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THESIS

FREE SPACE OPTICS COMMUNICATION FOR MOBILE MILITARY PLATFORMS

by

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December 2003

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Free Space Optics (FSO) is widely regarded as the next-generation high-speed wireless communication technology. FSO has demonstrated its capability to deliver data faster than any other state-of-the-art wireless communication technology. Today, terrestrial FSO links are able to reach 150 kilometers; unmultiplexed data rates of 2.5 Gbps have been achieved; Acquisition, Pointing, and Tracking (APT) systems have been successfully deployed between communication satellites; and carrier-class availability are being offered by FSO vendors. However, FSO has not seen widespread use in the military. This is attributed to the fact that military platforms are largely mobile, while the progress in the commercial arena has largely been confined to links between fixed sites.

This thesis analyzes the features of FSO technology while being mindful of how these apply to the military. These features include the bandwidth, spectrum use, bit error rates, communications security, free-space loss, and power consumption. The limitations and challenges presented by atmospheric effects, directional precision, line-of-sight obstructions, and laser safety are also studied. A final section will look at the acquisition, pointing, and tracking mechanisms that are necessary for deploying FSO on mobile platforms.

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FREE SPACE OPTICS COMMUNICATION FOR MOBILE MILITARY PLATFORMS

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LIST OF ACRONYMS

AEL	Accessible Emission Limit
AES	Advanced Encryption Standard
AFRL/SN	Air Force Research Laboratory Sensors Directorate
ANSI	American National Standards Institute
AO	Adaptive Optics
APT	Acquisition, Pointing and Tracking
AR	Antireflection
Artemis	Advanced Relay TEchnology MISsion
BER	Bit Error Rate, Bit Error Ratio
CDRH	Center for Devices & Radiological Health (Part of the FDA)
DC	Direct Current
DES	Data Encryption Standard
DGPS	Differential Global Positioning System
ECCM	Electronic Counter-Counter Measures
ECM	Electronic Counter Measures
EMR	Electro-Magnetic Radiation
ESA	European Space Agency
FCC	Federal Communications Commission
FDA	Food and Drug Administration
FOV	Field-of-View
FSO	Free Space Optics
FWHM	Full Width at Half Maximum
Gbps	Gigabits-per-second
GeoLite	Geosynchronous Lightweight Technology Experiment
GHz	Gigahertz (10^9 Hertz)
GPS	Global Positioning System
HARM	High-speed Anti-Radiation Missile
He-Ne	Helium-Neon
HF	1. High Frequency 2. Hydrogen Fluoride
HFR	Hybrid FSO/Radio
IEC	International Electrotechnical Commission
INS	Inertial Navigation System
IR	Infrared
ISM	Industrial, Scientific, and Medical
ISR	Intelligence, Surveillance, and Reconnaissance
ITU	International Telecommunication Union
LCT	Laser Communications Terminal
LLNL	Lawrence Livermore National Laboratory
LPD	Low Probability of Detection
LPE	Low Probability of Exploitation
LPI	Low Probability of Intercept
MHz	Megahertz (10^6 Hertz)

Microns	Micrometer (μm)
MPE	Maximum Permissible Exposure
MQW	Multiple Quantum Well
MRR	Modulating Retro-Reflector
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
Nd:YAG	Neodymium Yttrium Aluminum Garnet
NIPRNET	Non-Secure Internet Protocol Router Network
NRL	Navy Research Laboratory
NRO	National Reconnaissance Office
OICETS	Optical Inter-orbit Communications Engineering Test Satellite
OOK	On-Off Keying
OSI	Open Systems Interconnect
QAM	Quadrature Amplitude Modulation
RDF	Radio Direction Finding
RF	Radio Frequency
SATRN	Secure Air-Optic Transport and Routing Network
SILEX	Semiconductor laser Inter-satellite Link Experiment
SPOT	Systeme Pour l'observation de la Terre
SRS	Stimulated Raman Scattering
THz	Terahertz (10^{12} Hertz)
TSAT	Transformational Satellite
U-NII	Unlicensed National Information Infrastructure
UAV	Unmanned Aerial Vehicle
USAF	United States Air Force
UV	Ultra-Violet
VLF	Very Low Frequency
WDM	Wavelength Division Multiplexing
WRC	World Radiocommunication Conference

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As luck would have it, my classmates and I were deliberating on whether to study the deployment of laser communications for the U.S. Navy's new Seabasing concept. I had volunteered to lead the study and had begun research on the topic. At about the same time, I was speaking to various professors, soliciting their interests in thesis topics. After asking me about my background, the first topic that Professor Bert Lundy brought up was that of Free Space Optics. I cautiously questioned whether it was the same as laser communications. After confirming that they were the same, I was reveling at the coincidence, but never got to tell him about it – maybe until he reads this!

I must thank Professor Lundy for meeting me almost every week. His constant encouragement has certainly made me pursue greater breadths and depths on the topic. His knowledge of wireless networks and magnetism for thesis students pursuing topics on telecommunications and Free Space Optics allowed me to form a mini-network of like-minded students. One of whom I would especially like to thank is Oguzhan Timus from the Turkish Navy. Through exchanges of e-mail as well as personal meetings, Oguzhan was forthright about sharing the information he found. I feel bad about not being able to provide him as much useful information as he provided me.

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I. INTRODUCTION

Laser technology has greatly advanced since the first laser was demonstrated in 1960. It would seem from the ubiquitous fiber optic cable networks of today that attempting to use lasers to communicate through free space is a liberating step from the fixed and restrictive cabling installations. In fact, history has it that military applications were attempting to leverage on free space optics (FSO) ever since the 1960's. However, even until the late 1980's, FSO technology has been plagued by limited range, low capacity, alignment problems, as well as vulnerabilities to weather interferences.

In the military, operations demand secure, relevant, and timely information. The ability to relay massive amounts of information is becoming a critical determinant of military success. For this reason, information superiority on the battlefield is one of the first objectives. Furthermore, the complexity of military missions has also dramatically increased, with more diverse theaters of operation, expanded spectrums of conflict, and a tremendous increase in the requirement for information to be delivered almost immediately to the warfighter.

Today, FSO communication has not seen widespread use in the military. With the bandwidth available to FSO anywhere from 100 to 100,000 times higher than other radio frequency or microwave transmitters, use of FSO technology could give a military force much leverage over their rivals. While the technology has somewhat matured for fixed-site commercial deployments, FSO technology would be very much more useful to the military if it could be deployed on mobile platforms.

Intelligence, Surveillance, and Reconnaissance (ISR) platforms are seen as a major target for FSO technology as these platforms need to disseminate large volumes of sensor, imagery, and video to the fighting forces, often in real-time. Popular ISR platforms include planes, Unmanned Aerial Vehicles (UAV's), and satellites, although other platforms are certainly possible.

It is the intent of this thesis to study the feasibility of deploying FSO communication terminals on these mobile military platforms. Such a feasibility study would require much understanding of the various issues involved in FSO technology. Many of these issues would be equally applicable to non-mobile platforms.

While it is the aim of this report to provide good coverage of the various issues involved, it would not be possible within the scope of this study to discuss the issues unique to all the possible mobile platforms. For example, it should suffice to say that FSO is a line-of-sight communications technology and the transmitter's line-of-sight to the receiver should not be blocked. No attempt will be made to propose the location on planes, ships, or satellites where the FSO terminal should be placed.

This study will begin with a survey of the latest developments in FSO technology. Following this, an attempt will be made to understand the inherent benefits of FSO technology and how these can be leveraged on. This will be followed by a look of the limitations and challenges of this technology, and how they can be overcome. Finally, the study will look at the challenges of acquisition, pointing, and tracking, which are peculiar to line-of-sight mobile communications.

II. BACKGROUND AND RELATED WORK

To date, Free Space Optics (FSO) communication has been largely confined to communicating between fixed sites. For years now, companies like Terabeam, AirFiber and LightPointe have been installing FSO terminals behind windows, on rooftops, and on outdoor mounts. These systems have been installed for clients wishing to have broadband access without the hassle and costs of fiber optic cable solutions. The performance of these terminals has been encouraging, with bandwidths up to 2.5 Gbps and bit error rates of 10^{-9} (one in a billion) or better. However, other than the fact that these terminals are not installed on mobile platforms, the range of these systems has been limited to 4 km or less.

The Lawrence Livermore National Laboratory (LLNL), under the U.S. Department of Energy and operated by the University of California, had in early 2002 successfully tested a 28 km FSO link between the Laboratory (in Livermore, CA) and Mount Diablo under the Secure Air-Optic Transport and Routing Network (SATRN) program [Johnston 2002]. Data was transmitted at 2.5 Gbps. The wavelength and power used was not reported, although it was said to be optical, and that "the laser beams used for communication are not visible or harmful in any way." Bit-error rates were also quoted as "quite reasonable for an unoptimized system." Researches also say they have gained experience with operation in freezing temperatures, winds of up to 40 mph, low-visibility conditions and light fog. Tony Ruggeiro, the principal investigator on the LLNL project, said that the SATRN team plans to demonstrate a 28-km air-link with an aggregate bit rate of 100 Gbps.

Figure 1. A SATRN Team Member Standing Next to the Transceiver Telescope on Top of Mount Diablo (From: [Johnston 2002])

The range of an FSO link is usually limited only by the power used. While many demonstrations using “eye-safe” lasers has been limited to distances of 28 km or less, the United States Air Force Research Laboratory Sensors Directorate (AFRL/SN) claims to have successfully tested a 150 km link back in August and September 1995 [Gill 1997]. The tests were conducted between a laser terminal on Mount Mauna Loa on the island of Hawaii and a similar laser terminal on Mount Haleakala on the island of Maui. The power used in these lasers is reported to be greater than 200 mW. This is a high figure for lasers with an eye-safe distance of approximately 1.5 km. The AFRL/SN claims to have achieved a data rate of 1.1 Gbps and full duplex communications. Furthermore, the tests were conducted for follow-on air-to-air operations. A motion and vibration base was used to simulate an aircraft environment. Communication error rates of better than 10^{-6} were achieved during simulated motion. The AFRL/SN intends to demonstrate FSO links between aerial platforms at distances up to 500 km [Gill 1997].

An operational deployment of FSO links on mobile platforms has been achieved by the European Space Agency (ESA). The ESA is formed by 15 member states (Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, the Netherlands, Norway, Portugal, Spain, Sweden, Switzerland and the United Kingdom). In November 2001, the Artemis (Advanced Relay Technology Mission) and SPOT 4 (Systeme Pour l'observation de la Terre) satellites established 4 data links, lasting 4 to 20 minutes, with a data rate of 50 Mbps. This was using the SILEX (Semiconductor laser Inter-satellite Link Experiment) system. The Artemis satellite was in a parking orbit at 31,000 km, while the SPOT 4 satellite was orbiting at an altitude of 832 km. This would imply that the satellites were moving at roughly 7,000 mph and 16,600 mph respectively. The average distance between the satellites during communication was 38,500 km. The bit error rate for this space link was reported to be consistently in the range of 10^{-9} to 10^{-10} [Oppenhäuser 2001].

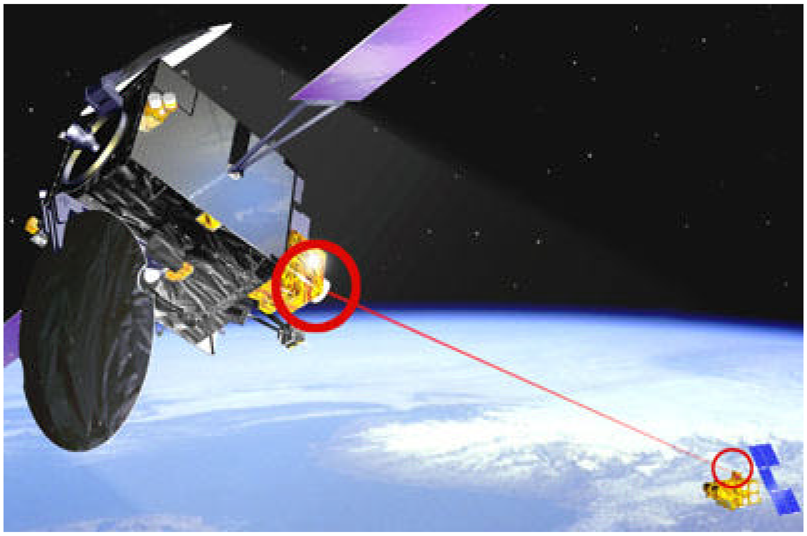

Figure 2. Artemis and SPOT 4 Communicating via the SILEX system – Artist's Impression (From: [Oppenhäuser 2001])

The U.S. National Reconnaissance Office (NRO) and the U.S. Air Force also have a laser communication experiment in orbit on the GeoLite (Geosynchronous Lightweight Technology Experiment) spacecraft. The platform, which was launched in May 2001, operates as a theater data-dissemination system in the Western Pacific [JIG 2002].

The experiments would allow the NRO to study advanced laser pointing instrumentation from a geosynchronous orbit. Manuel DePonte, general manager of the Milsatcom Division at the Aerospace Corporation, says that the data rates possible with laser communication would especially be important in commanding and obtaining intelligence from unmanned aerial vehicles (UAVs), and that achieving hundreds of gigabits per second would be a priority. The UAVs are eventually expected to be able to establish laser communication links to the Milstar and Defense Satellite Communications System (DSCS) communications-satellite networks [Covault 2002]. Unfortunately, further details of these experiments are classified.

In another article, Jane's Information Group reports that the U.S. Air Force has notional plans for spending US$7.6 billion over FY04 – FY09 on airborne laser communication terminals to be used on platforms such as the Global Hawk UAV, U-2 reconnaissance aircraft, E-3 Airborne Warning & Control System, E-8 Joint STARS ground surveillance platform, E-10 Multi-mission Command and Control Aircraft, the 'Smart Tanker' as well as 'Transformational Satellites' (TSATs) [JIG 2003-2]. The details of these plans are also expected to be highly classified.

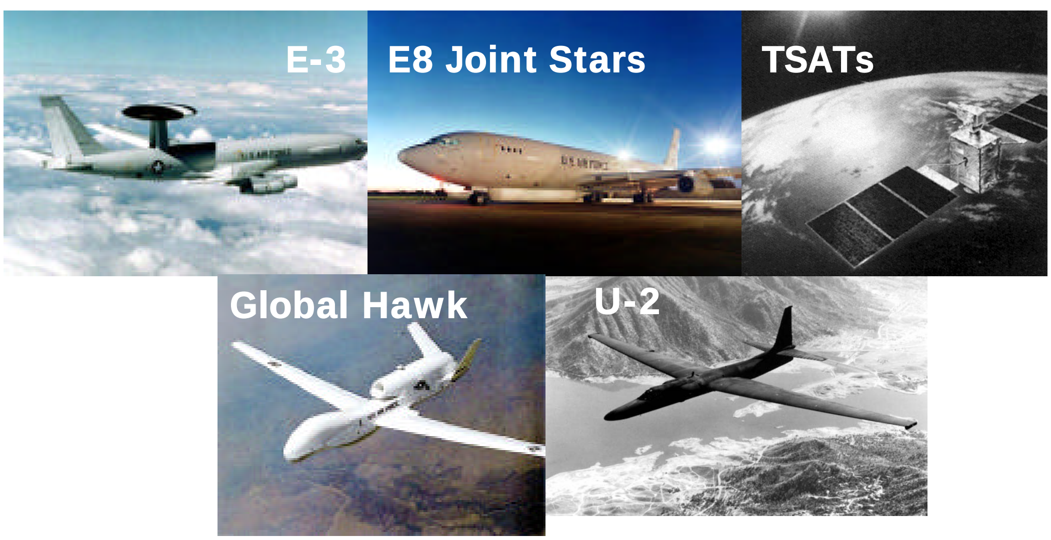

Figure 3. Some of the USAF-Proposed Platforms to be Equipped with Laser Communication Terminals (After: [JIG 2003-1])

III. LEVERAGING FSO TECHNOLOGY

Lasers operate in the infrared, visible and ultraviolet regions of the electromagnetic spectrum, from one millimeter down to 100 nanometers in wavelength. Typically, lasers are described by their wavelength as contrasted with radar systems that are characterized by frequency, because the laser's frequency is 10,000 to 1,000,000 times higher than typical microwave radars. Both microns (μm or 10^{-6} meters) or nanometers (nm or 10^{-9} meters) will be used in this study to characterize lasers. In contrast, radar systems usually have wavelengths on the order of millimeters to centimeters. This chapter explores the inherent benefits of using lasers for communication.

A. BANDWIDTH

Military operations demand secure, relevant, and timely information. For this reason, information superiority on the battlefield is one of the first objectives. Large volumes of Intelligence, Surveillance, and Reconnaissance (ISR) imagery and video are increasingly being sent from sensors to shooters. Faster data links are needed for faster response timelines. Also, new missions may be enabled, like the sending of video instead of still imagery, or the sending of higher quality imagery and video. With faster links, all of this can be achieved while still meeting the required response times. FSO systems operate at significantly higher frequencies than the other RF systems of today. Therefore, they have the potential of reducing the timeline for delivering information. This section looks at the implications of operating in the EMR bands used for FSO.

1. Higher Frequencies

A signal of higher frequency can potentially send data at a higher rate. If the distortion and attenuation effects of the atmosphere are non-existent, then the data rate theoretically possible from an electro-magnetic radiation (EMR) wave is directly proportional to its frequency (called the carrier). Of course, suitable modulation schemes need developing to take advantage of this carrier frequency. Table 1 gives an indicative range of frequencies for the different 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 1 Table of EMR Frequency Bands

The radio and microwave bands are widely used today for wireless communication. Above the frequency of 3 Terahertz (3.0×10^{12} Hz) starts the infrared band. Visible light takes up a small range of frequencies above infrared (2.0×10^{14} to 4.3×10^{14} Hz) while ultraviolet radiation has the highest frequencies of the optical wavelengths (7.5×10^{14} to 6.0×10^{16} Hz).

Many of the FSO systems available today operate in the near infrared band, which has a frequency range on the order of magnitude of 10^{14} Hz. Comparing this with microwave frequencies (magnitude of 10^{9} to 10^{12} Hz), FSO systems in the near infrared band can potentially provide a 100 to 100,000 times higher data rate than the microwave radios we have today. Of course, this depends on the type of modulation used (i.e. how the carrier is changed or varied so that it becomes an information-bearing signal).

LightPointe's [LightPointe 2003] FlightApex is one of the highest bandwidth commercially available FSO products today. It uses lasers at a frequency of almost 200 Terahertz (2×10^{14} Hz) to achieve full-duplex speeds of 2.5 Gbps for distances of up to 1km.

Figure 4. LightPointe's FlightApex Linkhead (From: [LightPointe 2003])

The Lawrence Livermore National Laboratory has demonstrated an FSO link of the same data (2.5 Gbps) over a distance of 28 km. With the help of wavelength division multiplexing (WDM), the LLNL had previously managed to scale the capacity of an FSO link to 20 Gbps between buildings. Tony Ruggeiro, principal investigator of the LLNL SATRN project, says that they intend to further demonstrate a WDM link with an aggregate bit rate of 100 Gbps over a distance of 28 km [Johnston 2002].

2. Modulation Schemes

The maximum data rate that can be transmitted does not solely depend on the frequency of the signal used. A lot depends on the modulation scheme, which is how information is encoded within the signal. FSO systems, not unlike the fiber optic cable networks of today, largely employ on-off keying (OOK) modulation or some variant. OOK is where the presence of a signal represents a binary "1", while the absence of the signal represents a binary "0". This presents a fundamental limitation of sending one bit per period of the carrier.

