NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

THESIS

FREE SPACE OPTIC COMMUNICATION FOR NAVY SURFACE SHIP PLATFORMS

by

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March 2004

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REPORT DOCUMENTATION PAGE | *Form Approved OMB No. 0704-0188*

1. AGENCY USE ONLY *(Leave blank)*	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 2004	Master's Thesis

4. TITLE AND SUBTITLE: Free Space Optics Communication for Navy Surface Ship Platforms

5. FUNDING NUMBERS

6. AUTHOR(S) Oguzhan Timus

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)
N/A

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited

12b. DISTRIBUTION CODE

13. ABSTRACT (maximum 200 words)

Free Space Optics (FSO) technology is an alternative broadband technology, which provides fast, secure and reliable data transmission. The FSO systems are being used for commercial systems between fixed sites and are being considered for military systems because of their inherent benefits, which are security and high data rates. In military communications security is the first priority. The small divergence of the laser beam makes FSO systems more secure than the existing radio frequency (RF) based wireless systems, because it is highly difficult to detect and intercept a laser beam due to the nature of the laser and the small divergence angle of the transmitter. However, FSO implementation on mobile platforms such as ships is still challenging.

This thesis analyzes the feasibility of deploying FSO system on navy surface ships. It discusses the FSO technology and the latest studies in maritime optical communication links. In addition, the benefits and challenges of FSO technology specific to this study are studied. The final section discusses the required systems to improve the performance of FSO systems on ships. The thesis concludes that FSO technology, while not ready for deployment, looks very promising for the near future.

14. SUBJECT TERMS
Free Space Optics, FSO, Laser Communication, Navy, Ship

15. NUMBER OF PAGES
91

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18

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FREE SPACE OPTICS COMMUNICATION FOR NAVY SURFACE SHIP PLATFORMS

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Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN COMPUTER SCIENCE

from the

NAVAL POSTGRADUATE SCHOOL
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ACKNOWLEDGMENTS

Several people deserve a word of thanks for their support during this research. First, I must thank Professor Bert Lundy for his guidance and support during thesis work. It has been my privilege to work with him. I also thank Soo Sim Daniel Neo from Singapore Defense Science and Technology Agency, who graduated last quarter, for his support.

I must also thank Naval Research Laboratory for providing their latest research reports. They were very helpful for the thesis.

I especially thank to my wife Gulbahar for her support, understanding and patience during the last two years.

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I. INTRODUCTION

Free Space Optics (FSO) technology is a wireless technology that uses lasers, instead of radio waves, to transmit data between two terminals in line-of-sight. The first known FSO system was demonstrated by Alexander Graham Bell in 1880, called “photophone,” which never became a commercial reality. The first significant FSO technology advancements began in the 1960’s, but these early FSO systems were limited by range, could transmit only a few kilobits per second and had vulnerabilities to weather interferences.

Since the 1980’s, by addressing the principal challenges, FSO technology has been successfully deployed and today FSO systems are mostly used in commercial business for communication between fixed sites. The FSO systems are being considered for military systems since they provide higher data rates and more secure communication links than existing radio frequency (RF) technologies.

This thesis will study the feasibility of deploying FSO systems on navy surface ships by covering the specific benefits and the challenges as well as the required systems for moving platforms. This study will begin with the background of FSO technology and the latest studies in maritime optical communication links. This will be followed by the benefits and the challenges of FSO technology specific for implementation on ship platforms. Finally, this thesis study will look at the ship motions and the required systems to compensate these movements as well as acquisition, tracking and pointing of the terminals.

In Chapter II, the history and the development of FSO technology will be discussed and a comparison with RF technology for ship-to-ship communication will be made. In addition, considerable studies for ship-to-shore FSO link conducted by Lucent Technologies and long-range, maritime optical communication link conducted by the Naval Research Laboratory will be discussed.

In Chapter III, the inherent benefits of FSO technology, specific for ship platform implementation, such as security, bandwidth, bit-error rate, and spectrum licensing will be discussed. However, other benefits like last-mile access, low cost, protocol independence, and rapid deployment will not be covered.

In Chapter IV, the challenges and limitations of FSO technology will be discussed. The main challenge is caused by the atmospheric effects especially fog which severely reduces the laser power and the range of the optical link. In addition to atmospheric effects, line-of-sight (LOS), directional precision, and laser safety limit the performance and the range of the FSO links and must be taken into consideration for designing FSO terminals to be deployed on ships.

In Chapter V, the need for FSO technology on ship platforms, the effects of ship motion, and the required systems to improve the performance of the FSO communication on ships will be discussed. In order to maintain a communication link on moving ships *Acquisition, Tracking and Pointing* (ATP) systems are required. In addition, implementing *Fast-steering Mirrors* (FSM) would also be useful for compensating beam wander caused by turbulence and/or ship motion.

Finally, Chapter VI, the conclusion of this thesis, will summarize the results.

Among all the advantages, communication security will be stressed in this thesis. Establishing and maintaining a secure communication link is a priority for military operations. The RF based wireless systems severely limit use of current military communication systems in terms of security. Especially for the Navy, use of the RF based communication systems provides an opportunity for the detection of the ship by opposing forces. For this reason, the Navy favors technologies that eliminate RF emissions, which are crucial during emission control (EMCON) periods. The EMCON usually means either full radio silence or very limited radio use depending on the given order against a particular threat. Using FSO systems would eliminate the communication shortcomings during EMCON periods.

The FSO systems operate in the unregulated infrared portion of the electromagnetic spectrum. In addition, interference with the commercial systems or other military systems is not a concern for the FSO systems. For all given benefits, deploying FSO systems on the surface ship platforms would be very useful.

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II. FREE SPACE OPTICS TECHNOLOGY

Free Space Optics (FSO) technology is gaining popularity as an alternative broadband technology by providing fast, secure and reliable data, voice and video transmission for military and commercial business. Unlike other wireless technologies, FSO uses laser beams, instead of radio waves, to transmit data through the air. Modulated low power laser beams are transmitted through the free space from one “telescope” to another to provide an optical communication link.

Historically, the first known FSO system was demonstrated by Alexander Graham Bell on June 3, 1880. In this experiment, Bell converted voice sounds into telephone signals and transmitted them on a beam of light for a distance of 600 feet. Bell called this invention the “photophone”, which never became a commercial reality [Lucent 2004] [FSONA 2004]. Figure 1 shows the photophone tests.

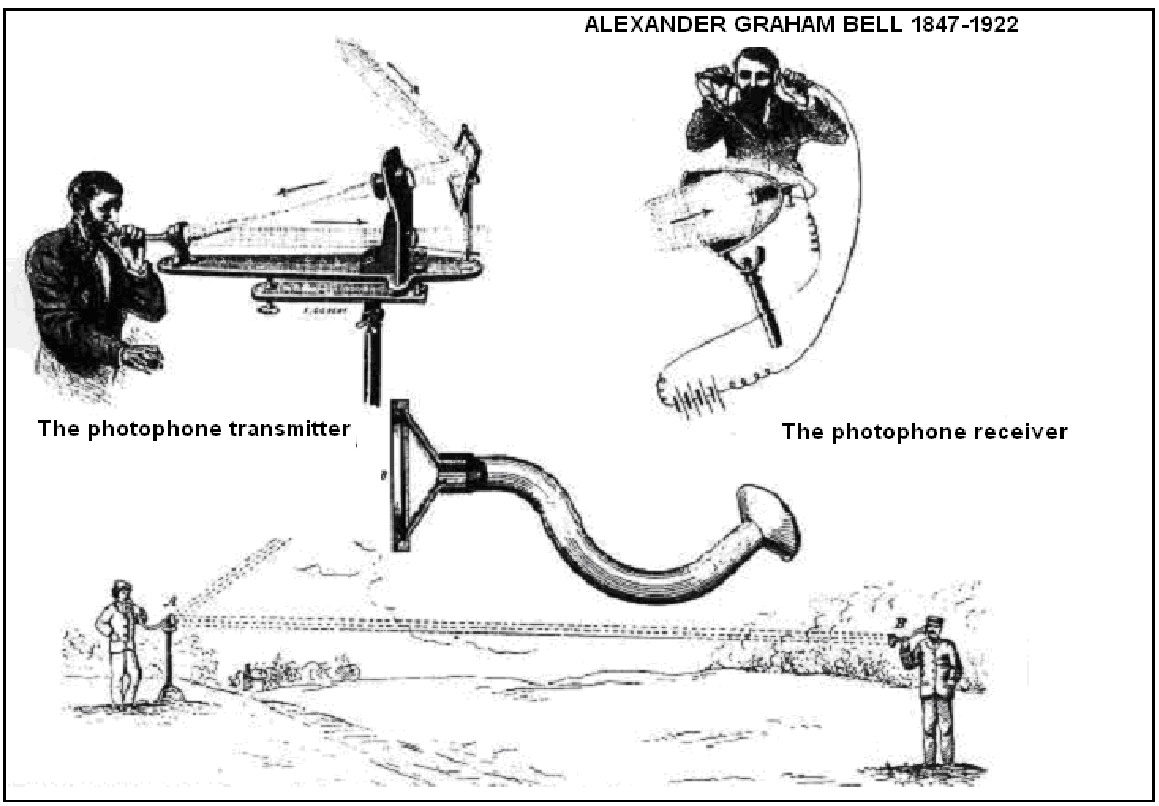

Figure 1. Bell demonstrated “photophone” in 1880 (After: [SC 2003])

Basically, voice sounds were projected through an instrument toward a mirror inside. The sound waves caused vibrations in the mirror, where the sunlight was directed, and the modulated light waves were reflected to the receiver. Then the receiver converted received signal back into sound [AL 2004].

However, the first significant FSO technology advancements began in the 1960's. Military researchers and engineers applied FSO technology in communication devices for providing secure data and voice transmissions. These devices would not be susceptible to "jamming" like radio frequency-based systems. But, the early FSO systems were limited by range, could transmit only a few kilobits per second and had vulnerabilities to weather interferences [LightPointe 2003].

Since the 1980's, by addressing the principal challenges, Free Space Optics (FSO) technology has been successfully deployed. Today, FSO systems are mostly used for communication between fixed sites. As the communication technology advances, demand for high bandwidth increases. Commercially available FSO products offer bandwidths up to 2.5 Gbps. In addition to high bandwidth, vendors claim that their FSO products have bit error rates (BER) of 10^{-9} (one bit in a billion bits). Low BER's enable FSO technology to be more reliable than other wireless technologies. However, lower BER in FSO products is not always the case because BER depends on various conditions such as distance, weather, sensitivity of the receiver, etc. With lasers alone most of the FSO systems, under good weather conditions, achieve can 99.99% ("four nines") availability in distances up to two miles where 99.999% ("five nines") availability in distances up to 450 feet. However, 99.999% availability that major service providers demand in distances up to two miles can be achieved by FSO devices with a radio (RF) back-up. On the other hand, since FSO systems operate narrow laser beams, these systems are susceptible to atmospheric attenuation. Severe weather conditions, especially fog rather than rain, drastically degrades the availability and the effective range of FSO systems.

As war technology advances, the need for more secure, more reliable and faster communication in the military becomes more imperative. Distribution of timely information to the battle units while maintaining the secure communication channels is always the first priority in the battlefield where using of the radio frequency (RF) spectrum severely limits use of current military communications systems. Especially for the Navy, use of the radio frequency (RF) spectrum for communications provides an opportunity for the detection and direction finding of military platforms by opposing forces. Advanced radio-frequency identifier systems enable ships not only to detect but also to locate the originator of the signal. Sometimes just the direction of the target ship can be sufficient information for guided missiles. Figure 2 illustrates a scenario of ship-to-ship communication at sea.

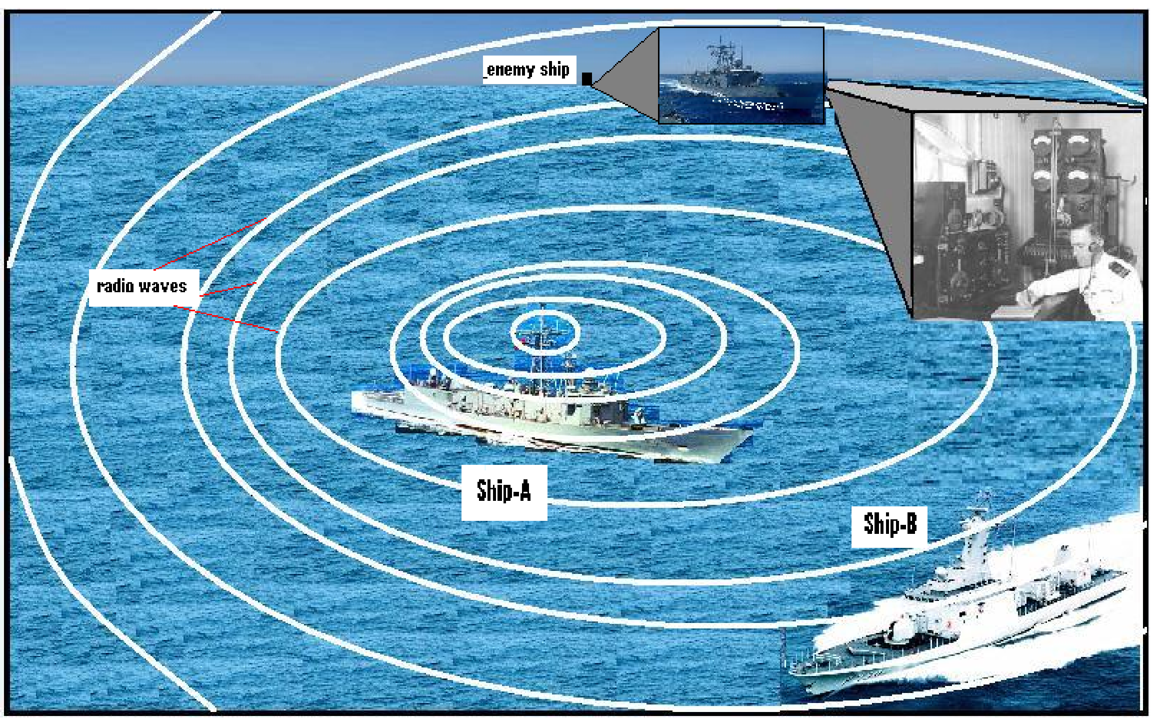

Figure 2. Communicating ships with RF system

In this first scenario Ship-A is communicating with Ship-B by establishing a radio link. Information is being sent by RF antennas, which transmit electromagnetic waves omni-directionally. A secure communication link could be maintained by using strong encryption techniques and frequency shifting but the location of the ships is still compromised. Transmitted signals can easily be intercepted by opposing forces, which would lead them to identify the sender ship by analyzing the frequency of the signal. Every radio device operates on a frequency unique to the device called fingerprint, which can later be used to identify the platform as long as the opposing force has the particular fingerprint information. In addition to be identified, direction of the sender ship can be easily calculated by the opposing force, consequently gives the opportunity to launch a strike against the detected ship by guided missiles.

A second scenario is based on using FSO systems. Unlike RF emissions, FSO devices transmit the signal directly to the receiver. Figure 3 illustrates the optical communication link established between Ship-A and Ship-B.

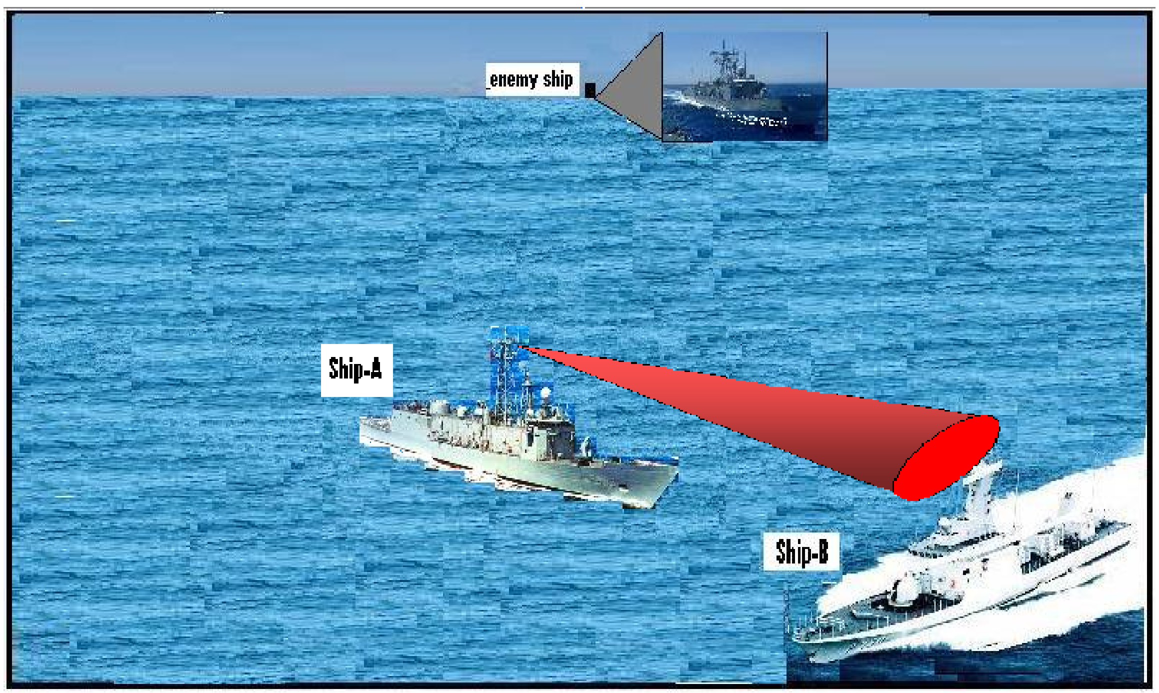

Figure 3. Communicating ships with FSO system

In this scenario detection and interception of the signal is highly unlikely for the opposing forces because non-visible narrow laser beams are being used instead of radio waves, which could be intercepted from long distances depending on the frequency used. If opposing force has no units line-of-sight to Ship-A, it is impossible for the opposing force to detect any transmissions from Ship-A. Using FSO systems enables Ship-A to communicate securely with Ship-B as well as remains both ships undetected.

