be provided at the end of the section to summarize the results. After the table, a diagram will illustrate all the possible transmission paths.

The second nominal scenario is the transmission of the maritime-based terminal to land-based terminal in scope 1, which generated 10 traces. Trace 1/scope 1 is displayed in Figure 35 with a total time of 52.6 seconds and with clear conditions for transmission. In this trace, the user generated the transmission on the maritime-based terminal and sent the laser transmission to a land-based terminal. The space-based relay received the laser transmission. The space-based relay transmitted the laser beam to the intended land-based terminal and displayed it on an interface.

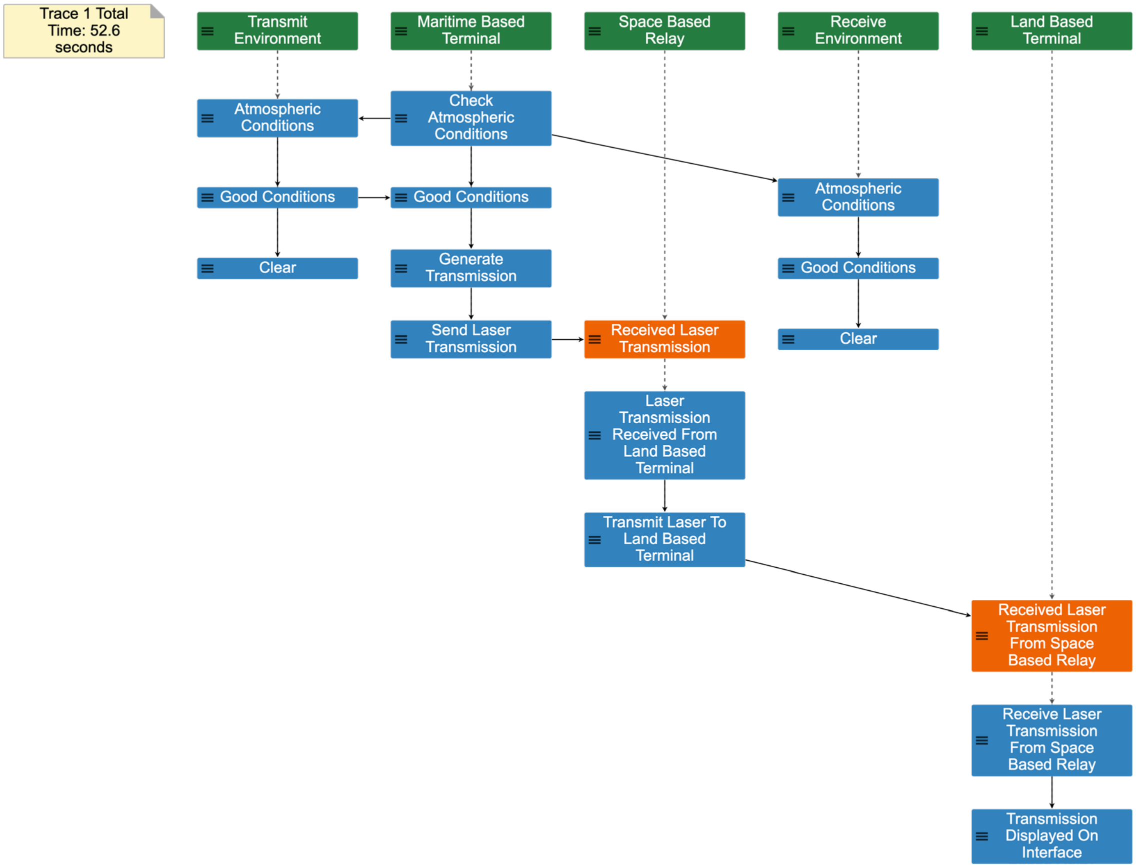


Figure 35. Nominal Successful FSO OTH Communication from a Maritime-based Terminal to a Land-based Terminal

The maritime-based terminal to a land-based terminal scenario event traces identify expected and unexpected behaviors. The low number of traces is a result of the limitations of a maritime-based terminal when atmospheric conditions inhibit laser transmissions. If a maritime-based terminal is operating independently or if in a group, weather and atmospheric conditions can influence laser communications for a significant amount of time.

Trace 2, shown in Figure 36, is an example of unexpected behavior. In this example, the atmospheric conditions are good at both the transmit environment and the receive environment. Despite the nominal conditions and the successful laser transmission to the space-based relay, the land-based terminal did not receive the laser transmission.

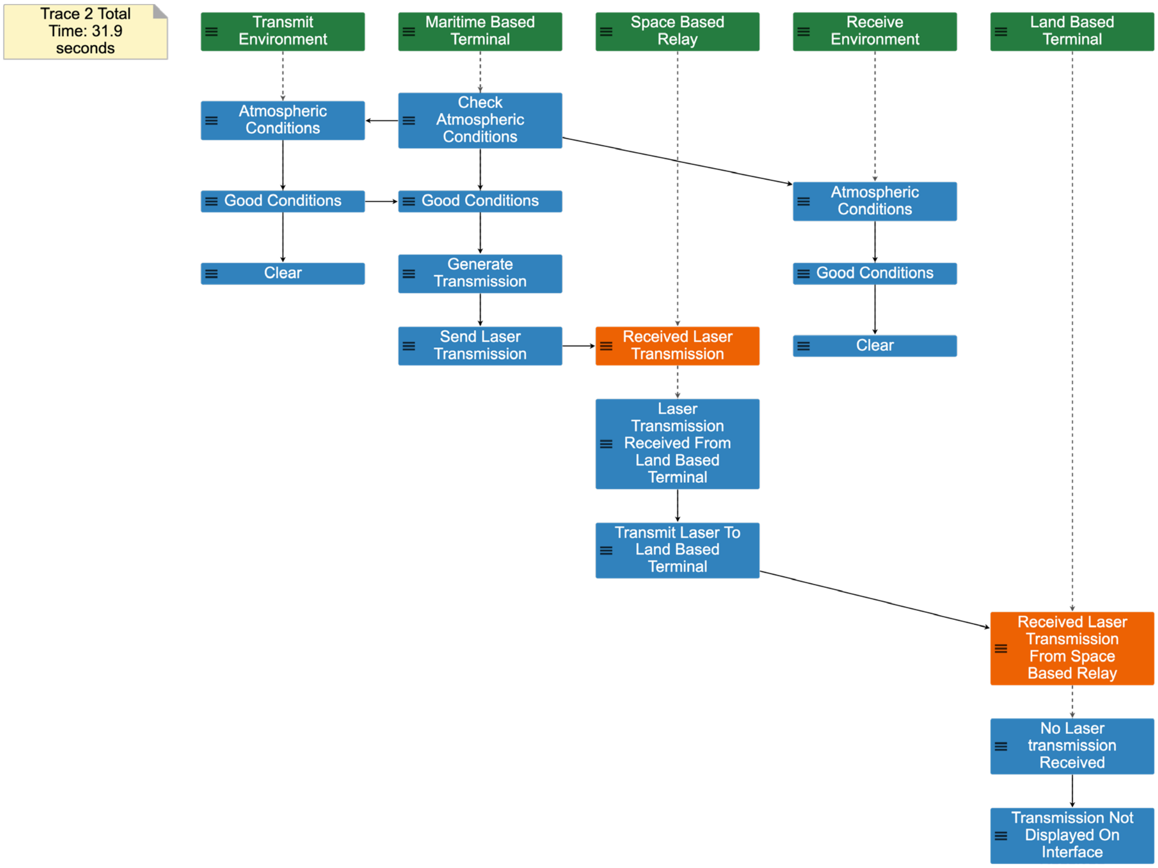


Figure 36. Nominal Unsuccessful FSO OTH Communication from a Maritime-based Terminal to a Land-based Terminal

The last two types of traces, traces 3–6 and 7–10, are expected behaviors. Traces 3–6 are successful transmissions through good conditions in the transmit environment; however, the receive environment had bad conditions and required a crosslink transmission to another satellite to transmit to an alternative land-based terminal. Figure 37 demonstrates the crosslink transmission to an alternative land-based terminal from Trace 5 due to thermal turbulence.

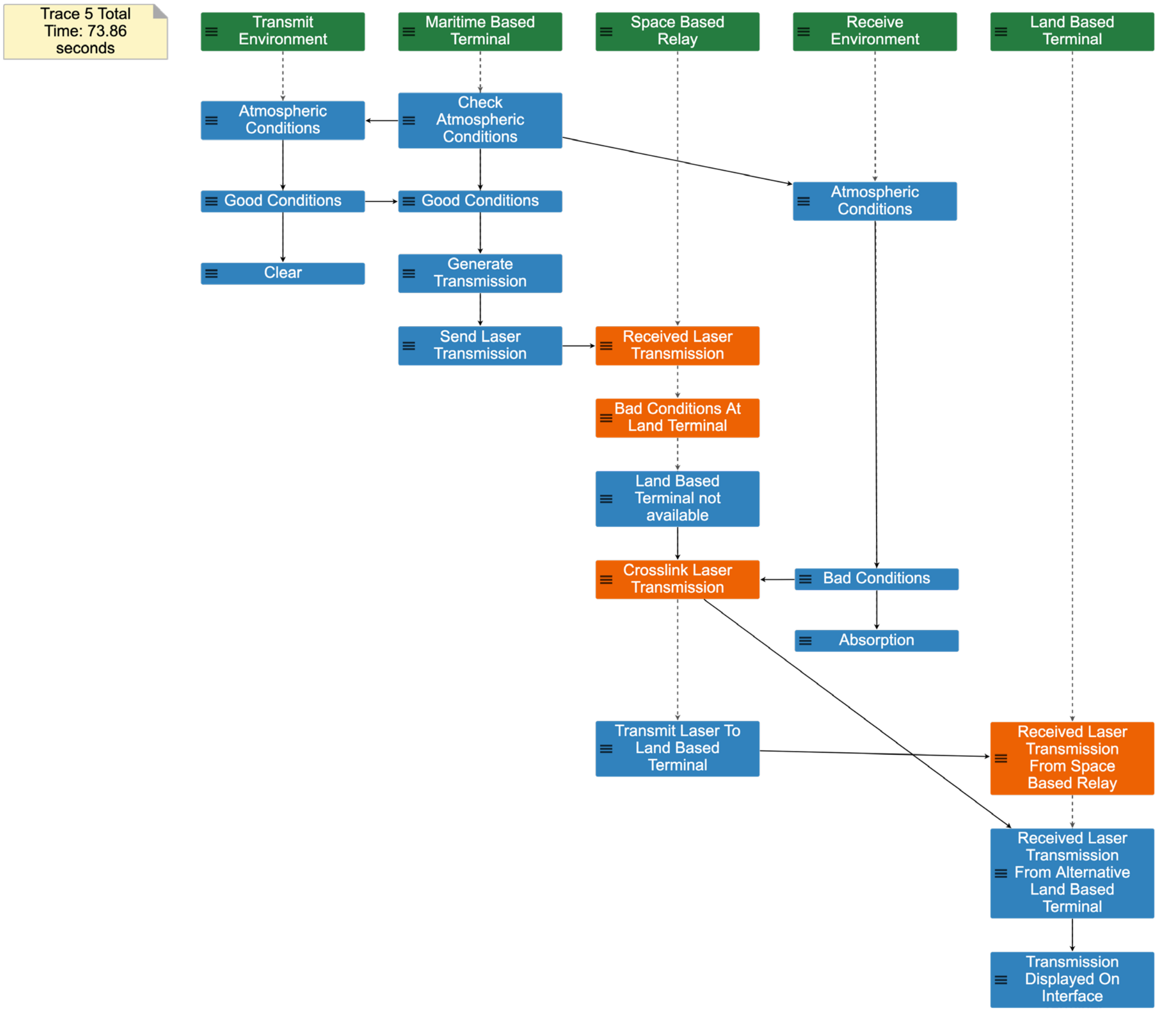


Figure 37. Off-Nominal Successful FSO OTH Communication from a Maritime-based Terminal to a Land-based Terminal

The size and speed of the atmospheric conditions can impede the ability for the maritime-based terminal to transmit laser communications. Therefore, the terminal cannot send a laser transmission if an alternative medium for communication does not exist. Figure 38 illustrates Trace 9, which has atmospheric absorption as the bad transmit environment.