RF systems, on the other hand, make use of very developed modulation schemes. Some schemes like spread spectrum techniques send redundant signals to attain more robustness as well as anti-jamming effects. Therefore, spread spectrum techniques do not usually aim to attain high data rates with the available bandwidth. Other modulation techniques like the Quadrature Amplitude Modulation (QAM) combine amplitude modulation and phase shift keying to attain higher data rates while still only using the same carrier frequency. While a detailed discussion of QAM is not within the scope of this report, it is necessary for this discussion to understand that QAM is able to send more data every period of the carrier signal because the varied amplitude and phase of the signal allows each signal to represent a series of binary digits rather than just a single bit. For example, 4-QAM is where there are 4 combinations of amplitude and phase of the signal, and therefore each symbol in 4-QAM represents 2 binary digits (since 2 bits can represent 4 levels). Therefore, 4-QAM can theoretically send 2 bits for every symbol it transmits. 64-QAM, which is a popular modulation scheme for microwave frequency radios, makes use of 64 combinations of amplitude and phase, and therefore each symbol in 64-QAM represents 6 bits. As a result, 64-QAM can theoretically send 6 bits for every symbol it transmits. Microwave radios are usually limited to 64-QAM or sometimes 128-QAM because increasing the number of levels of QAM makes the signal more susceptible to noise.

Modulation schemes like QAM make more efficient use of the bandwidth than schemes like OOK. Therefore, the maximum data rate that an EMR signal can achieve cannot be determined solely from the frequency of the signal. That is, a laser signal cannot be said to be capable of sending data x times faster than a microwave transmission simply because the frequency used by the laser is x times higher.

Researchers have found it difficult to apply advanced modulation techniques like QAM on lasers because of the way lasers are generated. If this were achieved, lasers should be able to attain greater QAM levels than microwaves because of their high signal-to-noise ratio. This will be discussed further in the section on bit error rate (BER). Of course, there are others who say that applying more bandwidth-efficient techniques to lasers is not necessary because of the wide bandwidth available to lasers. Furthermore, lasers are unlikely to interfere with other laser signals because of their small beam spread. Therefore, there is not a high motivation to research bandwidth-efficient modulation for lasers.

B. SPECTRUM LICENSING

Mobile communications, computer data, radio stations, aircraft, taxis, and even astronauts rely on radios to keep in touch with one another. Because this radio spectrum cannot be expanded, it is coming under increased pressure to carry more and more communications. The worldwide introduction of digital mobile communications is causing concerns of a spectrum drought on several continents. Of late, industry comments have shown that spectrum and bandwidth will become a tradable commodity in the near term, fetching high prices because of supply and demand.

The radio-frequency spectrum is the world's natural resource, and it needs to be well-managed to ensure that systems do not interfere with one another. The International Telecommunication Union (ITU) regulates the use of radio frequencies throughout the world. Nations are obligated to comply with the spectrum allocations specified in the ITU Radio Regulations' Article S5 (International Table of Frequency Allocations). However, domestic spectrum uses may differ from the international allocations provided these domestic uses do not conflict with neighboring spectrum uses that do comply with international regulations or bi-lateral agreements.

The World Radiocommunication Conference held in year 2000 (WRC-2000) extended the mandate of the ITU radio regulations from 400 GHz to 1000 GHz (1 THz). Although the ITU did not make any specific allocations to radiocommunication services, it has set a preliminary agenda to review studies and consider allocations in the frequency bands above 275 GHz during WRC-2007. Therefore, the ITU does not currently regulate frequencies in the optical spectrum (above 3 THz), although it is known that studies have begun on this [IARU 2002].

Most nations regulate the use of radio frequencies by requiring that the use of these frequencies be licensed. In the United States, the Federal Communications Commission (FCC) issues these licenses. Obtaining a license may involve equipment tests (for intentional and unintentional radiations), examinations for operators, and a license fee which pays for a license that will usually be valid for a specified number of years. The FCC does not require a license for the Industrial, Scientific, and Medical (ISM) bands (between 902 – 928 MHz and 2.4 – 2.484 GHz) and the Unlicensed National Information Infrastructure (U-NII) bands (between 5.725 – 5.825 GHz). However, the FCC rules as specified in Part 15 of Title 47 of the Code of Federal Regulations still apply. Therefore, the use of microwave frequencies may require a license, and FCC rules should be adhered to.

The ITU and the FCC do not control the use of optical frequencies, although it certainly may in the years to come. FSO systems that have been deployed are still few and far between, and the highly directional nature of optical transmissions imply that issues of interference would be rare. Furthermore, optical signals are highly attenuated by the atmosphere. Therefore, the likelihood of a stray optical signal interfering with another system is highly unlikely.

The need to control the use of FSO systems come from a safety aspect rather than managing spectrum use. Laser safety is governed internationally by the International Electrotechnical Commission (IEC), while within the United States, the Center for Devices and Radiological Health (CDRH) and the American National Standards Institute (ANSI) ensure product and user safety respectively. Laser safety will be discussed in much greater detail in a later section.

C. BIT ERROR RATE

There is disagreement in the industry as to whether the acronym BER stands for bit error rate or bit error ratio. Proponents of the latter argue that BER is a measure of erroneous bits with respect to the total number of bits transmitted, received, or processed. It is not a measure with respect to time, and so, many deprecate the term bit error rate. However, the term bit error rate is more popularly used in technical literatures. In this report, no distinction is made between the two terms and they may be used interchangeably.

Many papers have been written (often by FSO vendors themselves) that FSO systems typically have lower BER than other radio frequency (RF) communication systems. This may mislead a reader to infer that FSO is a better technology than other RF systems. In actuality, the BER from a system does not depend on the technology alone. It depends on the quality of the transmitted signal, the power used by the transmitter, the resilience of the transmission over the medium, the distance between transmitter and receiver, the sensitivity of the receiver, the electronics involved, etc.

For example, a particular FSO system may be specified to have a much lower BER than an RF system. However, the FSO system only operates over 1 km, while the RF system operates over 5 km. If the FSO transmitter and receiver were placed 5 km apart instead, the BER on the FSO system would likely experience a much higher BER than that of the RF system. As another example, an FSO system may be specified to have a lower BER than an RF system, and both operate over the same distance. While this may be true on a clear day, this may not be so in the event of heavy fog. Once again, the FSO system is likely to experience a much higher BER than the RF system.

Therefore, it is important to note that whatever BER values that are quoted for a communications system are specific to that system, and may vary depending on factors such as distance and weather. Since it is not possible to declare whether FSO or RF systems have better BER, this report will instead analyze the issues that contribute to BER.

In this report, BER is understood to be the number of erroneous bits received out of the total number of bits transmitted. This is also sometimes called the transmission BER. For example, a BER of 10^{-6} means that on average, one erroneous bit is received out of a million bits transmitted.

Indeed, FSO systems do have a quality that allows them to attain low BER. This is attributed to the fact that the lasers that are used in FSO systems typically have much smaller spectral widths than RF systems. *Spectral width* is a measure of the range of frequencies that are transmitted. An ideal transmission is one where only one frequency is transmitted. Such a transmission is said to be fully coherent. A laser source is said to be fully coherent if the electromagnetic waves in the source have a constant phase relationship. This implies that there is only a single frequency being transmitted, which is difficult to achieve practically. A laser transmission will usually consist of a small range of frequencies together with the intended frequency (usually called the carrier).

This non-ideal output of lasers is attributed to what is called *Doppler broadening*. Doppler broadening is caused by the thermal motion of the atoms in the material which generates the laser. This thermal motion causes a Doppler shift in the frequencies of the photons emitted by these atoms. This range of frequencies theoretically forms a Gaussian distribution [Nave 2003]. In the fields of probability theory and statistics, a Gaussian distribution is also called a normal distribution.

This spread of frequencies is known as its spectral width. The usual method of specifying spectral width is the full width at half maximum (FWHM). As indicated in Figure 5, the FWHM is the width of the spectrum taken at half of the maximum output intensity. Therefore, the figure shows a laser with a FWHM of 2 nm. Lasers typically have a FWHM of less than 5 nanometers (5×10^{-9} meters).

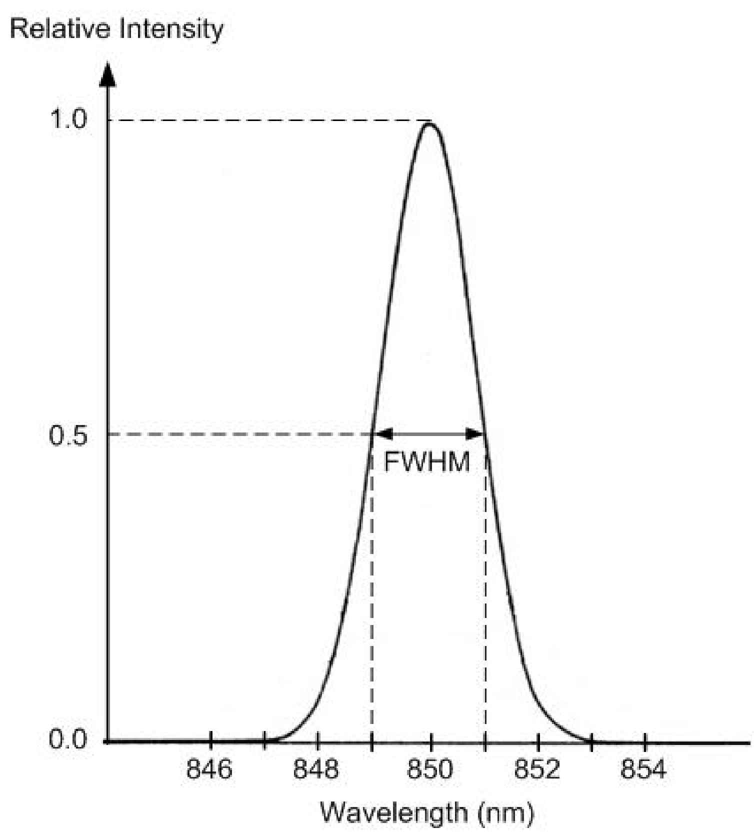

Figure 5. Gaussian Distribution of Laser Output

The knowledge that the distribution of frequencies follows a Gaussian distribution allows us to infer additional information about the laser source. Firstly, it can be shown that the value of FWHM corresponds to 2.355 times the standard deviation of a Gaussian distribution [Nave 2003]. This is illustrated in Figure 6.

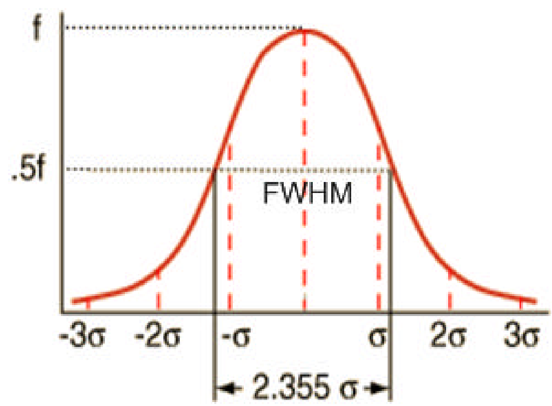

Figure 6. Relationship Between FWHM and the Standard Deviation (After: [Nave 2003])

Therefore, for our laser in Figure 5 which has an FWHM value of 2 nm, the standard deviation, σ, is equal to the FWHM (2 nm) divided by 2.355, which gives roughly 0.85 nm.

A property of the Gaussian distribution is that 68.26% of the observations will be found within 1 standard deviation of the mean. 95.46% of the observations will be found within 2 standard deviations, while 99.73% will be found within 3 standard deviations. This is illustrated in Figure 7.

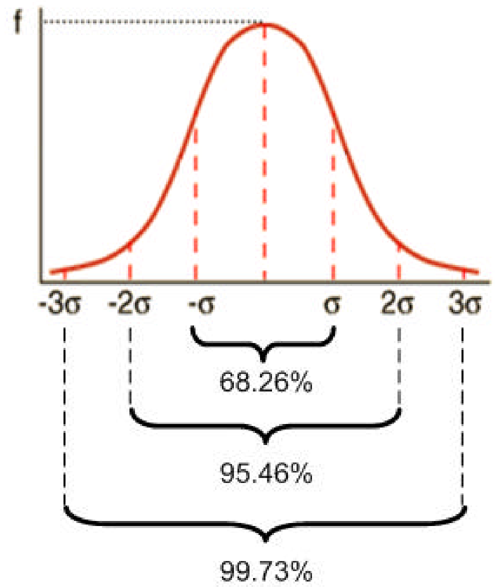

Figure 7. Percentage of Observations of a Gaussian Distribution

Therefore, for our example laser with carrier frequency of 850 nm, FWHM of 2 nm, and calculated standard deviation of 0.85 nm, 68.26% of the laser power will be within the range of 849.15 to 850.85 nm, 95.46% (most) of the laser power will be within the range of 848.30 to 851.70 nm, and 99.73% (almost all) of the laser power will be within the range of 847.45 to 852.55 nm.

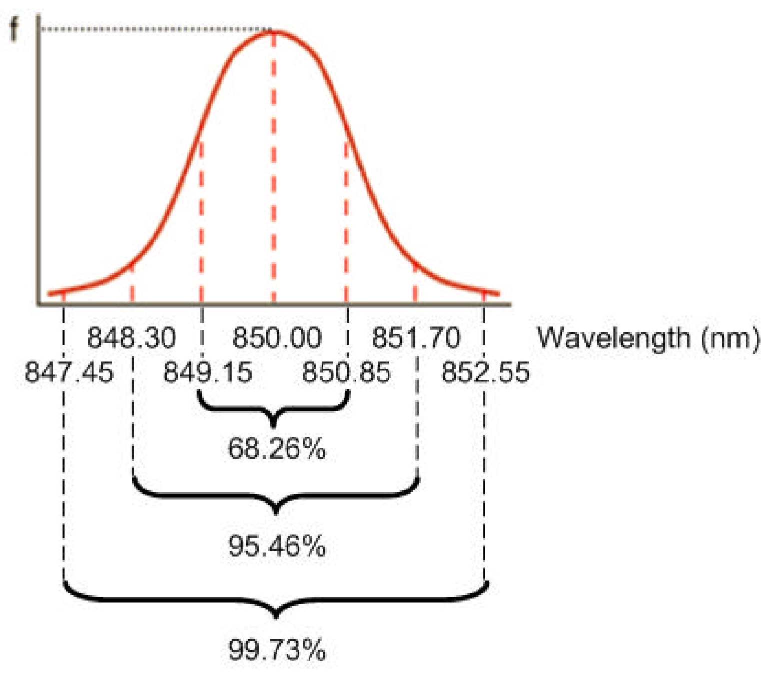

Figure 8. Distribution of Laser Power

Understanding the statistics involved in a Gaussian distribution allows us to calculate the percentage of power in any arbitrary interval of wavelengths. The existence of Gaussian tables also means that heavy mathematical calculations need not be involved. For example, the percentage of laser power within the FWHM interval (between 848 and 852 nm) can be found to be approximately 76%.

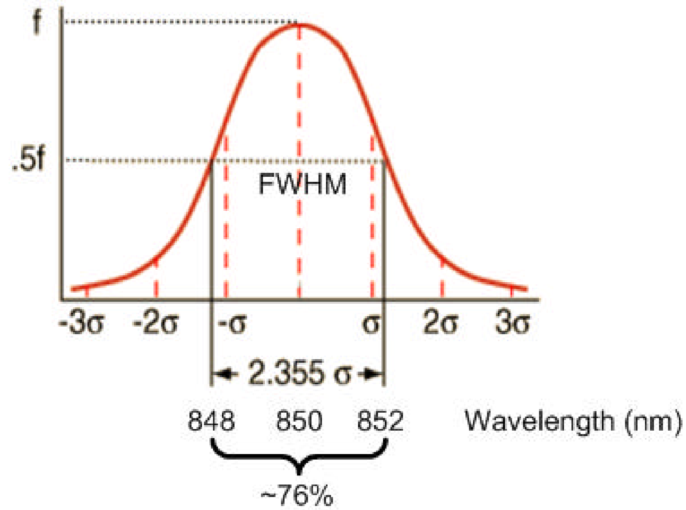

Figure 9. Percentage of Laser Power within FWHM

The narrower the spectral width of a laser source, the more energy is concentrated around the central (carrier) frequency. Figure 10 illustrates two lasers which have the same input power, but where laser A has a spectral width of 2 nm, while laser B's spectral width is twice that of laser A (4 nm). It can be seen that laser A's peak power at the central frequency (850 nm) is twice that of laser B, even though the same total power is applied to both lasers.

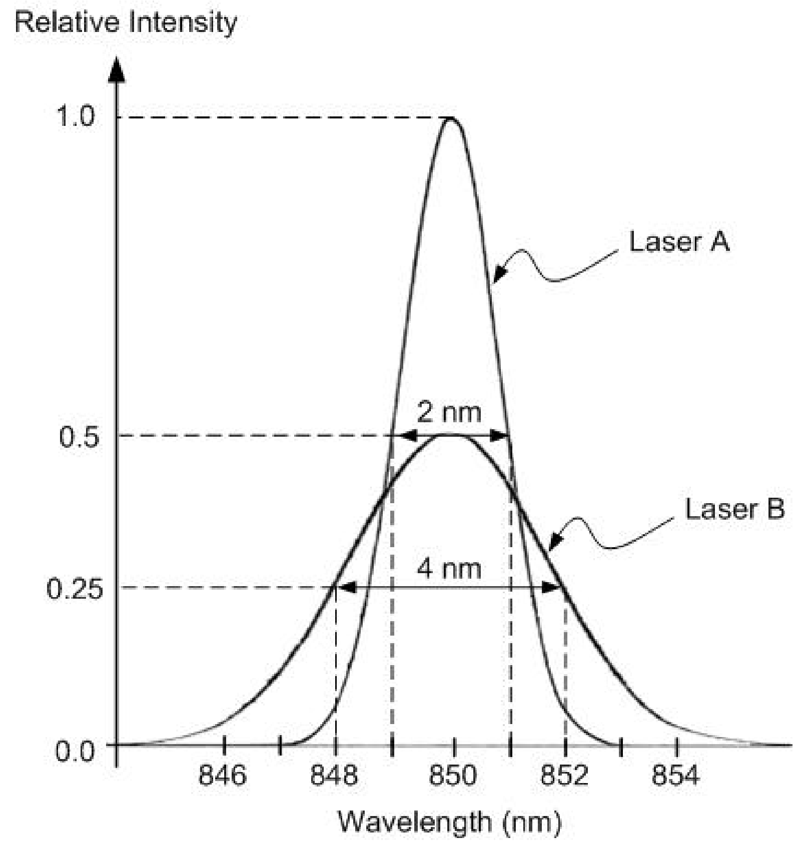

Figure 10. Comparison of Laser Outputs with Different Spectral Widths

A sharper profile is desirable of a laser source so that the transmitted pulse can be distinguished from the ambient noise in the atmosphere (typically from the sun). Furthermore, as a laser leaves its cavity, its signal is degraded through absorption, scattering, and dispersion. *Absorption* is where the laser's energy is lost to the atmosphere at the molecular or atomic level. *Scattering* is a phenomenon in which the direction, frequency, or polarization of the wave is changed when the wave encounters discontinuities in the medium, or interacts with the material at the atomic or molecular level. *Dispersion* occurs when the various wave components (i.e. frequencies) of the signal have different propagation velocities within the physical medium. All these phenomena will be discussed in greater detail in a later section on the atmospheric effects. These phenomena cause the laser source to be attenuated, and therefore much less useful energy will be able to reach the receiver.

Yet another reason why not all the transmitted power may reach the receiver is because of the divergence of a laser beam as it travels great distances. The size of the beam at the location of the receiver may be too large for any practical receiver to collect. Beam divergence will be discussed in further detail in a later section on security.

Instead of measuring the spectral width of transmissions (which is a measure of the range of wavelengths), microwave and other RF transmitters provide their bandwidth figure instead. This is a measure of the range of frequencies instead of wavelengths. However, this can be easily converted to wavelengths in order make a comparison of spectral widths. The bandwidth of RF transmissions is sometimes called the transmission purity. The popular measure of purity for an RF signal is the Q factor, which is basically the intended transmit frequency divided by its bandwidth.