The requirement for deploying a secure communication system to support operational activities on the deck of individual ships and between ships becomes more important. Technologies that eliminate RF emissions are favored by the Navy. Free Space Optics (FSO) addresses the need for secure, reliable and fast communication means by providing almost undetectable and interruptible optical link with high data rates and low bit error rates (BER). In addition, FSO eliminates RF emissions in the communication channel [DoD 2003].

Another important issue is that military systems do not interfere with commercial systems. Free Space Optics (FSO) works on the unregulated infrared portion of the electromagnetic spectrum. Current FSO technologies operate in wavelengths of 850 nanometers (nm) and 1550 nm. The technology that uses the wavelength of 850 nm is more economical but 1550 nm technology can safely transmit 50 times more optical power than 850 nm wavelength without damage to the human eye [Nykolak 1999]. Table1 shows the Maximum Permissible Exposure (MPE) limit for unaided viewing with different wavelengths.

Wavelength	750 nm	850 nm	1310 nm	1550 nm
Maximum Permissible Exposure (MPE)	1.2 mW / cm^2	2.0 mW / cm^2	40 mW / cm^2	100 mW / cm^2

Table 1. Maximum Permissible Exposure Limit for unaided viewing (From: [Nykolak 1999])

Considerable research for implementation of FSO communication for the Navy surface ship platforms in the marine environment has been conducted in the last decade. Lucent Technologies conducted tests during the period of

February 11, 1999 to March 23, 1999. Between the USS John C Stennis (CVN 74) and the Port Operations Building, at the US Navy North Island Facility, in San Diego, CA an optical wireless OC-3 (155 Mbps) Network was established. The USS John C Stennis (CVN 74) was moored 183 yards away from the Port Operations Building. In this 40 day experiment, “ship-to-pier” Free Space Optics communication network demonstration was successfully implemented with an availability of 99.96%, almost error free, and 99.92% error free seconds, by using auto-tracking systems, excluding outages resulting from power supplies. This experiment demonstrated that ship to shore communication with FSO systems from a moored vessel could be accomplished at high levels of system availability and quality [Nykolak 1999].

U.S. Naval Research Laboratory (NRL) has also been conducting several experiments in the past few years by operating a long-range, maritime, FSO communication facility. This facility is located between Chesapeake Bay, MD and Tilghman Island, MD. The one-way distance from Chesapeake Bay Detachment (CBD) to Tilghman Island is 16.2 km and the roundtrip distance from transmitter to receiver is 32.4 km. In this testbed, one-way link distance of 72 km is achieved by using a conservative estimate for the signal returned to the receiver by the retro-reflectors [Moore 2002].

Figure 4 illustrates the geometry of Chesapeake Bay Testbed.

Figure 4. Chesapeake Bay Testbed Geometry (From: [Vilcheck 2003])

In the initial experiments, conducted in 2002, NRL studied the stability and quality of the testbed including bit error rate measurements, probability density functions, power spectrum densities, and angle of arrival measurements [Moore 2002]. U.S. Naval Research Laboratory (NRL) has continued the experiments in 2003. In these new experiments NRL studied fast steering mirror implementation for reduction of focal-spot wander in a long-distance free-space communication link, spatial intensity correlation and aperture averaging measurements, performance of the link by using multiple quantum well modulating retro-reflectors, low frequency sampling adaptive thresholding for FSO communication receivers with multiplicative noise, passive optical monitor for atmospheric and wind speed, and progress in high-speed communication at the NRL Chesapeake Bay Lasercomm testbed [Suite 2003] [Moore 2003] [Mahon 2003] [Burris 2003] [Stell 2003] [Vilcheck 2003]. Results of these experiments will be discussed in further detail in the next chapters.

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III. BENEFITS OF FSO TECHNOLOGY

Free Space Optics (FSO), also known as wireless optical communication systems, is a medium to transmit modulated low power laser beams through the atmosphere from one “telescope” to another in the teraHetz (THz) frequency spectrum. The optical link is full-duplex, meaning that data can be transmitted in both directions on a signal carrier simultaneously. Commercially available FSO products have data rates of 2.5 Gbps, which is not possible to achieve using radio frequency (RF) technology. In addition to very high data rates, the optical communication link is more secure than RF links. Due to the wavelengths of the lasers used, FSO technology is considered to be eye-safe. Further more, FSO systems operate in the infrared portion of the electromagnetic spectrum, which is not currently regulated by the Federal Communications Commission (FCC). These inherent benefits make FSO technology more desirable for military operations and commercial applications.

This chapter explores the benefits of Free Space Optics (FSO) technology.

A. SECURITY

One of the biggest reasons for considering deployment of FSO systems on navy surface ship platforms is the secure communication need for the military. The need for more secure and faster communication medium becomes more important as the Electronic Warfare (EW) technology advances.

Security techniques for military systems have been used for centuries but even the most advanced military systems suffer from exploits caused by the technologies used. In the twentieth century, wireless military communication systems have been developed to account for ever-increasing sophistication in Electronic Warfare (EW) while the opposing force has employed Electronic Countermeasures (ECM), the division of EW involving actions taken to prevent or reduce an enemy’s effective use of the electromagnetic spectrum by detecting the presence, disrupting the transmission and exploiting the signals. The ECM techniques have forced the military to use Electronic Counter-Counter Measures (ECCM), the division of electronic warfare involving actions taken to ensure friendly effective use of the electromagnetic spectrum despite the enemy's use of EW. Consequently, military systems have been developed to counteract jamming (denial of access), spoofing, and detection using anti-jam, anti-spoofing, and low-probability-of-intercept methods.

This section will look at the security benefits of FSO systems for navy surface ships.

1. Detection

The conventional RF systems severely limit use of current military communication systems in terms of security. Especially for the Navy, use of the RF based communication systems provides an opportunity for the detection of the ship by opposing forces. Deploying secure communication system to support operational activities on the deck of individual ships and between ships without being detected is always desired. However, the nature of RF based systems make the communication of the ships very hard without being detected.

Detection of the signal gives initiative to the opposing force. Use of spectrum analyzers or RF meters enables navy units to detect RF signals. However, these devices cannot detect laser signals due to the nature of lasers. In order to detect a laser transmission, a detector/infrared viewer or receiver must be located within the laser beam cone, between the transmitters or behind the receiver to intercept uncollected part of the beam, but this is highly unlikely.

Some factors may increase the low probability of laser signal detection such as beam divergence, power of the signal and weather conditions. Divergence of the laser beam depends on the divergence angle of the transmitter and forms a spherical cone. Microwave transmitters have a divergence angle of a few degrees where FSO systems have a few milliradians (1 mrad=0.0573 degree).

The size of the beam cone increases by distance. In order to find the volume of the cone, the formula $V_c = 1/3x\pi \text{ x } r^2 \text{ x } h$ is used, where *r* is the radius of the base of the cone, and *h* is the distance from the transmitter to the receiver. Since line-of-sight (LOS) is mandatory for FSO communication, for realistic comparison, distance *h* is 16 km (approximate distance of horizon for a transmitter mounted 20 meters high above the sea level).

The formula of radius is $r = h \times \tan(\theta/2)$, which gives the beam size on receiver's end $d = 2 \times r$. For a microwave transmitter with a divergence angle of 3 degrees,

$$r = 16{,}000 \times \tan(3/2)$$

$$r = 419 \text{ m}$$

the size of the beam is:

$$d = 2 \times r = 838 \text{ m}$$

so the volume of the cone is:

$$V_c = 1/3 \times \pi \times r^2 \times h$$

$$V_c = 1/3 \times 3.14 \times 419^2 \times 16{,}000$$

$$V_c = 2{,}940{,}061{,}546 \text{ m}^3$$

For a FSO transmitter with a divergence angle of 2 mrad (0.1146 degrees),

$$r = 16{,}000 \times \tan(0.1146/2)$$

$$r = 16 \text{ m;}$$

the size of the beam is:

$$d = 2 \times r = 32 \text{ m}$$

so the volume of the cone is:

$$V_c = 1/3 \times \pi \times r^2 \times h$$

$$V_c = 1/3 \times 3.14 \times 16^2 \times 16{,}000$$

$$V_c = 4{,}287{,}147 \text{ m}^3$$

For a microwave transmitter with a divergence angle of 3 degrees results a cone volume of 2,940,061,546 m^3 where for a laser transmitter with a divergence angle of 2 mrad (0.1146 degrees) results a cone volume of 4,287,147 m^3. The volume of the transmission cone for the microwave transmitter is almost 686 times greater than that of the laser transmitter, which means detection of the microwave transmission is 686 times more likely compared to laser detection [Neo 2003].

In conclusion, detection of laser communication between ships is highly difficult due to the nature of the laser and the divergence angle of the transmitter. On the other hand detection of RF based technologies is not that hard by using spectrum analyzers or RF meters.

2. Interception

In Electronic Warfare (EW) intercepting the signal comes right after the detection of enemy's transmission. Many RF systems radiate radio signals in all directions making the signal accessible to anyone with a receiver while point-to-point microwave systems transmit directional beam. Even so, divergence of the beam increases the probability of interception of microwave systems. However, intercepting a laser transmission is very difficult.

In order to intercept, the optical link has to be tapped with a matching transceiver carefully aligned. In addition, tapping the laser signal is very hard without disrupting it while the diffraction characteristics of RF transmissions enable microwave signal tapping easier. The interruption of the laser signal would result a sudden drop in received power at which point the manager software built in the systems may notice and cease the transmission, which may not be sufficient to extract information.

The possibility of interception of the laser beam includes the possibility of detection, as mentioned in previous section it is highly unlikely, and it can be reduced by using smaller divergence angle. However, in some cases, such as poor weather conditions, increasing divergence angle might be necessary for ship-to-ship communication to compensate the change in the direction of the laser beam caused by the ship movements. Even so, interception of the ship-to-ship laser transmission is extremely difficult and highly unlikely because communicating platforms are mobile.

In conclusion, unlike the RF technologies, the probability of interception of the laser signal is not a concern for Navy surface ships since the communicating platforms are mobile and divergence of the beam is much less. In addition, the effect of increased divergence angle, to compensate ship movements, is not as threatening as for the microwave technology.

B. BANDWIDTH

Free Space Optics (FSO) systems have potential of significantly reducing the time-line for delivering information and enabling new missions like the transmission of high resolution graphics and videos. High resolution graphics and videos require fast transmission channels due to their sizes. The speed of a given transmission channel, called data rate, is measured by the amount of bits transmitted in a second. Currently, commercially available FSO products provide data rates of 2.5 Gbps. Demonstration systems report data rates as high as 160 Gbps. Higher data rate makes FSO systems superior to existing fixed wireless technologies, such as Institute of Electrical and Electronics Engineers (IEEE) 802.11, Local Multi-point Distribution Services (LMDS), and Multi-channel Multi-point Distribution Systems (MMDS).

Bandwidth is closely related to data rate. High data rates require a lot of spectrum, which is why FSO technology is becoming more popular. Higher frequencies enable higher data rates. Table 2 shows range of frequencies for the different electro-magnetic radiation (EMR) bands.

EMR Bands	Frequencies, f (Hertz)
Radio	30×10^{3} to 3.0×10^{9}
Microwave	3.0×10^{9} to 3.0×10^{12}
Infrared	3.0×10^{12} to 4.3×10^{14}
Far Infrared	3.0×10^{12} to 2.0×10^{13}
Long Wavelength Infrared (LWIR)	2.0×10^{13} to 3.8×10^{13}
Mid Wavelength Infrared (MWIR)	3.8×10^{13} to 1.0×10^{14}
Short Wavelength Infrared (SWIR)	1.0×10^{14} to 2.0×10^{14}
Near Infrared	2.0×10^{14} to 4.3×10^{14}
Visible Light	4.3×10^{14} to 7.5×10^{14}
Ultraviolet	7.5×10^{14} to 6.0×10^{16}

Table 2. Table of EMR Frequency Bands (From: [Neo 2003])

As it can be seen from the Table 2, radio and microwave bands allocate frequencies between 30×10^{3} Hertz and 3×10^{12} Hertz (30 KHz-3 THz). In this frequency portion of EMR spectrum wireless technologies IEEE 802.11, LMDS and MMDS operate. So-called teraHertz (THz) spectrum starts with the frequencies above 3×10^{12} Hertz where infrared band operates. In this frequency band lasers are non-visible. The visible light band comes after infrared with the frequency allocation between 4.3×10^{14} to 7.5×10^{14} Hertz (430-750 THz).

Free Space Optics (FSO) lasers mostly used in one of the two wavelength portions; 780nm-900nm and 1500nm-1600nm. Lasers of 850nm wavelength (corresponds to 353 THz) are considered as short wavelengths and are more susceptible to atmospheric attenuation than the wavelength of 1550nm (corresponds to 194 THz). As it can be derived from the corresponding frequencies many of the FSO systems operate in the near infrared band where the frequencies are much higher than radio and microwave bands. The higher frequencies in this band provide 100 to 100,000 times higher data rates than the radio and microwave band wireless technologies mentioned in the previous paragraph.

Data rate of 2.5 Gbps was demonstrated over a distance of 28 km by the Lawrence Livermore National Laboratory, under the U.S. Department of Energy and operated by the University of California, in early 2002. The link was established between the Laboratory (in Livermore, CA) and Mount Diablo under the Secure Air-Optic Transport and Routing Network (SATRN) program. This test represents one of the longest terrestrial high-capacity FSO links ever achieved [Neo 2003].

Figure 5. A SATRN team member standing next to the transceiver telescope on top of Mount Diablo (From: [Neo 2003])

The longest and the highest speed FSO laser communication link near ground level was demonstrated by NRL, in 2002. U.S. Naval Research

Laboratory (NRL) has been conducting several experiments in the past few years by operating a long-range, maritime, FSO communication facility. This facility is located between Chesapeake Bay, MD and Tilghman Island, MD. The one-way distance from Chesapeake Bay Detachment (CBD) to Tilghman Island is 16.2 km and the roundtrip distance from transmitter to receiver is 32.4 km. In this testbed, one-way link distance of 72 km is achieved by using a conservative estimate for the signal returned to the receiver by the retro-reflectors [Moore 2002]. Initial tests at the CBD-Tilghman Island test bed successfully demonstrated data rates up to 500 Mbps.

Figure 6. NRL-CBD to Tilghman Island FSO lasercomm test bed. Bistatic transmitter and receiver at CBD (left) and corner-cube retro-reflector arrays mounted on the tower on Tilghman Island (right) (From: [NRL 2004])

Further tests in the same test bed reported data rates of 622 Mbps at 1542nm wavelength were achieved across 34.4 km distance, on July 2003 [Vilcheck 2003]. These tests demonstrate that a high-speed free space laser communication link in a maritime environment is possible.

C. BIT ERROR RATE

The acronym BER bit error rate stands for bit error rate that measures the number of error bits received in a transmission for a given amount of sent data. For example, if a transmission has BER of 10^{-9}, there is one error bit received out of one billion bits transmitted. The BER indicates how often a packet or data unit has to be retransmitted due to the receiving of error bit. Data rate of a system might be adjusted according to the BER value. Slower data rate would improve overall transmission time of a given amount of transmitted data if the BER were too high. By reducing the data rate, the BER value might be decreased by lowering the number of packets that have to be resent [TechTarget 2004].

The BER value depends on different factors such as distance of the transceivers, weather conditions, sensibility and size of the receiver, power consumed by the sender, etc. Most of the FSO vendors claim that their products have BER up to 10^{-9} but this is misleading since there are uncontrolled factors affecting BER value such as weather conditions.

However, FSO systems have a feature of attaining lower BER values than the RF systems since FSO systems have smaller spectral widths, range of transmitted frequencies, than RF systems. The range of transmitted frequencies theoretically forms a Gaussian distribution, also known as normal distribution [Neo 2003].

The narrower spectral width enables more concentrated energy around the carrier (central) frequency. For example, the laser of 850 nm wavelength that has more power concentrated around the carrier frequency (850 nm) is less susceptible to the atmospheric attenuation than the same wavelength but less power concentrated one.

Figure 7 shows two lasers with the same wavelength and same input power. The Laser-A has spectral width of 2 nm while Laser-B has 4nm.