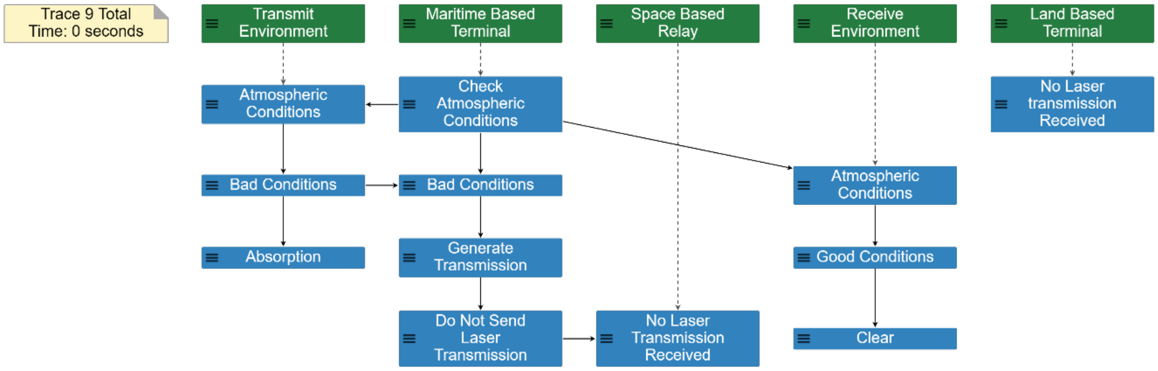


Figure 38. Off-Nominal Unsuccessful FSO OTH Communication from a Maritime-based Terminal to a Land-based Terminal

Table 10 summarizes the traces in the Maritime-based Terminal to Land-based Terminal by category. The table describes the four categories and lists whether the transmission was successful, identifies the trace numbers, and identifies whether the behavior was expected or unexpected.

Table 10. Maritime-based Terminal to Land-based Terminal Scenario Categories

Category Number	Category Description	Transmission	Trace Number(s)	Behavior Type
1	Good conditions at both the transmit environment and the receive environment	Successful	1	Expected
2	Good conditions at both the transmit environment and the receive environment	Unsuccessful	2	Unexpected
3	Good transmit environment condition, bad receive environment conditions with crosslink to an alternative space-based relay and land-based terminal	Successful	3, 4, 5, 6	Expected
4	Bad transmit environment, good receive environment	Unsuccessful	7, 8, 9 ,10	Expected

Figure 39 illustrates the transmission paths that can occur in nominal and off-nominal conditions for a laser transmitted from a maritime-based terminal to a land-based terminal. The arrows, green for a nominal scenario and red for the different alternative off-nominal scenarios, depict the direction of the transmission, solid lines depict FSO laser transmission, and dashed lines depict fiber transmission.

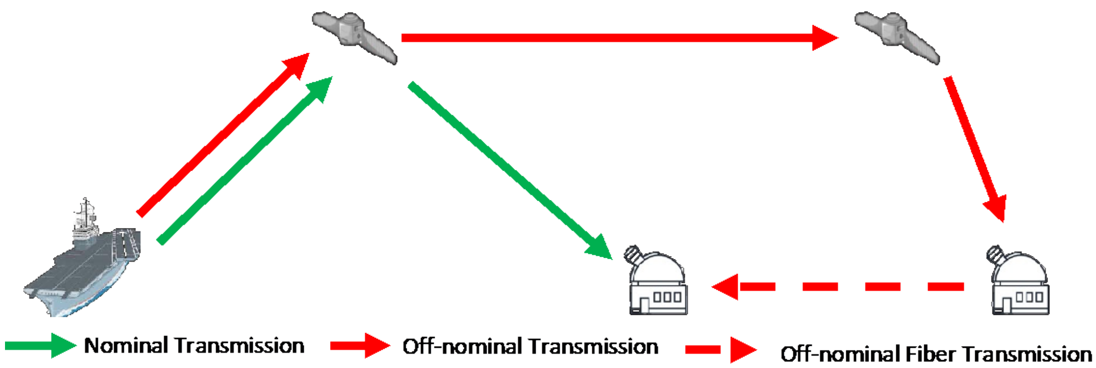


Figure 39. Maritime-based Terminal to Land-based Terminal Possible Transmission Concept

D. MARITIME-BASED TERMINAL TO MARITIME-BASED TERMINAL MP MODEL

This section will present the maritime-based terminal to maritime-based terminal results in three different categories. Each category will be described and will be provided with an example event trace in graph view. A table will be provided at the end of the section to summarize the results. After the table, a diagram will illustrate all the possible transmission paths.

The third nominal scenario that was explored in this thesis was the laser transmission of data and information between maritime-based terminals. Scope 1 generated six traces. Figure 40 shows Trace 1 in scope 1 had clear conditions and had a total time of 42.28s. In this trace, a maritime-based user transmitted information using its laser. The space-based relay received the laser transmission and then transmitted the laser beam to the other maritime-based terminal, which displayed the message. This example trace shows expected behavior for this type of scenario.

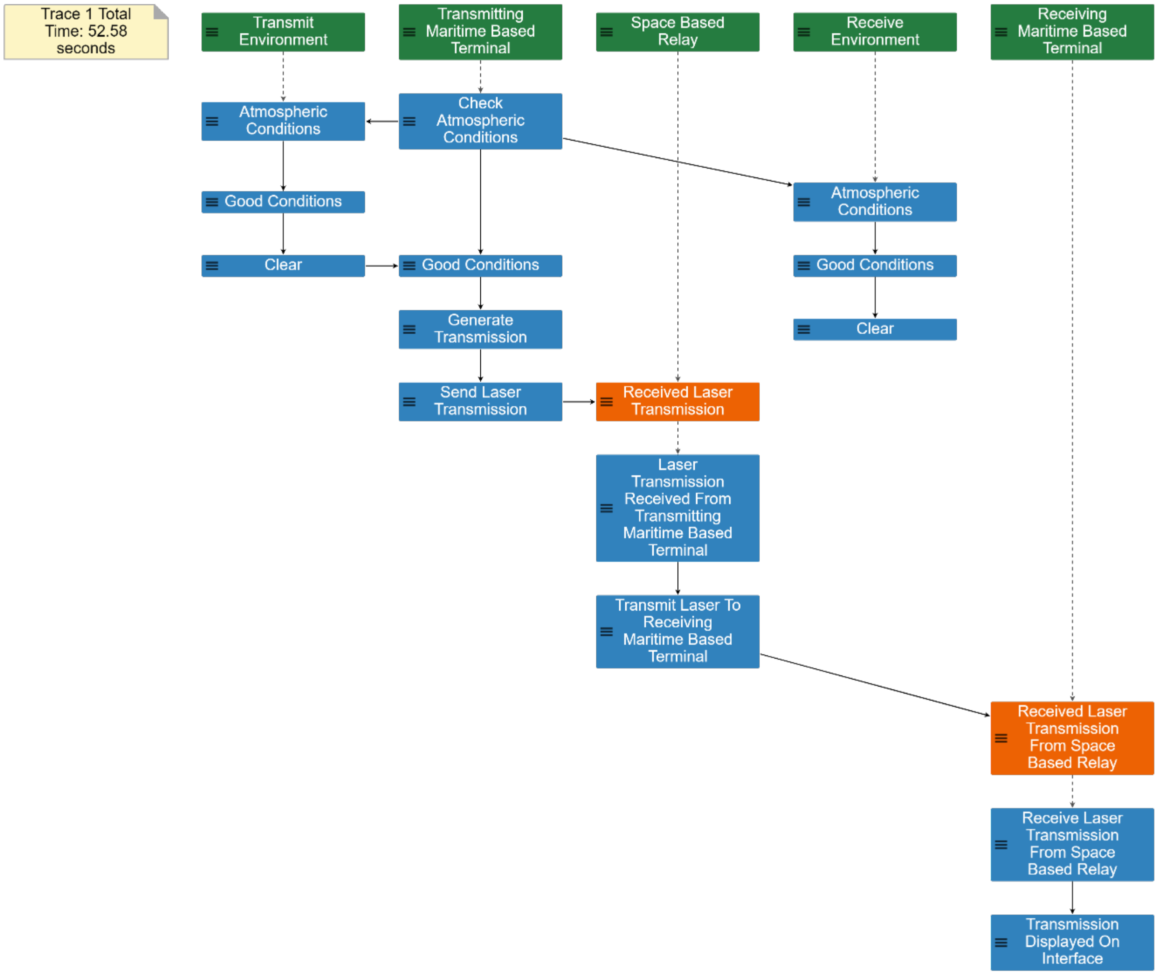


Figure 40. Nominal Successful FSO OTH Communication from a Maritime-based Terminal to another Maritime-based Terminal

Figure 41 shows Trace 2, which had clear conditions in both the receive and transmit environments. In this trace, the user generated the transmission on the maritime-based terminal and sent the laser transmission to another maritime-based terminal. The space-based relay received the laser transmission. The space-based relay transmitted the laser to the other maritime-based terminal, but the transmission was not displayed on the interface. This trace example shows unexpected behavior.