For a fair comparison, we first look at the bandwidth used for an RF transmission which is only attempting to transmit a single frequency. While the spectral widths of laser transmitters are typically less than 5 nm, that of microwaves and other RF communications may range from 100 nm to a few hundred microns, depending on the resonator/transducer/oscillator used. Therefore, the spectral purity of laser transmissions may be 2 to 5 orders of magnitude finer than other RF communications. In other words, an RF transmission may require up to 10,000 times more power to attain the same signal-to-noise ratio as laser transmitters.

Having said this, much research is underway to improve the Q factor of RF transmissions. Microwave radios using Sapphire resonators and more recently SiO_2 monocrystals have reportedly been able to achieve spectral widths as narrow as 4 nm [Salzenstein 2002]. However, these resonators are yet to see widespread use.

The modulation of an EMR signal plays a big role in its BER. Spread spectrum schemes used in RF communication transmit multiple redundant frequencies for every bit of information. One might think that since multiple frequencies were used, then more power would have to be used in order for the collection of frequencies to be detected with the same BER. However, one of the main purposes of spread spectrum is a low probability of detection. Therefore, the power used for transmitting the individual frequencies is not increased since they are redundant and a few of them can be lost without losing information.

Other RF modulation schemes like Quadrature Amplitude Modulation (QAM) are designed for maximum data rate over a single carrier frequency. A QAM receiver needs to be able to differentiate between signals which have small differences in amplitude and phase. As a result, these signals are more susceptible to noise as a small change in amplitude or phase of the signal may cause the receiver to misinterpret the received data.

Laser communication systems largely use on-off keying (OOK) or a variant. As explained previously, this is where the laser is either on or off. When the laser is on, its narrow spectral width presents a high signal-to-noise ratio and hence low BER. Other RF systems have much wider spectral widths and hence higher BER. Certain schemes of modulation of RF signals (e.g. QAM) reduce the acceptable signal-to-noise ratio and hence cause these RF signals to have higher BER.

D. COMMUNICATIONS SECURITY

The success of modern military forces depends a great deal on the effective use of sophisticated radio communication and navigation systems. Historically, the enemy has employed electronic countermeasures (ECM) to detect the presence of these radio signals and either disrupt them or exploit them. Radio systems can be disrupted by jamming or by locating and destroying them. On the other hand, exploitation involves using the transmissions for intelligence and counter-intelligence purposes. Prior to the development of high quality data security and transmission security techniques, it was possible to gather intelligence from the received signals by demodulating and decoding (deciphering) them. For simple systems it is also possible to "spoof" (or mimic) them to provide false information (counter-intelligence). Radio transmissions can also be exploited, even when they employ high quality security techniques, by simple radio direction finding (RDF) or position monitoring. A scenario of these basic ECM techniques is shown in Figure 11.

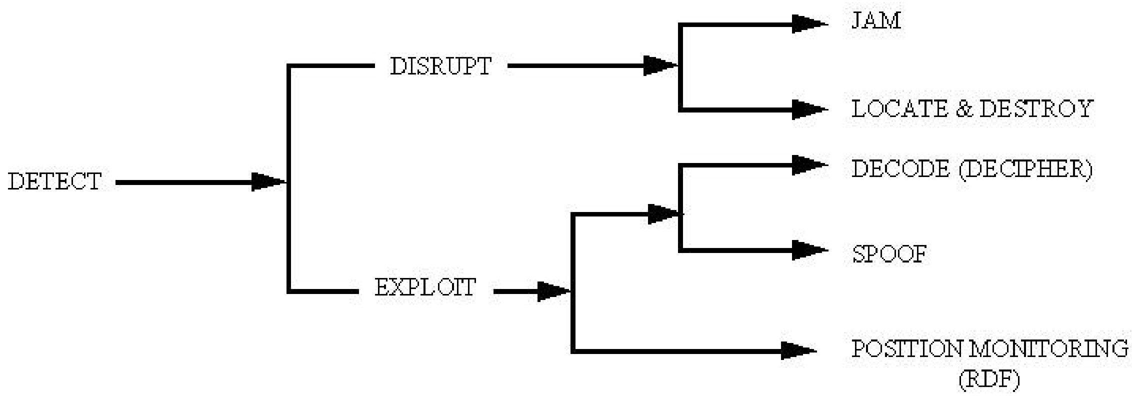

Figure 11. Electronic Warfare Overview for Military Systems (After: [Russell 1997])

Various concepts have been developed to counter these ECM techniques. These have been called the Electronic Counter-Counter Measures or ECCM. Low Probability of Detection (LPD) is concerned with preventing the enemy from detecting a transmission. Low Probability of Intercept (LPI) is concerned with preventing the enemy from tapping onto the transmission. Low Probability of Exploitation (LPE) is concerned with preventing the exploitation of the signal by decoding, spoofing, or position monitoring. LPE design would deny the enemy knowledge of the system, its modulation characteristics, its use, and its users. Anti-Jamming (AJ) is the prevention of a denial-of-service (DoS) attack by spurious signals sent from a jammer.

This section will look at all these concepts in turn and see how FSO technology performs in each of them.

1. Probability of Detection

The conventional way of detecting an RF transmission is through the use of spectrum analyzers or RF meters. These cannot be used to detect laser transmissions. In order to detect a laser transmission, a compatible FSO receiver or some form of electro-optical system needs to convert the optical frequencies to electrical signals.

Generally, there are two places in which a laser beam can be detected. Firstly, it can be detected from within the beam. The beam divergence determines the probability of detection from within the beam. Secondly, the beam may be "seen" from outside the beam. In this case, the "visibility" of the beam determines whether it can be detected.

a. Beam Divergence

An ideal electromagnetic transmission will travel directly to the receiver. However, this requires a fully coherent source. That is, the electromagnetic waves in the source have a constant phase relationship. This implies that there is only a single frequency being transmitted, which is difficult to achieve practically. If a source is non-coherent, the electromagnetic waves in the source will interfere with one another, causing the beam to diverge.

Figure 12. An ideal transmission with no divergence

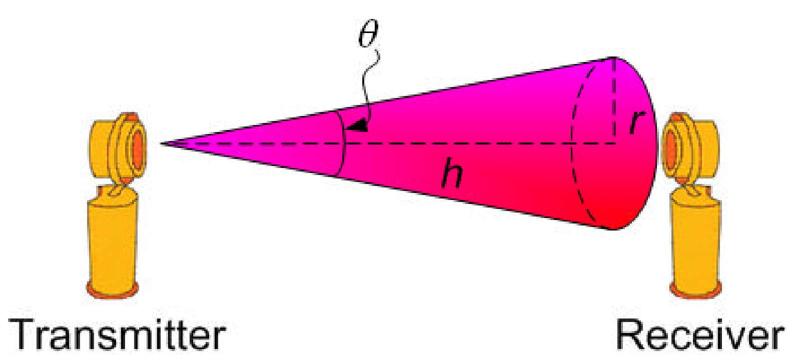

Figure 13. A non-coherent transmission source diverges

As shown in Figure 13, when a transmitted signal diverges, it forms a cone with the tip at the transmitter end. Practically, this is a spherical cone i.e. the base of the cone is curved. However, for simplicity, we assume that the base is flat, giving a normal cone.

State-of-the-art radio and microwave transmitters have a divergence angle (θ) of a few degrees. Lasers, on the other hand, are generated through wavelength-controlled photon emissions. Most of them generate light in a very narrow band around a single, central wavelength. Because this characteristic manifests itself in visible lasers as a very pure, single color, the narrow linewidth is termed *monochromaticity.* For example, the neodymium laser used in most laser designators (the ubiquitous "Nd:YAG") generates an output beam at 1.064 microns, with a typical bandwidth of 0.00045 microns, an amazingly narrow linewidth of 0.04 percent of the central wavelength.

Therefore, laser emissions are highly coherent. Therefore, laser beams typically have a divergence of less than a milliradian (approximately 0.057 degree). Some systems can be designed to have sub-microradian divergences. A small laser beam with a one milliradian divergence would expand to about one meter in diameter after traveling a kilometer.

Because of their small size, semiconductor diode lasers usually have divergences measured in degrees, expanding rapidly. However, this beam divergence can be substantially reduced by using collimators. A *collimator* is a device for changing the diverging light or other radiation from a point source to a parallel beam. A laser system with an output beam diameter of one meter could readily have a 0.05 milliradian beam divergence, expanding to only about 25 meters after traveling 500 kilometers. This pencil-like beam of light permits highly accurate placement of energy on a target for efficient communication links. The beam can be used for covert applications because it is very difficult to detect the beam without intercepting it. The disadvantage, of course, is that pointing the beam requires a high degree of precision, which will be discussed later in this report.

The locations in which an enemy could detect a laser transmission is effectively anywhere within the volume of the cone described earlier. A highly divergent beam implies that there are more locations in which the enemy could detect the transmitted signal. The volume of the cone is found by the formula $\frac{1}{3}pr^2h$, where *r* is the radius of the base of the cone, and *h* is the furthest distance from the transmitter in which the transmitted signal is still of sufficient power to be detected.

For comparison purpose, assume that a transmitted signal can reach a distance of 20 km (i.e. h = 20,000 m).

For a microwave transmitter with a divergence angle of 2 degrees,

$$r = h.\tan \frac{q}{2}$$

$$= 20{,}000 \times \tan \frac{2}{2}$$

$$= 349.1 \text{ m}$$

$$\text{Volume of cone} = \frac{1}{3} p r^2 h$$

$$= \frac{1}{3} p (349.1)^2 20000$$

$$= 2{,}552{,}456{,}276 \text{ m}^3$$

For a laser transmitter with a divergence angle of 2 arcseconds,

$$r = h.\tan \frac{q}{2}$$

$$= 20{,}000 \times \tan \left(\frac{2}{3600} \times \frac{1}{2} \right)$$

$$= 0.1 \text{ m}$$

$$\text{Volume of cone} = \frac{1}{3} p r^2 h$$

$$= \frac{1}{3} p (0.1)^2 20000$$

$$= 209 \text{ m}^3$$

The volume of the transmission cone for the microwave transmitter is more than 12 million times greater than that of the laser transmitter. It may be interpreted that an adversary is 12 million times more likely to detect the transmission.

Many factors may affect whether an eavesdropper may be able to locate a detector within the volume of the cone. For example, locating a detector between two planes or between a ship and a plane may be much more difficult than between two land systems. Therefore, while the divergence angle greatly influences the probability of detection of laser transmissions, the feasibility of locating a detector within that transmission cone is also an important factor.

It should be highlighted that while the notion of beam divergence is an acceptable description of a laser transmission, it is usually not so for other RF transmissions. Spurious transmissions outside the main beam are usually transmitted by RF antennas. These spurious transmissions are called side lobes. Larger RF antennas usually reduce the intensity of these side lobes. However, many applications require the antennas to be small. These side lobes provide more opportunity for an eavesdropper to detect the transmitted signal.

RF transmissions have an azimuth pattern similar to that shown in Figure 14. The majority of the power of an RF antenna would be concentrated in a main lobe. The figure also illustrates that the beam divergence (θ) of RF transmissions is determined by taking the angle formed by the main lobe at the half-power points ($1/2P_0$). θ is also known as the half power beam width.

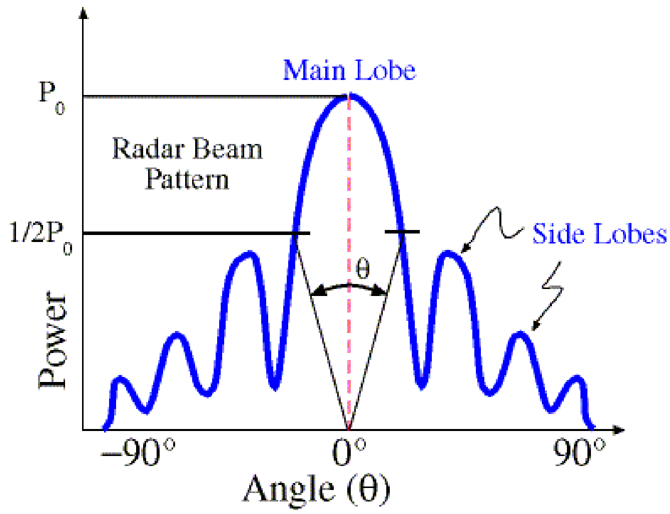

Figure 14. Azimuth Pattern of an RF Transmission (From: [Atkins 2002])

Other than the main lobe, several side lobes may be formed. Although these side lobes are of lower power than the main lobe, they still represent spurious emissions outside the intended direction of communication. Several antenna designs even have emissions behind the antennas. Therefore, an eavesdropper may be able to detect these spurious emissions if he is close enough to the transmitter.

Figure 15 illustrates a typical azimuth pattern of a laser transmission. An azimuth pattern shows the angular direction of transmissions. As can be seen from the figure, laser beams usually only radiate in the direction that it is pointing.

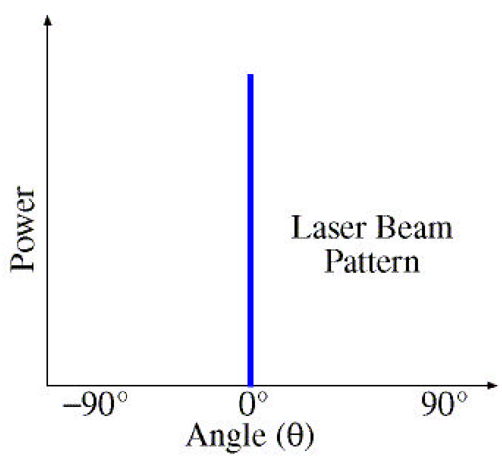

Figure 15. Azimuth Pattern of a Laser (After: [Atkins 2002])

In summary, lasers have a much lower probability of detection than other RF transmissions because of the small beam divergence and the absence of spurious emissions like side lobes.

b. Visibility

Many vendors claim that one of the reasons FSO links are secure is because the lasers used are in the near-infrared band and therefore invisible and covert. Therefore, an enemy would not be able to detect an FSO link. While this is somewhat true, an FSO beam can still be detected if the enemy has the appropriate tools and environment to detect the beam.

In a scene often played in the movies, a hero needs to get to the other end of a room to retrieve some prized treasure. It is known that this room is protected by motion sensors. Our hero puts on an awkward pair of goggles. At first, the room looks no different. Smoke is sprayed into the room. Slowly, a mesh of laser beams is revealed. Our hero then performs some incredible acrobatics, avoids the laser beams, and gets to the other end of the room without setting off the alarm. Science fiction? Maybe not.

The goggles used by our hero may well be infrared (IR) goggles. IR goggles convert invisible infrared light into light that can be seen by the human eye. Figure 16 shows a hands-free version of the 6100 IR goggles by Electrophysics Corporation [Electrophysics 2003].

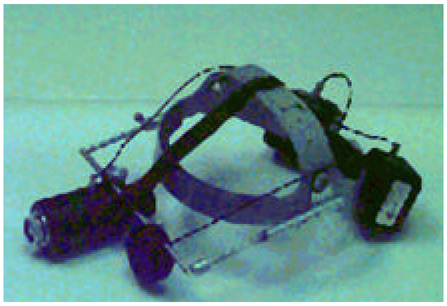

Figure 16. The 6100 IR Goggles from Electrophysics Corporation (From: [Electrophysics 2003])

The spectral sensitivity of the 6100 IR goggles is from 0.4 to 1.3 microns. Visible light is from 0.4 to 0.7 microns. Therefore, normal light can still be seen through these goggles. This explains why our hero is able to see normally through the goggles.

Near-infrared light is from 0.7 to 1.5 microns. Although these goggles do not cover the full spectrum of near-infrared wavelengths, it will be able to sense a near-infrared laser as long as its wavelength is between 0.7 and 1.3 microns. Common wavelengths used in FSO lasers are 0.80, 0.85, and 1.55 microns. Therefore, while the 6100 IR goggles from Electrophysics should be able to sense lasers at 0.80 and 0.85 microns, it will not be able to sense lasers at 1.55 microns.

It is left to explain why our hero had to use smoke before he could see the laser beams. Light from lasers is highly directional and generally only travels to where it is pointed at. For example, the laser pointers used in boardroom presentations use a visible laser. While a bright spot can be seen where the laser is pointed, we usually cannot see the laser light along the path from the laser pointer to the bright spot. Smoke particles scatter the laser beam so that some portion of the beam will be scattered towards an observer. A successful scatter will require that the size of the smoke particles be of the same order as the wavelength of the laser light. Scattering will be discussed in much greater detail in the section on atmospheric effects.

Therefore, an enemy may be able to detect an FSO link if IR goggles were used. Some means to scatter the laser beam is needed. Smoke may be present from pollution, or in a wartime scenario, the smoke may come from fires. Laser beams are also greatly scattered by fog and haze. Therefore, a foggy day may be a good time to spot laser beams.

To minimize the probability of a laser beam being detected, transmitters should not use excessive power. This will reduce the amount of light scattered and hence reduce the probability of detection.

2. Probability of Intercept

Intercepting a laser transmission is the tapping of the signal sent from the transmitter. While detecting the laser beam can be accomplished within or outside the beam, intercepting the beam will require placing the sensing device within the laser beam. As laser transmissions are highly directional, a sensor which relies on the scatters outside the beam would only receive very weak signals, which may not be sufficient to extracting information. Furthermore, the scatters coming from different portions of the beam represent signals from different phases in time of the transmission. Therefore, scattered signals may interfere with one another, resulting in noise.

The probability of intercept of a laser beam includes the probability of detection from within the beam and therefore depends on the beam divergence. However, intercepting a laser transmission usually has an additional requirement that the transmission should not be disrupted. This is because the laser transceivers usually have some form of flow control protocol to ensure that the transmitter does not flood the receiver. If intercepting the laser transmission blocks the signals from reaching the receiver, then the receiver would not request for more information from the transmitter. Therefore, the intercept of information would fail.

Herein lies another distinguishing factor between RF and FSO "antennas." RF antennas usually consist of a series of waveguides which are used to sense the RF transmissions. While some portion of the transmission is converted to electricity, much of the transmitted signal passes between the waveguides unchanged. FSO "antennas" on the other hand usually consist of a lens which focuses all the light which falls on the lens onto a detector which may then convert the signal to electrical form. Therefore, signals that encounter such a detector would be entirely blocked from the receiver and the intercept of further data may fail.

Intercepting a laser transmission is difficult to achieve without disrupting it. This is explained by the small beam divergence of the beam. Since most of the signal falls within the receiver, blocking part of the beam would imply a significant amount of power from reaching the receiver. Even if sufficient power reaches the intended receiver such that it is still able to interpret the data, intelligence can be built into the receiver such that it knows that a sudden drop in power may be caused by an intercept.

While intercepting a laser beam would generally disrupt the transmission, this may not be the case for long-haul links. A typical 0.5 milliradian FSO beam would extend a circle of diameter 10 meters after traveling 20 km. The size of the optics for an FSO receiver usually has a diameter of no more than 0.3 meters. Therefore, there is sufficient opportunity for an intercepting receiver to tap the transmitted signal without disrupting the signal to the intended receiver.

From the security perspective, it makes sense to have a beam with as small a divergence angle as possible. However, this also means difficulty in positioning the beam, especially for long-haul links. Therefore, many FSO systems are designed where not the entire beam falls within the optics of the receiver.

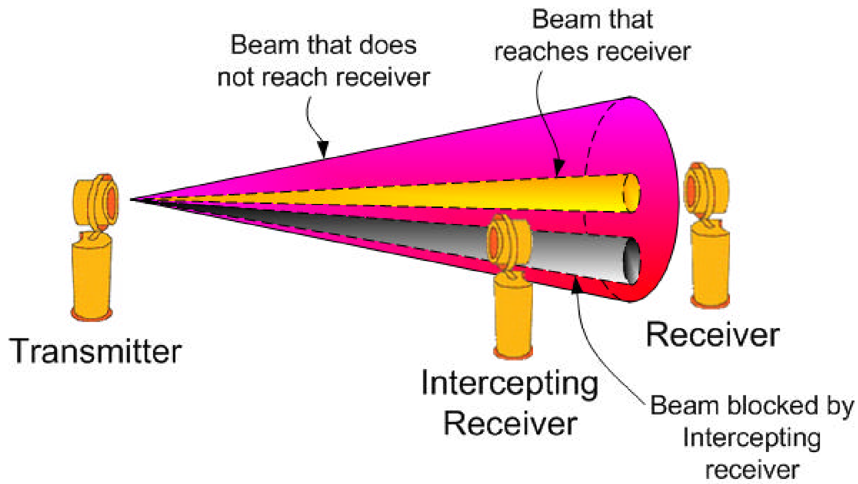

Figure 17. Intercepting a Long-Haul Laser Transmission

Even if the entire transmit beam is focused onto the receiver, it is still possible to tap the signal without blocking the transmission. One way is through the use of beam splitters.