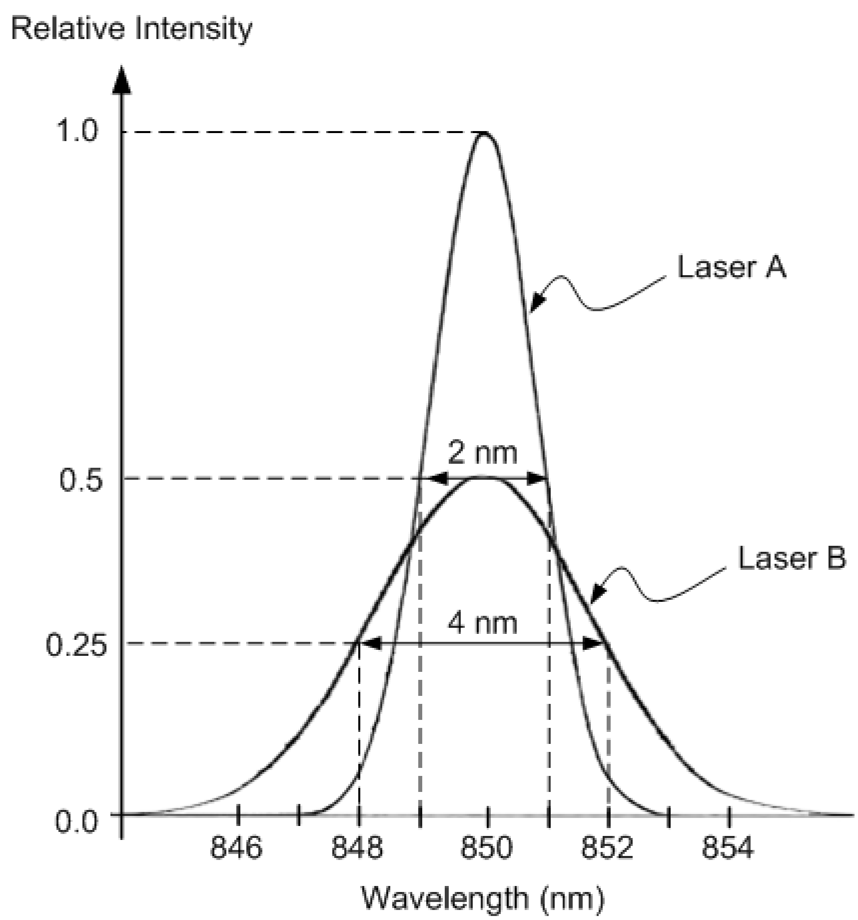

Figure 7. Comparison of Laser Outputs with Different Spectral Widths (From: [Neo 2003])

Laser-B, which has twice the spectral width, has less power concentrated around the carrier frequency (850 nm). The power has proportioned among the side frequencies. Since Laser-A has more power concentrated, it will attenuate less than the Laser-B.

As previously mentioned the BER of FSO systems are mostly declared by FSO vendors. In order to get realistic values, BER measurements have to be performed for different data rates under different weather conditions. The Naval Research Laboratory (NRL) has conducted BER measurements in two separate tests at the same test bed Chesapeake Bay, MD in 2002 and 2003. The first test was performed by a link of 72 km. To lessen the effect of beam wander due to the turbulence, test was carried out when the turbulence conditions were low.

There was neither active aiming nor adaptive optics to improve the link performance. The BER measurement was performed at four data rates of 100 Mbps, 200 Mbps, 300 Mbps and 500 Mbps. The BER measurement results are shown in Figure 8.

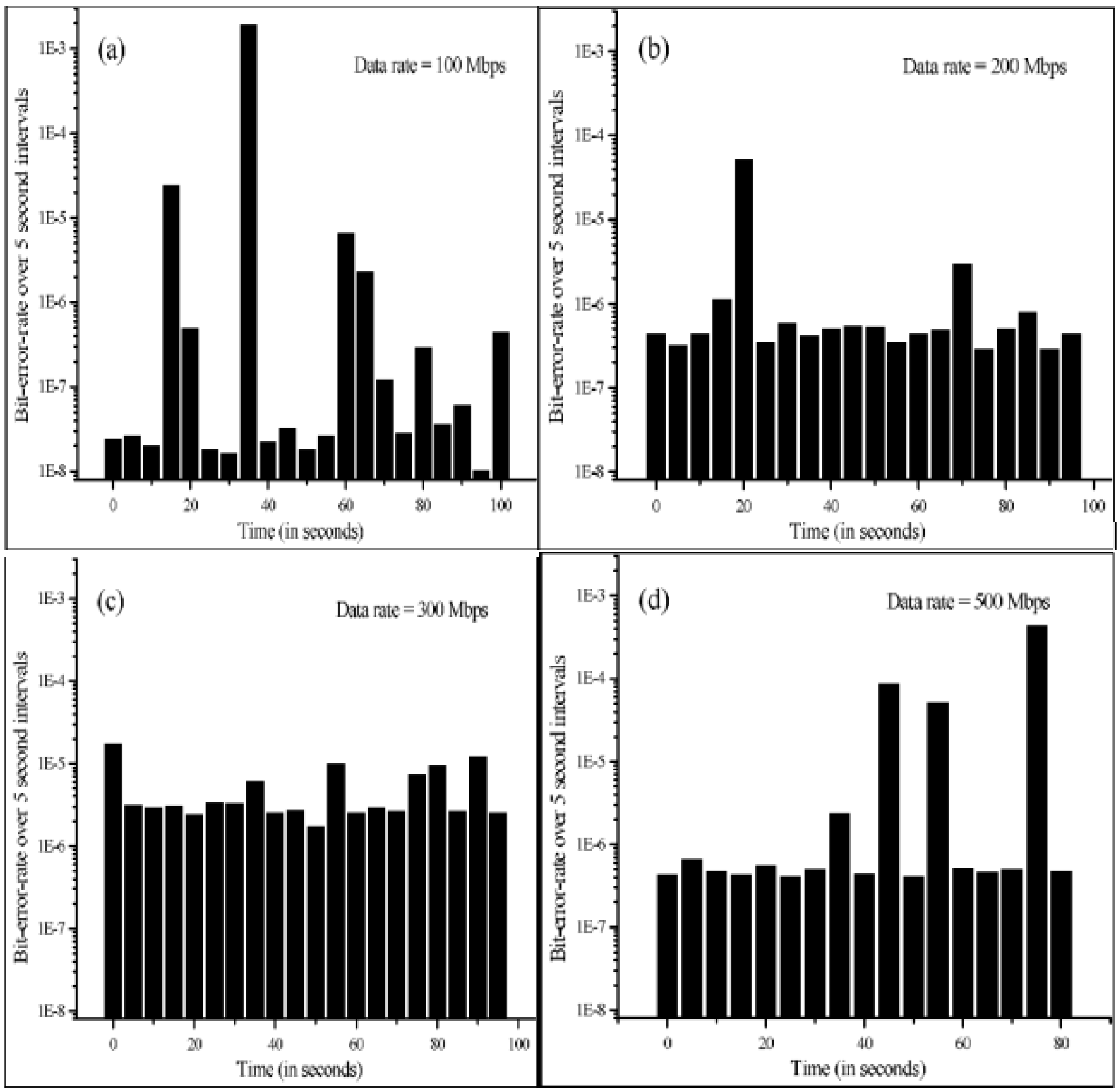

Figure 8. Bit error rates at four data rates. (From: [Moore 2002])

Each graph shows the BER over approximately 90 seconds with each bar representing the average BER over a 5 second interval. The result of the initial test is somehow promising for a long-range (72 km) maritime link. Testing at different data rates have shown a BER below 10^{-5} 90% of the time in low turbulence conditions with no active aiming and no adaptive optics. The NRL reports that the BER above 10^{-5} were likely due to the angle-of-arrival fluctuations causing poor coupling to the receiver fiber and a resultant low power on the receiver [Moore 2002].

The test conducted on July 11, 2003 at the same test bed over the link of 34.4 km. The BER was calculated in one-minute intervals spanning an hour for two different hours in the afternoon. Data rates of 622 Mbps at 1542 nm propagated across the link. Figure 9 shows the BER test in the first hour.

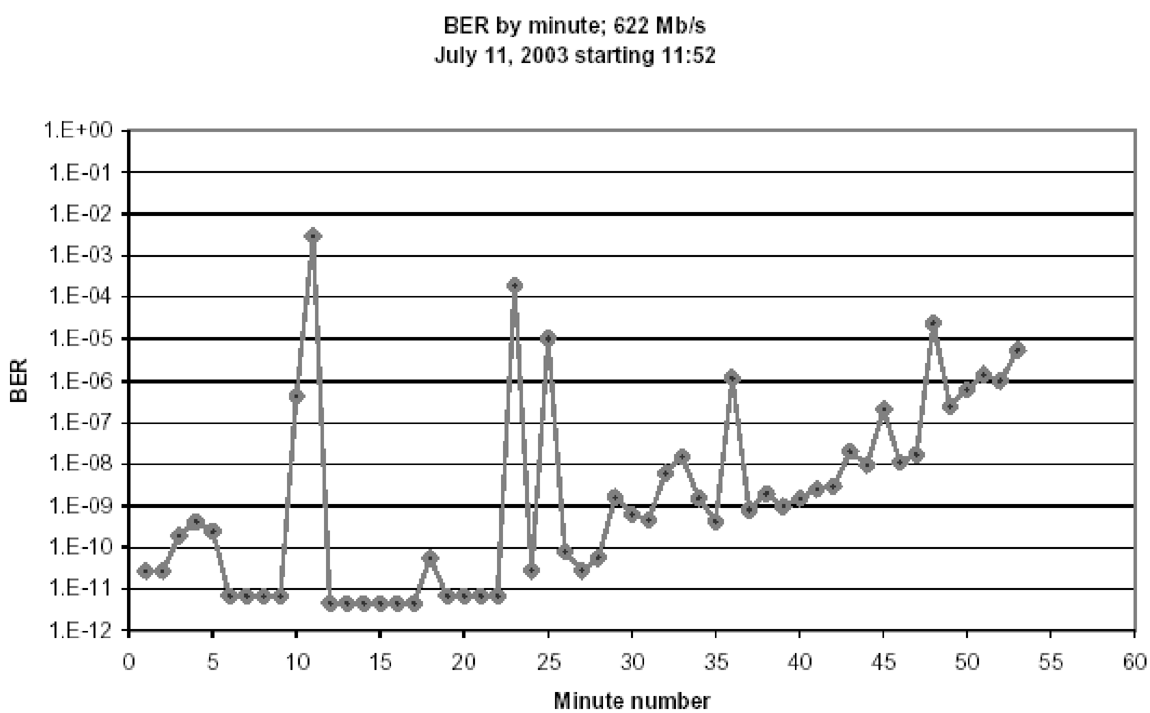

Figure 9. BER test 1. (From: [Vilcheck 2003])

As it can be seen clearly, the BER is increasing after 23 minutes. The change was caused by the temperature because as the temperature gradient over the water changes throughout the day, the resulting index of refraction gradient changes the pointing of the transmitter beam. Due to the lack of active aiming, beam wander increased the BER.

For the second part of the test, pointing offsets caused by temperature gradients were corrected before the measurement. Figure 10 shows the BER results for the second test.

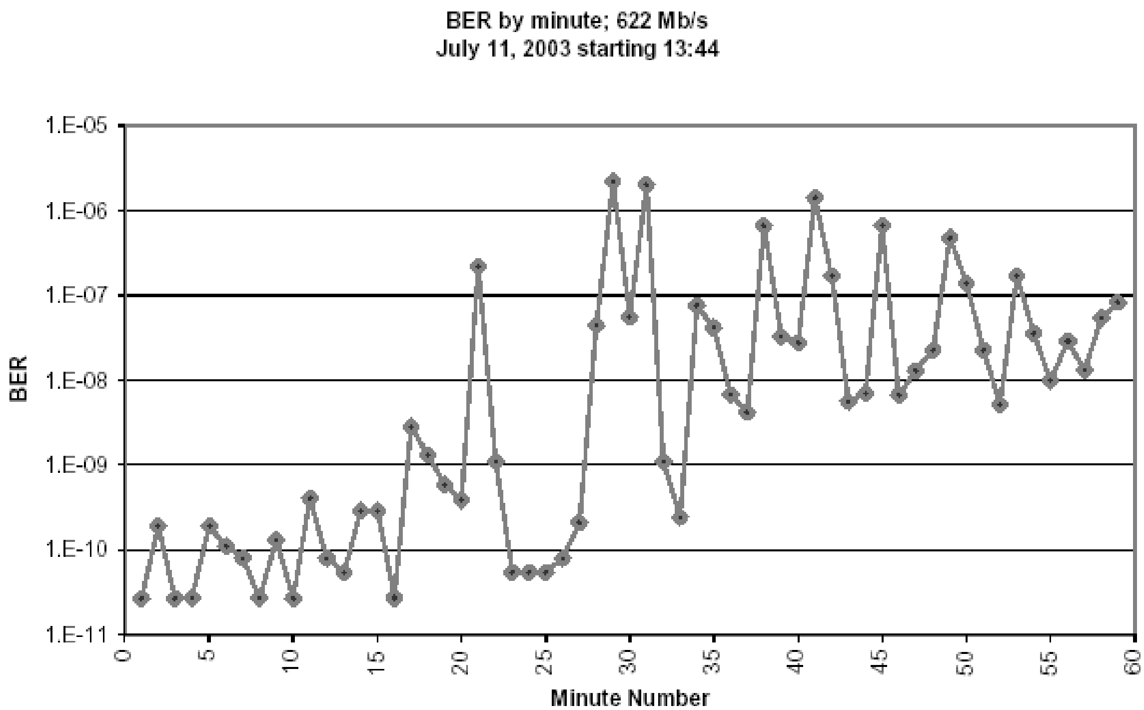

Figure 10. BER test 2. (From: [Vilcheck 2003])

Similarly, the change in the BER was noticed after a certain amount of caused by the same effect, the temperature gradient change. The BER is calculated less than 10^{-6} at data rates of 622 Mbps. This result is achieved with no active pointing, no adaptive optics, no forward error corrective coding, and no adaptive thresholding [Vilcheck 2003]).

The tests conducted two years in a row show that even without any corrective methods such as adaptive optics and active aiming, long-range maritime laser communication link can be established at data rates of 622 Mbps with BER around 10^{-6} for fixed sites. Implementation of FSO for ship-to-shore and ship-to-ship would be more challenging. However, active aiming and tracking systems, adaptive optics such as fast-steering mirrors, forward error corrective coding, adaptive thresholding, and aperture averaging might compensate the challenge of moving platforms.

D. SPECTRUM LICENCING

Adopting a particular technology for military operations is more challenging in terms of selecting an appropriate portion from electromagnetic spectrum. The biggest concern is interference with existing commercial and military systems. Current radio frequency based technologies are limited by the frequencies they operate. Free Space Optics (FSO) systems take advantage of using the infrared portion of the electromagnetic spectrum, which is not currently regulated by International Telecommunications Union (ITU).

The ITU is the authority for regulating the radio frequencies worldwide with 187 member countries. Frequency bands are allocated to the different services either worldwide or regionally. Band allocations are set out in the table called Table of Frequency Allocations where each band may be allocated to one or more services, with equal or more rights. The world is divided into three regions for purposes of frequency allocation. Turkey is in Region 1 and the U.S. is in Region 2 [ITU 2004].

In the United States, the Federal Communications Commission (FCC) is the authority for regulating domestic radio frequencies and issuing spectrum licenses. Currently, the frequencies above 300 GHz (less than 1 mm in wavelength) have not been regulated by FCC. Free Space Optics (FSO) systems use frequencies above 3 THz so they do not require spectrum licensing. In addition, the probability to interfere with another transmissions is highly unlikely because FSO terminals use narrow laser beams transmitted directly to the receiver terminals which is one of the biggest concerns for RF based technologies.

IV. CHALLENGES OF FSO

Free Space Optics (FSO) technology provides fast, secure and reliable data transmission for military and commercial business. FSO uses laser beams to transmit data through the air. Despite of the inherent benefits, FSO technology has limitations that affect link performance. The most significant challenge is effects of atmosphere.

As the laser beam propagates through the air it attenuates. The atmospheric attenuation is low when the weather is clear, but it could become very high during poor weather conditions like heavy rain and severe in dense fog. The second challenge is the requirement for line-of-sight (LOS).

Since FSO systems use highly directional narrow laser beams to communicate, there must not be any physical obstruction between the transmitter and the receiver. Physical obstruction may block the laser beam either partially or completely resulting insufficient or no laser power on the receiver side. Other than LOS, directional precision is an important challenge since this thesis work focuses on ship platforms, which are mobile and are not stable on sea.

The FSO systems have a very small beam divergence, which provides great security for the ship-to-ship communications, making to point the laser beam more difficult to the receiver. In addition to these challenges, distance between the communicating platforms and the visibility of the area are important parameters.

These challenges limit FSO technology to shorter distances. This chapter explains the challenges of FSO systems.

A. ATMOSPHERIC EFFECTS

Clean, clear atmosphere is composed of oxygen and nitrogen molecules. In addition, the weather can contribute large amounts of water vapor. These particles can scatter or absorb signals operated in infrared band as they propagate in the atmosphere. On the other hand, it is possible to take advantage of optimal atmospheric windows by choosing the transmission wavelengths accordingly.

The FSO systems operate in the infrared (IR) range in order to ensure a minimum amount of signal attenuation from scattering and absorption. As mentioned in the previous chapter, FSO systems operate in the near infrared portion of the frequency spectrum (200 THz - 400 THz) mostly around wavelengths of 850 nm and 1550 nm [Ghuman 2002]. The wavelengths in ranges between 300-500 nm and 800-1400 nm are more susceptible to the atmospheric attenuation then the wavelengths of 850 nm and 1550 nm.

The effects of atmosphere to a signal consist of absorption, scattering and turbulence.

1. Absorption

Gases, found in the atmosphere, drastically absorb the signals in infrared band and ultraviolet band. In the atmospheric window most commonly used for FSO, infrared range, the most common absorbing particles are water, carbon dioxide, and ozone. A typical atmospheric transmittance spectrum is shown in Figure 11.