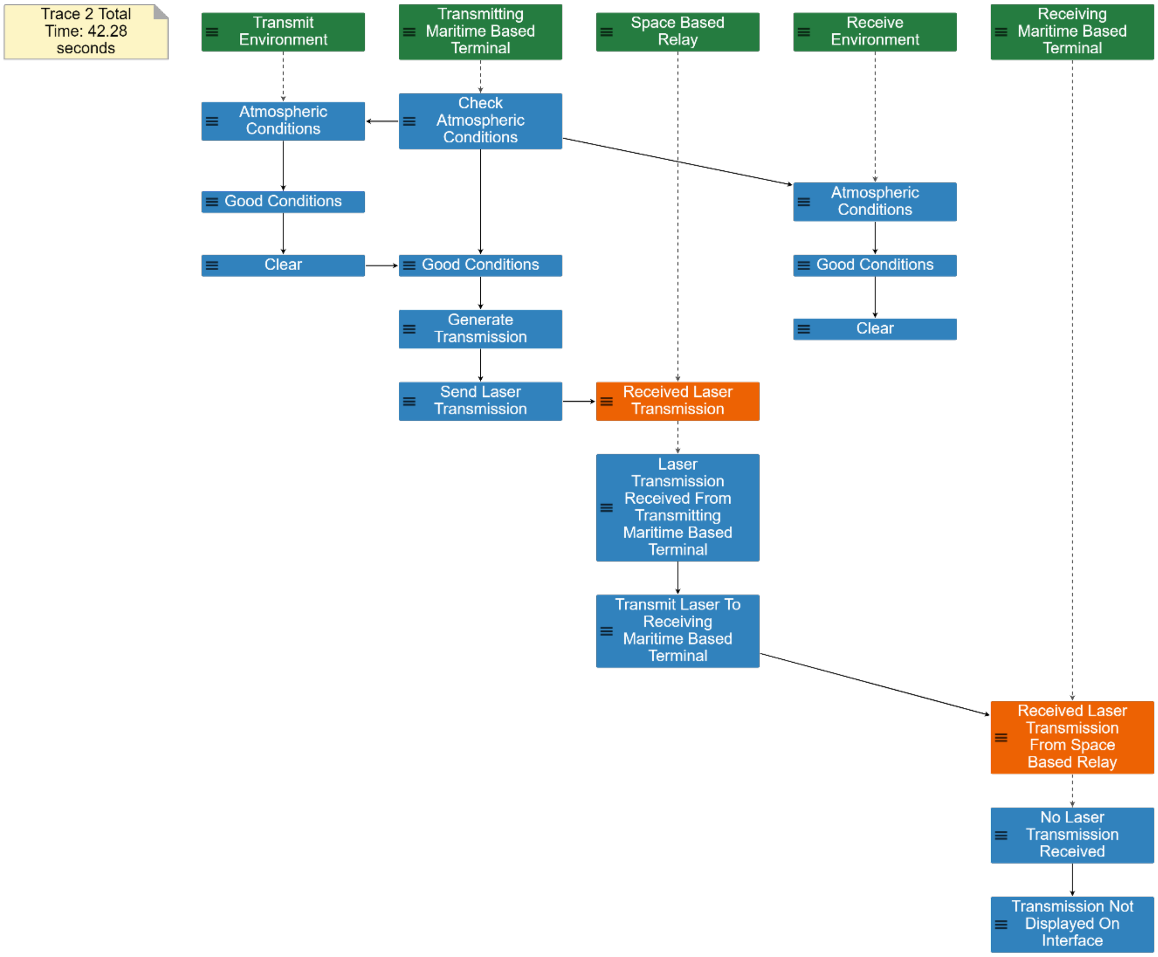


Figure 41. Nominal Unsuccessful FSO OTH Communication from a Maritime-based Terminal to another Maritime-based Terminal

Traces 3, 4, 5, and 6 were not successful transmissions and are examples of expected behavior due to bad conditions at the transmit environment. Shown in Figure 42, precipitation was the obstructing atmospheric condition.

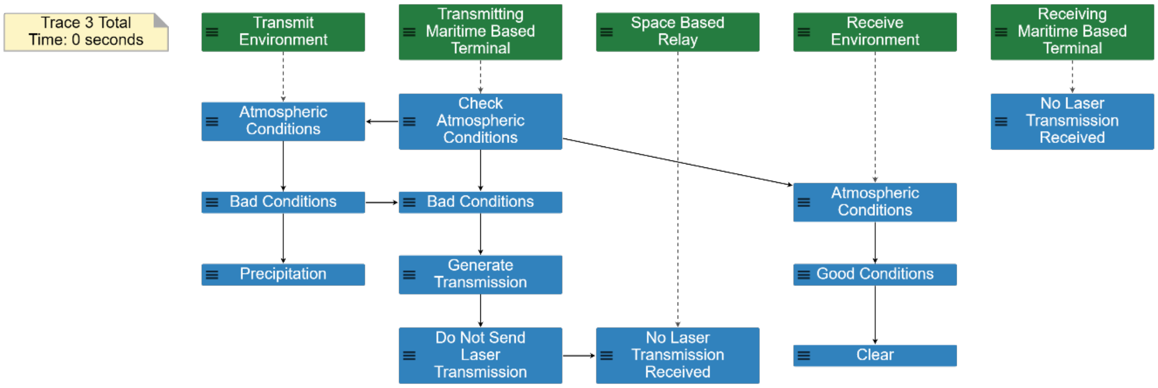


Figure 42. Nominal Unsuccessful FSO OTH Communication from a Maritime-based Terminal to another Maritime-based Terminal

A summary of the traces in the Maritime-based Terminal to Maritime-based Terminal by category, trace number and identification of the trace behavior as expected or unexpected is in Table 11.

Table 11. Maritime-based Terminal to Maritime-based Terminal Scenario Categories

Category Number	Category Description	Transmission	Trace Number(s)	Behavior Type
1	Good conditions at both the transmit environment and the receive environment	Successful	1	Expected
2	Good conditions at both the transmit environment and the receive environment	Unsuccessful	2	Unexpected
3	Bad transmit environment, good receive environment.	Unsuccessful	3, 4, 5, 6	Expected

Figure 43 illustrates the possible transmissions that can be sent from a maritime-based terminal to a maritime-based terminal. The arrows, green for a nominal scenario and red for the different alternative off-nominal scenarios, depict the direction of the transmission, solid lines depict FSO laser transmission, and dashed lines depict fiber transmission.

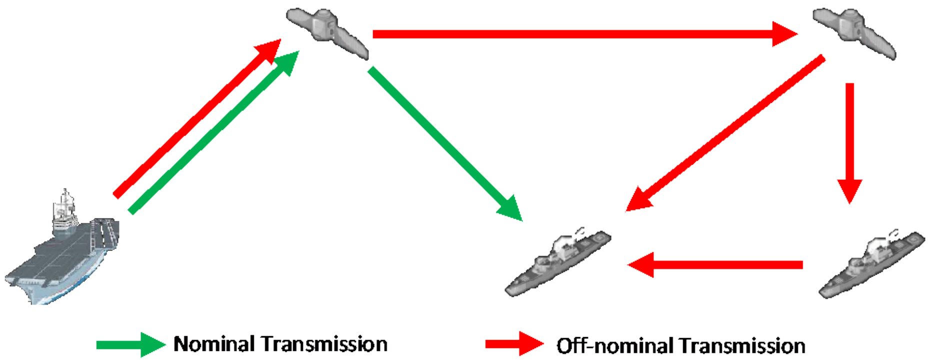


Figure 43. Maritime-based Terminal to Maritime-based Terminal Possible Transmission Concept

A closer look at each of the event traces in each model reveals a pattern of expected and unexpected behavior traces. The number of event traces are significantly different in each model. This is due, in part, to the model coordinate syntax. The coordinate functions in the maritime-based terminal to maritime-based terminal made the model too restrictive, producing a small unrealistic trace set. The other reason is that this type of communication, depending on the direction of communication, had limited alternatives using FSO as the communication medium due to weather and maneuvering limitations. Atmospheric conditions, maritime environments, and mission objectives can make FSO communications difficult; however, the challenges are beneficial due to high data rate transmission and low susceptibility to jamming and spoofing.

E. SUMMARY

This chapter presented the MP model and analysis that captured the conceptual system's behavior. The MP model captured three scenarios developed from the CONOPS: land-based terminal to maritime-based terminal communication, maritime-based terminal to land-based terminal communication, and maritime-based terminal to maritime-based terminal communication. These scenarios were developed from examples of nominal events. The MP modeling analysis produced off-nominal events that would constrain communications up to the space-based relay or down to the receiving terminal. The off-nominal events would occur due to atmospheric effects that negatively impact communication and laser operations. The MP models used the physical models and scenarios to observe emergent behavior. The atmospheric effects for off-nominal conditions used in the MP models included precipitation, thermal turbulence, absorption, and scattering. The models produced 74 event traces in the land-based terminal to maritime-based terminal communication MP model, ten event traces in the maritime-based terminal to land-based terminal communication MP model, and six event traces in the maritime-based terminal to maritime-based terminal communication MP model. The event traces uncovered several examples of expected and unexpected emergent behavior.

VI. RESULTS ANALYSIS

This chapter presents the results of the system and MP modeling analysis that were described in Chapters IV and V. This chapter begins with a discussion of the benefits and shortfalls or constraints of the analysis and subsequent results. The next section summarizes the results of the MP modeling analysis, indicating successful and unsuccessful transmission and transmission times. Next, the chapter describes the emergent behavior of the FSO laser transmission concept based on the MP modeling analysis, examining unexpected behavior and root causes. Finally, the chapter discusses how the validated the needs requirements.

A. BENEFITS AND SHORTFALLS OF RESULTS

The results analysis in the previous chapter focused on the MP model to verify the requirements and the functional, physical, and conceptual models. The three MP models produced different numbers of traces. The land-based terminal to maritime-based terminal significantly produced the highest number of event traces. This is because of the constraints that the maritime-based terminal to land-based terminal scenario and the maritime-based terminal to maritime-based terminal scenario required to make the code produce event traces that were realistic and practical. An example of this would be that if the transmitting terminal did not send a transmission due to bad conditions, then the receiver should not receive a transmission.

The coordinate functions are used to set precedence for events; however, the coordinate functions constrain the MP code. Coordinate functions, depending on the root events, composite events, and atomic events, limit the number of event traces that the code produces. The code in the maritime-based terminal to land-based terminal scenario and the maritime-based terminal to maritime-based terminal scenario is written with more possible events in the third root event. The higher the number of possible events at the end of a possible trace combined with the coordinate functions necessary to make the traces feasible produced ten and six event traces respectively. Depending on the scenario and the code, MP can be a limiting factor when trying to compare scenarios that have slightly different event paths.

Despite the MP model's constraints, MP was able to provide behavior information about the conceptual FSO OTH Communication System. Giammarco and Auguston (2013, 282) stated that "the MP approach is a force multiplier for system architects that is open for implementation in any academic, government, or commercial modeling tool or environment whose objective involves architecting complex systems." This statement holds validity regarding complex systems. MP is a constructive method to model and analyze system architecture behavior.