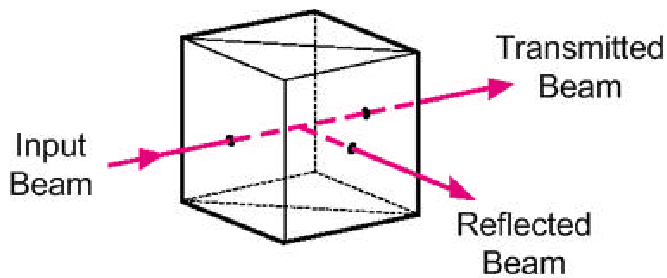

Figure 18. Beam Splitter Cube

Figure 18 shows a 45^{o} beam splitter cube which allows some portion of the input beam to pass through unchanged, while some portion of the beam will be reflected at 90^{o}. The intensity of the transmitted and reflected beams add up to equal that of the input beam. The relative intensity of the reflected and transmitted beams (known as the R/T ratio) is typically 50:50. That is, both the reflected and transmitted beams are of half the power of the input beam.

While the above beam splitter cube allows some portion of the input beam to pass through, the received beam must be of sufficient power for the intended receiver. Furthermore, if the receiver is able to detect the sudden reduction in receive power, it may raise an alarm that the transmission has been intercepted.

In summary, to reduce the probability of intercept of a laser transmission, the beam divergence should not be larger than necessary. Furthermore, it would be good if the receiver is capable of raising an alarm if there is a disruption or an unexpected reduction of power in the received laser beam.

3. Probability of Exploitation

In the field of communications security, the probability of exploitation includes the likelihood of the signal being decoded / deciphered, an enemy transceiver spoofing as a legitimate transceiver or receiver, and the enemy being able to locate the position of the transmitter and/or receiver.

a. Decoding

Most FSO systems today employ on-off keying (OOK) modulation or some variant. OOK is where the presence of a signal represents a binary “1”, while the absence of the signal represents a binary “0”. Therefore, if an enemy were able to intercept a laser transmission, there should be little difficulty in extracting the 1’s and 0’s. While it has been explained that FSO links have a low probability of intercept, there is still that small probability of intercept. Therefore, encrypting FSO links is still recommended.

FSO is a layer 1 service in the OSI model (physical transmission). Most networks of today do not attempt to encrypt the layer 1 modulation. Encryption is usually left to the higher layers in the OSI model. This is so that even if the enemy were able to obtain the series of 1’s and 0’s from the physical transmission, it would be extremely difficult to make sense of them.

While it is generally accepted to leave encryption to the higher layers of the OSI, there are indeed methods of encrypting layer 1 physical transmissions. In the field of chaotic communication, the complexity of the carrier used in the transmitter is intentionally increased to an extent that an observer would only experience random signals. Popular methods of message encoding and decoding in chaotic communications include chaos masking, chaos shift keying, and chaos modulation [Tang 2002]. Synchronizing these transceivers has proved challenging, and practical implementations for lasers have largely been confined to fiber optic cables. The range of an FSO link which employs chaotic communication is expected to significantly decrease because of the sensitivity to changes in the signal.

Not only are chaotic communication signals difficult to decode, they are also difficult to reproduce. Security proponents know that this means difficulty for an adversary to carry out man-in-the-middle attacks. This is where the adversary blocks the transmitted signal from the intended receiver and regenerates a modified version to the receiver.

Chaotic communication is currently still in its infancy and is not recommended for use on FSO links. The main reason for this is that it results in shorter range, which is already a problem with current links. Furthermore, encryption provided by the higher OSI layers together with the low probability of intercept should be able to provide sufficient protection from an adversary attempting to decode the signal.

b. Spoofing

Spoofing is where an adversary masquerades as a friendly transceiver. A spoofed transmitter may send false and harmful information (compromise in data integrity), while a spoofed receiver may steal sensitive or classified information (compromise in data confidentiality).

Spoofing is usually avoided through the use of some secure authentication scheme. This usually involves the exchange of secret passwords. Authentication usually takes place all the way up at the application layer in the OSI model.

At the lower layers of the OSI model, authentication between transceivers can take place (albeit informally) through the use of encryptors. Encrypted data sent to a spoofed receiver would be of little use. A friendly receiver expecting to receive encrypted data would reject data that is either not encrypted or is incorrectly encrypted.

The directionality of the laser beams in FSO may also reduce the likelihood of a spoofed transceiver. If the locations of the transceivers are known and they are pointed to one another, the likelihood of spoofing is low. Spoofing would require that the spoofed transceiver be located along the line-of-sight between the two friendly transceivers.

c. Position Monitoring

Determining the location of line-of-sight transmitters like microwave radio and FSO links is generally more difficult than locating omni-directional radio transmissions.

The directionality of microwave and FSO links may seem to easily give away the direction in which the beam is coming from and going towards. However, the direction of an omni-directional transmitter can also be determined by scanning the direction in which the received signal is strongest. This also means that the direction in which an omni-directional transmitter is located can be determined virtually anywhere around the transmitter. In contrast, the direction of a line-of-sight microwave radio or FSO transmitter can only be determined by an interceptor located within that line-of-sight. The more directional the link, the less opportunity there is for the interceptor to locate itself within that line-of-sight. Therefore, a FSO link with a typical beam divergence of about 0.05 degrees is less likely to reveal its position than a microwave radio transmission with a typical beam divergence of 2 degrees. Therefore, the probability of position monitoring depends on the probability of intercept of the transmission, which has been discussed earlier.

Knowing the direction in which a transmitter can be located is only half the problem of determining the position of the transmitter. The other parameter needed is the distance. Using only one sensor, the distance from the sensor to the transmitter can only be estimated if the transmit power is known. Since the transmit signal is attenuated with distance, the distance of the transmitter from the sensor can be estimated by knowing the atmospheric attenuation as well as the received power. For example, if the transmitter is known to emit a laser of power 100 mW, the atmospheric attenuation is 3 dB/km (halfing of power per km), the received power is 50 mW, then the transmitter would be estimated to be 1 km away.

If the transmit power or the atmospheric attenuation is not known, a more accurate method of determining the location of the transmitter is by pinpointing through the use of two or more sensors. Figure 19 illustrates how two sensors can pinpoint an omni-directional transmitter. The two sensors are spaced apart and individually determine the direction (bearing) in which the transmission is strongest. The intersection of these bearings would be the location of the transmitter.

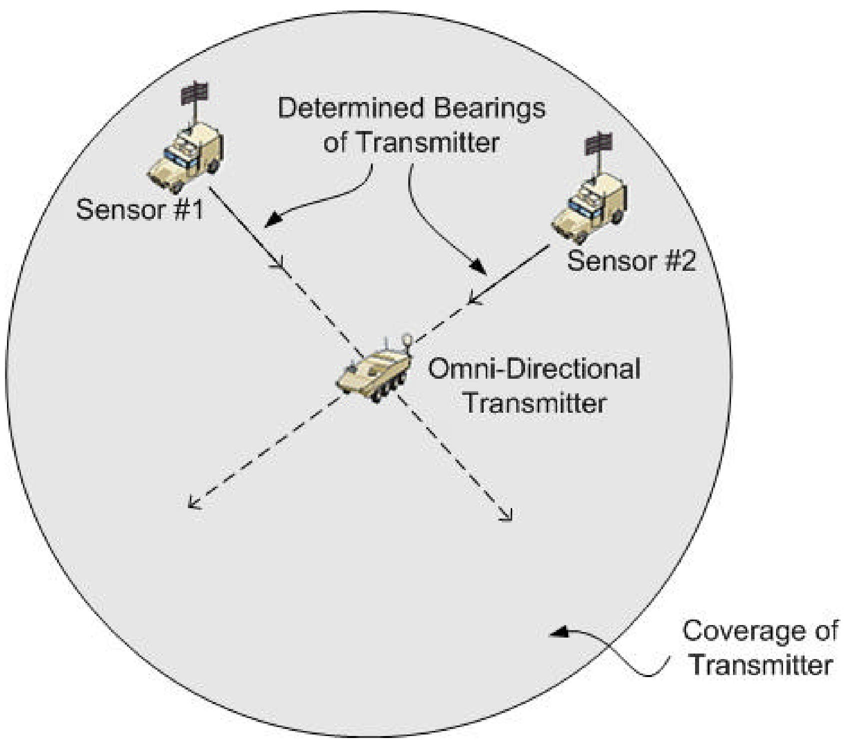

Figure 19. Pinpointing an Omni-Directional Transmitter

The same pinpointing method can be applied to directional antennas. Such antennas with higher power and longer ranges can be more easily pinpointed. This is because even though directional antennas like that used for microwave radio have small divergence angles of about 2 degrees, the spread of the signal quickly increases with distance. This is illustrated in Figure 20.

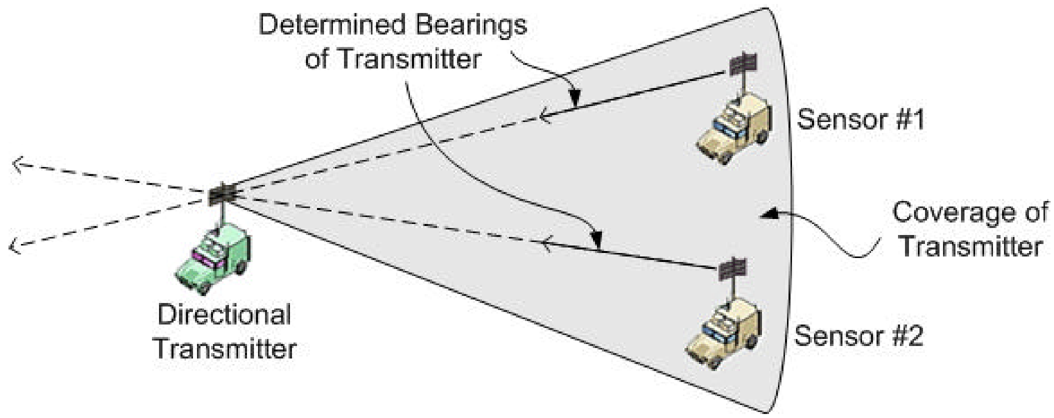

Figure 20. Pinpointing a Directional Transmitter

The smaller the divergence of the transmit signal, the harder it is to pinpoint the location of the transmitter. The width of a microwave transmission with a divergence of 2 degrees is roughly 350 m after 10 km. This should give sufficient spacing for the sensors to estimate the location of the transmitter. An FSO transmitter with a typical beam divergence of 0.05 degrees would have a beam width of less than 10 m after traveling 10 km. This separation of sensors may not be sufficient to give a good estimate of the location of the transmitter when considering the errors in determining the direction of the transmitter.

It should be highlighted that directional transmissions also give an adversary a rough indication of the location of the receiver. In this case, the more directional the transmission, the easier it would be to locate the receiver. Therefore, directional transmissions like FSO and microwave radio give an adversary a better idea of where the receiver is located, while an omni-directional transmitter does not reveal this.

In the earlier section on the probability of detection of FSO transmissions, it was presented that the invisible near-infrared lasers used by FSO systems can still be "seen" from outside the laser beam through the use of special electro-optical devices which convert the invisible wavelengths to visible ones. This requires a reasonable amount of dispersion of the laser, possibly by fog or smoke. This "visibility" of laser beams may directly divulge the location of FSO transmitters and/or receivers.

4. Denial-of-Service

The last Electronic Counter-Counter Measure is the prevention of denial-of-service attacks. In ECCM, denial-of-service largely refers to jamming. Jamming is the sending of an interference signal to a receiver, such that the receiver is no longer able to perform its function because of a decrease in signal-to-noise ratio. While jamming attempts to increase the noise level in the receiver, another way to decrease the signal-to-noise ratio is by decreasing the signal that reaches the receiver. The fact that FSO links are inherently line-of-sight links because of the lasers used implies that it is possible to block the lasers from reaching their intended receivers. Denial-of-service also includes the probability of an adversary destroying a communications system. This final sub-section takes a look at whether there can be an equivalent to the High-speed Anti-Radiation Missiles (HARM) which are able to lock-on and destroy RF communication antennas.

a. Jamming

It is the challenge of communication receivers to extract the transmitted signal out of the unwanted noise signals. It then comes naturally that if an adversary wants to disrupt communications, he can introduce "noise" to the receiver such that it is no longer able to distinguish the wanted signal from the noise.

Bandpass filters used in most communication receivers to reject unwanted noise can also be effective against jamming. As FSO systems typically only use a single frequency, any other received frequency should be discarded as noise. This presents difficulty for the jammer as it needs to know the frequency in use. Sending jamming signals at other frequencies would be simply discarded by the receiver.

If the jammer knows the frequency in use, one simple method of reducing the probability of interference by the jammer is to reduce the Field-of-View of the receiver (sometimes called the field-of-regard).

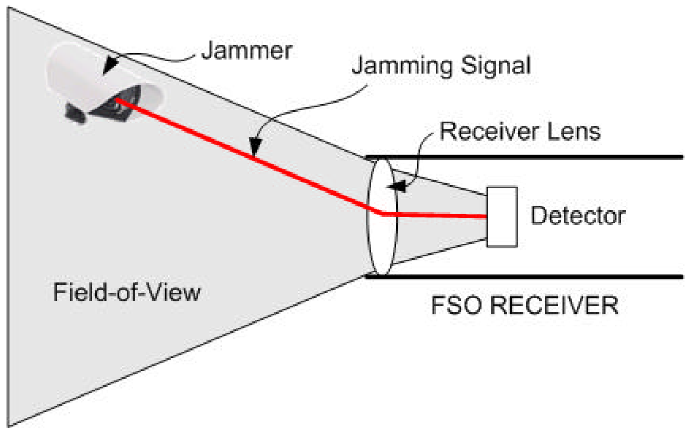

Figure 21. FSO Receiver with a Wide Field-of-View

Figure 21 shows an FSO receiver with a wide field-of-view (FOV). There is more opportunity for a jammer to send its jamming signal into the receiver. The jamming signal gets focused onto the detector of the FSO receiver by the receiver's lens.

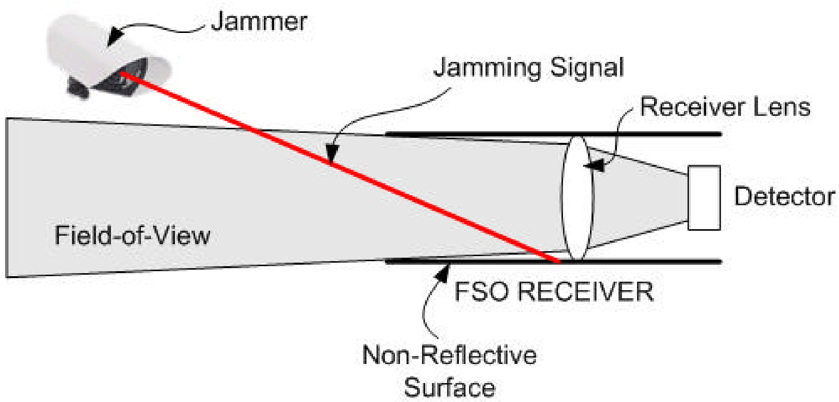

Figure 22. FSO Receiver with a Narrow Field-of-View

As shown in Figure 22, if the lens and detector are recessed into the cavity of the receiver, a much narrower field-of-view results. A jammer not in the FOV will not be able to jam the receiver because its jamming signal does not enter the receiver. Typical figures for FOV are from tenths of degrees up to 15 degrees or even more in some cases [Schenk 2000] [Cowan 2000] [Oppenhäuser 2001]. A smaller FOV is more resistant to jamming. However, a small FOV would represent difficulty in detecting the signal from the legitimate transmitter. Where possible, a wide FOV may be used to establish communications, while a narrow FOV may be used once the location of the transmitter has been established.

b. Blocking the Signal

While jamming attempts to increase the noise level in the receiver, another way to decrease the signal-to-noise ratio is by decreasing the signal that reaches the receiver. The fact that FSO links are inherently line-of-sight links because of the lasers used implies that it is possible to block the lasers from reaching their intended receivers.

Blocking a laser transmission can be as simple as mobilizing some platform to block the laser beam. While a solid and opaque platform is ideal to use for blocking the beam, strategically smoke from fires may be able to sufficiently reduce the strength of the signal that reaches the receiver. The scattering of a laser signal will be discussed in much greater detail in the section on atmospheric effects.

c. Destruction of Transceivers

Denial-of-service also includes the probability of an adversary destroying a communications system. Evidently, if an adversary knows the geographical coordinates of a transceiver, a bombardment of shells could potentially destroy the transceiver. However, bombarding a certain position would usually require some degree of proximity, while missiles and other long-range munitions may not be accurate enough to destroy a small transceiver.

High-speed Anti-Radiation Missiles (HARM) like the AGM-88 have been successfully deployed by U.S. Defense Forces in destroying enemy radar-equipped air defense systems. The HARM seeks and destroys the radars by locking in on the signals emitted by these radars. The HARM was designed to seek and destroy antennas that emit RF signals, but not at laser frequencies.

The original AGM-114 Hellfire I missiles, previously used on the U.S. Comanche and Apache helicopters, were laser-seeking missiles. A laser beam is aimed at the target either by a gunner on the helicopter, or by ground forces. The laser pulses on and off in a particular coded pattern. Before giving the firing signal, a computer tells the missile's control system the specific pulse pattern of the laser. The missile has a laser seeker on its nose that detects the laser light reflecting off the target. In this way, the missile can “see” where the target is. The guidance system calculates which way the missile needs to turn in order to head straight for the reflected laser light.

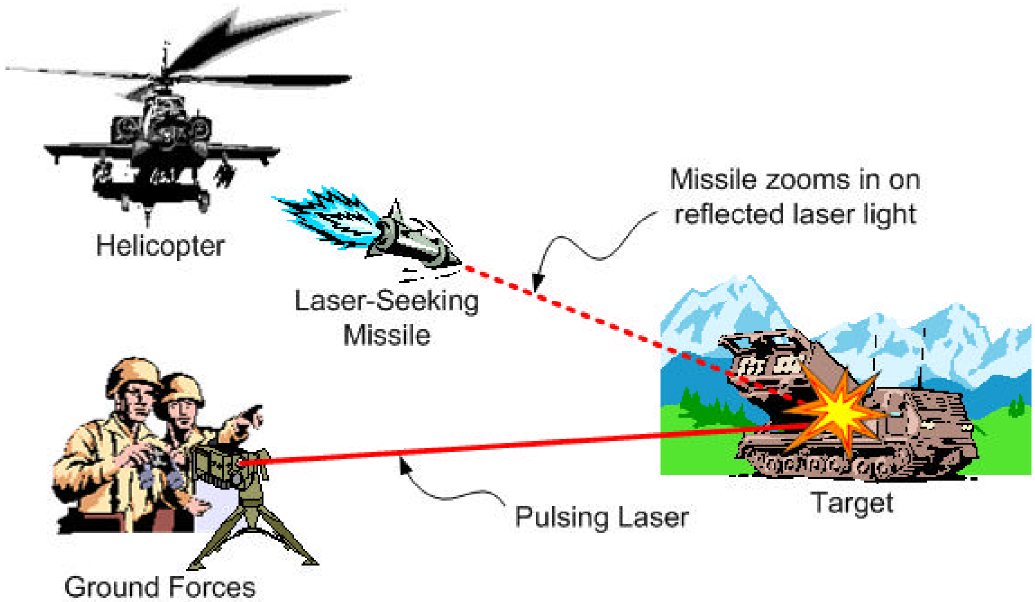

Figure 23. Deployment Scenario of a Laser-Seeking Missile

It would seem that a combination of the technologies of the HARM and Hellfire missiles would give a missile that can seek and destroy an FSO transmitter. However, once again, the small divergence angle of a laser beam proves advantageous for FSO. The HARM seeks a radar signal which is broadcast throughout the airspace, while the Hellfire requires a good reflection of the laser beam from the target so that it can "see" the laser beam.