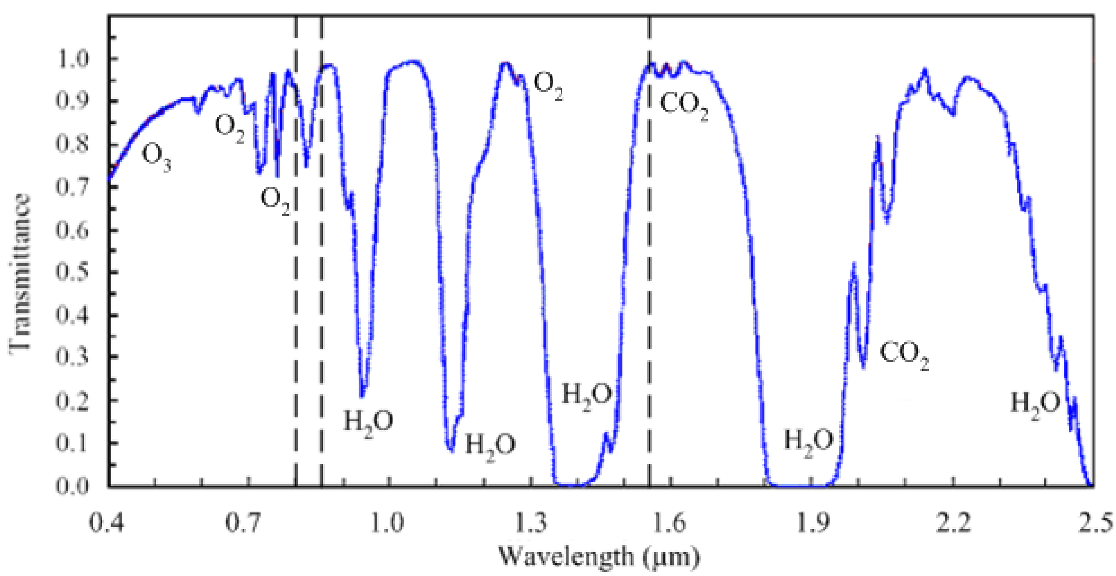

Figure 11. Visible and Infrared Atmospheric Transmittance (From: [Neo 2003])

The figure above shows the transmittance of the atmosphere on the wavelengths in the visible band and infrared band. It can be seen that the absorption is caused by H_2O (water), O_2 (oxygen), O3 (ozone) and CO_2 (carbon dioxide).

The wavelengths between 0.4 μm to 0.7 μm belong to the visible light portion of the EMR bands. In these wavelengths ozone and oxygen gases slightly absorb the signal. The near infrared wavelengths remain in the wavelengths between 700 nm (0.7 μm) to 1500 nm (1.5 μm). Water molecules are the dominant absorption factor for these frequencies. This portion of the EMR spectrum is used by FSO systems. The wavelengths above 1.5 μm (1500 nm) are operated by microwave and radio technologies and affected primarily by water and carbon dioxide.

Figure 11 also demonstrates why commonly used wavelengths of 800 nm (0.8 μm), 850 nm (0.85 μm), and 1550 nm (1.55 μm) are chosen for FSO systems. High atmospheric transmittance values are the main reason for selecting these wavelengths, shown with dotted lines [Neo 2003].

2. Scattering

Light scattering can drastically impact the performance of the FSO systems. The particles or atmospheric molecules that the light encounters during the propagation to its destination cause scattering. Several scattering regimes exist, depending on the characteristic size of the particles. Compared to infrared wavelengths, usually used in FSO, the radius of the water particles in fog is about the same size [Ghuman 2002]. This is the reason why fog highly reduces the performances FSO systems by scattering the signal rather than rain or snow. The sizes of rain and snow particles are larger than the infrared wavelengths and do not cause the same effect as fog. On the other hand, the sizes of the raindrops are close to the wavelengths of microwave signals consequently rain drastically scatters the signal rather than fog.

As mentioned, depending on the characteristic size of the particles several scattering regimes exist such as Raman scattering, Rayleigh scattering, and Mie scattering.

Atmospheric molecules or particles of sizes from 10% to 150% of the wavelength of the incident light cause Raman scattering and the sizes less than 10% cause Rayleigh scattering. The energy of incident light photons determines the frequency of light. In Raman scattering, energy of the incident photons of light is either gained or the lost and the emitted light is of the different frequency from the incident light, but in Rayleigh scattering energy remains unchanged therefore the emitted light is of the same frequency as the incident light. In addition, Raman scattering is usually negligible unless a powerful laser source is used [Neo 2003].

Longer wavelengths (lower frequencies) experience substantially lower Rayleigh scattering than the shorter wavelengths. Figure 12 demonstrates the relationship between infrared wavelengths with Rayleigh scattering.

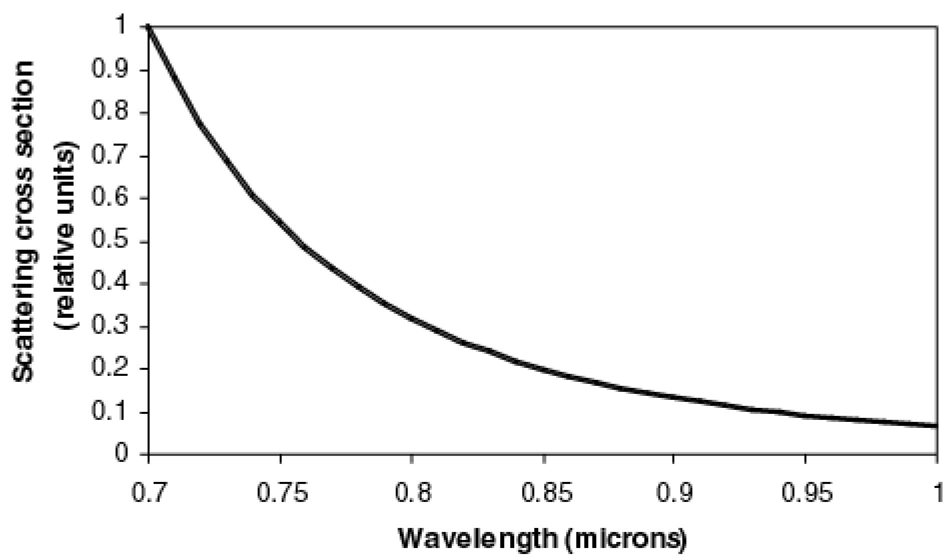

Figure 12. Rayleigh scattering cross section versus infrared wavelength (From: [Ghuman 2002])

Mie scattering, as the third scattering regime, is similar to Rayleigh scattering because the frequency of scattered light has the same frequency as the incident light but the distribution of the scattered light is different. The distribution of the scattered light is smaller for Mie scattering. Figure 13 demonstrates the differences in distribution of scattered light.

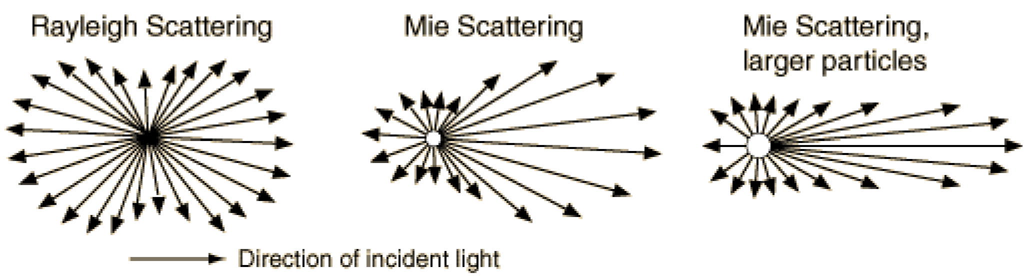

Figure 13. Comparison Between Rayleigh and Mie Scattering (From: [Neo 2003])

For Rayleigh scattering, the intensity of the scattered light is largely uniform while it is greatest in the direction of the incident light for Mie scattering. In addition, larger scattering particles decrease the loss of incident light intensity caused by Mie scattering [Neo 2003].

In summary, scattering decreases the performance of the wireless technologies depending on the wavelength used. The FSO technology is severely affected by fog rather than rain due to the smaller sizes of water particles in fog, which are close to the size of the infrared wavelengths. On the contrary, microwave systems (especially for frequencies above 11 GHz) are affected more by rain than fog because of the close sizes of raindrops to their wavelengths.

3. Turbulence

So far, dry and hot weather might seem perfect for an FSO system. On the contrary, in hot and dry climates, turbulence might cause problems with the transmission. As the sun heats up the air, some air cells or air pockets heat up more than others. This causes changes in the index of refraction, which corresponds to the speed that the light may travel through air. This later can change the path that the light takes while it propagates through the air. Since these air pockets are not stable in time or in space, the change of index of refraction appears to follow in a random motion, which appears as turbulent behavior to the outside observer.

The refractive index structure coefficient (C_n^2) is a good measure of turbulence. Since the air needs time to heat up, the turbulence is typically greatest in the middle of the afternoon where C_n^2 is around 10^{-13} $m^{-2/3}$. Similarly, the turbulence is typically weakest after the sunrise or sunset where C_n^2 is around 10^{-17} $m^{-2/3}$. The refractive index structure coefficient is usually largest near to the surface, decreasing with altitude [Ghuman 2002]. Different surfaces such as water, deck of the ship or ground may affect in different ratios.

The Naval Research Laboratory (NRL) has conducted several tests on the Chesapeake Bay. One of these tests was conducted for determining the turbulence levels for a 10-mile (16.2 km) path across the Chesapeake Bay, MD [Stell 2003]. In order to measure the turbulence effects a turbulence monitor was used. In this experiment, 622 Mbps laser communication link with 10^{-10} bit error rate (BER) at a turbulence level of 5 x 10^{-13} $m^{-2/3}$ (significantly above the median observed C_n^2 value) was demonstrated.

As shown in Figure 14, a spotlight placed on a tower on Tilghman Island acted as the light source for the monitor. The spotlight was a few feet above the retro-reflector array used in NRL's laser communication experiments across the bay.

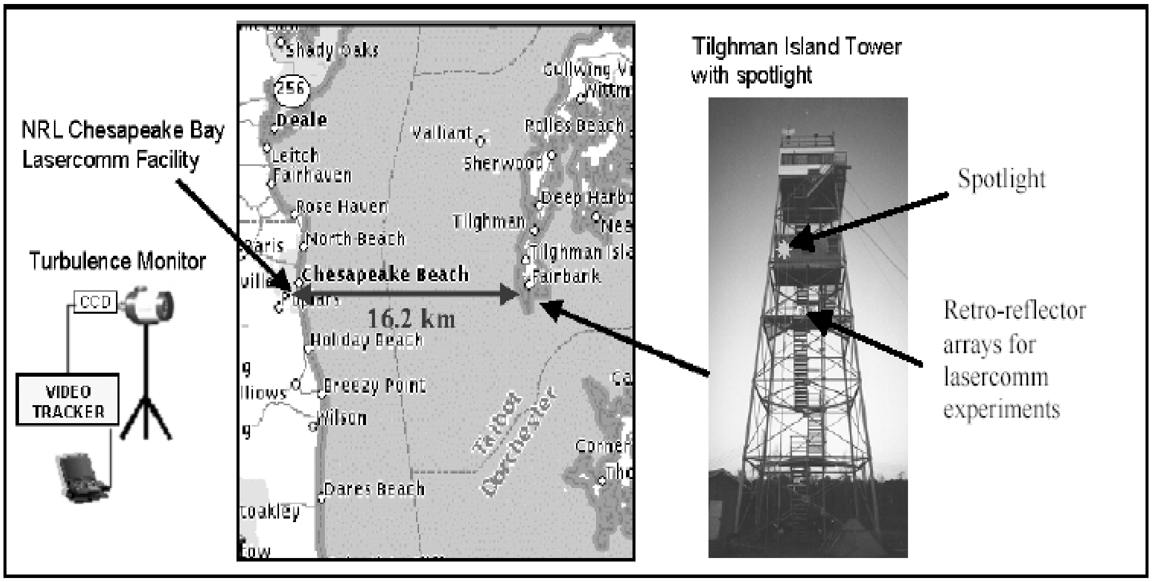

Figure 14. Turbulence measurement across the Chesapeake Bay (From: [Stell 2003])

The effect of turbulence across the Chesapeake Bay is clearly illustrated in Figure 15 with snapshots taken by the CCD camera attached to the monitor under three different turbulence conditions.

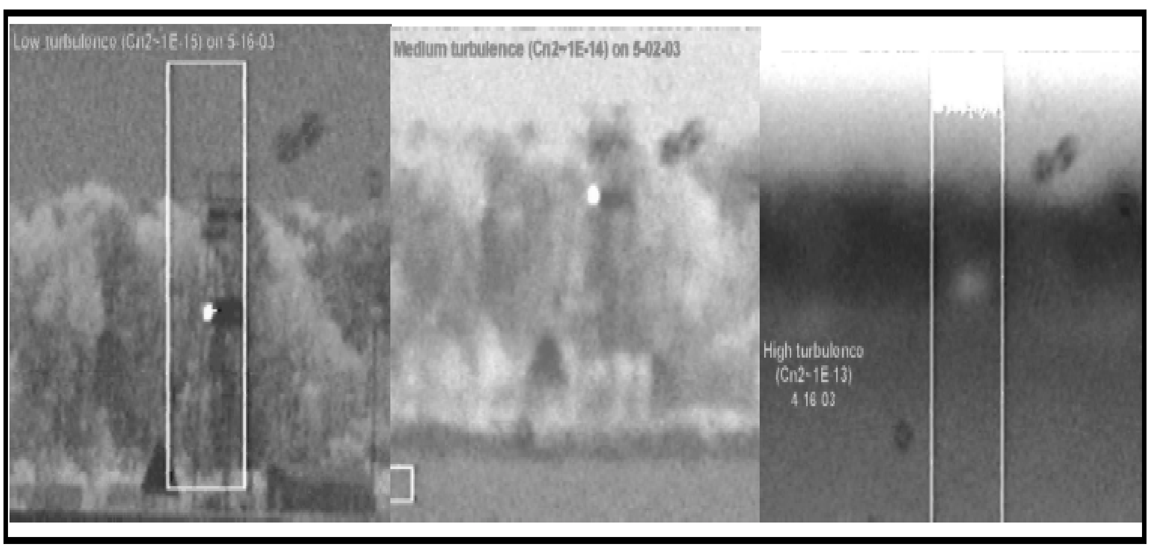

Figure 15. The Tilghman Island tower as imaged through the monitor under three different levels of turbulence (From: [Stell 2003])

The first snapshot was taken under low turbulence conditions ($Cn^2 \sim 10^{-15}$ $m^{-2/3}$) and the tower and the spotlight are clearly visible. However, even under such low turbulence, significant angle-of-arrival variation due to the length of the path was experienced.

The second snapshot was taken under medium turbulence conditions ($Cn^2 \sim 10^{-14}$ $m^{-2/3}$). Even though it is distorted, the spotlight and tower are still visible. However, high spatial frequency objects have disappeared and a video stream showed large variations of the image in time. In addition, the lensing effect was induced by thermal layers over the water. This lensing effect made the bottom of the image seem elongated while the top of the image appears compressed.

The third snapshot was taken under high turbulence conditions ($Cn^2 \sim 10^{-13}$ $m^{-2/3}$). In this snapshot, the tower has disappeared entirely. Under these conditions, the spotlight was a flashing blurred light that varied strongly in intensity.

Laser beams experience three effects under turbulence: scintillation, beam wander, and beam spreading.

a. Scintillation

The effects of atmospheric scintillation could be observed even with a naked eye. A mirage that appears as a lake in the middle of hot asphalt can be an example for the effect of scintillation. Of the three turbulence effects, FSO systems are most affected by scintillation.

Zones of different densities act as lenses, scattering light away from its intended path. Effects of scintillation can cause different parts of a laser beam to travel slightly different paths and then combine. The recombination may be destructive or constructive at any particular time resulting in recurring momentarily losses of signal, which degrades the performance of the FSO systems. Scintillation is greatest in hot sunshine (especially in the middle of the afternoon), when air is visibly shimmering, but occurs all the time, and is the reason stars twinkle in the night sky [Zaatari 2003]. Figure 16 demonstrates the effect of scintillation on a laser beam.

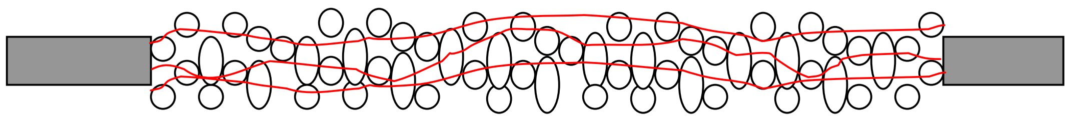

Figure 16. Effect of scintillation on a laser beam

Scintillation effects for small fluctuations follow a log-normal distribution, characterized by the variance, σ_i, for a plane wave given be the following formula; $\sigma_i^2 = 1.23 \times C_n^2 \times k^{7/6} \times L^{11/6}$, where $k = 2\pi / \lambda$, λ is wavelength and L is distance. From the formula it can be derived that larger wavelengths would experience a smaller variance. For FSO systems with a narrow, slightly diverging beam, the plane wave expression is more appropriate than that for a spherical beam. Even if the wave front is curved as it reaches the receiver, the transmitting beam is so much larger than the received that the wave front would be effective flat. The expression for the variance for large fluctuations ($\sigma^2_{high}=1.0+0.86 \times (\sigma^2)^{-2/5}$) suggests that shorter wavelengths would experience a smaller variance [Ghuman 2002].

One way to combat scintillation effect in marine environment is deploying the FSO transceiver high on the mast of the ship. Surfaces of the open decks of the ship get hot from the sun and heat up the air pockets causing scintillation. Deploying the device on a higher place would degrade the negative effects of scintillation. Other solutions include using large aperture receivers and multiple transmitters, which may not be feasible for ships regarding to deploy the transceivers on the mast.

b. Beam Wander

Beam wander arises from turbulence, causing a slow but significant, displacement of the transmitted beam. For a beam in the presence of large cells of turbulence compared to the beam diameter, geometrical optics can be used to describe the radial variance, σ_r, as a function of wavelength, λ, and distance, L, is $\sigma_r = 1.83 \times C_n^2 \times \lambda^{-1/6} \times L^{17/6}$ [Ghuman 2002].