B. RESULTS OF MODEL TESTING

The three MP models provide several examples of the FSO OTH communication system working as intended. Table 12 depicts the total number of successful and unsuccessful transmissions for each type of scenario. The first scenario, a transmission from a land-based terminal to a maritime-based terminal, had almost twice as many unsuccessful transmissions as successful transmissions. The second scenario, a maritime-based terminal to land-based terminal transmission, performed an equal number of successful transmissions to unsuccessful transmissions. The third scenario, a maritime-based terminal to maritime-based terminal, had only one successful transmission and five unsuccessful transmissions.

Table 12. MP Model Mission Outcome Totals

MP Model Scenario	Successful Transmissions	Unsuccessful Transmissions
Land-based Terminal to Maritime-based Terminal	25	49
Maritime-based Terminal to Land-based Terminal	5	5
Maritime-based Terminal to Maritime-based Terminal	1	5

In terms of time, the MP models had varying results. Table 13 displays the transmission times for the first scenario, a land-based terminal to a maritime-based terminal. A nominal scenario transmission with good conditions at both the transmit and receive environment occurs in 73.06 seconds for 25 different traces. The longest time to send a transmission in this scenario was 83.36 seconds (occurred in 20 of the event traces). This longer time was due to because of bad conditions at both the transmitting terminal and the receiving terminal, requiring an alternative land-based terminal to make the transmission to the space-based relay then crosslink the transmission to another space-based relay to an alternative maritime-based terminal. If the transmission was transmitted from the land-based terminal and then relayed by the space-based relay but was not received by the maritime-based terminal as in 5 of the event traces, the transmission took 62.76 seconds. Since the transmission was not received, feedback notification would be required to be sent back to the transmitting terminal. This feedback notification of non-receipt would be vital so that another transmission could be sent to ensure proper communication.

Table 13. Land-based Terminal to Maritime-based Terminal Scenario Event Traces in Seconds

Land-based Terminal to Maritime-based Terminal Scenario Event Traces	Total Traces	Time (s)
29, 44, 59, 74	4	0
11, 12, 13, 14	4	41.52
25, 26, 27, 28, 40, 41, 42, 43, 55, 56, 57, 58, 70, 71, 72, 73	16	51.82
2, 4, 6, 8, 10	5	62.76
1, 3, 5, 7, 9, 16, 18, 20, 22, 24, 31, 33, 35, 37, 39, 46, 48, 50, 52, 54, 61, 63, 65, 67, 69	25	73.06
15, 17, 19, 21, 23, 30, 32, 24, 36, 38, 45, 47, 49, 51, 53, 60, 62, 64, 66, 68	20	83.36

Four of the event traces involved bad atmospheric conditions at the receiver's location requiring a crosslink to another space-based relay. These events took 41.52 seconds but resulted in a communication failure as the space-based relay was unable to transmit to the land-based terminal. This type of event could occur, as it did in traces 11–14, because the relay determined that the transmission would not be successful. If the transmit environment has bad conditions and successfully transmitted out of an alternative land-based terminal and the receive environment also had bad conditions requiring a crosslink, but the alternative space-based relay did not transmit to the receiving maritime-based terminal since the relay determined an unsuccessful transmission, then the alternative relay can determine that the transmission would not be successful. If the transmitting and receive environments are bad, the user can determine that the transmission should not be sent and therefore it would not have a transmission time.

The second scenario times are presented in Table 14. The maritime-based terminal to land-based terminal nominal transmission Trace 1 occurred in 52.6s. An off-nominal scenario which the transmission was sent from the maritime-based terminal to space-based relay and then the land-based terminal but was not received by the land-based terminal took 31.9s since it was not processed by the interface, as indicated in Trace 2. Traces 3–6 are successful transmissions in 73.86s from the maritime-based terminal but require a crosslink to an alternative space-based relay due to bad conditions at the receive environment. Traces 7–10 do not have transmission times since the user determined that the transmission should not be sent due to the bad conditions.

Table 14. Maritime-based Terminal to Land-based Terminal Scenario Event Trace Times in Seconds

Maritime-based Terminal to Land-based Terminal Scenario Event Traces	**Total Traces**	**Time (s)**
7, 8, 9, 10	4	0
2	1	32.9
1	1	52.6
3, 4, 6	3	73.86

The trace times for the third scenario, a maritime-based terminal to maritime-based terminal, are displayed in Table 15. The nominal condition for this scenario is demonstrated in Trace 1, which occurred in 52.58s. This time is like the nominal condition in the second scenario. Trace 2 had good conditions at both the transmit and receive environments, and the transmission was relayed by the space-based relay but was not received by the receiving maritime-based terminal. The transmission time for this type of transmission lasted 42.28s. Traces 3–6 did not have a transmission time since the user determined that the laser should not be sent due to the bad conditions. A maritime-based terminal can experience bad conditions for a significant amount of time due to the slow speeds that maritime-based terminals transit. Additionally, operational requirements may require maritime-based terminals to remain in bad conditions inhibiting FSO communications.

Table 15. Maritime-based Terminal to Land-based Terminal Scenario Event Traces Scenario Event Trace Times in Seconds

Maritime-based Terminal to Maritime-based Terminal Scenario Event Traces	Total Traces	Time (s)
3, 4, 5, 6	4	0
2	1	42.28
1	1	52.58

Overall, OTH Laser communication transmissions are fast, less than two minutes, despite atmospheric conditions being a significant constraining factor. The transmit times are impacted by the decision to send or not send the transmission from the transmission terminal to the relay and subsequently from the relay to the intended receiver. The transmissions that were sent but not displayed on the interface require feedback to the transmitter so another transmission can be sent provided that the conditions are appropriate for transmission. This feedback would require time to realize that the transmission was not received, time to provide feedback to the transmitter, and then time to send another message essentially quadrupling the time it took to send the first message. User feedback will have to be based on expected transmission time, so time delays are minimized. The event traces that do not have a time does not consider bad weather conditions that a user observes from a DMSP source and decides not to send the FSO transmission. Atmospheric conditions have a significant impact on laser communication, especially in the maritime environment. This limitation of laser communication would be accounted for in user training and normal operations.

C. ANALYSIS OF EMERGENT BEHAVIOR

Emergent behavior exists in every system. Emergent behavior in a system is defined by Crawley et al. (2016, 10) as "what appears, materializes, or surfaces when a system operates." Emergent behavior in this system is unexpected behavior in the MP models from all scenarios. Crawley et al. (2016, 11) further elaborated that emergent value derived from function and performance "emerge over the life cycle of the system." The small scope used in the MP model exposes the emergent behavior since emergence, based on the Small Scope Hypothesis, can arise from small iterations. This thesis thus specifies emergent behavior as unexpected behavior, successful or unsuccessful, that may occur during system operation in the MP model. Table 13 displays the total number of expected behaviors and unexpected behaviors for each scenario.

Table 16. MP Model Mission Behavior Expectancy

MP Model Scenario	Expected Behavior	Unexpected Behavior
Land-based Terminal to Maritime-based Terminal	41	25
Maritime-based Terminal to Land-based Terminal	9	1
Maritime-based Terminal to Maritime-based Terminal	5	1

There is a higher number of expected behavior than unexpected behavior observed within each scenario and across all scenarios. The expected behavior includes event traces that are successful and unsuccessful. In completely clear conditions, the system should enable a user in a transmitting terminal to generate a transmission and communicate OTH to a receiving terminal for a user to interpret on an interface. Additionally, a user should be able to determine a successful transmission prior to sending by observing the weather and atmospheric conditions. The relay could prevent a transmission from occurring if the conditions are not conducive to FSO communication. The functional requirement of reliability requires that the system contains integration with DMSP satellite sources and automation to stop transmissions if conditions are not ideal, such as in the land-based terminal to maritime-based terminal scenario Event Traces 11−14. All the expected behaviors occurred in each of the MP models.

Unexpected events common to each scenario occurred in Trace 2 which has clear conditions at the transmit and receive environments and in which the relay received and transmitted the signal to the intended receiver, but the transmission was not received. This emergent behavior of the FSO OTH Communication System occurred in the event trace for a reason that is outside the atmospheric condition constraint. Although minimal user training for operations is a performance requirement, user error can impact the ability to receive a transmission, or a cause could be that a ship was required to turn covering the receiver. The harsh environment of ocean operations also has numerous effects on equipment including sea salt encrustation and corrosion which can be factors to limiting FSO communication. These factors can apply to Event Traces 16, 31, 46, and 61 which required a transmission to an alternative land-based terminal and to Event Traces 18, 20, 22, 24, 33, 35, 37, 39, 48, 50, 52, 54, 63, 65, 67, and 69 in the first scenario which required a transmission to an alternative land-based terminal and a crosslink to an alternative space-based relay. These event traces had the same result of the maritime-based terminal not receiving the transmission despite the space-based relay sending the transmission to the maritime-based terminal receiver.

There are conditions that exist which the land-based terminal and alternative land-based terminals have bad weather or are simply not available. In the first scenario, a land-based terminal to maritime-based terminal, Traces 29, 44, 59, and 74 had bad conditions at the transmit environment but good conditions at the receive environment. However, the transmission was not sent in these event traces even though the land-based terminal had the option to send the transmission to an alternative land-based terminal for transmission. Possible reasons could be that the land-based terminals were not available since they were all impacted by bad atmospheric conditions or there was damage to a land-based connection, or the system was affected by a cyber-attack.

The emergent behavior in the FSO OTH Communication System is analogous for all types of transmissions because the scenarios use the same system components. However, the first scenario developed the most emergent behavior event traces in the MP model. This is mostly because of the significantly higher number of event traces compared to the other scenarios. Therefore, the first scenario will have more emergent behavior examples. Despite not having many event traces, similar emergent behavior is likely in the second and third scenarios despite the outcome results of the second and third scenario MP models.

D. REQUIREMENTS VERIFICATION AND VALIDATION ANALYSIS

The laser communication system developed using FSO and space-based relays for OTH communication was modeled after conducting a requirements analysis. The MP model results provided examples on how the FSO OTH Communication system can be used successfully and unsuccessfully. Based on these results, the model verified and validated many of the stakeholder, operational, functional, and performance requirements. The safety requirements are assumed satisfied, as the users have not been exposed to hazards nor have the users been harmed during operation.

The operational requirements of capability, maintainability, repairability, survivability, and availability and reliability were able to be examined or assumed, in full or partly, in the MP model. The maintainability, repairability, survivability, and availability and reliability requirements are assumed to be met in the MP model since it cannot be modeled. The capability requirement entails high data rates, which is assumed, and fast, precise, and reliable OTH communication. The results indicate that communication transmission is fast, taking less than two minutes for the longest transmission.