FSO transmitters only direct their laser beams towards the receiver. A seeker outside of the beam is unable to detect the laser. Missiles are unlikely to be able to "ride" a narrow laser beam towards the transmitter because of the instabilities of flight. A slight shift in the position of the missile would cause it to lose the laser signal and hence the position of its target. Furthermore, a break in transmission from the transmitter would also cause the missile to lose its target.

E. FREE-SPACE LOSS

Free space loss is the signal attenuation that is caused by beam divergence. It is a measure of the transmitted signal that is received by the receiving "antenna." Recall the example of a transmitter and receiver which are 20 km apart. If the transmitter has a beam divergence of 2 degrees, then the circle formed at the receiver's end would have a radius of 349.1m. Theoretically, in order not to have any free-space loss, the receiver could be built so that the entire received signal would be received by the receiver. This would require the receiver to have a diameter of almost 700m! Even the largest satellite dish on earth is less than 50m across.

Because of the way lasers are generated, and with the added use of collimators, lasers can be constrained to very small divergence angles. In our example of a laser transmitter with a divergence angle of 2 arcseconds, the receiver would need to be of radius 0.1m, or 10 cm, which is a practical size for many deployments.

The general formula for free-space loss can be defined as:

$$\frac{Area\ of\ Beam\ at\ Receiver - Area\ of\ Receiver}{Area\ of\ Beam\ at\ Receiver}$$

If a microwave receiver of the same size as our laser receiver was used to receive the signal from the microwave transmitter which has a divergence angle of 2 degrees, then

$$\text{Free-Space loss} = \frac{Area\ of\ Beam\ at\ Receiver - Area\ of\ Receiver}{Area\ of\ Beam\ at\ Receiver}$$

$$= \frac{p(349.1)^2 - p(0.1)^2}{p(349.1)^2}$$

$$= 0.99999992$$

Engineers experienced at calculating the free-space loss of RF and microwave systems will know that free-space loss is traditionally calculated by first assuming isotropic (omni-directional) antennas, and thereafter considering the directionality of the antennas by including the gain factors for the transmitter and the receiver. It should be found that this is similar in concept to the above calculations where the beam divergence of the transmitter is known.

Once again, the area of the beam at the receiver is simplified to be that of a flat circle although in practice, it should be spherical in shape. The above calculation is only meant to illustrate that low free-space loss can be attained by FSO systems because of the low beam divergence.

F. POWER CONSUMPTION

The process of generating a highly coherent laser beam is usually very inefficient. The neodymium (Nd:YAG) laser is only about one percent efficient, while the popular helium-neon (He-Ne) laser is only about 0.001 percent efficient. Fortuitously, semiconductor lasers, which generate light by direct conversion of electrical current to photons, are very efficient, achieving 20 to 50 percent efficiencies.

In comparison, power amplifiers for the Very Low Frequency (VLF) up to the High Frequency (HF) bands are highly efficient, with conversion efficiencies from 85 to 90 percent. However, Microwave amplifier biasing arrangements have typical conversion efficiencies of only between 10 and 20 percent. Therefore, while microwave amplifiers are much more efficient than the Nd:YAG and He-Ne lasers, they are generally less efficient than semiconductor lasers.

Researchers at NASA Marshall Space Flight Center (MSFC) have applied the methodologies used in lower frequency amplifiers to the higher frequency microwave amplifiers to attain a 49.7% direct current (DC) to radio frequency (RF) conversion efficiency [Obenshain 2003]. With this, microwave amplifiers can equal or better the DC-to-RF conversion efficiencies of semiconductor lasers.

It is critical to determine where the remaining energy goes, which inevitably ends up as waste heat and must be removed from the laser system. In some lasers, like the hydrogen fluoride (HF) laser, the exhaust gases carry away the heat. In other lasers, such as the Nd:YAG or semiconductor laser, some method must be used to extract the heat from the laser, such as flowing cooled water within the laser. If it is allowed to remain in the laser, the performance of the laser is likely to be degraded or, in the extreme, the laser may be damaged. Dissipating heat in a spacecraft can pose serious problems.

As analyzed in the previous section on bit error rate (BER), laser systems usually have lower BER than other RF systems. This is due to the high spectral purity of laser signals which give laser systems a high signal-to-noise ratio. In RF systems which desire a high signal-to-noise ratio (e.g. QAM), much higher power is needed to attain low BER. Therefore, in order for an RF system to have a BER value comparable to that in laser systems, much higher power consumption is needed.

Yet another reason why laser systems consume less power is because of the low free space loss. Since lasers have small divergence angles, they are better able to focus the transmitted energy towards the receiver for power-efficient communication. RF systems on the other hand, have much higher divergence figures and hence much of the transmitted energy of RF systems does not reach the receiver. This represents a waste of power, and hence more power needs to be consumed by the RF transmitter in order for sufficient energy to reach the receiver.

Having low power consumption is especially important in mobile military platforms as the power source is usually limited. This can mean lower fuel or battery consumption on planes and ships, or a decreased solar array requirement for satellites. Typical power consumption figures for communication lasers are from 100 mW to a few Watts for laser with output powers of 30 to 200 mW [Biswas 1999] [CBL 2003] [Gill 1997] [Toyoda 2000].

IV. LIMITATIONS AND CHALLENGES

A. ATMOSPHERIC EFFECTS

1. Effects of the Atmosphere

The various gases in the atmosphere absorb and scatter EMR at different wavelengths and to various extents. Figure 24 illustrates an experiment which may have been carried out by students in a physics class. This experiment starts off with a white light source being split into an even spectrum of colors by a prism.

However, when a glass canister containing a certain type of gas is placed between the light source and the prism, dark bands are seen within the spectrum. These dark bands represent the wavelengths of light which have been absorbed or scattered by the gas. It is also found that different gases and particles absorb and scatter light at different wavelengths. Therefore, the location of the dark bands is different when different gases and particles are used.

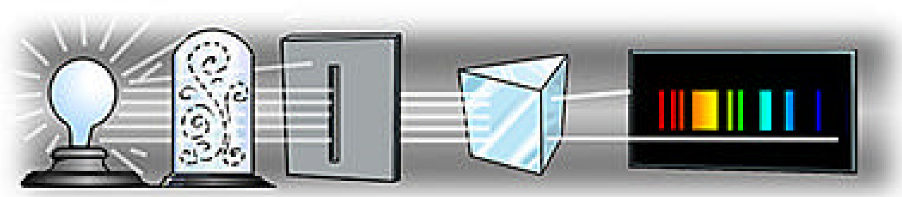

Figure 24. Absorption and Scattering of Light by Gases (From: [Colorado 2003])

a. Absorption

The above experiment illustrates the absorption and scattering of visible light. This phenomenon applies similarly to the invisible light waves in the infrared and ultraviolet bands. One main difference with infrared and ultraviolet light is that they are more readily absorbed by gases which can be found in our atmosphere. Figure 25 illustrates the absorptance of the various atmospheric gases with respect to the wavelength of EMR.

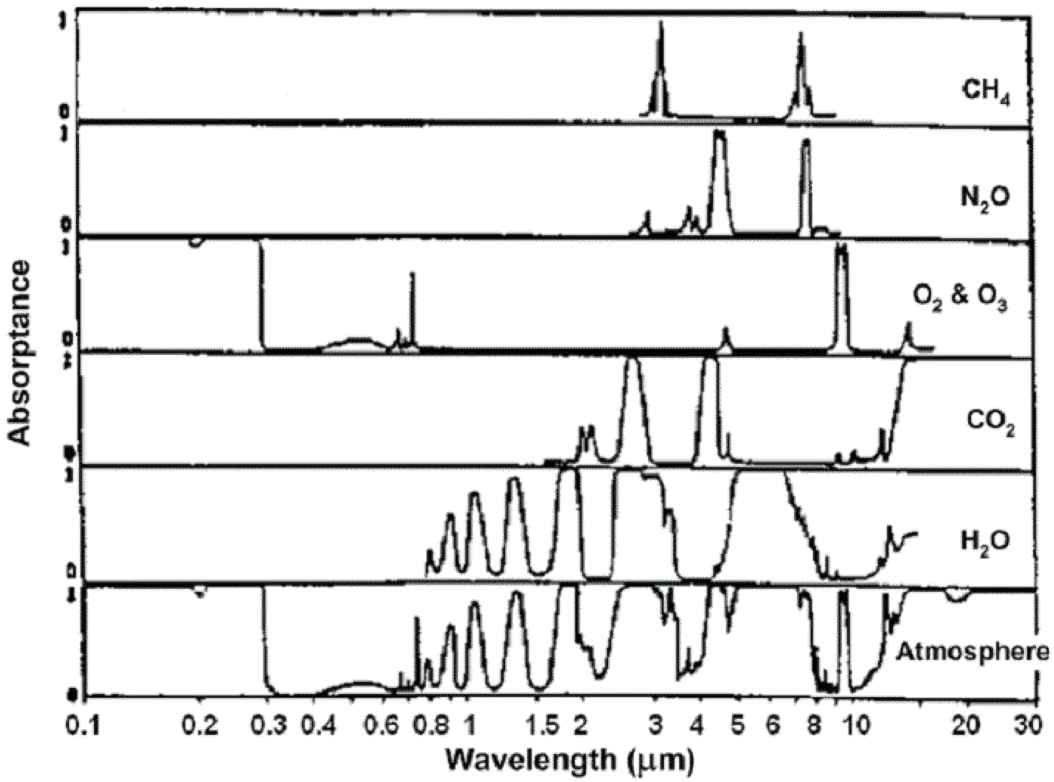

Figure 25. Absorptance of EMR by Atmospheric Gases (After: [Fleagle 1980])

There are a total of 6 graphs in Figure 25. The first 5 graphs show the absorptance of methane (CH_4), nitrous oxide (N_2O), oxygen and ozone (O2 & O_3), carbon dioxide (CO2), and water molecules (H_2O) respectively. The last graph shows the composite absorptance of all these gases and is basically the absorptance of the atmosphere.

The wavelengths of visible light are approximately from 0.4 to 0.7 microns (μm). As can be seen from Figure 25, visible light is only slightly absorbed by oxygen and ozone. The near infrared wavelengths (0.7 to 1.5 microns), which find popular use in FSO systems, have certain bands of wavelengths which are greatly absorbed by water molecules. The other infrared bands (above 1.5 microns) are affected by almost all the gases listed at various wavelengths at varying degrees. Ultraviolet light below 0.3 microns is greatly absorbed by oxygen and ozone.

Figure 26 zooms in on the visible and infrared EMR bands while showing the transmittance of the atmosphere instead of the absorptance. It is noted that the largest hindrance to transmittance is caused by water molecules. Absorption of visible and near-infrared radiation in the gaseous atmosphere is primarily due to H_2O, O_2, O_3, and CO2. Three dotted lines are marked in the figure to show the wavelengths used by many current FSO systems. These lines represent the wavelengths of 0.80, 0.85, and 1.55 microns. It is seen that these wavelengths have been chosen for high atmospheric transmittance.

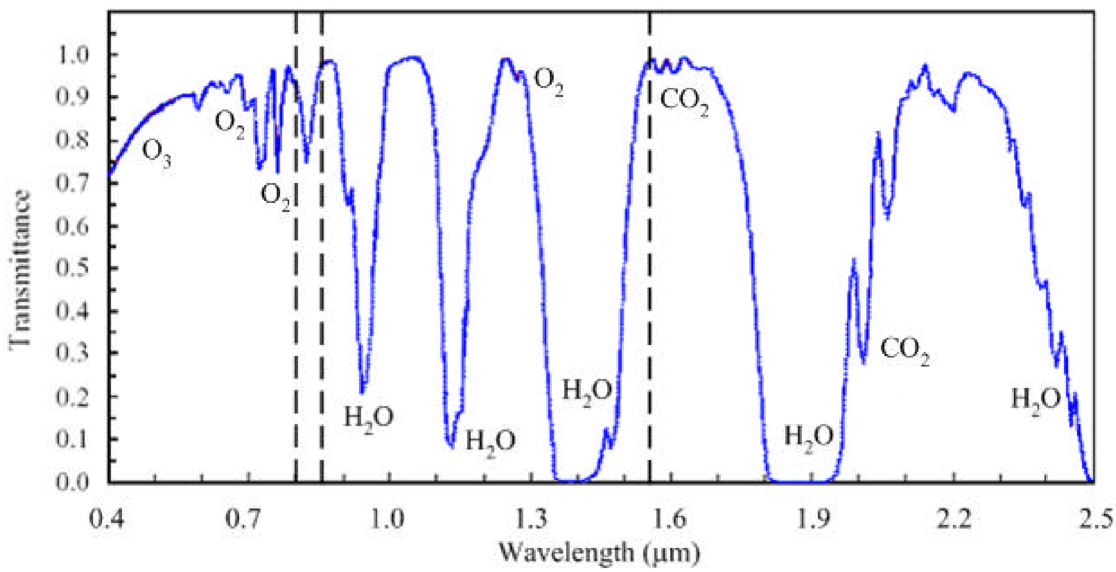

Figure 26. Visible and Infrared Atmospheric Transmittance (After: [Short 2002])

Figure 27 allows a comparison of the effect the absorptance of atmosphere has on visible and infrared EMR bands in comparison with today's microwave transmissions. While there are limited windows of higher transmittance within the infrared band, microwave frequencies are only minimally absorbed by the atmospheric gases. Attenuation of microwave frequencies in the 2 to 14 GHz frequency range is approximately 0.01 dB/mile, which is not significant.

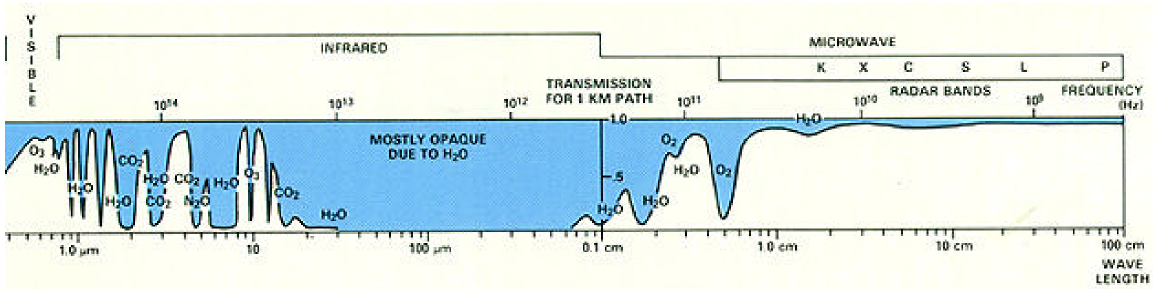

Figure 27. Visible, Infrared and Microwave Atmospheric Transmittance (From: [Short 2002])

b. Scattering

Other than absorbing light, the atmosphere scatters light as well. Scattering is caused by atmospheric molecules or particles which have dimensions of the same order or smaller than the wavelength of the incident light. For FSO, fog, haze and pollution (aerosols) are of concern because of the closeness in size of these particles to the wavelengths used in FSO systems. There are three forms of scattering: Raman, Rayleigh and Mie scattering.

Raman scattering is caused by atmospheric molecules or particles which are of sizes from 10% to 150% of the wavelength of the incident light. The photons of light interact with these particles in such a way that energy is either gained or lost. Since the energy of these photons determine the frequency of light, Raman scattering causes light emissions which are of different frequency from the incident light. The intensity of the scattered light due to Raman scattering is much lower than that from Rayleigh scattering. The American Institute of Physics [Weber 2000] approximates the magnitude of Raman scattering to be 10^6 to 10^8 times lower than that of Rayleigh scattering. Raman scattering is usually negligible unless a powerful laser source is used.

Rayleigh scattering is caused by atmospheric molecules or particles which are of magnitude less than 10% the wavelength of the incident light. The energy of the incident photons of light are unchanged by these particles and therefore the emitted light is of the same frequency as the incident light. The intensity of Rayleigh scattering is known to be:

$$I_S = \frac{8\pi^4\alpha^2}{\lambda^4 r^2}(1+\cos^2\theta)I_0$$

where I_S = intensity of scattering

I_0 = incident intensity

α = polarizability of particle

λ = wavelength of incident radiation

r = distance, center of scattering to detector

θ = angle incident /scattered ray

What is interesting about the Rayleigh scattering formula is that the intensity of Rayleigh scattering is inversely proportional to the fourth power of the wavelength of the incident light. This implies that light of shorter wavelength (higher frequency) experience substantially higher Rayleigh scattering than light of longer wavelengths (lower frequency).

Rayleigh scattering explains the colors of the sky. Firstly, the atmosphere certainly scatters the light from the sun. If it did not, then the sky would always look dark unless you are looking directly at the sun. Blue light, which is of shorter wavelength, is more readily dispersed than red light. Therefore, the sky looks blue during the day. During sunrise and sunset, the light from the sun has to travel a much further distance. Light of shorter wavelength would already have been scattered before it reaches an observer. Therefore, what the observer sees during sunrise and sunset are the longer wavelengths of red, orange, and/or yellow.

Rayleigh scattering depends on the size of the scattering particles (magnitude needs to be less than 10% of wavelength). Therefore, using the Rayleigh formula to compare the scattering intensities for microwave and FSO is difficult because of the big difference in wavelengths. However, comparing the scattering intensities of different wavelengths within the FSO band is possible since the difference in magnitude of the wavelengths within this band is not large. Knowing that the wavelengths of FSO systems in the near-infrared band range from 0.7 to 1.5 microns, the maximum difference in Rayleigh scattering intensity within the near-infrared band would be:

$$\frac{I_{0.7mm}}{I_{1.5mm}} = \left(\frac{1.5mm}{0.7mm}\right)^4 = 21.08$$

This means that even if two different frequencies within the near-infrared band were carefully chosen so that they have equally low absorption by the atmosphere, the range of the higher-frequency system could be up to 20 times shorter than the lower-frequency system due to Rayleigh scattering.

Mie scattering is similar to Rayleigh scattering in that the scattered light is of the same frequency as the incident light. However, the distribution of the scattered light is different for Mie scattering because of a larger scattering particle size (roughly of the same order of magnitude as the wavelength of the incident light).

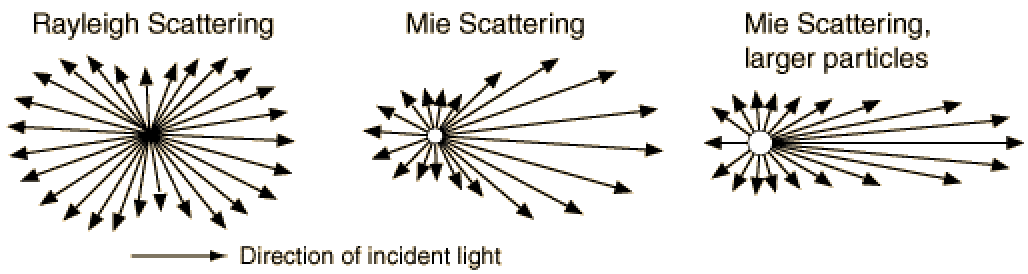

Figure 28. Comparison Between Rayleigh and Mie Scattering (From: [Meyer 1994])

Figure 28 illustrates the differences between Rayleigh and Mie scattering for an incident light which hits a particle from left to right. For Rayleigh scattering, the intensity of the scattered light is largely uniform, except for the scatter at right angles to the incident light, which is half the intensity of the forward scatter intensity.