This relationship implies that longer wavelengths will have less beam wander than the shorter wavelengths, even though the wavelength dependence is weak. However, keeping a narrow beam on track might be a problem. Using a tracking system might be useful for this problem. Figure 17 illustrates the beam wander caused by the turbulence.

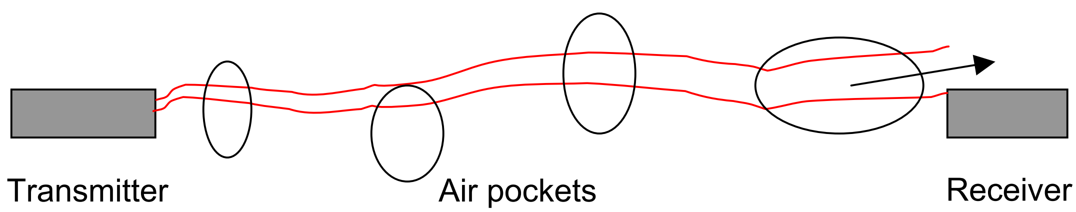

Figure 17. Beam wander caused by turbulence

c. *Beam Spreading*

Small temperature variations refract or bend rays of the laser spreading the energy of the beam. Too much beam spreading results in insufficient energy on the receiver side at longer distances.

The beam size can be characterized by the effective radius, a_t, the distance from the center of the beam (z = 0) to where the relative mean intensity has decreased by 1/e.

The effective radius is calculated by $a_t = 2.01 \times (\lambda^{-1/5} \times C_n^2 \times z^{8/5})$. From the formula it can be derived that the wavelength dependency on beam spreading is not strong. So, using short wavelengths would not make a difference instead of longer wavelengths [Ghuman 2002].

Unlike scintillation, beam spreading is not a concern for FSO implementations on the ship platforms, since FSO systems use narrow and highly directional laser beams. As mentioned in the previous chapter, FSO systems have a beam divergence of a few milliradians (1 mrad=0.0573 degree).

For example, a divergence angle of 1 mrad at distance of 16 km (approximate distance of horizon for a transmitter mounted 20 meters high) results 1,218 times smaller cone volume than a microwave system with a divergence angle of 2 degrees.

In conclusion, beam spreading decreases the power of the laser beam as it propagates to longer distances. However, it does not affect the performance of the laser communication link as much as scintillation and beam wander.

4. Impact of Weather

Various weather conditions affect the performance of the FSO systems by the change in the range of visibility. Table 3 shows the International Visibility Codes for weather conditions and precipitation.

Weather Condition	Precipitation		Amount mm/hr	Visibility	dB loss/km
Dense fog				0 m, 50 m	–271.65
Thick fog				200 m	–59.57
Moderate fog	Snow			500 m	–20.99
Light Fog	Snow	Cloudburst	100	770 m 1 km	–12.65 –9.26
Thin fog	Snow	Heavy rain	25	1.9 km 2 km	–4.22 –3.96
Haze	Snow	Medium rain	12.5	2.8 km 4 km	–2.58 –1.62
Light haze	Snow	Light rain	2.5	5.9 km 10 km	–0.96 –0.44
Clear	Snow	Drizzle	0.25	18.1 km 20 km	–0.24 –0.22
Very Clear				23 km 50 km	–0.19 –0.06

Table 3. International Visibility Codes for weather conditions and precipitation (From: [Ghuman 2002])

Fog is the most severe weather phenomenon to FSO because it is composed of small water droplets with radius about the size of the infrared wavelengths. The size distribution of the particles in the fog varies for different degrees of fog. In order to distinguish the different degrees of fog, descriptive words such as “dense fog”, “thick fog”, “moderate fog”, and “thin fog” are used. The visibility more than 2,000 meters is referred as *hazy* [Ghuman 2002].

Scattering is the major effect of fog. This reduces the performance of the FSO system. From the table above it can be seen that the impact of the rain is much less than fog. Even heavy rain has up to three times less path losses than the light fog. Lasers of wavelength 1550 nm have higher power than the lasers at 850 nm thus they are more preferred in areas with frequent fog.

Rain, on the other hand, has less effect on FSO systems, because the radius of rain droplets is larger than the size of the infrared wavelengths. However, for the radio and microwave systems rain is the biggest atmospheric challenge where the impact of fog is much less, due to the close size of wavelengths to the radius of rain droplets.

B. LINE OF SIGHT (LOS)

Free Space Optics (FSO) systems require totally clear line-of-sight (LOS), which means the transmitter and the receiver must see each other for transmission. Objects within the laser beam may obstruct the FSO links, even though they are rather small, such as birds. Birds generally cause temporary obstructions for the optical link. Resending the blocked data or forward error correction can overcome the effects of the bird obstructions.

Regarding the implementation of FSO technology on ship platforms, the bigger LOS problems occur with the bigger obstructions such as islands, upper structure of hosting ship and cruising ships blocking the transmission. Depending on the height over the sea level, ships partially or completely block the transmission. The downlink time may last longer than expected due to the speed and length of the blocking ship, because communicating FSO systems will lose the track of each other causing the auto-tracking systems to initiate the communication again. However, as an obstruction, islands make the FSO communication impossible between the ships. As a result, communication of Navy ships over long distances (up to horizontal distance) may be affected in the areas consist of islands.

Visual observation is the easiest way to find out whether LOS exists between two ships. Since FSO technology requires LOS, for ships the maximum distance for ship-to-ship communication depends on, but not limited to, the distance of horizon. The maximum achievable distance for a ship depends on the height of the location where FSO transmitter is located. The distance of horizon can be calculated.

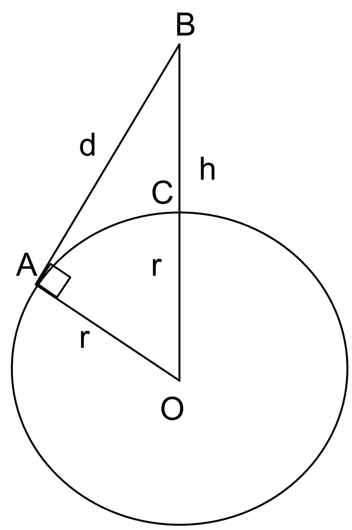

Figure 18. Distance of horizon calculation

Figure 18 is based on the fact that any angle between a tangent line to a circle and the radius of the circle is a right angle. Here, ‘h’ is the height of FSO transmitter mounted on the mast of the ship, ‘d’ is distance of horizon, and ‘r’ is the radius of the earth. Since we have a right triangle of AOB where AB=d;

$$BO = h+r$$

$$AO = r$$

$$(BO)^2 = (AO)^2 + (AB)^2$$

$$(h+r)^2 = r^2 + d^2$$

$$d = ((h+r)^2 - r^2)^{1/2}$$

This formula gives the geometrical distance, d, of horizon where the r (radius of the earth) is approximately 6,371 km. For a transmitter at the height of 20 meters above the sea level, the geometrical horizon distance is 16 km (8.64 nautical miles). However, the visible horizon distance is bigger than geometrical horizon distance due to atmospheric refraction.

Figure 19 illustrates two ships communicating with laser at the furthest distance of LOS.

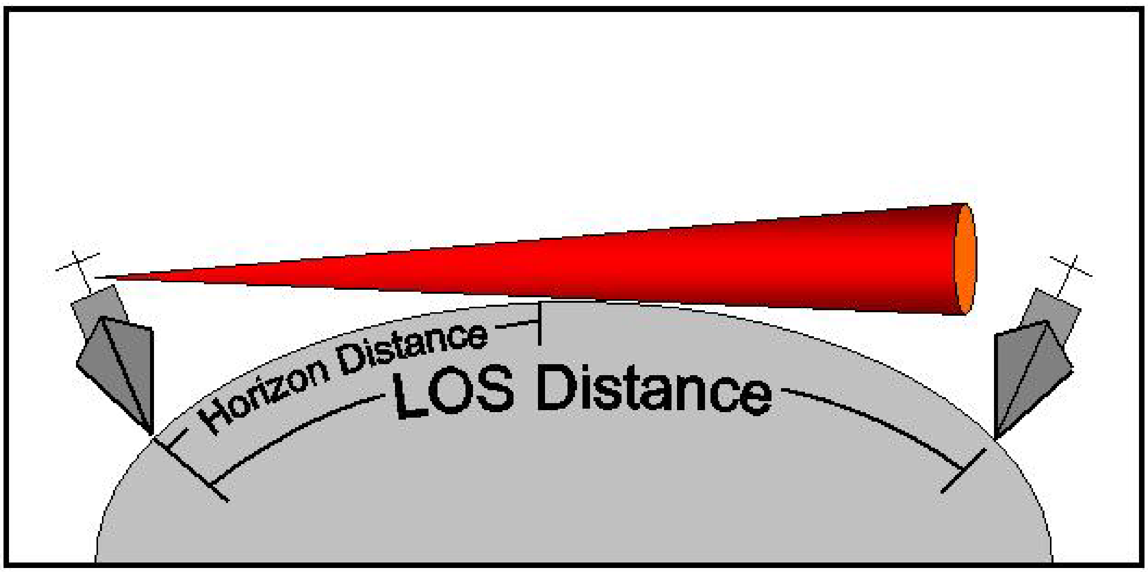

Figure 19. Communicating ships at the furthest distance of LOS

Figure above demonstrates that ship-to-ship communication is not limited to the horizon distance. For this particular scenario, the furthest LOS distance is twice the horizon distance (32 km) where the height of the transmitter is 20 meters above the sea level for both ships. This means ships are able to see each other from 32 km away.

C. DIRECTIONAL PRECISION

Free Space Optics (FSO) systems use narrow laser beams. Typically, commercially available FSO systems have a beam divergence from 0.1 degrees to 0.3 degrees, which is very small compared to microwave systems. For a beam divergence of 0.1 degrees, the diameter of the laser beam is 1.74 meters at a distance of 1 km. As mentioned in the previous chapter, having very small beam divergence makes FSO technology more secure compared to radio frequency (RF) technologies in terms of communications security.

However, under normal conditions, this feature makes pointing the laser beam at a receiver highly difficult. More over pointing gets more difficult by ship movements such as yaw, roll and pitch. Transmitters must adjust themselves according to these ship motions to keep the link active. Luckily, new generation FSO systems have tracking and active aiming systems within to make necessary adjustments to the transceivers. Pointing problems make *pointing resolution* an important factor for FSO systems.

Pointing resolution defines how much the laser beam can be shifted. The beam pattern at the receiver side with a pointing resolution equal to the beam divergence of θ is illustrated in Figure 20.

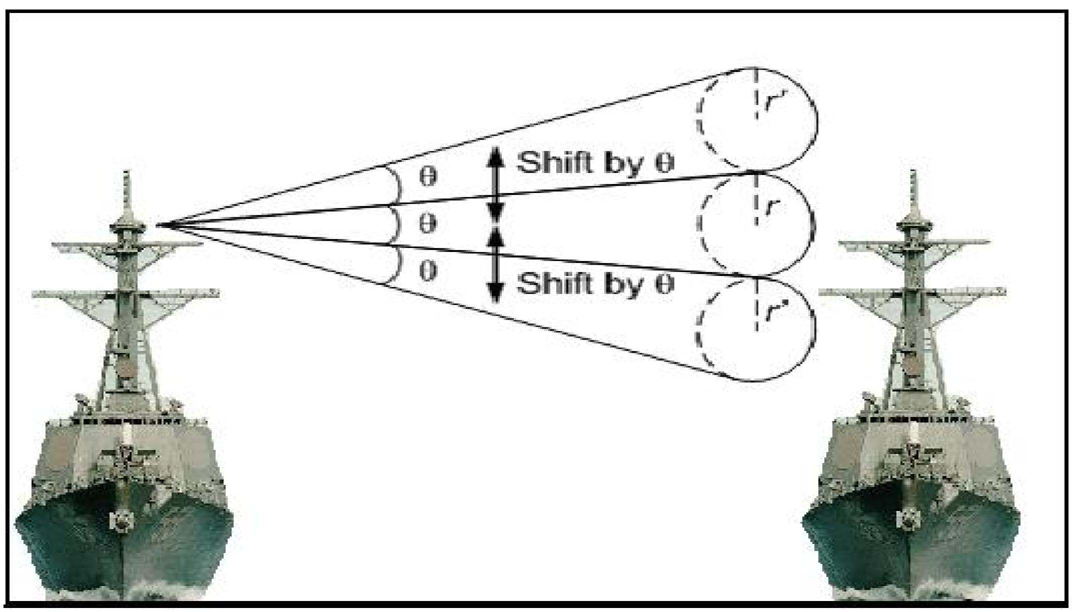

Figure 20. Beam pattern at the receiver side with pointing resolution of θ.

As it can be seen from the figure, pointing resolution of θ means that the laser beam can only be shifted by an angle of θ. Shifting the laser beam can be in either x or y direction. However, shifting the beam equal to beam divergence is not sufficient for continual coverage.

Pointing resolution equal to the beam divergence forms gaps in the beam pattern. These gaps in the beam pattern make it difficult to collect sufficient beam for the receiver [Neo 2003]. Figure 21 illustrates the gaps in the beam pattern with a pointing resolution of θ.

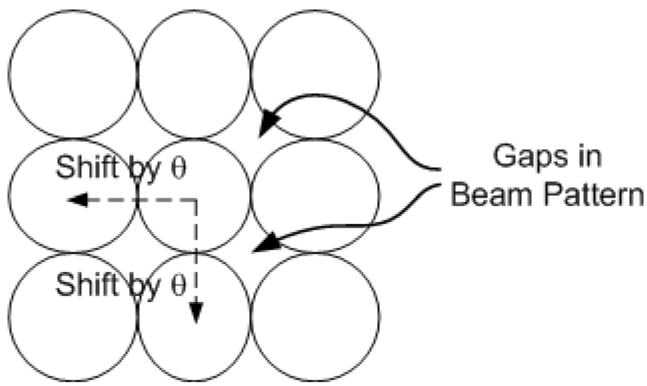

Figure 21. Gaps in beam pattern with pointing resolution of θ (From: [Neo 2003]).

The gaps formed by the pointing resolution equal to the beam diverge (here it is θ) can be filled in by selecting the pointing resolution at most half of the beam divergence (θ/2) [Neo 2003]. Figure 22 illustrates gaps in the beam pattern with pointing resolution of θ/2. As mentioned in the beginning of the section, commercially available FSO products have beam divergence around 0.1-0.3 degrees. Therefore, for a system with a beam divergence of 0.2 degrees a pointing resolution of at most 0.1 degrees is required to avoid gaps within the beam pattern.

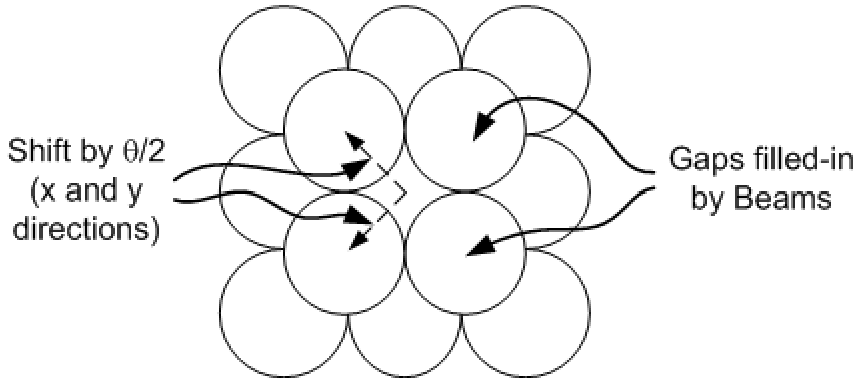

Figure 22. Gaps Filled-in by beams with pointing resolution of θ/2 (From: [Neo 2003])

D. LASER SAFETY

The safety of FSO technology is often a concern, since it uses lasers for transmission. LASER is an acronym that stands for Light Amplification by Stimulated Emission of Radiation. The laser produces an intense, highly directional beam of light. The unprotected human eye is extremely sensitive to laser radiation and can be permanently damaged from direct or reflected beams. The laser energy generated is in or near the optical portion of the electromagnetic radiation (EMR) spectrum, illustrated in Figure 23.

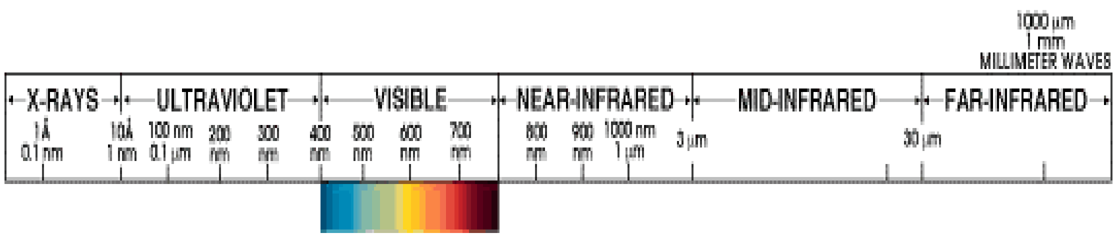

Figure 23. Optical portion of the EMR spectrum (From: [LIA 2004])

1. Eye Exposure to Laser

Laser light will be partially absorbed, raising the temperature of the surface and/or the interior of the object, potentially causing an alteration or deformation if directed, reflected, or focused upon an object. Under certain circumstances, laser exposure can result in damage to the eye and skin. The human eye is more vulnerable to injury than human skin. Unlike the skin, the cornea, the clear outer front surface of the eye, does not have an external layer of dead cells to protect it from the environment.

According to the Laser Institute of America (LIA) Laser Safety Information Bulletin, in the far-ultraviolet and far-infrared regions of the EMR, the cornea absorbs the laser energy and may be damaged due to the exposure.