The FSO OTH Communication System's precision is not enough to have a 99% reliability. The system's precision can be assessed with the emergent behavior results. Table 17 shows the transmission traces and total transmissions that were sent to the intended receivers successfully as precise transmissions and the transmissions that were unsuccessful as non-precision traces. These precise traces do not include traces that were not sent by the user or the relay. The first scenario had 24 precise traces and 26 non-precise traces, or about 48% precise traces of the total traces that had transmissions sent to the receiving terminal. The second scenario had five precise traces and one non-precise trace or about 83% precise total traces. The third scenario had one precise trace and one non-precise trace or about 50% precise total traces.

Table 17. MP Model Precision Results

MP Model Scenario	Precise Transmission Traces	Precision Total Traces	Non-Precise Transmission Traces	Non-Precise Total Traces
Land-based Terminal to Maritime-based Terminal	1, 3, 7, 9, 15, 17, 19, 21, 23, 30, 32, 34, 36, 38, 45, 47, 49, 51, 53, 60, 62, 64, 66, 68	24	2, 4, 5, 6, 8, 10, 16, 18, 20, 22, 24, 31, 33, 35, 37, 39, 46, 48, 50, 52, 54, 61, 63, 65, 67, 69	26
Maritime-based Terminal to Land-based Terminal	1, 3, 4, 5, and 6	5	2	1
Maritime-based Terminal to Maritime-based Terminal	1	1	2	1

The first scenario mostly produced non-precise transmissions. Although the exact reason is not clear, the possible reasons for the lack of precision are user error or, more likely, operating difficulties in maritime environments. The second scenario had the highest number of precise traces. Once the laser was able to transmit out of the maritime environment, the laser had higher success in getting to the intended receiver. The third scenario had the same number of precise transmissions as non-precise transmissions. The transmissions in the third scenario are operating in the maritime environment during transmitting and receiving and therefore the transmissions will be subject to the effects of the environment. Overall, the precision of the transmissions is not enough to meet the reliability operational requirement

The functional requirements were separated by the subcomponents of the maritime-based terminal, the space-based relay, and the land-based terminal. The requirements were modeled and decomposed in hierarchy diagrams. These diagrams were used to build the conceptual model. Each subcomponent functional requirement was modeled in each MP model.

The overall performance requirement is that the FSO OTH Communication System interface shall be intuitive to the user for operation and shall be able to use alternative land-based terminals that can send communication to the primary receiver in the case of inclement weather. Specific performance requirements will have to be assumed since it cannot be modeled in MP. The intuitive interface and operation to the user is assumed. The training for operations and maintenance and the environmental protection measures are assumptions in the models. The first scenario included several example traces that satisfied the requirement to use alternative land-based terminals in the case of inclement weather, such as Event Traces 15–28. The reliability performance requirements included being secure, the ability to be consistently available, and integration with DMSP. The system security and the system availability, when the atmospheric conditions permit, is a satisfied assumption. The integration of the DMSP is modeled and examples of this integration includes Event Traces 11–14, where the relay did not send the transmission, and Event Traces 29, 44, 59, and 74 which the user did not send the transmission due to the atmospheric conditions that would inhibit communication.

The stakeholder requirements comprise primary and secondary stakeholders. The primary stakeholders are the Program Management, Warfare offices of PMW 146, 170, and 760, the CNO, the geographic component commands, engineers, and users. The models assumes that the conceptual models were designed and developed with the full integration and support of PMW 146, 170, and 760 and the engineers that developed and integrated the laser transmitters and receivers into a OTH communication SoS. The FSO OTH Laser Communication System, with the optimal conditions, can make communication faster and close kill chains to satisfy the CNO's stakeholder requirements. The geographic component command's stakeholder requirements will be able to be satisfied once the system becomes operational. The user stakeholder requirements are to use the FSO OTH System and maintain a high level of proficiency. These requirements are assumptions since it cannot be modeled in MP. Once the system is fully operational, the user requirement of training other users on the maintenance and operations will be able to be met. The secondary stakeholders included military branches other than the USN, the USSF and NASA, and DMSP. The model does not specify that the maritime-based platform is a USN asset and can be used by USMC, USAF, USA, and the USCG when conducting mobile operations in a maritime domain. The space-based relays were able to be tracked from the USSF and NASA. The DMSP provided weather information to the user and the FSO OTH Communication System.

E. SUMMARY

The results analysis of the models validates and verifies the stakeholder, operational, functional, and performance requirements. The MP model results were cataloged as successful and unsuccessful transmissions. The land-based terminal to maritime-based terminal had 25 successful transmissions and 49 unsuccessful transmissions; the maritime-based terminal to land-based terminal had five successful transmissions and five unsuccessful transmissions; the maritime-based terminal to maritime-based terminal had one successful transmission and five unsuccessful transmissions. The transmission times are based on how long transmissions occurred in all three scenarios: land-based terminal to maritime-based terminal, maritime-based terminal to land-based terminal, and maritime-based terminal to maritime-based terminal. The time for the first scenario nominal condition was 73.06s, the second scenario nominal condition time was 52.6s, and the third scenario nominal condition time was 52.58s. Longer times for transmission were due to using alternative terminals for transmission and alternative relays using crosslink.

In terms of emergent behavior, the MP model had several examples of expected and unexpected behavior. The first scenario MP model had 41 event traces of expected behavior and 25 event traces of unexpected behavior; the second scenario had nine expected behavior event traces and one unexpected behavior event trace; and the third scenario had five expected event traces and one unexpected event trace. The unexpected behavior source in the models is not clear but can be attributed to user error and maritime environmental conditions.

The model verification and validation analysis compared the functional and physical models, the conceptual model, and the MP models to the requirements defined in Chapter III. All the functional requirements were modeled into the hierarchy diagrams, the conceptual model, and the MP model. The operational, safety, and stakeholder (both primary and secondary) requirements were included in the MP model or were assumed to be satisfied.

VII. CONCLUSION

The thesis's three objectives were to understand the Navy's needs and requirements for secure and reliable communications in the maritime and littoral domains; study FSO laser devices, space-based relays, and both mobile and stationary terminals for maritime OTH communications; and develop and evaluate a conceptual design and architecture of an OTH maritime communication SoS using FSO laser devices and space-based relay. The objectives were completed by conducting a stakeholder requirements analysis, a system requirements analysis, developing a CONOPS with multiple nominal and off-nominal scenarios, decomposing a functional model from the requirements analysis, decomposing a physical model from the functional models, developing a FSO OTH Communication System conceptual model, developed three MP models from the CONOPS scenarios, analyze results of the models, and verify and validate the models to the requirements. The study focused on highly columnated FSO lasers as the communication medium between maritime-based mobile terminals, land-based stationary terminals, and space-based mobile relays.

A. DISCUSSION OF RESULTS AND FINDINGS

The MP model reveals that each scenario model produced 74, ten, and six traces. The data revealed from traces include emergent behavior, transmission times, and verification and validation to requirements. The event traces for the scenarios yielded mostly unsuccessful transmissions. The MP model displays all the possible events that could occur when a user sends or does not send a transmission. Therefore, there are more outcomes that the transmission will be unsuccessful transmissions than successful transmissions. The transmission times measure the times for each event trace. The times show that the transmissions are fast, taking no longer than 83.36s. The emergent behavior is defined as unexpected behavior from the MP models. There are less unexpected behavior traces than expected behavior traces. The MP model does not explain why there was unexpected behavior in the models and unexpected causes requires conjecturing reasons for the unexpected behavior. The reasons could be due to laser system failures, user error, ship movement, and maritime environmental factors not modeled in the MP.

B. RECOMMENDATIONS

The interactions of the possible outcomes and coordinate functions in the maritime-based terminal to land-based terminal scenario and maritime-based terminal to maritime-based terminal scenario between the space-based relay root event and the receiver root event have limited the number of event traces possible in those scenarios compared to the land-based terminal to maritime-based terminal. A recommendation would be to use an alternative architecture model to find emergent behavior for maritime-based terminal to land-based terminal scenario and maritime-based terminal to maritime-based terminal scenario. The model assumes an equal probability of the good atmospheric conditions and the bad atmospheric conditions. Another recommendation would be to make the model more accurate and include data for the probability of clear conditions, precipitation, thermal turbulence, absorption, and scattering. The MP models did find that a laser communication system using space-based relays for fast communication between maritime-based terminals and land-based terminals is possible if the conditions are conducive to for laser operations, there is a high-level proficiency, and the ship position is well-known.

C. FUTURE WORK

Laser communication, specially FSO, is currently in its nascency with current technology limited to establish small distance communications consistently and tests have successfully transmitted lasers to satellites. This thesis studied a small aspect in the potential of laser communication specifically emergent behavior in one-way transmissions. Future work should apply a more accurate operational environment. Further studies should incorporate current atmospheric data into the model and simulate different beam sizes to minimize ship movement error. Additionally, alternative relays could be analyzed such as manned and unmanned aircraft in lieu of satellites.

Weather, specifically precipitation, is a significant factor for laser communications in the maritime environment. As discussed in Chapter II, Schimmel et al. (2018, 1338) conducted a study on using opto-mechanics to displace cloud and fog droplets. However, Schimmel et al.'s study did not experiment with long distances. The study inferred that "application to real-scale fog and clouds extending over long distance also implies maintaining a small enough beam diameter for the telecom laser" at a range of "1 mm (greater than 600μm)" requiring a significant amount of energy (Schimmel et al. 2018, 1340). Conclusions of emergent behavior found in the MP model, despite not specifically stated from MP rather reasoned from possible causes, was that the maritime environment was a significant factor in inhibiting precise and successful FSO transmissions. With further study and integration, opto-mechanical displacement for laser energy can be the required function to proliferate laser communications.