In Mie scattering, the intensity of the scattered light is greatest in the direction of the incident light. This difference increases with the size of the scattering particle. Therefore, the loss of source light intensity due to scattering actually decreases with an increase in the scattering particle size.

Therefore, FSO transmissions in the near-infrared band are scattered substantially by fog and clouds which have water droplets that are approximately of the same order of magnitude as its wavelength. However, FSO is less affected by rain, because the size of rain drops are much larger. Recall that it was explained through Figure 27 that microwave frequencies are less affected by the absorption of atmospheric gases. However, the wavelength of microwave transmissions are of the same order of magnitude as rain drops. Therefore, microwave transmissions, especially those of frequencies above 11 GHz, are greatly scattered by rain.

c. Dispersion

Dispersion is the process by which an electromagnetic signal propagating in a physical medium is degraded because the various wave components (i.e. frequencies) of the signal have different propagation velocities within the physical medium. As explained earlier in this report, practical lasers do not just emit one frequency, but a small range of frequencies. Dispersion therefore causes a laser signal to spread across time.

Dispersion can also occur in an ideal laser transmission (i.e. a laser which only emits one single frequency). If such an ideal laser beam passes through a uniform medium, the entire beam is slowed but the pattern of phases still moves together. In a non-uniform medium of different densities and temperatures, however, some parts of the beam are slowed more than others, leading to distortions in the uniform wavefront (i.e. dispersion).

Figure 29 illustrates dispersion effects on a rectangular source pulse. The received signal would have a lower peak power than the source because of the spreading. The attenuated signal needs to be higher than some arbitrarily set threshold so that a "1" signal can be differentiated from a "0".

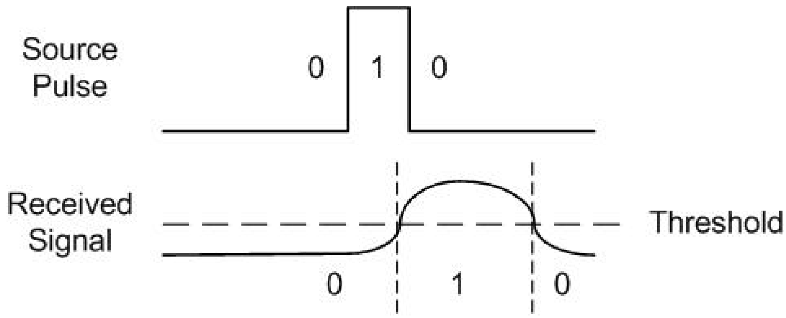

Figure 29. Dispersion of Rectangular Pulse

The received signal is also spread across time. This poses a limitation on the data rate that can be transmitted. This is illustrated in Figure 30, where the source is trying to send a pulse train to the receiver.

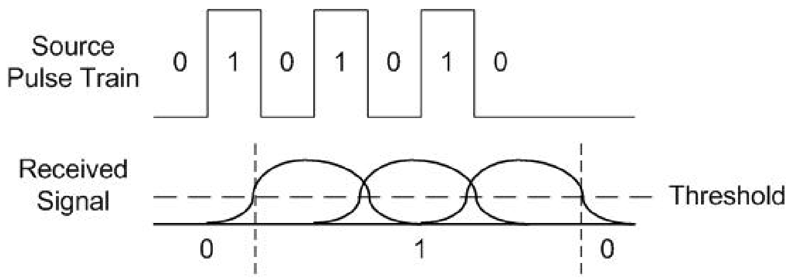

Figure 30. Dispersion of a Pulse Train

Because of the overlap in the received signal, the receiver will not be able to separate the pulses and the pulse train would be incorrectly interpreted by the receiver as a long period of a high ("1") signal.

2. Combating Atmospheric Effects

a. Adaptive Optics

The problem of dispersion is also encountered by astronomers who need to study the faint and blur images from the distant galaxies. Figure 31 shows such an image being enhanced by using Adaptive Optics (AO).

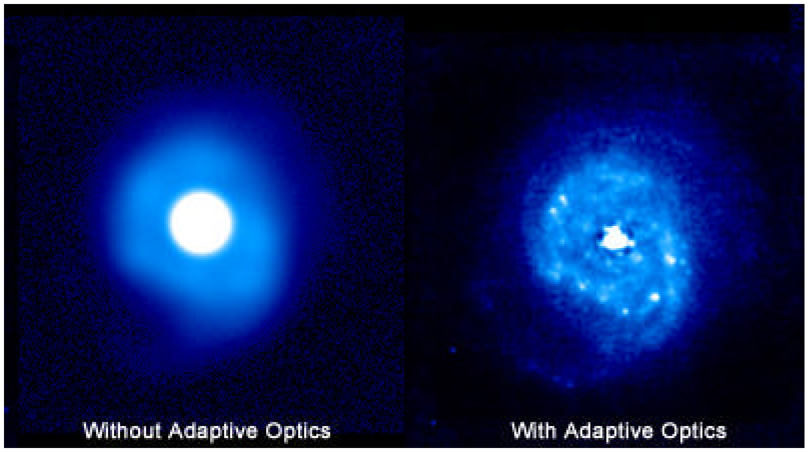

Figure 31. Nuclear Region of Galaxy NGC 7469 with and without Adaptive Optics (From: [CfAO 2003])

All AO systems work by determining the shape of the distorted wavefront, and use an "adaptive" optical element (usually a deformable mirror) to restore the uniform wavefront by applying an opposite canceling distortion. Current AO systems are able to update the shape of the deformable mirror several hundred times a second.

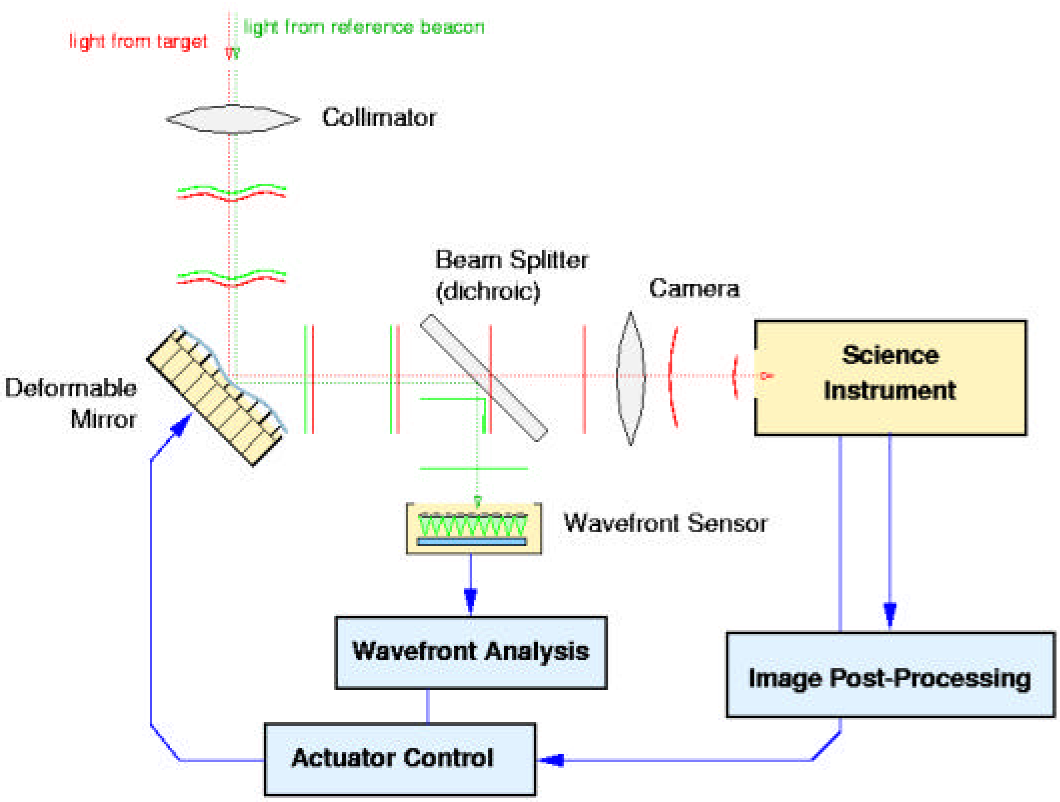

Figure 32. Adaptive Optics System used for Astronomy (From: [CfAO 2003])

Astronomers make use of a known light source (labeled as a reference beacon in Figure 32) like an adjacent star to determine how much the light from the target has been deformed. With this, the system will be able to know how to deform the mirror such that the expected signal from the reference beacon can be received.

However, in our application of using a laser source for communication, the light source from the transmitter is well understood. Therefore, there is no need for this reference beacon. The received laser signal can be duplicated to the wavefront sensor so that the required changes can be made to the deformable mirror.

Using adaptive optics, a received laser signal can be reconstructed, resulting in better range and allowing higher data rates for the FSO system. In early 2002, the Lawrence Livermore National Laboratory (LLNL) used adaptive optics to achieve a 2.5 Gbps laser link over a distance of 28 km. The tests represent one of the longest terrestrial high-capacity FSO links ever achieved to date.

b. Wavelength Variation Techniques

As seen earlier in this section, different atmospheric conditions affect different FSO wavelengths to different extents. The following sub-sections explore how this knowledge can be leveraged on to provide resistance against atmospheric attenuation.

(1) Tunable Lasers. While most lasers will only operate on discrete wavelengths, some types can be tuned over a range of wavelengths, giving an additional agility against atmospheric attenuation. Examples of tunable lasers include the titanium sapphire (Ti:S) laser, the chromium:LiSAF laser (where the host material is a crystal of $LiSrAlF_6$), and the chromium:LiCAF lasers (where the host material is a crystal of $LiCaAlF_6$). Table 2 shows the tuning range of these three lasers.

Laser Type	**Lasing Ion**	**Wavelength Range (microns)**
Titanium Sapphire	Ti^{3+}	0.66 to 1.18
Chromium LiSAF	Cr^{3+}	0.78 to 0.92
Chromium LiCAF	Cr^{3+}	0.72 to 0.84

Table 2 Typical Tunable Lasers [Rogers 1997]

Tunable lasers are seen as useful to adapt to the weather. Although the effect that water molecules have on particular wavelengths of EMR is quite well understood, water in the liquid state may affect the different wavelengths of EMR to different extents. This is because the size of the water droplets in the atmosphere (fog, clouds, and rain) may range anywhere from 1 μm to more than 5 mm. Tunable lasers allows the transmitter to use a frequency which is less hindered by the water droplets in the atmosphere.

(2) Nonlinear Optical Materials. Nonlinear optical (NLO) materials respond nonlinearly to light passing through them and can generate new wavelengths of light. NLO materials are the subject of contemporary research. The most common is the frequency doubling crystals that cut the wavelength in half, so that the infrared emission of a Nd:YAG laser (at 1064 nm) can be converted into a visible beam (at 532 nm). Frequency doubling can be fairly efficient, with reported values of 50 to 80 percent conversion from the fundamental wavelength to the doubled wavelength. Other nonlinear systems, like optical parametric oscillators (OPO), can generate a tunable output. While the technical details of such systems are beyond the scope of this study, they highlight the possibility of wavelength variability or the ability to tune the output wavelength of the laser. However, at this time, only a limited number of NLO materials are available. The efficiency at which they operate tends to be low. Also, obtaining efficient nonlinear effects requires high peak powers from the laser beam, which can damage the NLO material. Research in material science is likely to push back these limits.

Another NLO effect that can be used for wavelength shifting is Stimulated Raman Scattering (SRS). Raman scattering occurs when a beam of light passes through a material and excites a very weak transition within the material, leaving some of its energy. The emitted light is shifted to a longer wavelength. If the process is stimulated in a method analogous to the operation of a laser, a significant amount of the light can be shifted to the new wavelength. SRS is a complicated process beyond the scope of this study but offers great potential for laser systems.

(3) Multiline Emission Lasers. Some types of lasers operate on several different wavelengths simultaneously, such as the argon ion laser that emits most of its light at 488 nm and 514.5 nm. Multiline emissions are effectively redundant links which may provide some resiliency to atmospheric attenuation. This is more likely to succeed in such lasers where the emissions have wavelengths which are considerably separated. One disadvantage of multiline emission lasers is that it generally does not have the flexibility of selecting the frequency to transmit once the laser has been chosen.

(4) Redundant Frequency Links. A no-frills method of providing varied wavelength transmissions is the use of redundant frequency links. The redundant link may be another laser transmitter operating at a different frequency. This is not unlike the multiline emission lasers described earlier. However, redundant links do not require the use of special lasers which emit multiple frequencies. The frequency of the redundant links should be chosen so that both links can provide maximum resiliency against atmospheric effects. This would usually require that the links use substantially different frequencies.

An alternative redundancy option is to use a non-FSO link as standby to an FSO link. Microwave links are a suitable candidate for such a standby link as it is largely immune to fog, FSO's biggest adversary. FSO, on the other hand, is more resilient to rain, which poses a big problem for microwave. Furthermore, fog and rain do not occur at the same time. Therefore, FSO and microwave are good complements for one another. A disadvantage of using a microwave link as standby is that it operates at a lower frequency and would usually provide a lower data rate. Therefore, falling back on a microwave backup link could mean a drop in data throughput.

Airfiber [Bloom 2003] has a product called the Hybrid FSO/Radio (HFR) which combines the use of a 785 nm FSO link with a 60 GHz (5 mm wavelength) microwave transmission. Airfiber claims that its HFR product is able to provide 99.999% carrier grade wireless service.

Figure 33. Airfiber's Hybrid FSO/Radio with a 13-inch Parabolic Dish for Microwave Transmission (From: [Bloom 2003])

c. Spatially Diverse Redundant Links

A redundant link which has been separated in space from the primary link is not seen as an effective solution against atmospheric conditions. This is because weather conditions which cover either the transmitter or the receiver will hinder all links going in or out of these transceivers. However, there are still scenarios where spatially-diverse links can effectively provide alternate routes for communication.

Figure 34 shows an Unmanned Aerial Vehicle (UAV) trying to send data to its mother ship via an FSO link. However, the mother ship is engulfed in fog, so not only is its direct link blocked by the fog, a redundant link via a satellite would also not be able to be transmitted to the mother ship.

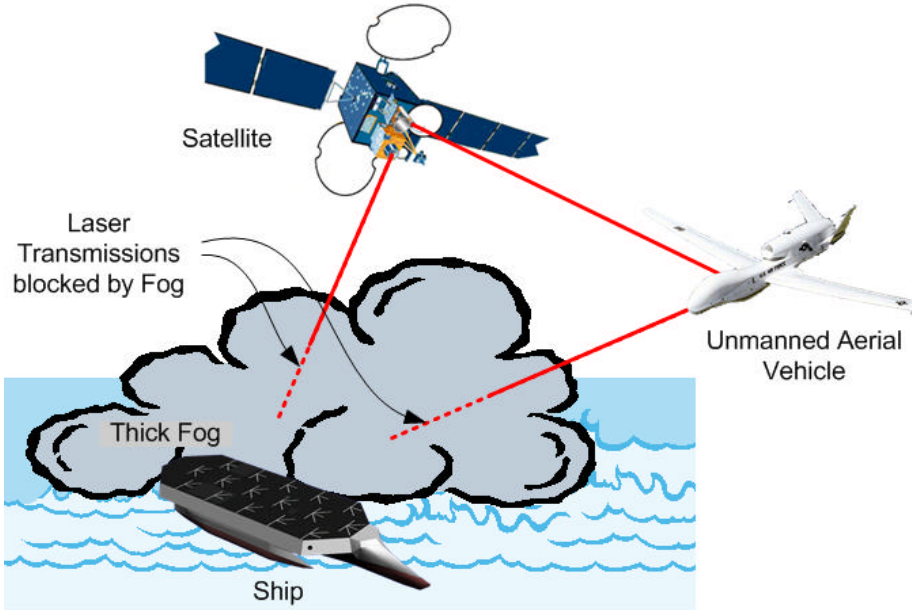

Figure 34. Ineffective Spatially Diverse FSO Links

If the atmospheric condition only blocks one of the redundant links, then the alternate link may be used to transmit data. Figure 35 shows a reconnaissance plane which is flying above some thick clouds that block its direct laser path to the mother ship. However, it is able to use a satellite to transmit its data since the path between the satellite and the mother ship is not blocked.

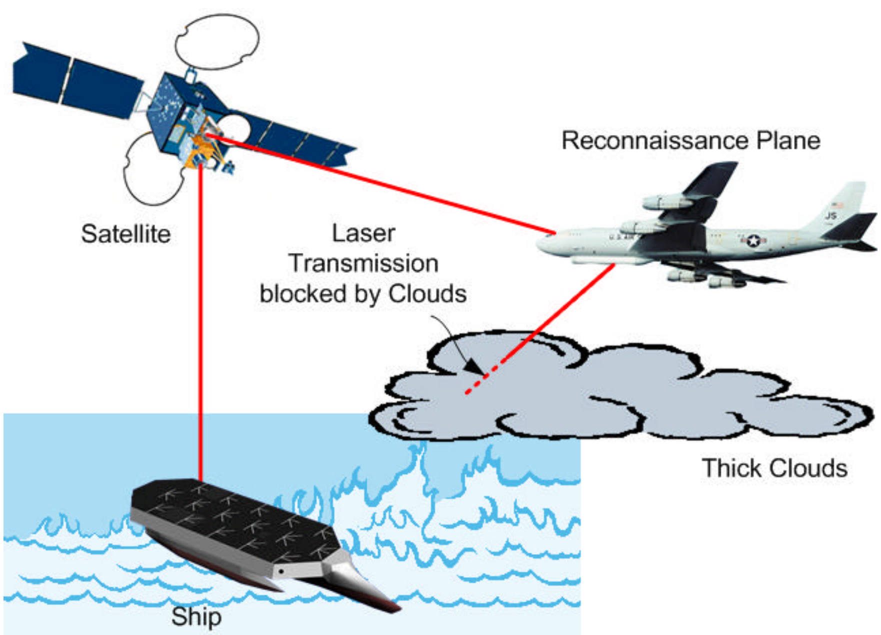

Figure 35. Effective Spatially Diverse FSO Links

d. Increasing Laser Power

An obvious solution to atmospheric attenuation is to increase the transmit power. This raises issues on the safety of these lasers, which will be discussed in a later section.

Products from Airfiber [Airfiber 2003] and LightPointe [LightPointe 2003] automatically adjust their laser power depending on the strength of the signal at the receiver's end.

3. Achievable Range and Bandwidth

Atmospheric absorption and scattering causes a laser to lose its power. Therefore, the receiver must be close enough to the transmitter so that sufficient power from the transmitter is able to reach the receiver. LightPointe's 2.5 Gbps FSO systems are limited to 1 km, the 155 Mbps systems are limited to 2 km, while the products with data rates of 52 Mbps and less can go up to 4 km [LightPointe 2003].

The Lawrence Livermore National Laboratory (LLNL), had in early 2002, demonstrated a 28 km FSO link between the Laboratory (in Livermore, CA) and Mount Diablo under the Secure Air-Optic Transport and Routing Network (SATRN) program. The tests represent one of the longest terrestrial high-capacity FSO links ever achieved. Data was transmitted at 2.5 Gbps with the aid of adaptive optics. The wavelength and power used was not reported, although it was said to be optical, and that "The laser beams used for communication are not visible or harmful in any way." Bit error rates were also quoted as "quite reasonable for an unoptimized system." Researches also claim to have gained experience with operation in freezing temperatures, winds up to 40 mph, low-visibility conditions and light fog [Johnston 2002].

If there were little or no atmosphere, then the range would largely only be limited by free space loss (the loss of power because not all of the sender's beam reaches the receiver). The European Space Agency (ESA) had in November 2001 established the first laser communications data link between satellites. The Artemis (Advanced Relay Technology Mission) satellite was in a parking orbit at 31,000 km, while the SPOT 4 satellite was orbiting at an altitude of 832 km. Links were established 4 times, lasting 4 to

20 minutes, where data was transferred at a rate of 50 Mbps. This was using the SILEX (Semiconductor laser Inter-satellite Link Experiment) system.