Figure 24 illustrates the absorption characteristics of the eye for different laser wavelength regions.

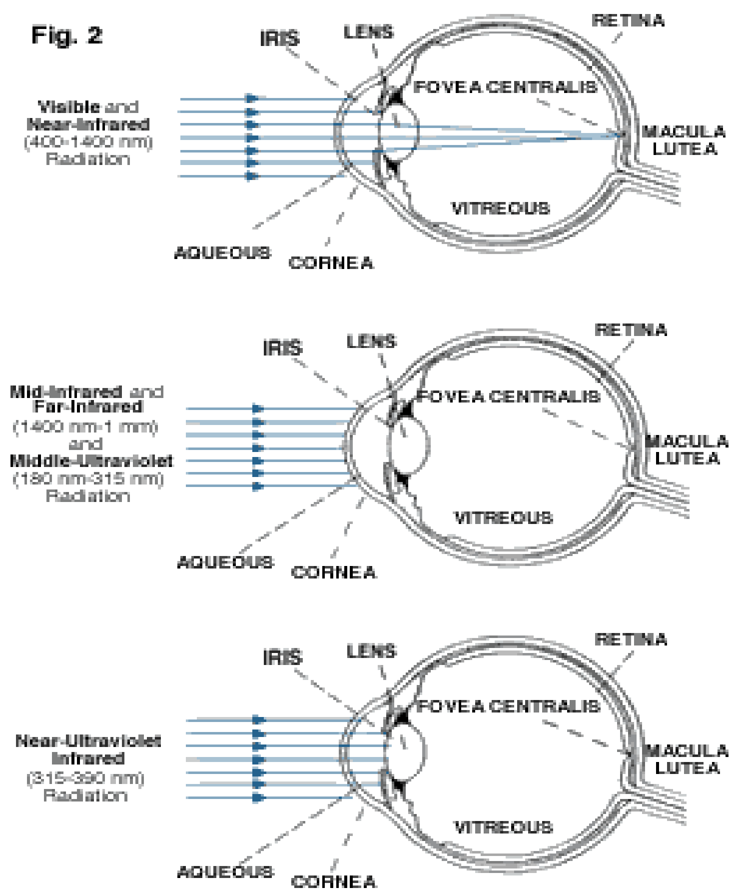

Figure 24. Absorption characteristics of the eye for different laser wavelength regions (From: [LIA 2004])

In the near-ultraviolet region and in the near-infrared region, the lens of the eye may be vulnerable to injury. The retinal hazard region of the optical spectrum is approximately between 400 nm (violet light) and 1400 nm (near-infrared) and including the entire visible portion of the optical spectrum. For the worst-case exposure, eye must be focused at a distance and a direct laser beam must enter the eye. The most interesting part of the laser is that the light entering the eye from a collimated beam in the retinal hazard region is concentrated by a factor of 100,000 times when it strikes the retina. As a result, a visible, 10 milliwatt/cm^2 laser beam would result in a 1000 watt/cm^2 exposure to the retina, which is more than enough power density to cause damage in the eye. However, if the eye is not focused at a distance or if the beam is reflected from a diffuse surface, there may not be damage in the eye since much higher levels of laser radiation would be necessary to cause injury [LIA 2004].

The FSO systems are considered to be eye-safe due to the wavelengths of the lasers used. However, the safety levels are not the same in these wavelengths. The technology that uses the wavelength of 1550 nm can safely transmit 100 times more optical power than 750 nm and 50 times more optical power than 850 nm wavelength without damage to the human eye [Nykolak 1999].

2. Laser Safety Standards

Since the devices first began appearing in laboratories more than two decades ago, laser safety has been a source of discussion and standardization efforts. The two major concerns are; human exposure to laser beams and high voltages within the laser systems and their power supplies. Several standards have been developed covering the performance of laser equipment and the safe use of lasers. According to these standards, safety of the lasers depends on the classification of the laser [LightPointe 2003].

There are three primary classification bodies: Center for Devices and Radiological Health (CDRH) and American National Standards Institute (ANSI), and International Electrotechnical Commission (IEC). The CDRH and the ANSI have jurisdictions in the U.S., while the IEC is an international organization.

Each of standards organizations categorize, slightly with different criteria, lasers into 4 classes where Class 4 is the most hazardous. Table 4 shows the classification of the lasers by the standardization organizations.

	Viewing Condition	CDRH	ANSI	IEC
Class 1 **Eye-Safe (all conditions)** **Eye-Safe w/o Optical Aids**	Aided Unaided	I -	1 1	1 1M
Class 2 **(Visible only: 0.4 – 0.7 μm)** **< 0.25 sec (eye aversion)** **< 0.25 sec (eye aversion)**	Aided Unaided	II -	2 2	2 2M
Class 3 **Minor Hazard** **Eye Hazard**	Any Any	IIIa IIIb	3a 3b	3R 3B
Class 4 **Eye Hazard**	Any	IV	4	4

Table 4. Classification of lasers (From: [Neo 2003])

The FSO systems commonly use Class 1 and Class 1M lasers. In addition to these classes, Class 3R and 3B are used by FSO systems for long-range and high data-rate links.

Class 1 lasers are eye-safe under aided or unaided viewing conditions. Most laser printers belong to this class. However, it may not be safe to view a Class 1M laser with an optical aid.

Class 2 lasers are safe only if viewed for less than 5 seconds. Class 2 lasers emit radiation in the visible portion of the spectrum, and protection is normally afforded by the normal human aversion response. The eye aversion is a reflex action will cause a person to turn away from a bright light source such as laser pointers.

Class 3a lasers would not produce hazard if viewed only momentarily with the unaided eye. However, they may present a hazard if viewed using collecting optics such as telescopes, microscopes, or binoculars.

Class 3b lasers may cause hazard through direct or specular exposure. Except for the higher power Class 3B lasers, this class of laser will not produce diffuse reflections.

Class 3R denotes lasers that normally would not produce a hazard if only viewed for momentary periods.

Class 4 lasers are a hazard to the eye from the direct beam and specular reflections and sometimes even from diffuse reflections. Unlike the other classes, Class 4 lasers can also start fires and can damage skin. Lasers operating at power levels greater than 500 mW for continuous wave lasers or greater than 0.03 J for a pulsed system belong to this class [UNC 2004] [Neo 2004].

In summary, most of the FSO systems use Class 1 and Class 1M lasers while some systems use Class 3B and Class 3R lasers. Therefore, Free Space Optics (FSO) technology is considered as “eye-safe” technology.

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V. FSO SYSTEMS FOR SHIP PLATFORMS

Free Space Optics (FSO) systems are becoming more popular for commercial use as an alternative broadband technology and are being considered for military systems because of their narrow divergence and high bandwidth benefits. The narrow divergence of the laser beam makes detection, interception and interference of FSO systems highly difficult. On the contrary, use of the radio frequency (RF) spectrum for military communications provides an opportunity for the detection and direction finding of military platforms by opposing forces.

Like most of the new technologies, FSO technology comes with some challenges for implementation on ship platforms. The most challenging factors are ship motion and pointing-tracking difficulties. Since the ships are not stable on sea, they experience motions known as *yaw*, *roll* and *pitch*. The effects of ship motions and atmospheric conditions (scintillation, turbulence, fog) make pointing and tracking of the target ship more difficult.

This chapter discusses the need for FSO technology, the effects of ship motion and the required systems to improve the performance of FSO communication on ship platforms.

A. THE NEED FOR FSO TECHNOLOGY

One of the biggest reasons for considering deployment of FSO systems on ship platforms is the need for secure communication. As war technology advances, the need for more secure, more reliable and faster communication mediums becomes more imperative. Free Space Optics (FSO) technology provides higher data rates and more secure communication links than existing RF based wireless technologies.

As discussed in the previous chapters, FSO systems use narrow laser beams operating at very high frequencies. Use of small divergence angles make the laser signal very difficult to detect and intercept by the opposing forces, which are crucial in emission control (EMCON) periods.

The EMCON is used to prevent an enemy from detecting, identifying, and locating friendly forces as well as minimizing electromagnetic interference among friendly systems. The EMCON usually means either full radio silence or very limited radio use depending on the given order against a particular threat. When EMCON is imposed, RF emissions must not exceed -110 dBm/meter^2 at one nautical mile. The calculation of the required RF emission is illustrated in Figure 25.

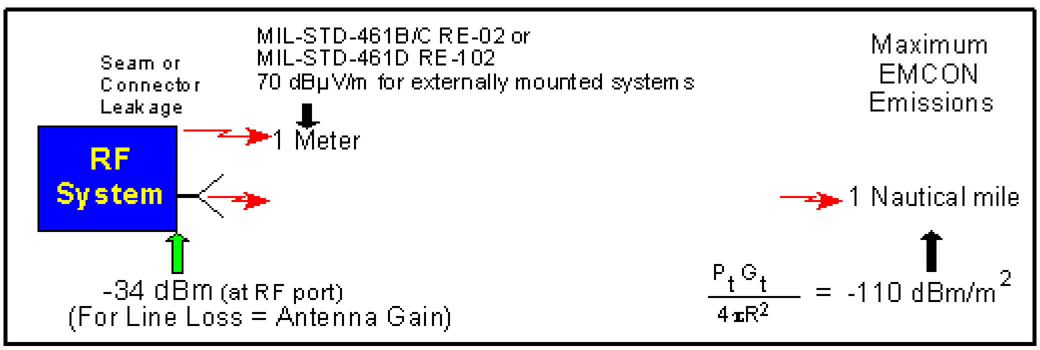


Figure 25. EMCON Field Intensity/Power Density measurements (From: [NAWCWD 2004])

Figure 25 states that for an antenna with the gain equal to line loss, the emissions must not exceed -34 dBm. The stated requirement at one nautical mile is converted to a measurement at the antenna of a point source [NAWCWD 2004]. However, the most secure RF technologies reduce, but do not eliminate, the possibility of detection during EMCON. The biggest concern is that any electromagnetic radiation would be immediately detected, and the position of the transmitting ship would be fixed by the opposing forces.

Since FSO systems use very small divergence angles it is much more difficult to detect the transmitted signal compared to RF radio and microwave systems. For a FSO system with a divergence of 1.3 mrad (0.07449 degrees), the beam size at the receiver ship at 10 km distance is 13 meters. For a microwave system with a divergence of 3 degrees, the beam size at the same distance is 524 meters. Moreover, RF radio systems with omni-directional antennas present even more security concerns since they do not transmit signals directionally. In addition to omni-direction transmission, RF waves may travel very long distances depending their low frequencies, which can be easily detected by spectrum analyzers.

In summary, FSO systems provides more secure communication links by using narrow divergence laser beams, which are highly difficult to be detected and intercepted. For the ship platforms, FSO technology is an excellent alternative for RF based technologies in terms of security.

B. SHIP MOTION

Free Space Optics (FSO) technology has mostly been implemented for commercial use between fixed sites such as metro network extensions, last-mile access, enterprise connectivity, and disaster recovery. However, FSO communication for mobile military platforms is more challenging. For the Navy, the biggest challenge is ship motion caused by sea conditions.

Ships are not stable on the sea. The displacement (movement) of a ship relative to its position when stationary in still water is an important design parameter. Waves and wind cause vertical and horizontal displacement (movement) of the ship. This varies by the architecture of the ship.

Ships have different characteristics according to their weight (displacement), length, beam (maximum width), draft length, upper structure height, and speed. Warships are designed to operate under severe weather and sea conditions. Applying additional structures such as fins on the hull reduce but not eliminate vertical movements.

Ship motion caused by waves present a challenge for FSO systems on ship platforms. Three important displacement components (yaw, pitch, and roll) are illustrated in Figure 26.

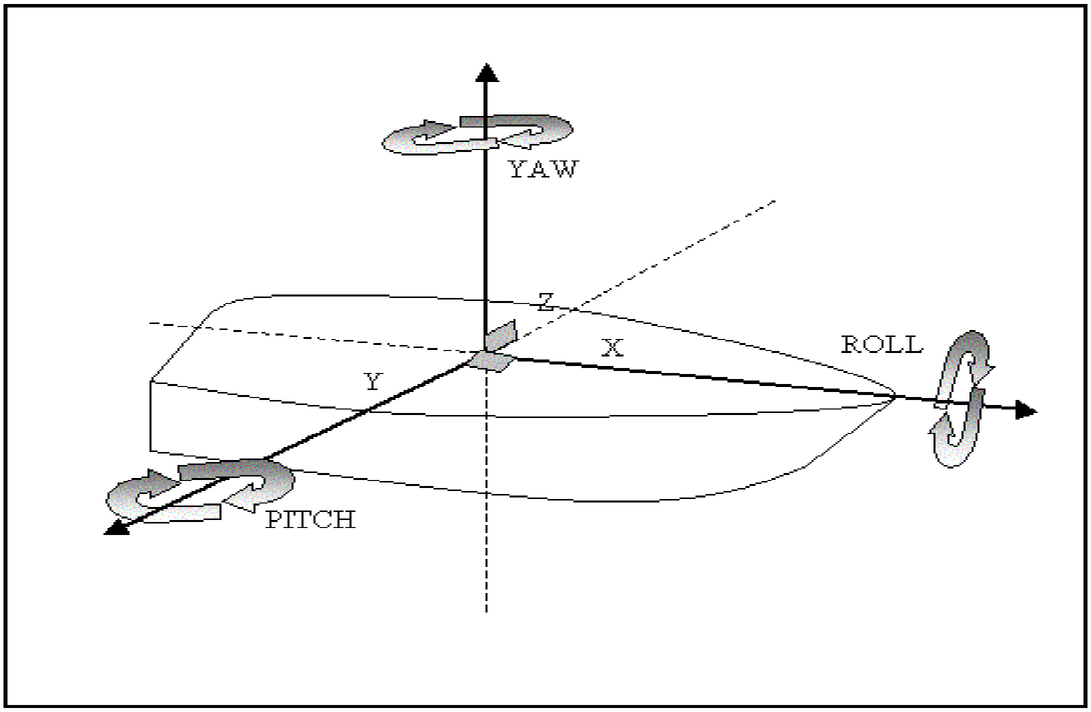


Figure 26. Ship motions: yaw, pitch, and roll

The actual motion of the ship depends upon the size of the ship relative to the waves. *Pitch* is a rotation around the transverse axis (*y*), *roll* is a rotation around the horizontal axis (*x*), and *yaw* is a rotation around the vertical axis (*z*) through the ship's center-of-gravity. The effects of these motions are illustrated in Figure 27.

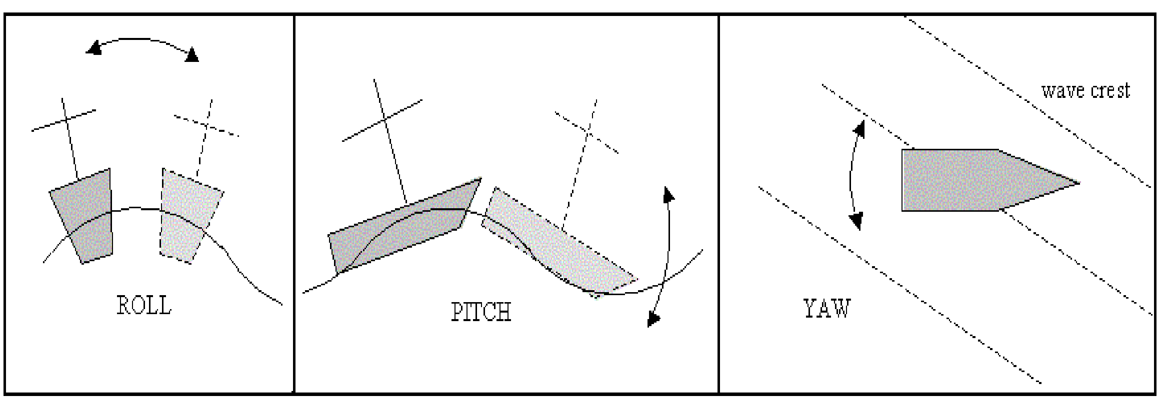


Figure 27. Effects of ship motion

As it can be seen in the Figure 27, pointing of FSO terminal would be difficult due to the effects of ship motions. Any drastic change in three axes (x,y,z) will result mispointing because of small divergence of the laser beam. Considering the speed of the communicating ships, tracking will also be very difficult unless auto-tracking/aiming is being used.

In order to avoid these problems, some techniques and systems may be implemented such as increasing the divergence and laser power, using Acquisition, Tracking and Pointing (ATP) systems, and implementing fast-steering mirrors (FSM). These systems will be covered in the next sections.

In summary, implementation of FSO communication for ship platforms has some challenges like ship motion caused by poor sea conditions and waves. However, these challenges may be overcome by implementing some techniques and systems.

C. INCREASING BEAM DIVERGENCE AND LASER POWER

Free Space Optics (FSO) systems use very narrow laser beams to transmit. As discussed in the previous chapters, the size of the beam depends on the divergence angle of the transmitter. The commercially available FSO systems have a beam divergence of a few milliradians (1 mrad=0.0573 degrees). Depending on the desired data rates, smaller divergence angles can be used but pointing will be more difficult because of the smaller beam size at the receiver side.

For mobile platforms such as ships, pointing is difficult considering the size of the beam and the motions of the ships. However, increasing beam divergence would increase the probability of pointing because the beam size at the receiver size will enlarge and cover more area on the receiver side.

Figure 28 illustrates the effect of increasing the beam divergence for a ship on a roll motion.