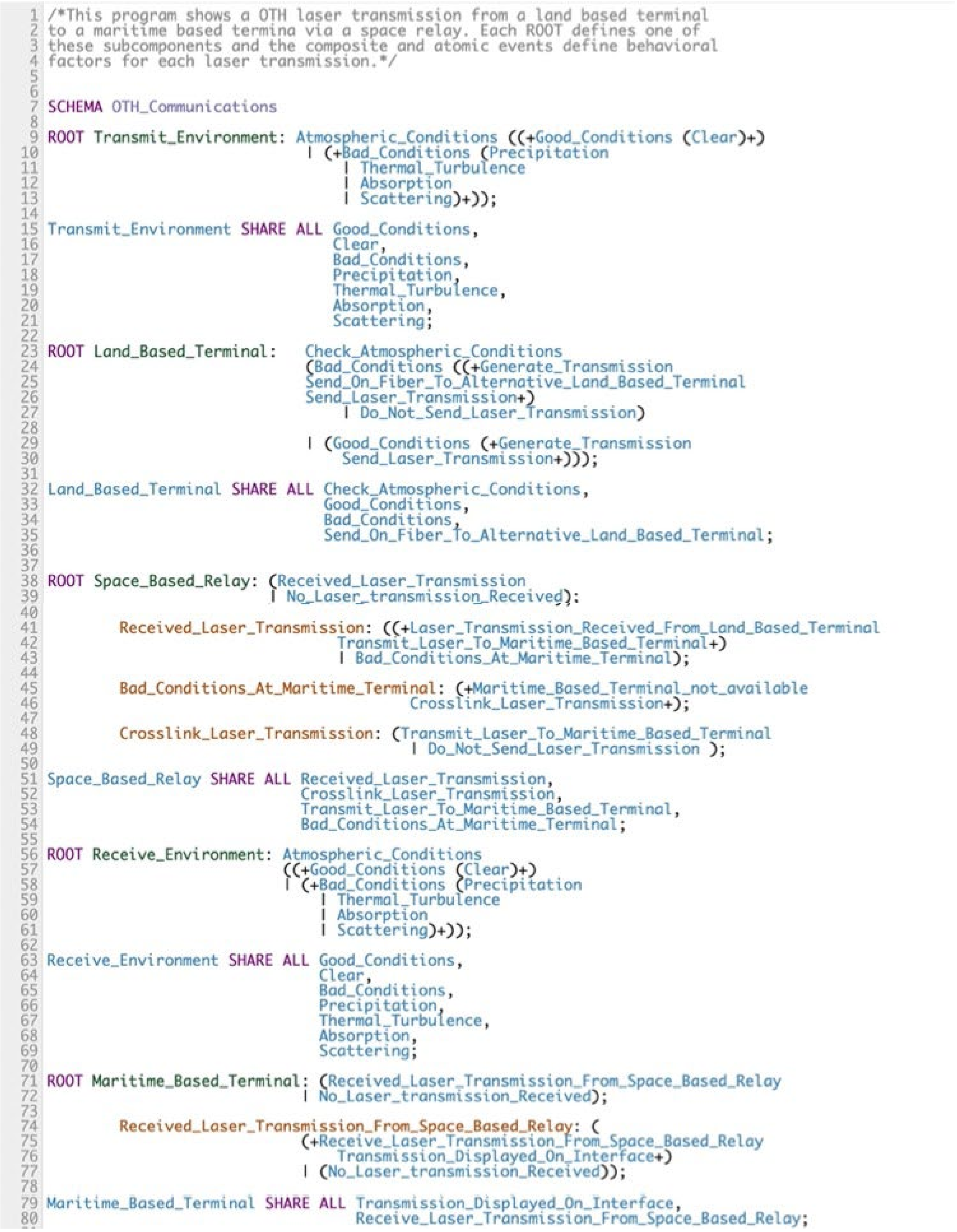
D. SUMMARY

This thesis conducted a requirements analysis, decomposed functional and physical diagrams from the requirements analysis, developed a conceptual model from the functional and physical models, and developed a CONOPS with nominal and off-nominal transmission scenarios. Three scenarios from the CONOPS combining nominal and off-nominal conditions were developed into MP models. The MP models were analyzed and traced back to the requirements for validation and verification. The conclusion included a discussion of findings, recommendations, and future work.

The event traces generated for each scenario yielded results including successful and unsuccessful transmissions, transmission times, emergent behavior, and requirements verification and validation. There were more unsuccessful transmissions than successful transmissions and the longest transmission was 83.36s. The number of unsuccessful transmissions because the MP model incorporates more constraints on bad conditions than good conditions. Emergent behavior is defined as unexpected behavior. There was more expected behavior than emergent behavior. The MP models do not state why there was emergent behavior but imagining possible reasons for the emergent behavior includes user error, ship movement, and the maritime environment. The MP model for the second and third scenarios are coded to have more outcomes at the relay and transmitter. The second and third scenarios required coordinate functions to make the model perform realistically which limited the number of output event traces.

MP generated event traces in the first scenario that could find patterns of emergent behavior. However, MP limited the number of traces and emergent behavior outcomes in the second and third scenarios. Additionally, the MP models placed an equal probability on clear conditions, precipitation, thermal turbulence, absorption, and scattering. More precise probabilities for these conditions would make the results more realistic to the operational environment. Future work should include current atmospheric data into the model and simulate different beam sizes to minimize ship movement error. Due to the maritime environment constraining FSO transmissions, integrating opto-mechanical functions into laser communications will be FSO communications in the maritime environment more successful.

APPENDIX A. LAND-BASED TERMINAL TO MARITIME-BASED TERMINAL MP CODE



```
/*This program shows a OTH laser transmission from a land based terminal
to a maritime based termina via a space relay. Each ROOT defines one of
these subcomponents and the composite and atomic events define behavioral
factors for each laser transmission.*/


SCHEMA OTH_Communications

ROOT Transmit_Environment: Atmospheric_Conditions ((+Good_Conditions (Clear)+)
                            | (+Bad_Conditions (Precipitation
                                | Thermal_Turbulence
                                | Absorption
                                | Scattering)+));

Transmit_Environment SHARE ALL Good_Conditions,
                               Clear,
                               Bad_Conditions,
                               Precipitation,
                               Thermal_Turbulence,
                               Absorption,
                               Scattering;

ROOT Land_Based_Terminal:   Check_Atmospheric_Conditions
                            (Bad_Conditions ((+Generate_Transmission
                            Send_On_Fiber_To_Alternative_Land_Based_Terminal
                            Send_Laser_Transmission+)
                                | Do_Not_Send_Laser_Transmission)

                            | (Good_Conditions (+Generate_Transmission
                                Send_Laser_Transmission+)));

Land_Based_Terminal SHARE ALL Check_Atmospheric_Conditions,
                              Good_Conditions,
                              Bad_Conditions,
                              Send_On_Fiber_To_Alternative_Land_Based_Terminal;


ROOT Space_Based_Relay: (Received_Laser_Transmission
                        | No_Laser_transmission_Received):

        Received_Laser_Transmission: ((+Laser_Transmission_Received_From_Land_Based_Terminal
                                Transmit_Laser_To_Maritime_Based_Terminal+)
                                | Bad_Conditions_At_Maritime_Terminal);

        Bad_Conditions_At_Maritime_Terminal: (+Maritime_Based_Terminal_not_available
                                          Crosslink_Laser_Transmission+);

        Crosslink_Laser_Transmission: (Transmit_Laser_To_Maritime_Based_Terminal
                                        | Do_Not_Send_Laser_Transmission );

Space_Based_Relay SHARE ALL Received_Laser_Transmission,
                            Crosslink_Laser_Transmission,
                            Transmit_Laser_To_Maritime_Based_Terminal,
                            Bad_Conditions_At_Maritime_Terminal;

ROOT Receive_Environment: Atmospheric_Conditions
                          ((+Good_Conditions (Clear)+)
                          | (+Bad_Conditions (Precipitation
                              | Thermal_Turbulence
                              | Absorption
                              | Scattering)+));

Receive_Environment SHARE ALL Good_Conditions,
                              Clear,
                              Bad_Conditions,
                              Precipitation,
                              Thermal_Turbulence,
                              Absorption,
                              Scattering;

ROOT Maritime_Based_Terminal: (Received_Laser_Transmission_From_Space_Based_Relay
                            | No_Laser_transmission_Received);

        Received_Laser_Transmission_From_Space_Based_Relay: (
                            (+Receive_Laser_Transmission_From_Space_Based_Relay
                                Transmission_Displayed_On_Interface+)
                            | (No_Laser_transmission_Received));

Maritime_Based_Terminal SHARE ALL Transmission_Displayed_On_Interface,
                                  Receive_Laser_Transmission_From_Space_Based_Relay;
```

```
/*interactions for events*/

COORDINATE $x: Check_Atmospheric_Conditions FROM Land_Based_Terminal,
           $y: Atmospheric_Conditions       FROM Transmit_Environment
         DO ADD $x PRECEDES $y; OD;

COORDINATE $x: Check_Atmospheric_Conditions FROM Land_Based_Terminal,
           $z: Atmospheric_Conditions       FROM Receive_Environment
         DO ADD $x PRECEDES $z; OD;

COORDINATE $a: (Send_Laser_Transmission | Do_Not_Send_Laser_Transmission) FROM Land_Based_Terminal,
$d: (Received_Laser_Transmission | No_Laser_transmission_Received)        FROM Space_Based_Relay
DO
IF $a IS Send_Laser_Transmission AND $d IS Received_Laser_Transmission
OR $a IS Do_Not_Send_Laser_Transmission AND $d IS No_Laser_transmission_Received THEN
ADD $a PRECEDES $d;
ELSE REJECT;
FI;
OD;

COORDINATE $a: (Good_Conditions | Bad_Conditions) FROM Transmit_Environment,
$d: (Good_Conditions | Bad_Conditions)            FROM Land_Based_Terminal
DO
IF $a IS Good_Conditions AND $d IS Good_Conditions
OR $a IS Bad_Conditions AND $d IS Bad_Conditions THEN
ADD $a PRECEDES $d;
ELSE REJECT;
FI;
OD;

COORDINATE $a: Bad_Conditions_At_Maritime_Terminal  FROM Space_Based_Relay,
           $d: Bad_Conditions                       FROM Receive_Environment
         DO ADD $a PRECEDES $d; OD;

COORDINATE $x: Transmit_Laser_To_Maritime_Based_Terminal          FROM Space_Based_Relay,
           $y: Received_Laser_Transmission_From_Space_Based_Relay FROM Maritime_Based_Terminal
         DO ADD $x PRECEDES $y; OD;

/* Add duration attributes*/

COORDINATE  $a1: Send_On_Fiber_To_Alternative_Land_Based_Terminal    DO SET $a1.duration  AT LEAST 10.30; OD;
COORDINATE  $a2: Send_Laser_Transmission                             DO SET $a2.duration  AT LEAST 20.60; OD;
COORDINATE  $a3: Received_Laser_Transmission                         DO SET $a3.duration  AT LEAST 20.72; OD;
COORDINATE  $a4: Crosslink_Laser_Transmission                        DO SET $a4.duration  AT LEAST 20.92; OD;
COORDINATE  $a5: Transmit_Laser_To_Maritime_Based_Terminal           DO SET $a5.duration  AT LEAST 21.02; OD;
COORDINATE  $a6: Received_Laser_Transmission_From_Space_Based_Relay  DO SET $a6.duration  AT LEAST 21.14; OD;
COORDINATE  $a7: Transmission_Displayed_On_Interface                 DO SET $a7.duration  AT LEAST 31.44; OD;

/*SAY or display information*/

SAY("Trace " trace_id " Total Time: " THIS.duration " seconds");

/* Build global reports*/

ATTRIBUTES {number  accumulated_max,
                    accumulated_min,
                    accumulated_durations,
                    smallest_trace_id,
                    longest_trace_id;   };

GLOBAL.accumulated_durations +:= THIS.duration.smallest;

IF GLOBAL.accumulated_max < THIS.duration.largest THEN
    GLOBAL.accumulated_max := THIS.duration.largest;
    GLOBAL.longest_trace_id := trace_id;
FI;

IF GLOBAL.accumulated_min >= THIS.duration.smallest OR
    GLOBAL.accumulated_min == 0
    THEN
    GLOBAL.accumulated_min := THIS.duration.smallest;
    GLOBAL.smallest_trace_id := trace_id;
FI;

GLOBAL

REPORT Duration_Statistics_Report { TITLE ("Scope "$$scope" Duration Statistics");
                                    };
    CLEAR Duration_Statistics_Report;

SAY("There are " #$$TRACE " traces total." )
    => Duration_Statistics_Report;
SAY("Trace "longest_trace_id " has the max duration of " accumulated_max" seconds." )
    => Duration_Statistics_Report;
SAY("Trace "smallest_trace_id " has the min duration of " accumulated_min" seconds." )
    => Duration_Statistics_Report;

SHOW Duration_Statistics_Report;

SHOW ACTIVITY DIAGRAM Transmit_Environment,
                      Land_Based_Terminal,
                      Receive_Environment,
                      Space_Based_Relay,
                      Maritime_Based_Terminal;
```