The average distance between the satellites during communication was 38,500 km. This huge distance of transmission is possible as there is practically no atmosphere in space, and therefore no atmospheric absorption or scattering. The bit error rate for this space link was reported to be consistently in the range of 10^{-9} to 10^{-10}. Beam divergence was approximately 2 arcseconds (0.000556 degrees), and the wavelength used was around 0.8 μm [Oppenhäuser 2001].

B. DIRECTIONAL PRECISION

As discussed in Chapter III, lasers have a very small beam divergence. While this provides greater security against eavesdroppers, it also means that it is much more difficult to point the laser beam at a receiver.

Figure 36 illustrates the beam pattern at the receiver end for a transmitter with a pointing resolution equal to the beam divergence of θ. A pointing resolution of θ implies that the beam can only be shifted by an angle of θ in either the x or y direction.

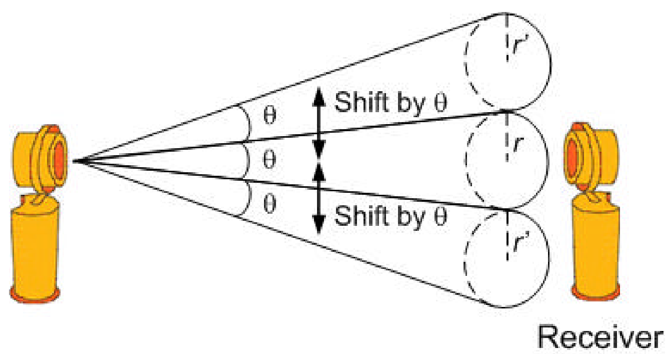

Figure 36. Beam Pattern at Receiver with Pointing Resolution of θ

While this may seem to provide continual coverage of the receiver's space, in practice, gaps will form in a pattern of beams if the pointing resolution of the transmitter were only θ. These gaps mean that the transmitter will not be able to effectively point its laser beam should the transmitter be located in one of these gaps. This is illustrated in Figure 37.

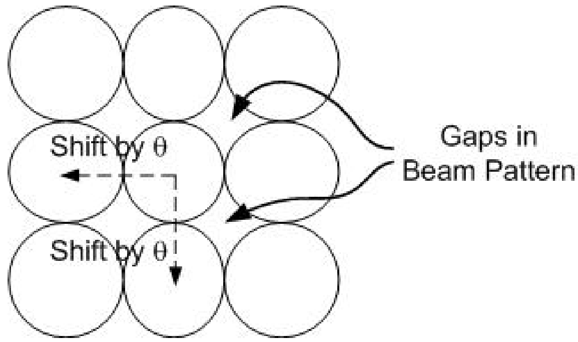

Figure 37. Gaps in Beam Pattern with Pointing Resolution of θ

It should be found that the pointing resolution of a laser transmitter should be at most half the beam divergence. This is so that the gaps as described earlier can be "filled-in."

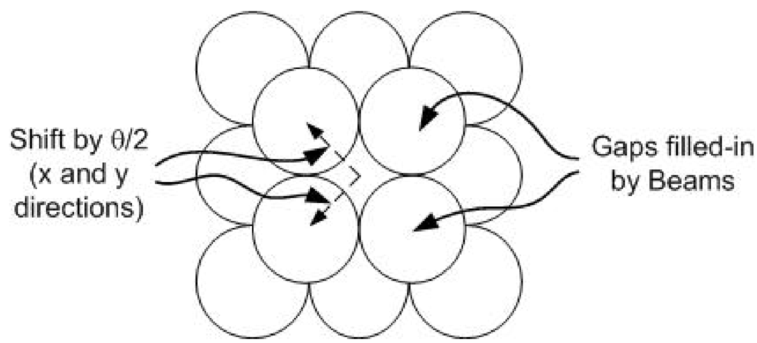

Figure 38. Gaps Filled-in by Beams with Pointing Resolution of θ/2

By the above analysis, the FSO systems which are available today, which have a typical beam divergence of 0.5 milliradian, will require a pointing resolution of at most 0.25 milliradian (~0.014 degree). The SILEX laser system by the ESA, which are mounted on two satellites, has a beam divergence of 2 arcseconds (1 arcsecond is $\frac{1}{3600}$ degree) [Oppenhäuser 2001]. Therefore, the pointing resolution required of the laser transmitter would be at most 1 arcsecond (~0.00028 degree).

Therefore, while a beam of small divergence allows greater security and more efficient placement of energy (as discussed earlier), this has to be matched by a system which allows the laser beam to be intricately focused onto the receiver.

Of course, if the security and received energy are not crucial in a particular FSO system, then the beam divergence can be allowed to be bigger (possibly through adjustments in the collimators). This will allow a less stringent pointing resolution requirement. Further analysis of the pointing requirement will be discussed in the section on Acquisition, Pointing and Tracking (APT) systems.

C. LINE-OF-SIGHT OBSTRUCTIONS

Like all line-of-sight links (e.g. microwave radio), FSO links may be obstructed by objects such as buildings, trees and planes. However, because of the small beam and high data rates typical of FSO links, FSO links may also be affected by smaller objects like birds.

Error correction is seen as the most effective solution against temporal obstructions like flying birds. However, spatially diverse links should be employed when obstructions are expected to occur for extended periods of time.

Figure 39 shows an Unmanned Aerial Vehicle (UAV) whose direct link to its mother ship is blocked by some trees. However, it is still able to send data to its mother ship via satellite.

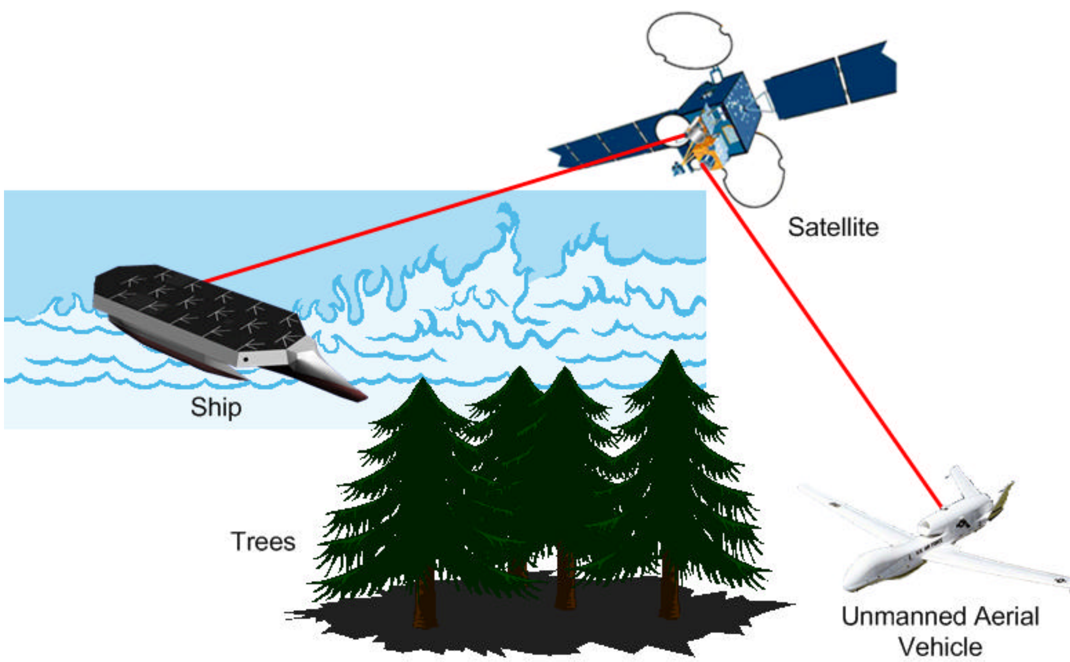

Figure 39. Spatial Diversity to Overcome Line-of-Sight Obstructions

D. LASER SAFETY

Laser beams contain energy in the form of electromagnetic radiation that travels at the speed of light and has no mass. Continuous Wave (CW) output is usually characterized by the power in the beam measured in Watts, while pulsed output is characterized by the energy in each pulse, in Joules. Repetitive pulsed systems are also characterized by their average power.

All of the laser power is concentrated in a small solid angle due to the narrow beam. This means that even small lasers, like the helium neon (He-Ne) lasers frequently used as pointers, have output beams that are brighter than the sun. Here the term *brightness* is rigorously used to mean the amount of power being emitted per unit area of the source per solid angle.

1. Human Exposure to Lasers

Human exposure to lasers pose a greater danger to the eyes than any other part of the body. A basic knowledge of the parts of the eye is required to understand laser safety.

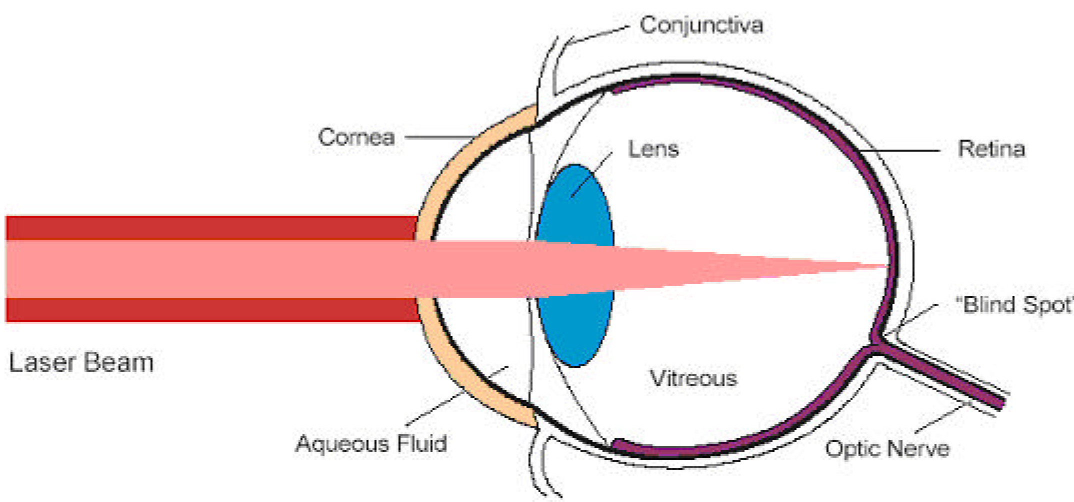

Figure 40. Parts of the Eye

Figure 41 shows a laser beam entering the human eye. The laser first contacts the cornea, followed by the aqueous fluid, the lens, the vitreous humor, and finally the retina, which allows the eye to see the light. What injury occurs to the eye depends on the wavelength of the laser.

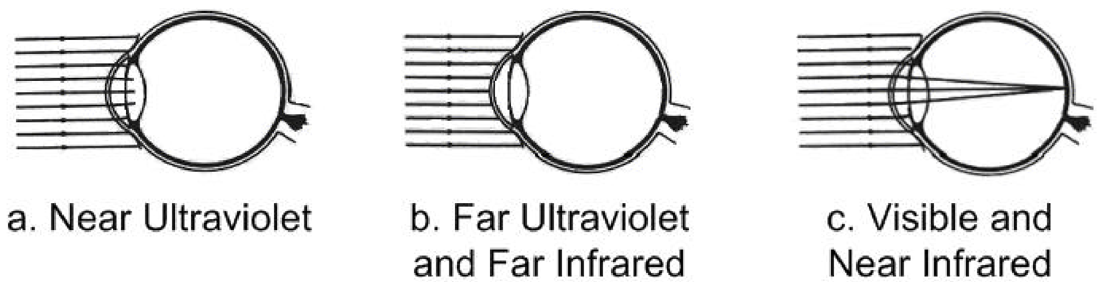

Figure 41. Penetration of the Eye by Lasers

a. Near Ultraviolet (0.3 – 0.4 μm)

The cornea, aqueous humor, and lens absorb ultraviolet radiation of these wavelengths and the principal absorber is the lens. Photochemical processes denature proteins in the lens resulting in the formation of cataracts. Cataracts are basically the clouding of the lens. As this clouding is opaque, this hinders the vision of the eye. Cataracts can be treated by removing the old lens material and replacing it with a flexible plastic lens.

b. Far Ultraviolet (0.1 – 0.3 μm) & Far Infrared (1.4 – 100.0 μm)

The surface of the cornea absorbs these wavelengths producing photokeratitis (keratitis refers to an inflammation of the cornea). Photokeratitis is a temporary condition because the corneal tissues regenerate very quickly. However, deep cornea burns are permanent, although corneal transplants are possible. Far infrared wavelengths may penetrate deeper and lead to the development of cataracts resulting from the heating of proteins in the lens.

c. *Visible Light & Near Infrared (0.4 – 1.4 mm)*

The cornea, aqueous humor, lens, and vitreous humor are called the ocular media. The ocular media are transparent to electromagnetic radiation of these wavelengths.

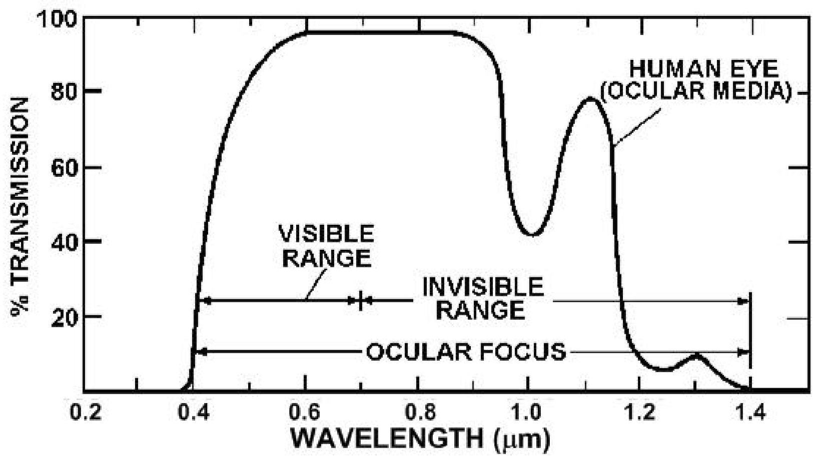

Figure 42. Wavelength Transmission of the Ocular Media

As can be seen from Figure 42, the ocular media is transparent not only to visible light, but also to a large part of the near infrared band (shown as the invisible range in the figure). Furthermore, the focusing effects of the cornea and lens will increase the irradiance of these wavelengths on the retina by up to 100,000 times. It should be noted that this focusing also applies to the near infrared wavelengths even though humans are not capable of seeing these wavelengths.

For visible light (0.4 – 0.7 μm), the aversion reflex of the eye causes a person to turn away from a bright light source. This takes 0.25 seconds, and therefore reduces exposure to these wavelengths. This reflex will not provide protection if the intensity of the laser is great enough to produce damage in less than 0.25 seconds or when light in the near infrared band is used, as the eye is insensitive to these wavelengths.

Many products have been labeled as "eye-safe" as long as they do not use lasers which belong to the visible or near-infrared wavelengths. Indeed, the other wavelengths are unlikely to cause retina burns. However, as seen from the previous sections, much damage may be caused to the eye even though these products have been misleadingly labeled as "eye-safe."

2. Laser Standards Organizations

Organization	Jurisdiction	What they classify
CDRH Center for Devices & Radiological Health	United States; Part of the FDA	Product safety (labeling, installation, etc.)
ANSI American National Standards Institute	United States; Recognized by U.S. Department of Labor: Occupational Safety and Health Administration (OSHA)	User safety (maximum permissible exposure)
IEC International Electrotechnical Commission	Much of the world; Generally associated with the CE Mark (the abbreviation of French phrase "Conformité Européene" which means "European Conformity")	Product and user safety

Table 3 Laser Standards Organizations

Table 3 shows the standards organizations for lasers, their jurisdiction, and what they classify. CDRH and ANSI have jurisdictions in the U.S., while the IEC is an international standards organization.

3. Laser Safety Standards

Each of the standards organizations mentioned earlier have slightly different criteria for classifying laser products. However, all of them categorize lasers into 4 classes, with Class 4 being the most hazardous.

	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)** **< 0.5 sec (eye aversion)** **< 0.5 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

The parameters used to classify lasers are:

i. Laser output energy or power

ii. Radiation wavelengths

iii. Exposure duration

iv. Cross-sectional area of the laser beam at the point of interest

v. Accessible emission limit

The IEC has classifications which distinguish whether an optical aid was used in viewing the laser. An aid may be a telescope, binoculars, or fiber optics loupe. These aids magnify the irradiance of the incident laser onto the eye. The CDRH and ANSI categorize aided and unaided viewing conditions under the same category numbering.

Class 1 lasers are eye-safe for two reasons. Firstly, it may be because the energy output is so low that aided or unaided viewing cannot cause injury to the eye. However, a laser may also be classified under Class 1 even if it is not eye-safe. This applies to lasers which have safeguards in place to ensure that the lasers would not be exposed under normal operation. For example, laser printers use lasers of considerable power. However, human access to the laser radiation should not occur under normal use. As a result, most laser printers are categorized under Class 1. Also, it should be noted that it may not be safe to view a Class 1M laser with an optical aid. The Accessible Emission Limit (AEL) of Class 1 lasers, which is the maximum permitted level of accessible emitted radiation, is 0.4 mW.

Class 2 lasers are safe only if viewed for less than 0.5 seconds. This takes into consideration the eye aversion time, which is a reflex action which will cause a person to turn away from a bright light source within 0.25 seconds. As mentioned earlier, eye aversion only occurs when the light source is visible light. Therefore, Class 2 lasers are all visible light lasers. The AEL for Class 2 lasers is from 0.4 to 1.0 mW.

Class 3A denotes lasers that normally would not produce a hazard if only viewed for momentary periods. For Class 3A lasers using visible wavelengths, their power is up to 500 mW since human eyes are protected by eye aversion. In addition, there is a requirement that their irradiance, which is the incident power per unit area, does not exceed 25 W/m^2. For Class 3A lasers using invisible wavelengths, a much lower AEL limit of 2 mW is specified since eye aversion does not take place.

Class 3B denotes lasers that can produce a hazard if viewed directly. This includes intrabeam viewing or specular reflections. Viewing the diffuse reflections from Class 3B lasers should be limited to 10 seconds. The AEL limit for Class 3B lasers is different for continuous wave (500 mW) and pulsed sources (105 J/m^2).

Class 4 lasers can produce a hazard not only from direct or specular reflections, but also from a diffuse reflection. In addition, such lasers may produce fire and skin hazards. Class 4 lasers include all lasers in excess of Class 3 limitations. Also, a laser is classified as a Class 4 laser if the output power exceeds 0.5 watts. This is quite a contrast to a 100-watt light bulb that emits its energy in all directions. The is because of the high irradiance of these lasers.

It has been mentioned that products which are "eye-safe" belong outside the visible or near-infrared wavelengths. However, "eye-safe" lasers may also be classified up to Class 4, where they may easily cause damage to the eyes and even human skin. Class 4 "eye-safe" products are certainly not safe to the eye.

Class 3B and 4 lasers require controlled access. Filtering goggles and safety training is required to enter the area. Class 2, 2M and 3R lasers require restricted access. This is where access is permitted only to those that have completed laser safety training. Class 1 lasers are allowed in areas in which access is unrestricted.

Many FSO systems belong to Class 1 and 1M. However, Class 3R and 3B FSO systems are common for long-range, high data-rate links.

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V. ACQUISITION, POINTING, AND TRACKING

This chapter takes a look at the requirements specific to deploying an FSO system on mobile platforms. Like most line-of-sight mobile wireless communication systems, FSO systems first require the transmitter to know the location of the receiver. This is called the acquisition phase. The transmitter must then accurately send its signal towards the receiver (pointing phase). As the transmitter and/or receiver may be moving, the system must also be able to change the direction of the beams so that continued communication can be attained (tracking phase). This chapter takes a look at the challenge of acquisition, pointing, and tracking for FSO systems on mobile platforms.