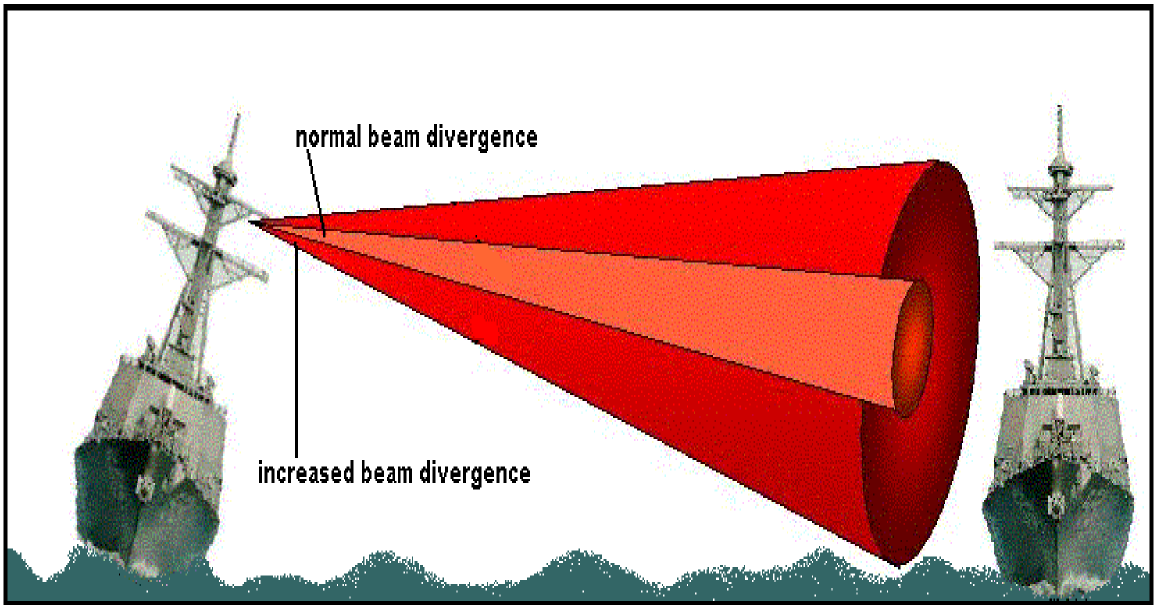


Figure 28. Increasing beam divergence

As it can be seen in Figure 28, the beam size increases with the divergence angle, therefore transmitter ship will keep pointing the laser to the receiver although it experiences vertical displacement (roll). The receiver terminal will remain within the laser beam. However, the intensity of the laser will reduce mainly outer parts of the beam center and this may result in insufficient laser power on the receiver (considering atmospheric attenuation). For this reason, increasing the laser power may be required. Some advanced FSO products automatically adjust their power depending on the strength of the signal at the receiver's end.

Increasing the beam divergence and the laser power raise the probability of detection in terms of security. However, the probability of detection will still be much smaller than RF based radio systems.

D. ACQUISITION, TRACKING AND POINTING SYSTEMS

Acquisition, Tracking and Pointing (ATP) systems are highly required for FSO implementation on mobile platforms. The ATP systems are currently being used in satellite FSO communications. There are three stages for ATP systems: acquisition, pointing, and tracking.

1. Acquisition

Unlike conventional FSO systems operating between fixed sites, mobile platforms must know the location of the receiver platform before each transmission. Transmitters for fixed sites are carefully aligned to point each other after being deployed, thus additional acquisition is not required each time before transmitting.

For ship platforms, acquisition stage, where two terminals try to locate each other, is necessary before communicating. However, this is not trivial for two moving platforms, especially when they are experiencing ship motions such as roll, pitch, and yaw. The small divergence feature of the lasers mainly causes this problem. One of the approaches to locate the target ship is using "beacon beam," mainly implemented in satellite FSO communications.

There are two effective approaches to enable acquisition between two moving platforms: Beacon beam and Microelectromechanical system (MEMS) corner cube reflectors (CRRs).

a. Beacon Beam

For acquisition of two moving platforms beacon beam may be implemented. Beacon beam has much wider beam divergence than normal communicating beam. Transmitting ship first uses beacon beam scanning the area where the target ship may be located. In those cases visual observation to determine the estimate location of the target ship may be used.

As the receiver ship detects the beacon beam, it transmits a communication beam to notify the transmitting ship. After detecting the communication beam, the transmitter ship stops scanning with beacon beam, and switches from the beacon beam to communicating beam [Neo 2003]. This scenario is illustrated in Figure 29.

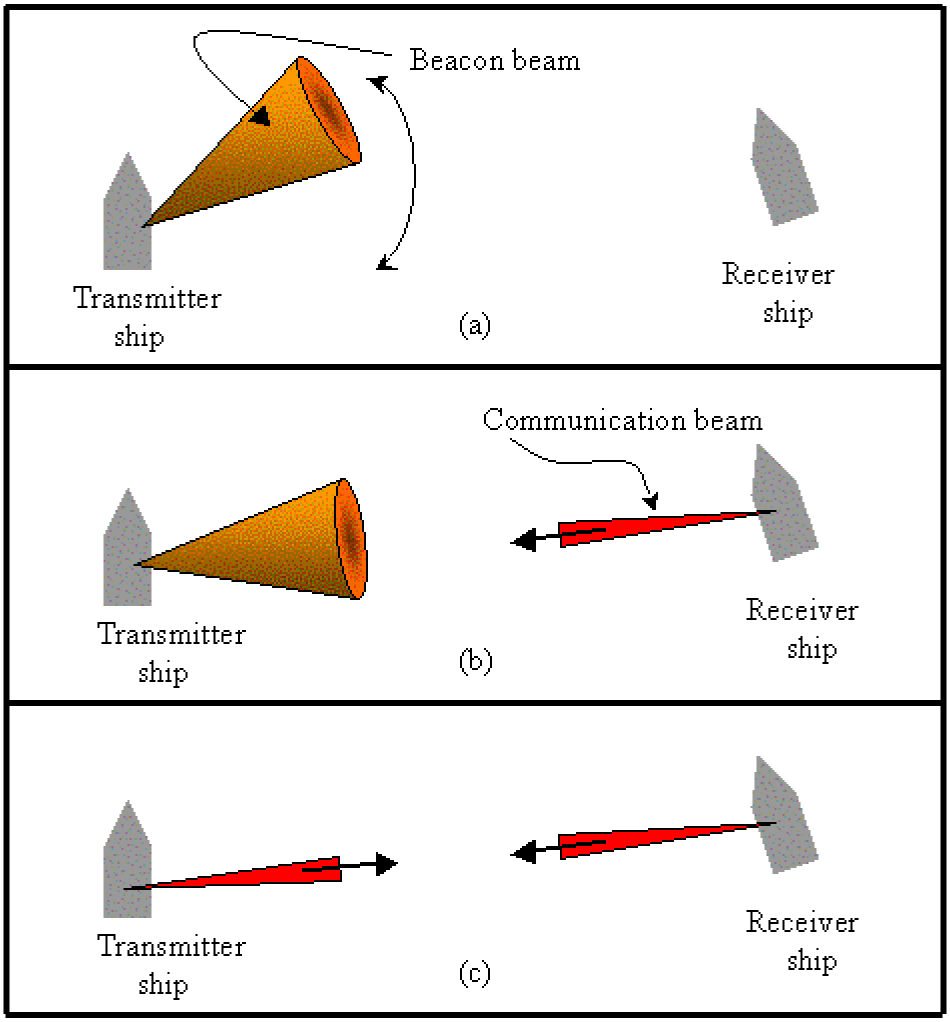
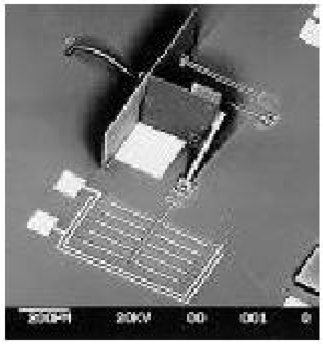


Figure 29. Using beacon beam for acquisition and pointing

b. MEMS Corner Cube Reflectors (CCRs)

Another acquisition technique is based on using Microelectro-mechanical system (MEMS) corner cube reflectors (CRRs), which aids beacon beam based acquisition systems. Corner cube reflectors are used in low power, line-of-sight (LOS) communications and identifying friendly or foe [Stevens 2004].

Figure 30 demonstrates MEMS corner cube reflectors with integrated optical components.



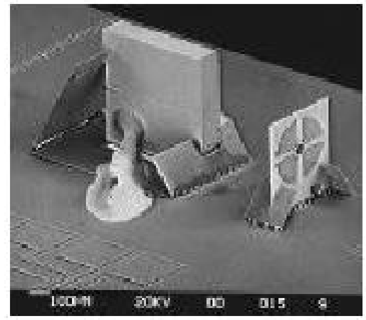


Figure 30. MEMS corner cube reflectors and integrated optical components (After: [Stevens 2004])

Corner cube reflectors (CCRs) use the basic reflection principle. A CCR is composed of three orthogonal mirrors. In modulated CCRs one of these mirrors can be moved to turn the CCR on/off while other two mirrors are fixed. By using the reflection principle, CCRs reflect incident light back to the source. Figure 31 illustrates the working principle of modulated CCRs.

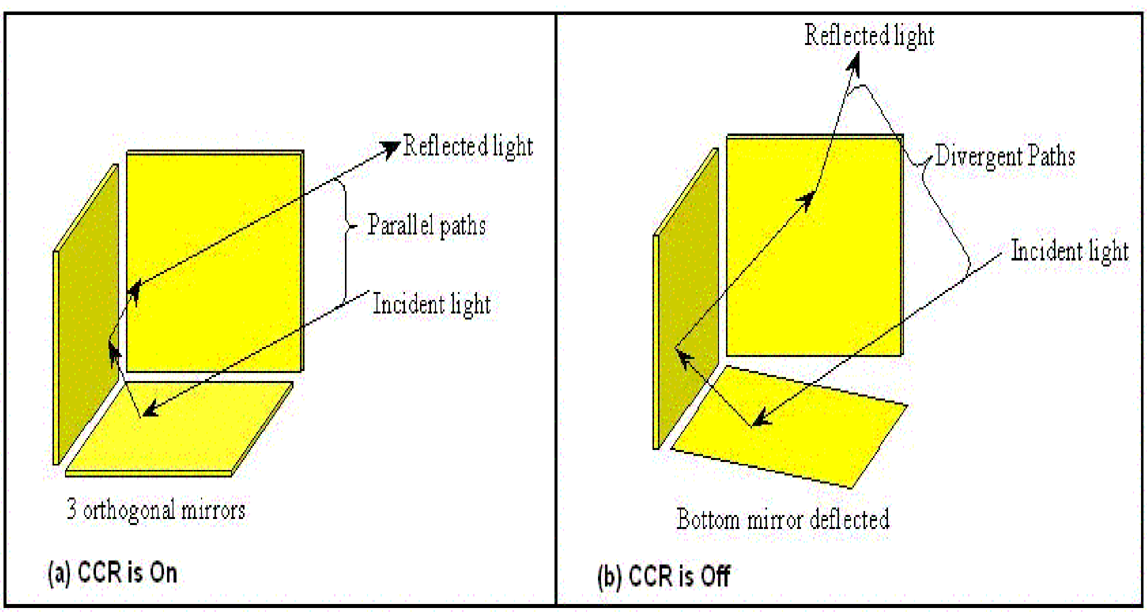


Figure 31. Modulated Corner Cube Reflectors (After: [Sporian 2004])

The beacon beam is reflected back to the source when modulated CCR is on, thus the transmitter will detect the location of the receiver and switch from beacon beam to narrow communication beam. When the modulated CCR is off, the beacon beam will not be reflected to the source.

This kind of reflection is called a retro-reflection, which is commonly used for test conducted by Naval Research Laboratory (NRL) in the Chesapeake Bay, MD. In those tests multiple quantum well (MQW) modulating retro reflectors (MRR) have been used [Mahon 2003]. Figure 32 shows an array of multiple quantum well modulating retro-reflectors used by the NRL.

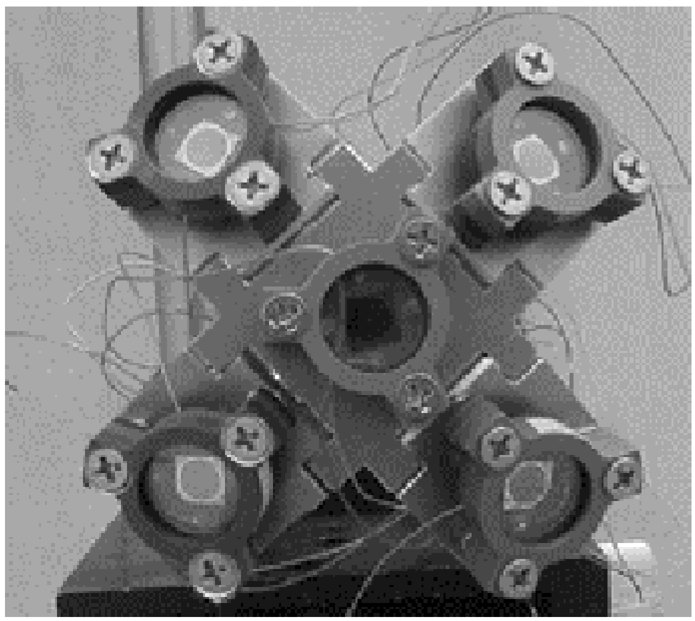


Figure 32. Array of five modulated retro-reflectors (From: [Mahon 2003])

The MWQ MRR can be used when one end of the link cannot accommodate the weight of a laser communication terminal such as small boat, helicopter, and small Unmanned Aerial Vehicle (UAV). The link is achieved by a modulating retro-reflector that couples a passive optical retro-reflector such as a corner cube (deployed on UAV or helicopter) with electro-optic modulator. On one end of the link there is an actively pointed terminal that interrogates the MMR with continuous laser beam. The laser beam is passively retro-reflected back to interrogator by corner cube reflectors. The reflected beam is modulated with a signal imposed by the modulator [Mahon 2003].

2. Pointing

The second stage in ATP systems is pointing. Pointing is an important issue in mobile platforms for both the transmitter and the receiver. The problem for pointing is caused by the small divergence of the laser beams. Any change on the platform locations raises pointing problems, including ship motions. As mentioned in previous chapter regarding directional precision, the smallest angle for adjusting the pointing angle is called pointing resolution, which is at most half of the divergence angle. Since the transmitter has to be pointed accurately to ensure sufficient energy received on the receiver's end, pointing resolution must carefully be calculated.

Referring previous section, pointing problem may be overcome by increasing the beam divergence (implies the increase of pointing resolution) and laser power. However, this would increase the probability of being detected.

ATP systems ensure continuous pointing by shifting the beam according to the speed of the transmitting platform and the location of the receiver. Commercial FSO systems have divergence of a few milliradians. For a platform with a divergence angle (θ) of 2 mrad (0.1146 degrees) the pointing resolution is at most half of the divergence angle ($\theta/2$), which is 1 mrad (0.0573 degrees), in order to avoid gaps in the beam patterns (refer to Figure 22). This means that FSO system can shift the beam 1 mrad according to the tracking frequency. Tracking systems effectively reduce the pointing jitter as well as allow using small divergence. These systems will be covered in the next section.

3. Tracking

Tracking is a basic requirement for ship-to-ship FSO communications. Since the transmitter and/or the receiver ships are moving, the FSO terminals must actively change the direction of their beams in order to maintain the communication link.

Tracking frequency refers to the time when FSO terminal needs to change the direction of the beam to keep the track of the receiver position. The relative speed and location of the receiver determine the changes to be made in the direction of the laser beam. In order to calculate the necessary tracking frequency, the highest speed must be taken into consideration, which is the maximum relative speed.

The maximum relative speed is calculated where the both ships are cruising at their maximum speed and are moving in opposite directions of one other. For example, Ship A and Ship B belong to the same ship-class and have maximum speed of 35 knots (40.25 mph, 64.42 kph). Both ships are cruising in opposite directions; Ship A, the transmitter, is headed to 090^{o}-East while Ship B, the receiver, is headed to 270^{o}-West. In this particular case the relative speed for Ship B is 70 knots (80.5 mph, $\sim$129 kph). In addition to the relative speed, the least time period that Ship B stays within the beam must be calculated.

The least time within the beam is experienced when both ships are in the closest range of one other. For this example, the closest distance is where both ships see each other with the relative bearing of 90^{o} port side; meaning one ship is directly below the other. In this period, Ship B is within the beam for the shortest amount of time and Ship A has to shift the direction of the beam sooner than for the other positions. This particular time determines the minimum tracking frequency needed for the FSO terminals. The least time may practically be calculated by the distance Ship B cruised in that duration time, which corresponds to approximate value of the beam size at Ship B.

Figure 33 illustrates the example scenario for calculating the tracking frequency.