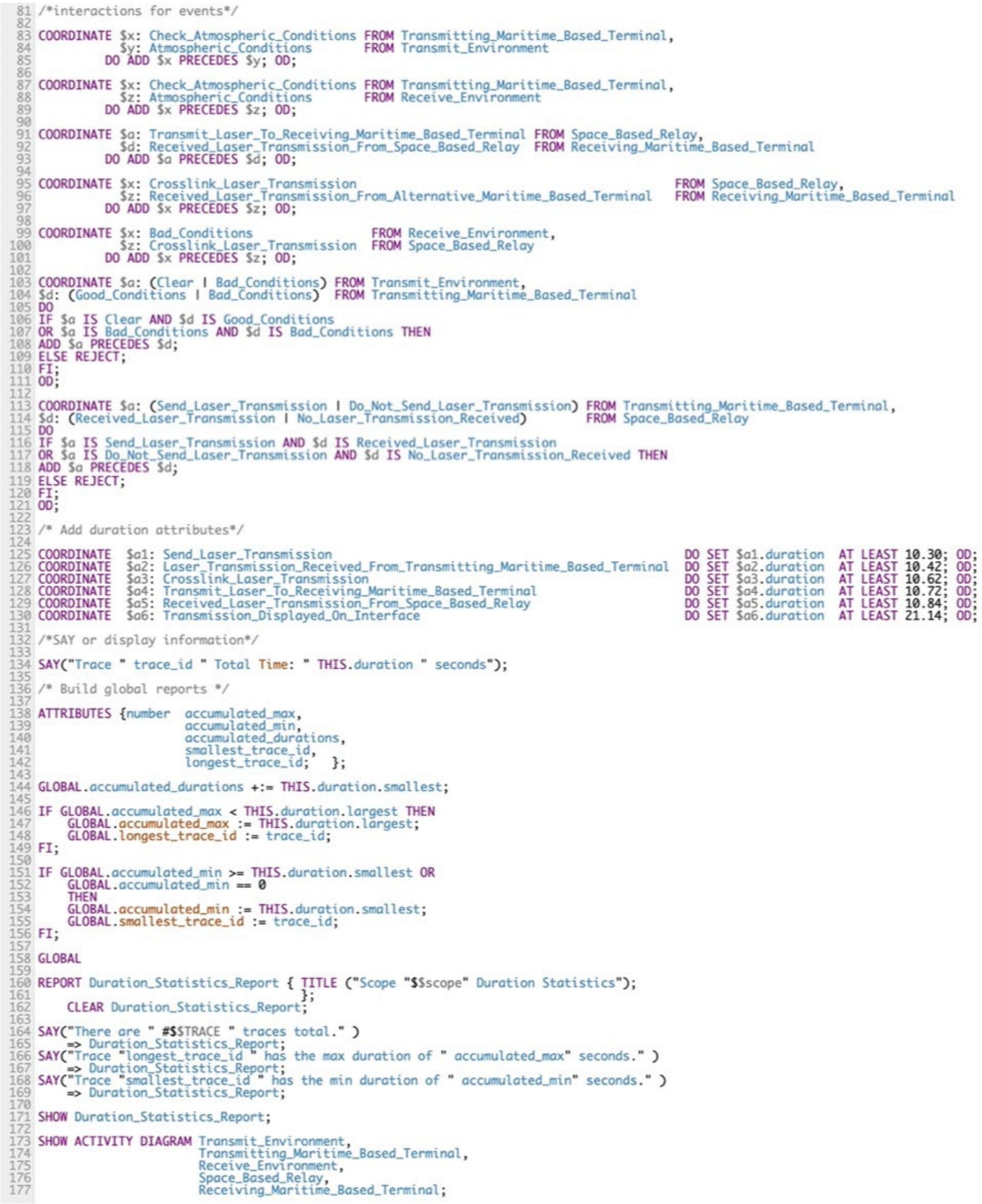
APPENDIX B. MARITIME-BASED TERMINAL TO LAND-BASED TERMINAL MP CODE

```
/*This program shows a OTH laser transmission from a land based terminal
to a maritime based termina via a space relay. Each ROOT defines one of
these subcomponents and the composite and atomic events define behavioral
factors for each laser transmission.*/


SCHEMA OTH_Communications

ROOT Transmit_Environment: Atmospheric_Conditions ((+Good_Conditions (Clear)+)
                          | (+Bad_Conditions (Precipitation
                              | Thermal_Turbulence
                              | Absorption
                              | Scattering)+));

Transmit_Environment SHARE ALL Good_Conditions,
                               Clear,
                               Bad_Conditions,
                               Precipitation,
                               Thermal_Turbulence,
                               Absorption,
                               Scattering;


ROOT Maritime_Based_Terminal: Check_Atmospheric_Conditions
                            ((Good_Conditions (+Generate_Transmission
                                Send_Laser_Transmission+))

                            | (Bad_Conditions (+Generate_Transmission
                            Do_Not_Send_Laser_Transmission+)));

Maritime_Based_Terminal SHARE ALL Check_Atmospheric_Conditions,
                              Good_Conditions,
                              Bad_Conditions;


ROOT Space_Based_Relay: (Received_Laser_Transmission
                        | No_Laser_Transmission_Received);

        Received_Laser_Transmission: ((+Laser_Transmission_Received_From_Land_Based_Terminal
                                Transmit_Laser_To_Land_Based_Terminal+)
                               | Bad_Conditions_At_Land_Terminal);

        Bad_Conditions_At_Land_Terminal: (+Land_Based_Terminal_not_available
                                       Crosslink_Laser_Transmission+);

        Crosslink_Laser_Transmission: (Transmit_Laser_To_Land_Based_Terminal
                                       | Do_Not_Send_Laser_Transmission );

Space_Based_Relay SHARE ALL Received_Laser_Transmission,
                            Crosslink_Laser_Transmission,
                            Transmit_Laser_To_Land_Based_Terminal,
                            Bad_Conditions_At_Land_Terminal;

ROOT Receive_Environment: Atmospheric_Conditions
                          ((+Good_Conditions (Clear)+)
                          | (+Bad_Conditions (Precipitation | Thermal_Turbulence | Absorption | Scattering)+));

Receive_Environment SHARE ALL Good_Conditions,
                              Clear,
                              Bad_Conditions,
                              Precipitation,
                              Thermal_Turbulence,
                              Absorption,
                              Scattering;

ROOT Land_Based_Terminal: (Received_Laser_Transmission_From_Space_Based_Relay
                            | No_Laser_transmission_Received);

        Received_Laser_Transmission_From_Space_Based_Relay: (
                            (+Receive_Laser_Transmission_From_Space_Based_Relay Transmission_Displayed_On_Interface+)
                            | (+Received_Laser_Transmission_From_Alternative_Land_Based_Terminal
                                Transmission_Displayed_On_Interface+)
                            | (+No_Laser_transmission_Received Transmission_Not_Displayed_On_Interface+));

Land_Based_Terminal SHARE ALL Received_Laser_Transmission_From_Space_Based_Relay,
                              No_Laser_transmission_Received,
                             Received_Laser_Transmission_From_Alternative_Land_Based_Terminal,
                             Transmission_Displayed_On_Interface,
                             Transmission_Not_Displayed_On_Interface;
```

```
/*interactions for events*/

COORDINATE $x: Check_Atmospheric_Conditions FROM Maritime_Based_Terminal,
           $y: Atmospheric_Conditions       FROM Transmit_Environment
         DO ADD $x PRECEDES $y; OD;

COORDINATE $x: Check_Atmospheric_Conditions FROM Maritime_Based_Terminal,
           $z: Atmospheric_Conditions       FROM Receive_Environment
         DO ADD $x PRECEDES $z; OD;


COORDINATE $a: (Good_Conditions | Bad_Conditions) FROM Transmit_Environment,
$d: (Good_Conditions | Bad_Conditions)            FROM Maritime_Based_Terminal
DO
IF $a IS Good_Conditions AND $d IS Good_Conditions
OR $a IS Bad_Conditions AND $d IS Bad_Conditions THEN
ADD $a PRECEDES $d;
ELSE REJECT;
FI;
OD;

COORDINATE $a: (Send_Laser_Transmission | Do_Not_Send_Laser_Transmission) FROM Maritime_Based_Terminal,
$d: (Received_Laser_Transmission | No_Laser_Transmission_Received)        FROM Space_Based_Relay
DO
IF $a IS Send_Laser_Transmission AND $d IS Received_Laser_Transmission
OR $a IS Do_Not_Send_Laser_Transmission AND $d IS No_Laser_Transmission_Received THEN
ADD $a PRECEDES $d;
ELSE REJECT;
FI;
OD;

COORDINATE $x: Bad_Conditions               FROM Receive_Environment,
           $z: Crosslink_Laser_Transmission  FROM Space_Based_Relay
         DO ADD $x PRECEDES $z; OD;

COORDINATE $x: Crosslink_Laser_Transmission                                    FROM Space_Based_Relay,
           $z: Received_Laser_Transmission_From_Alternative_Land_Based_Terminal       FROM Land_Based_Terminal
         DO ADD $x PRECEDES $z; OD;

COORDINATE $x: Transmit_Laser_To_Land_Based_Terminal             FROM Space_Based_Relay,
           $z: Received_Laser_Transmission_From_Space_Based_Relay FROM Land_Based_Terminal
         DO ADD $x PRECEDES $z; OD;

/* Add duration attributes*/

COORDINATE  $a1: Send_Laser_Transmission                                          DO SET $a1.duration  AT LEAST 27.30; OD;
COORDINATE  $a2: Received_Laser_Transmission                                      DO SET $a2.duration  AT LEAST 27.42; OD;
COORDINATE  $a3: Crosslink_Laser_Transmission                                     DO SET $a3.duration  AT LEAST 27.62; OD;
COORDINATE  $a4: Transmit_Laser_To_Land_Based_Terminal                            DO SET $a4.duration  AT LEAST 27.72; OD;
COORDINATE  $a5: Received_Laser_Transmission_From_Space_Based_Relay               DO SET $a5.duration  AT LEAST 27.84; OD;
COORDINATE  $a6: Received_Laser_Transmission_From_Alternative_Land_Based_Terminal DO SET $a6.duration  AT LEAST 38.14; OD;
COORDINATE  $a7: Transmission_Displayed_On_Interface                              DO SET $a7.duration  AT LEAST 48.44; OD;

/*SAY or display information*/

SAY("Trace " trace_id " Total Time: " THIS.duration " seconds");

/* Build global reports*/

ATTRIBUTES {number  accumulated_max,
                    accumulated_min,
                    accumulated_durations,
                    smallest_trace_id,
                    longest_trace_id;   };

GLOBAL.accumulated_durations +:= THIS.duration.smallest;

IF GLOBAL.accumulated_max < THIS.duration.largest THEN
    GLOBAL.accumulated_max := THIS.duration.largest;
    GLOBAL.longest_trace_id := trace_id;
FI;

IF GLOBAL.accumulated_min >= THIS.duration.smallest OR
    GLOBAL.accumulated_min == 0
    THEN
    GLOBAL.accumulated_min := THIS.duration.smallest;
    GLOBAL.smallest_trace_id := trace_id;
FI;

GLOBAL

REPORT Duration_Statistics_Report { TITLE ("Scope "$$scope" Duration Statistics");
                                  };
    CLEAR Duration_Statistics_Report;

SAY("There are " #$$TRACE " traces total." )
    => Duration_Statistics_Report;
SAY("Trace "longest_trace_id " has the max duration of " accumulated_max" seconds." )
    => Duration_Statistics_Report;
SAY("Trace "smallest_trace_id " has the min duration of " accumulated_min" seconds." )
    => Duration_Statistics_Report;

SHOW Duration_Statistics_Report;

SHOW ACTIVITY DIAGRAM Transmit_Environment,
                      Land_Based_Terminal,
                      Receive_Environment,
                      Space_Based_Relay,
                      Maritime_Based_Terminal;
```

APPENDIX C. MARITIME-BASED TERMINAL TO MARITIME-BASED TERMINAL MP CODE

```
/*This program shows a OTH laser transmission from a maritime based terminal
to a maritime based termina via a space relay. Each ROOT defines one of
these subcomponents and the composite and atomic events define behavioral
factors for each laser transmission.*/


SCHEMA OTH_Communications

ROOT Transmit_Environment: Atmospheric_Conditions ((+Good_Conditions (Clear)+)
                          | (+Bad_Conditions (Precipitation
                              | Thermal_Turbulence
                              | Absorption
                              | Scattering)+));

Transmit_Environment SHARE ALL Good_Conditions,
                               Clear,
                               Bad_Conditions,
                               Precipitation,
                               Thermal_Turbulence,
                               Absorption,
                               Scattering;

ROOT Transmitting_Maritime_Based_Terminal:  Check_Atmospheric_Conditions
                            ((Good_Conditions (+Generate_Transmission
                                Send_Laser_Transmission+))

                            | (Bad_Conditions (+Generate_Transmission
                            Do_Not_Send_Laser_Transmission+)));

Transmitting_Maritime_Based_Terminal SHARE ALL Check_Atmospheric_Conditions,
                              Good_Conditions,
                              Bad_Conditions,
                              Send_Laser_Transmission,
                              Do_Not_Send_Laser_Transmission;

ROOT Space_Based_Relay: (Received_Laser_Transmission
                        | No_Laser_Transmission_Received);

        Received_Laser_Transmission: ((+Laser_Transmission_Received_From_Transmitting_Maritime_Based_Terminal
                                Transmit_Laser_To_Receiving_Maritime_Based_Terminal+)
                                | Bad_Conditions_At_Receiving_Maritime_Based_Terminal);

        Bad_Conditions_At_Receiving_Maritime_Based_Terminal:
                                        (+Maritime_Based_Terminal_Not_Available
                                        Crosslink_Laser_Transmission+);

        Crosslink_Laser_Transmission: (Transmit_Laser_To_Alternative_Maritime_Based_Terminal
                                        | Do_Not_Send_Laser_Transmission );

Space_Based_Relay SHARE ALL Received_Laser_Transmission,
                            Transmit_Laser_To_Receiving_Maritime_Based_Terminal,
                            Crosslink_Laser_Transmission,
                            No_Laser_Transmission_Received,
                            Transmit_Laser_To_Alternative_Maritime_Based_Terminal,
                            Bad_Conditions_At_Receiving_Maritime_Based_Terminal;

ROOT Receive_Environment: Atmospheric_Conditions ((+Good_Conditions (Clear)+)
                          | (+Bad_Conditions (Precipitation
                              | Thermal_Turbulence
                              | Absorbtion
                              | Scattering)+));

Receive_Environment SHARE ALL Good_Conditions, Clear, Bad_Conditions, Precipitation, Thermal_Turbulence, Absorbtion, Scattering;

ROOT Receiving_Maritime_Based_Terminal: (Received_Laser_Transmission_From_Space_Based_Relay
                                         | No_Laser_Transmission_Received);

        Received_Laser_Transmission_From_Space_Based_Relay:
                            ((+Receive_Laser_Transmission_From_Space_Based_Relay
                            Transmission_Displayed_On_Interface+)
                            | (+Received_Laser_Transmission_From_Alternative_Maritime_Based_Terminal
                            Transmission_Displayed_On_Interface+)
                            | (+No_Laser_Transmission_Received
                                Transmission_Not_Displayed_On_Interface+));

Receiving_Maritime_Based_Terminal SHARE ALL Received_Laser_Transmission_From_Space_Based_Relay,
                                            Received_Laser_Transmission_From_Alternative_Maritime_Based_Terminal,
                                            No_Laser_Transmission_Received,
                                            Receive_Laser_Transmission_From_Space_Based_Relay;

```



```
/*interactions for events*/

COORDINATE $x: Check_Atmospheric_Conditions FROM Transmitting_Maritime_Based_Terminal,
           $y: Atmospheric_Conditions        FROM Transmit_Environment
         DO ADD $x PRECEDES $y; OD;

COORDINATE $x: Check_Atmospheric_Conditions FROM Transmitting_Maritime_Based_Terminal,
           $z: Atmospheric_Conditions        FROM Receive_Environment
         DO ADD $x PRECEDES $z; OD;

COORDINATE $a: Transmit_Laser_To_Receiving_Maritime_Based_Terminal FROM Space_Based_Relay,
           $d: Received_Laser_Transmission_From_Space_Based_Relay  FROM Receiving_Maritime_Based_Terminal
         DO ADD $a PRECEDES $d; OD;

COORDINATE $x: Crosslink_Laser_Transmission                                           FROM Space_Based_Relay,
           $z: Received_Laser_Transmission_From_Alternative_Maritime_Based_Terminal   FROM Receiving_Maritime_Based_Terminal
         DO ADD $x PRECEDES $z; OD;

COORDINATE $x: Bad_Conditions                FROM Receive_Environment,
           $z: Crosslink_Laser_Transmission  FROM Space_Based_Relay
         DO ADD $x PRECEDES $z; OD;

COORDINATE $a: (Clear | Bad_Conditions) FROM Transmit_Environment,
$d: (Good_Conditions | Bad_Conditions)  FROM Transmitting_Maritime_Based_Terminal
DO
IF $a IS Clear AND $d IS Good_Conditions
OR $a IS Bad_Conditions AND $d IS Bad_Conditions THEN
ADD $a PRECEDES $d;
ELSE REJECT;
FI;
OD;

COORDINATE $a: (Send_Laser_Transmission | Do_Not_Send_Laser_Transmission) FROM Transmitting_Maritime_Based_Terminal,
$d: (Received_Laser_Transmission | No_Laser_Transmission_Received)        FROM Space_Based_Relay
DO
IF $a IS Send_Laser_Transmission AND $d IS Received_Laser_Transmission
OR $a IS Do_Not_Send_Laser_Transmission AND $d IS No_Laser_Transmission_Received THEN
ADD $a PRECEDES $d;
ELSE REJECT;
FI;
OD;

/* Add duration attributes*/

COORDINATE  $a1: Send_Laser_Transmission                                               DO SET $a1.duration  AT LEAST 10.30; OD;
COORDINATE  $a2: Laser_Transmission_Received_From_Transmitting_Maritime_Based_Terminal DO SET $a2.duration  AT LEAST 10.42; OD;
COORDINATE  $a3: Crosslink_Laser_Transmission                                          DO SET $a3.duration  AT LEAST 10.62; OD;
COORDINATE  $a4: Transmit_Laser_To_Receiving_Maritime_Based_Terminal                   DO SET $a4.duration  AT LEAST 10.72; OD;
COORDINATE  $a5: Received_Laser_Transmission_From_Space_Based_Relay                    DO SET $a5.duration  AT LEAST 10.84; OD;
COORDINATE  $a6: Transmission_Displayed_On_Interface                                   DO SET $a6.duration  AT LEAST 21.14; OD;

/*SAY or display information*/

SAY("Trace " trace_id " Total Time: " THIS.duration " seconds");

/* Build global reports */

ATTRIBUTES {number  accumulated_max,
                    accumulated_min,
                    accumulated_durations,
                    smallest_trace_id,
                    longest_trace_id;   };

GLOBAL.accumulated_durations +:= THIS.duration.smallest;

IF GLOBAL.accumulated_max < THIS.duration.largest THEN
    GLOBAL.accumulated_max := THIS.duration.largest;
    GLOBAL.longest_trace_id := trace_id;
FI;

IF GLOBAL.accumulated_min >= THIS.duration.smallest OR
    GLOBAL.accumulated_min == 0
    THEN
    GLOBAL.accumulated_min := THIS.duration.smallest;
    GLOBAL.smallest_trace_id := trace_id;
FI;

GLOBAL

REPORT Duration_Statistics_Report { TITLE ("Scope "$$scope" Duration Statistics");
                                    };
    CLEAR Duration_Statistics_Report;

SAY("There are " #$$TRACE " traces total." )
    => Duration_Statistics_Report;
SAY("Trace "longest_trace_id " has the max duration of " accumulated_max" seconds." )
    => Duration_Statistics_Report;
SAY("Trace "smallest_trace_id " has the min duration of " accumulated_min" seconds." )
    => Duration_Statistics_Report;

SHOW Duration_Statistics_Report;

SHOW ACTIVITY DIAGRAM Transmit_Environment,
                      Transmitting_Maritime_Based_Terminal,
                      Receive_Environment,
                      Space_Based_Relay,
                      Receiving_Maritime_Based_Terminal;
```

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