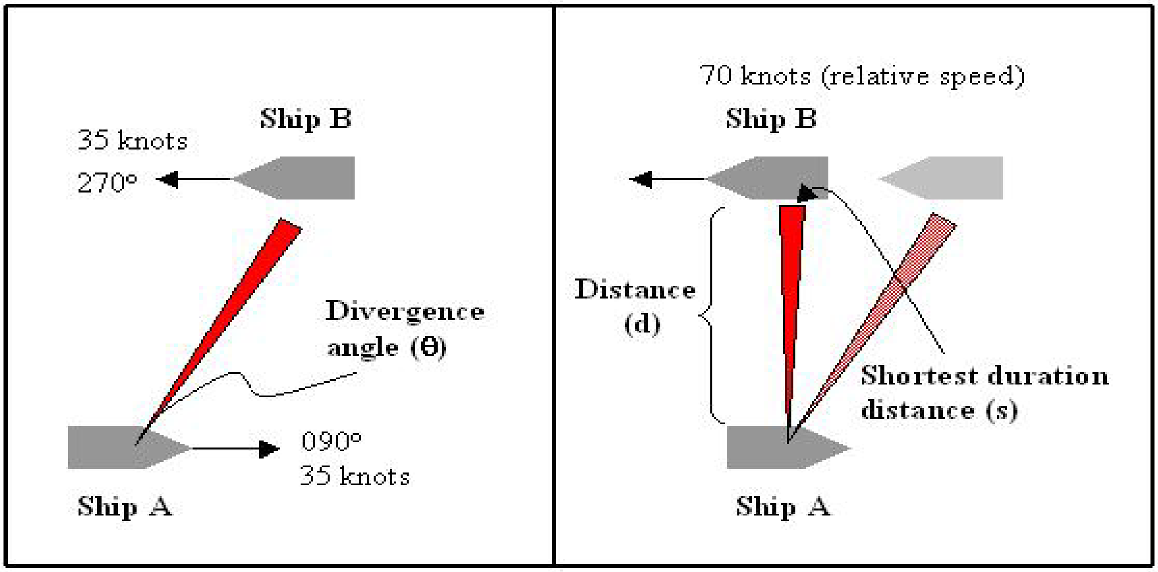


Figure 33. Calculation of tracking frequency

The tracking frequencies for different divergence angles and distances for the example scenario are presented in Table 5.

Divergence Angle (θ)	Distance (d) [m]	Beam Size = Duration Dist. (R = s) [m]	Duration Time (t) [sec]	Tracking Frequency (f) [Hz]
2 mrad	500	1	0.0279	34.84
	1,000	2	0.0558	17.92
	8,000	16	0.4457	2.24
	32,000	32	1.785	0.56
3 mrad	500	1.5	0.0418	23.89
	1,000	3	0.0837	11.94
	8,000	24	0.671	1.49
	32,000	96	2.68	0.373

Table 5. Tracking Frequencies

Table 5 covers the parameters for 2 mrad and 3 mrad divergence ship-to-ship FSO communication systems from short distance of 500 m to longest achievable distance of 32 km (with an FSO system 20 m high above sea level). As it can be seen in the table, the shortest duration times for both systems are for the shortest distance (500 m). These results show that transmitters has to change the direction of the beam faster in short ranges, which gives the required tracking frequency for a given FSO system. In this case, for 2 mrad divergence system, the tracking system should have a tracking frequency faster than 34.84 Hz. Similarly, for 3 mrad divergence system, the required tracking frequency should be more than 23.89 Hz (both results are based on 70 knots (80 mph) relative speed).

The shortest distance value used for the calculations is 500 meters, which is the approximate value for the standard distance between two small ships (ships less than 450 feet long) is a formation. Formations are ordered arrangements of two or more ships and commonly used in the Navy. For large ships (ships longer than 450 feet) the standard distance in a formation is 1000 yards (~914 meters).

In summary, tracking is highly required for FSO ship communications. The most important parameter for the tracking systems is the tracking frequency, which depends on the relative speed of the communicating ships and the divergence of the FSO systems used.

E. FAST STEERING MIRROR

Like movements of the platforms, atmospheric turbulence limits the stability and quality of the FSO links. Beam motion or received spot wander causes power loss in the communication link. A fast-steering mirror (FSM) controlled by a position-sensing detector (PSD) is used by the Naval Research Laboratory (NRL) in the tests conducted in the Chesapeake Bay, MD to correct for beam wander at the detector.

Fast-steering mirror implementation has the potential to correct for a significant portion of the focal spot position fluctuations caused by atmospheric turbulence. In addition, FSM increases tracking bandwidth. The NRL has combined a PSD with an FSM in order to actively compensate for the angle-of-arrival (AoA) fluctuations resulting more robust link in strong turbulence conditions [Suite 2003]. This technique may also be useful for compensating the effects of ship motions on the link.

The FSM test was conducted on the link between the Chesapeake Bay, MD and Tilghman Island, MD, distance of 10 miles. As a link distance of 20-mile round-trip was achieved by target planes with retro-reflectors mounted in asymmetric distributions on a tower on Tilghman Island. The FSM was mounted at a 45° angle behind a 16-inch Meade telescope with a focal length of 4 meters to steer the beam on to the PSD. Figure 34 illustrates the FSM system with PSD.

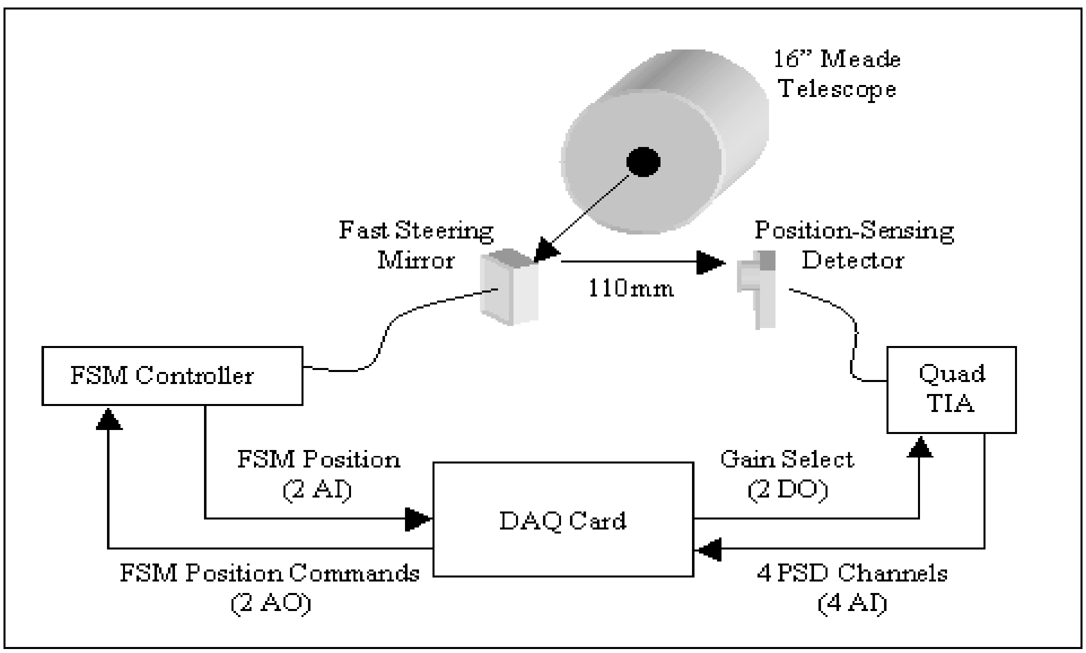


Figure 34. Receiver Block Diagram for characterization of the FSO+PSD compensation tests (From: [Suite 2003])

In the system, the PSD was positioned in the focal plane of the Meade. The focal spot was approximately in the center of the PSD active area. The FSM unit had an optical angular range of $\pm 3^{o}$ with resolution of ≤ 2μrad rms and the mirror had an anti-reflection coating at 1550 nm. During the test, the beam was transmitted across the Chesapeake Bay and reflected back with retro-reflectors through the telescope to the detector via the FSM. Also, data was taken with and without the FSM activated.

Figure 35 shows an example of the motion of the received energy detected by the PSD.

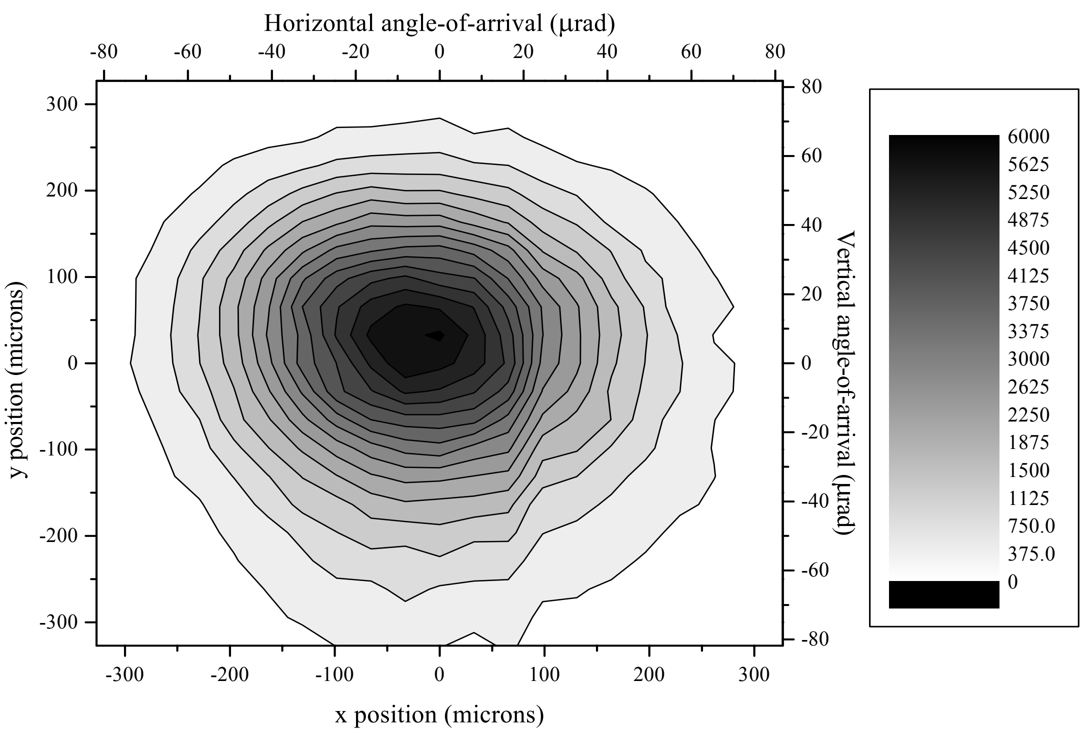


Figure 35. Histogram of the received spot centroid over 2 minutes of acquisition time (From: [Suite 2003])

Data was taken during the early morning when the atmospheric turbulence was very low to compare the performance of the system to an uncorrected baseline. Since the propagation path was horizontal, stronger influence of the turbulence in the vertical direction was mitigated by the time-of day.

Figure 36 shows the comparison between the data collected with and without FSM correction.

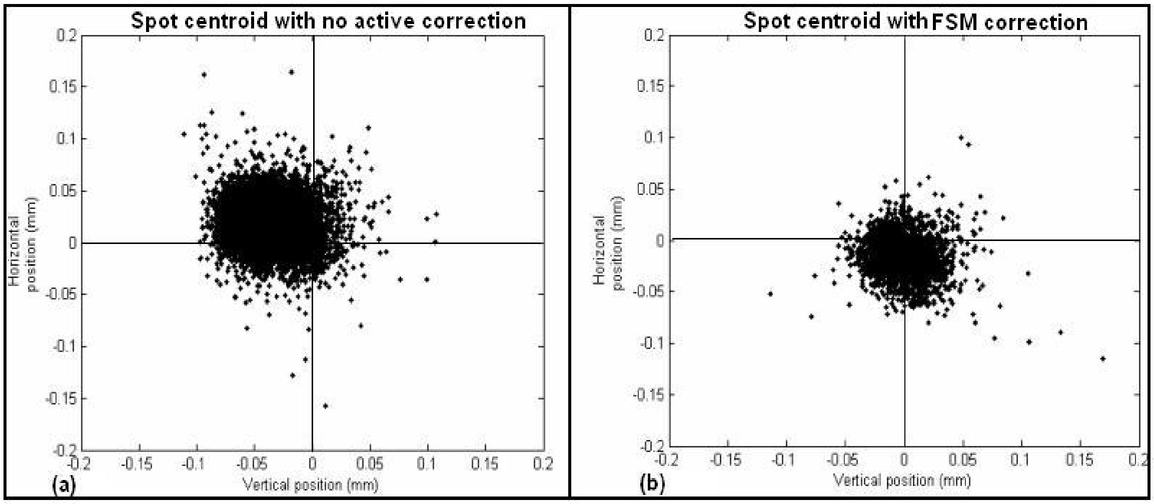


Figure 36. Spot centroid motion over 3 minutes (a) with no correction (b) with correction by the FSM (After: [Suite 2003])

As it can be derived from the Figure 36 (a), the spot centroid fluctuates 100-125 microns over the period of time data collected without FSM correction. The beam wander can be seen on the PSD. As expected, the improvement with FSM correction can easily be seen in Figure 36 (b). The fluctuation of the centroid is approximately 75 microns and more important part is that the spot is centered much closer around (0,0) on the PSD [Suite 2003].

This test demonstrates that the performance of the FSO link could be improved by using fast-steering mirrors (FSM) to actively compensate the beam wander, thus it would be useful to apply FSM to compensate the effects of relatively small amount of ship motions for FSO implementation on ship platforms.

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VI. CONCLUSION

Free Space Optics (FSO) technology is gaining popularity as an alternative broadband technology by providing fast, secure and reliable data transmission. The FSO systems are mostly being used for commercial systems between fixed sites and are being considered for military systems because of their inherent benefits.

In this thesis the feasibility of deploying FSO system on navy surface ships is studied by discussing the benefits, challenges, and required systems to improve the performance of the links. Communication security seems to be the most important benefit for considering FSO technology for ship platforms.

Communication security is the first priority in military operations. The optical link provided by an FSO system, is full-duplex, meaning that data can be transmitted in both directions on a signal carrier simultaneously. Moreover, the small divergence of the laser beam makes FSO systems more secure than the existing radio frequency (RF) based wireless systems, because it is highly difficult to detect and intercept a laser beam due to the nature of the laser and the small divergence angle of the transmitter. Microwave systems are considered to secure RF systems since they transmit directionally. Even though, the comparison of FSO system with microwave system given in Chapter III Section A proves that FSO systems are more secure.

For an FSO system with divergence of 2 mrad (0.1146 degrees), the beam size at the receiver is 32 meters for the distance of 16 km (10 miles), while the beam size is 838 meters at the same distance for a microwave system with divergence of 3 degrees. In addition to beam size, for the same microwave system, the volume of the cone is 686 times higher, which makes it less secure than the FSO system. In addition, RF waves may travel very long distances depending their low frequencies. Considering other RF technologies with omni-directional antennas, the possibility of detection is much higher than with FSO.

Since most of the existing commercial FSO products are designed to operate between fixed sites, they are not ready to be used on mobile platforms. Unlike for mobile platforms, some challenges do not apply to these platforms such as displacement of the terminal. On the other hand, FSO systems used for satellite communication are capable of operating on moving platforms by the help of the Acquisition, Tracking and Pointing (ATP) systems. As discussed in the previous chapter, the ATP system compensates the moving effects of the platform.

Thus, the operating concept of FSO systems on ship platforms must be similar to the FSO systems on satellites. However, the divergence angle and the laser power are exempt since the operating ranges of the satellites are much longer. For this reason, FSO systems on ships should have bigger divergence angle and use less laser power.

One of the other benefits of FSO technology is high data rate. Commercially available FSO products have data rates of 2.5 Gbps, which is not possible to achieve using radio frequency (RF) technology. However, these fast systems operate in short distances, and it is not always the case for ship-to-ship communication. However, some research to increase the data rate for long-range communication links is promising. According to the Naval Research Laboratory (NRL), data rate of 622 Mbps is achieved with a bit error rate less than 10^{-6} for a 34.4 km (~21.5 miles) link in marine environment without any corrections such as forward error correction, automatic aiming, and fast-steering mirrors [Vilcheck 2003]. Applying these corrections will increase the data rate. However, before deciding to deploy FSO systems on ship platforms, the atmospheric conditions should be taken into account.

As discussed in this study, FSO technology has some challenges and limitations apart from implementing on moving platforms. The biggest challenge seems to be the atmospheric attenuation. In particular, fog presents the most challenging factor for FSO technology.

Fog severely attenuates the power of the lasers and severely limits the range of the optical link. The achievable maximum range was calculated as twice the horizon distance, approximately 20 miles (32 km) for FSO systems deployed 20 m high above the sea level. Due to the atmospheric attenuation, this range is hard to achieve and it is practically impossible for foggy areas. This implies that the availability of FSO systems is much less than RF technologies for operating areas where fog is frequently experienced. Increasing the laser power and using 1550 nm wavelength lasers reduces the effect of fog but only for short ranges.

For this reason, using 1550 nm wavelengths would be useful for short-range links. It is also more desirable for eye-safety, since it is 100 times more secure than 750 nm wavelengths.

Another atmospheric challenge for FSO systems is turbulence. Turbulence causes scintillation, beam wandering, and beam spreading, which reduce the performance of the FSO links. As discussed, increasing the laser power, using ATP systems, and implementing FSM may overcome the effects of turbulence.

Ship motion introduces a new challenge for ship platforms. Various weather conditions and waves cause ship motion such as yaw, roll, and pitch resulting mispointing of the laser beam. Considering the mobility of the communicating ships, tracking will also be very difficult. As a result, increasing the divergence and the laser power, using ATP systems, and implementing FSM reduce or eliminate these effects. However, in severe weather conditions FSO communication between two ships will still be difficult and these systems may not be very effective.

The Line-of-sight (LOS) requirement requires FSO systems to be deployed in a prominent place on the ship such as the masts. The LOS must be maintained during the FSO communication between the ships. Physical obstructions such as islands or a passing ship may block the signal and must be avoided during the operation. In addition to these, some parts of the hosting ship may present an obstruction to LOS. Before mounting a FSO system, these parts, especially the upper structure of the ship, must be taken into consideration and the most suitable place on the ship must be selected to deploy.

In summary, FSO systems help to fill the gap for secure and fast communication system for surface ship platforms. The tests presented in this thesis work conducted by the NRL show that high-speed FSO laser communication in a maritime environment is possible. However, FSO implementation on ship platforms is still challenging. The research still continues to develop a better system.

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