A. ACQUISITION

For two terminals to communicate, they must know the position of the other terminal. The acquisition phase is where the terminals try to locate one another. The small divergences of the laser beams used in FSO systems require highly accurate knowledge of the other terminal's position.

It is also because of the small divergence of laser beams that using these beams to scan the wide expanse of possible locations is usually not feasible. Furthermore, most applications require a short acquisition time for on-demand communications.

To start with, some rough locale can be exchanged through systems like the Global Positioning System / Inertial Navigation System (GPS/INS). Since the FSO link has not been set up, this exchange is usually done via RF or microwave radio. The resolution of the coordinates provided by GPS systems is generally not accurate enough for directing laser beams. Good GPS systems have uncertainties of +/- 5 meters in longitude and latitude, and altitude readings are notoriously inaccurate because of the variances in the atmosphere. Newer Differential GPS (DGPS) systems are accurate to +/- 1 meter in longitude and latitude, and barometric and radar altimeters are usually much more accurate than GPS systems in providing altitude. Combining these readings in real-time to another fast-moving terminal would be challenging.

For platforms like non-stationary satellites which have somewhat fixed flying profiles, tracking software can provide a general indication of the position of such a platform.

To lock-in on the FSO transceiver of the opposite terminal, usually a *beacon beam* is used. This is a laser beam with a beam divergence much wider than that of its communication beam. In certain literatures, the beacon beam is also called the probe beam. Figure 43 illustrates how a beacon beam is used between the ESA's Artemis satellite and Japan's OICETS (Optical Inter-orbit Communications Engineering Test Satellite) satellite. Live tests for this procedure were successfully conducted from 9 to 14 September 2003 [JAXA 2003].

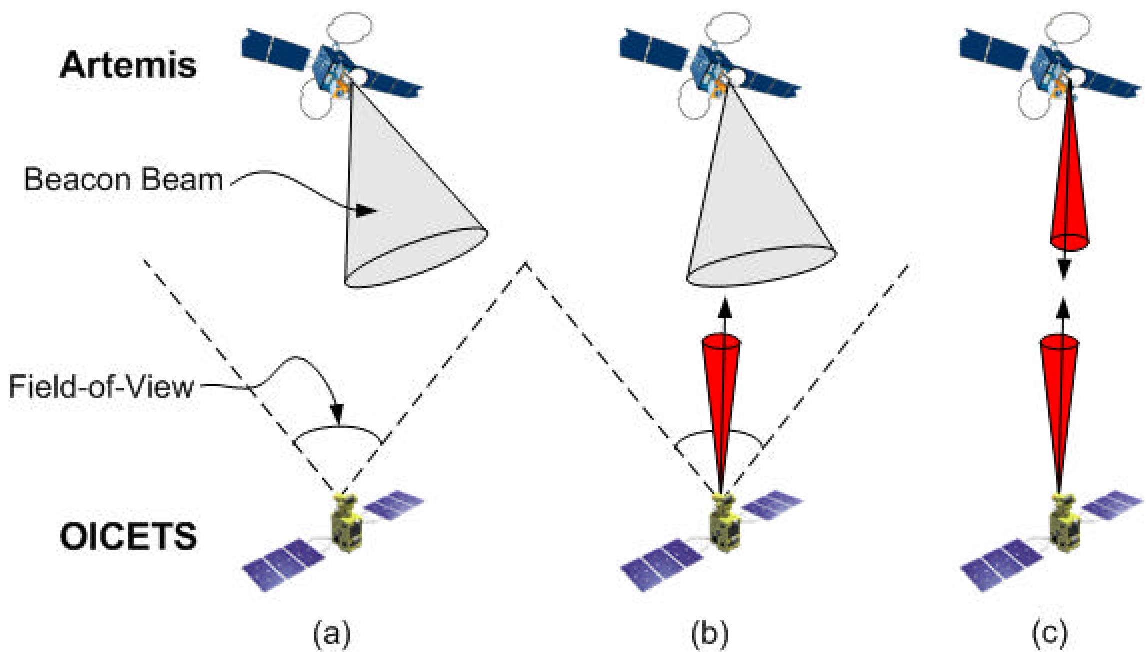

Figure 43. Using a Beacon Beam for Acquisition and Pointing [Arai 2001]

Artemis first scans the uncertainty area where OICETS may be located with its beacon beam. Initial acquisition efforts through the use of GPS or other means may have narrowed down the uncertainty area to about $1^{o} \times 1^{o}$. Meanwhile, OICETS ensures that its field-of-view covers the locations in which Artemis may be located (Figure 43a).

Upon detecting the beacon beam from Artemis, OICETS immediately transmits a communication beam to Artemis (Figure 43b). Once Artemis detects the communication beam from OICETS, Artemis stops scanning the beacon beam. It then transmits a communication beam to OICETS, and switches off its beacon beam. OICETS receives the communication beam from Artemis (Figure 43c). To initiate optical inter-orbit communications, each satellite continuously transmits the communication beam towards the other to enable the counter satellite to improve its pointing accuracy.

Another device that can aid in the acquisition of a communications link is a corner cube reflector, as shown in Figure 44. A corner cube reflector consists of 3 orthogonal mirrors. The property of the corner cube reflector that makes it useful in acquisition is that it reflects incident light in the same direction back to the source of the incident light. This reflection is called a retro-reflection.

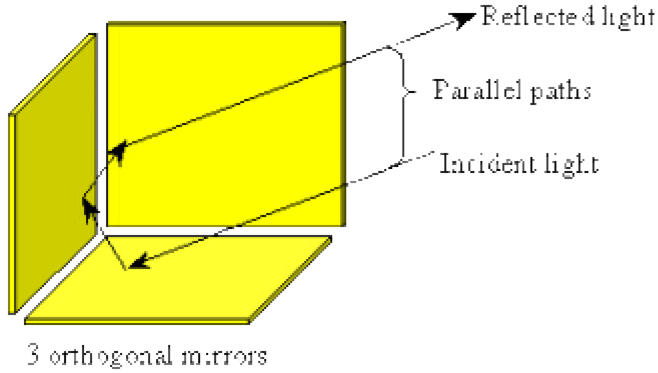

Figure 44. Corner Cube Reflector (After: [Sporian 2003])

The corner cube reflector can be used to reflect light from a beacon beam. The sender of the beacon beam would then detect the light from the corner cube reflector and know that it has found the receiver. The transmitter can then use a narrow beam to start the communication.

B. POINTING

After the acquisition phase, the transmitter would have accurate knowledge of the location of the receiver. The problem of pointing involves accurately placing the laser beam such that it is indeed pointing towards the receiver. The small divergence beam of lasers requires very fine adjustments in the pointing angle. The smallest degree in which the pointing angle can be adjusted is called the pointing resolution. Of course, this difficulty may be alleviated through the use of a more divergent beam, however, as discussed earlier in this report, this means a compromise in power efficiency and security of transmission.

The laser link between the ESA's Artemis satellite and the French SPOT 4 satellite will be used as an example of determining the required pointing resolution. The pointing resolution can be understood as the minimum shift in the pointing angle of the laser beam so that it will be able to continually track the target. Figure 45 illustrates that in order for Artemis to continually track a faster-moving SPOT 4 satellite, the angular resolution of the tracker will have to be at most θ, which is also equal to the beam divergence.

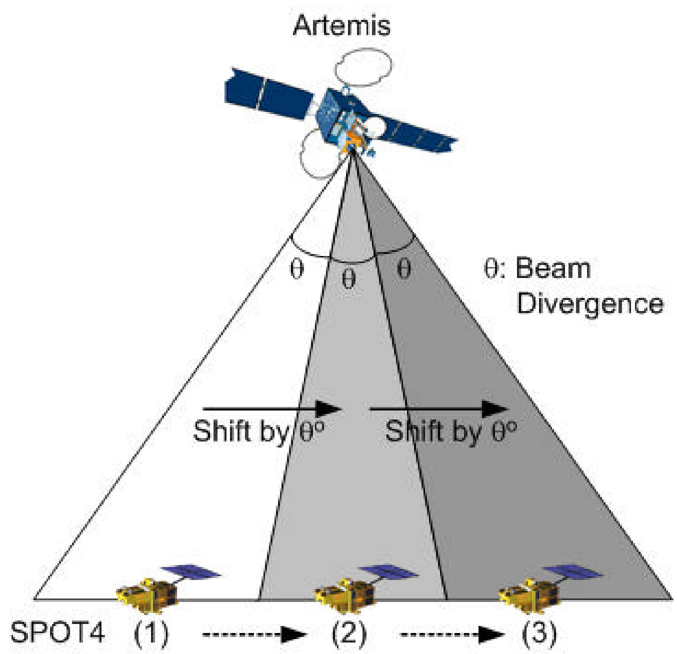

Figure 45. Pointing Resolution of Tracker

However, as analyzed in an earlier section on directional precision, a pointing resolution equal to the beam divergence will result in many gaps in the beam pattern seen at the receiver's location. These gaps mean that the transmitter will not be able to effectively point the laser beam at the receiver. It was also earlier pointed out that the maximum pointing resolution will have to be $\theta/2$ or less. The beam divergence from the Artemis satellite is known to be 2 arcseconds (0.000556 degrees). From the above analysis, the pointing resolution will have to be at most 1 arcsecond (~0.000278 degree).

Typical pointing resolutions range from 1 to 200 μrad (0.00002865 to 0.00573 degrees), although most systems typically have a pointing accuracy of 10 to 50 μrad (0.0002865 to 0.0014325 degrees) [Reyes 2002] [Wilson 2000] [Lee 2000] [Korevaar 1999].

FSO terminals on mobile platforms will usually be subject to the effect of wind. It is important to know the direction and velocity of the wind common to the deployment scenario. Laser terminals and their supporting structures must be able to prevent these forces from affecting the pointing accuracy or causing damage to the structures on which the components are mounted. FSO terminal designs react differently to wind forces, depending on the area presented to the wind. This is known as wind loading.

The Air Force Research Laboratory Sensors Directorate (AFRL/SN) mounted what they called their Laser Communications Terminal (LCT) in a turret on the underside of the fuselage of a T-39A (or Sabreliner 40) test aircraft (Figure 46). The turret protects the LCT from wind effects.

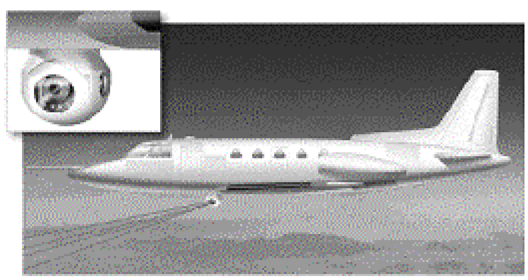

Figure 46. The AFRL/SN's T-39A Test Aircraft with Laser Communication Terminal (From: [Gill 1997])

At least part of the turret needs to be transparent to allow the laser's signal to propagate through. However, these glass windows tend to reflect light, causing a loss in the laser power transmitted or received. The amount of light reflected is higher for higher-index glass. However, the refractive index of glass is usually at least 1.4, which gives a maximum reflectance of about 4% at normal incidence.

Antireflection (AR) coatings are usually applied to the turret window to minimize reflectance. These are usually thin, dielectric or metallic films that can reduce reflections down to a fraction of a percent, depending on the type of coating used.

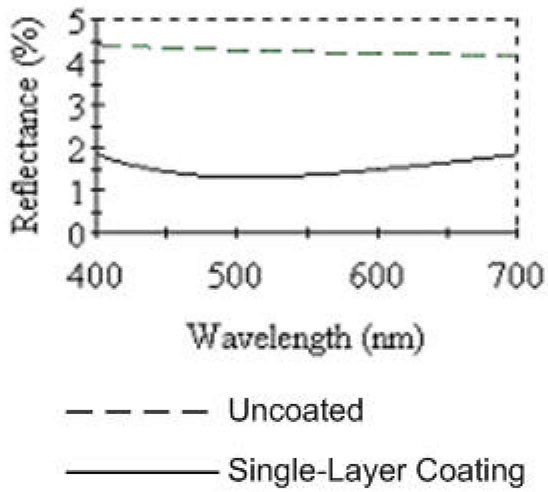

Figure 47. Reflectance of BK7 Glass with Single-Layer Coating at Normal Incidence (After: [AOPL 2003])

Figure 47 shows the reduction in reflectance of BK7 glass when a single-layer coating of MgF_2 (made by Astro Optics Pvt. Ltd.) is applied. Reflectance values of above 4% are reduced to about 1.5%. The resultant reflectance behavior is a curve which can be tuned for minimal reflectance at other wavelengths from UV to IR [AOPL 2003]. Single-layer coatings are widely used because of the low cost.

Astro Optics also makes V-coatings specially designed for specific wavelengths, which is useful for laser optics. As can be seen from Figure 48, the V-shaped graph of reflectance gives very low reflectance (less than 0.3%) at the tuned frequency of 1064 nm, while other frequencies experience higher reflectance.

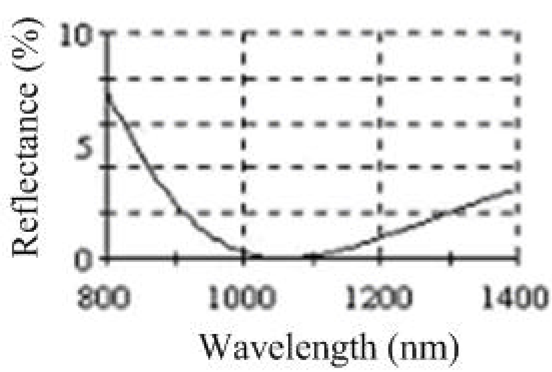

Figure 48. Reflectance of BK7 Glass with V-Coating at Normal Incidence (After: [AOPL 2003])

The higher reflectance at frequencies other than the tuned frequency is useful in attenuating unwanted signals. Many AR coatings are also designed not only to withstand high laser powers, but also meet military environment requirements for salt-fog and humidity.

C. TRACKING

For mobile platforms, the problem of tracking is to ensure that laser beams are continually pointed towards the receiver. One of the basic requirements of tracking is the frequency in which the direction of the laser beam needs to change in reaction to a change in relative location of the receiver. This is referred to as the tracking frequency.

Consider the example of the Artemis and SPOT 4 satellites. It is known that before Artemis reached its geo-stationary orbit, it was moving at 7,000 mph. SPOT 4, which was at an altitude of 832 km, would have been moving at approximately 16,600 mph. To determine the tracking frequency requirement, the worst case of relative speed would have to be taken. This would be where both satellites were moving in opposite directions of one another. In this case, it can be said that SPOT 4 was moving at a relative speed of 16,600 + 7,000 = 23,600 mph away from Artemis.

With this speed, it is necessary to determine the shortest duration of time that SPOT 4 would be within Artemis' laser beam. This is because the shortest duration will determine the minimum frequency that Artemis should be able to update its beam position so that it does not lose the SPOT 4 satellite. Figure 49 illustrates that this shortest duration occurs when the SPOT 4 satellite is directly below Artemis. SPOT 4 spends the shortest duration in an Artemis laser beam in this position because the distance it needs to traverse is the shortest. By simple geometry, this distance is found to be approximately 293 m.

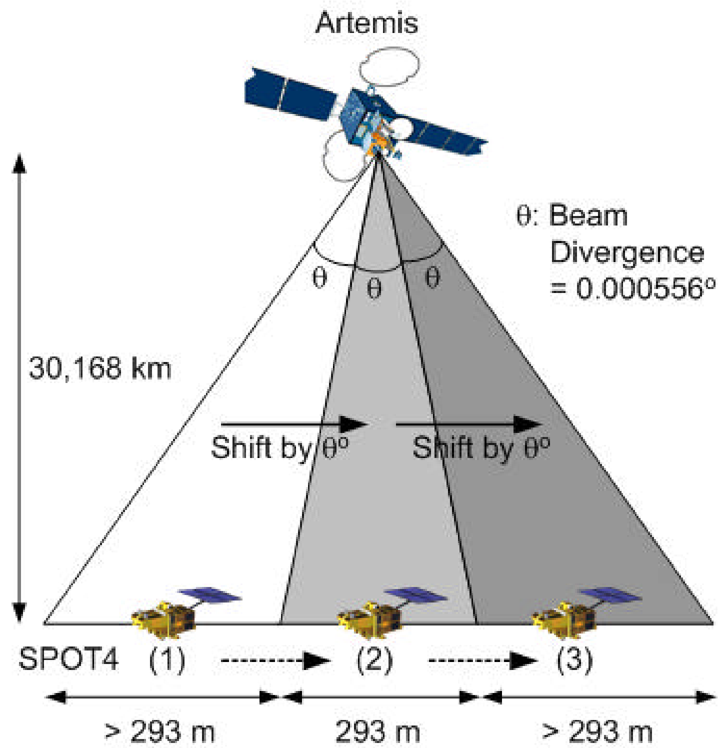

Figure 49. Tracking Frequency

With SPOT 4 moving at a relative speed of 23,600 mph, it would take less than 30 milliseconds (ms) for it to travel 300m. Therefore, in order for Artemis to be able to continually track SPOT 4, it should be able to change the direction of its laser beam once every 30 ms. In other words, the laser tracker should have a tracking frequency which is faster than 33 times per second or 33 Hertz. Once again, a more divergent laser beam would lower the tracking frequency requirement, but this would be at the cost of power efficiency and security of transmission.

It is noted that the example of ESA satellites is more elementary from a tracking point of view because the satellites are traveling in well-understood orbital paths. This means that the next location in which the laser beam should be pointed can be calculated beforehand by tracking software. There is less need for one satellite to sense the direction in which the other satellite is headed. This would be necessary in the case of other mobile platforms like planes and ships where the course of the receiving terminal is not known beforehand.

Conventional trackers have their lasers mounted on gimbals which are controlled by mechanical servos. A *gimbal* is basically a device that permits a body (in this case the laser) to incline freely in any direction. The OPALE and PASTEL optical terminals on board the Artemis and SPOT 4 satellites respectively were of this design.

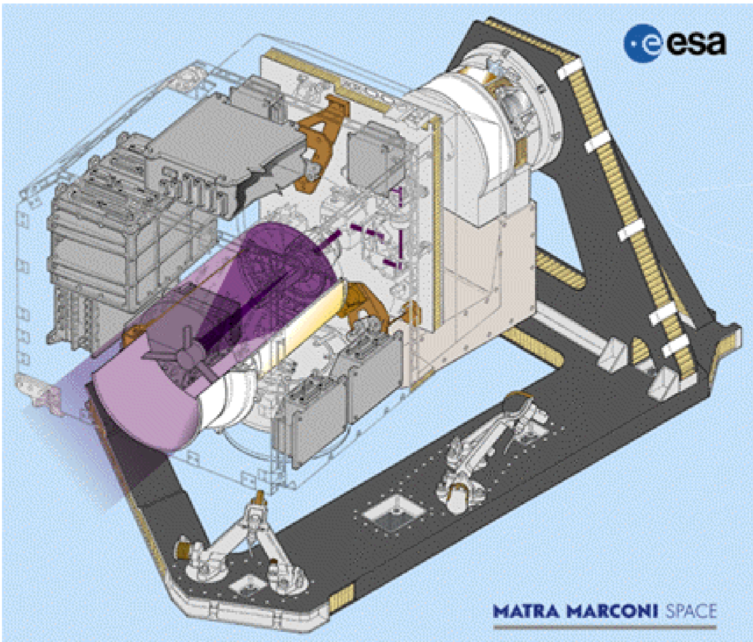

Figure 50. The PASTEL Optical Terminal on board the SPOT 4 Satellite (From: [CNES 2000])

Non-mechanical beam steering, which involves tracking with no moving parts, is being developed to permit high speed tracking of targets such as satellites and planes. Furthermore, non-mechanical beam steering does not cause jitter to the platform on which the laser terminal is mounted. Satellites are particularly prone to jitter caused by the moving of the relatively bigger optical terminals. Figure 51 shows the prototype of a non-mechanical pointing and tracking system built for the U.S. Air Force Research Lab (AFRL).

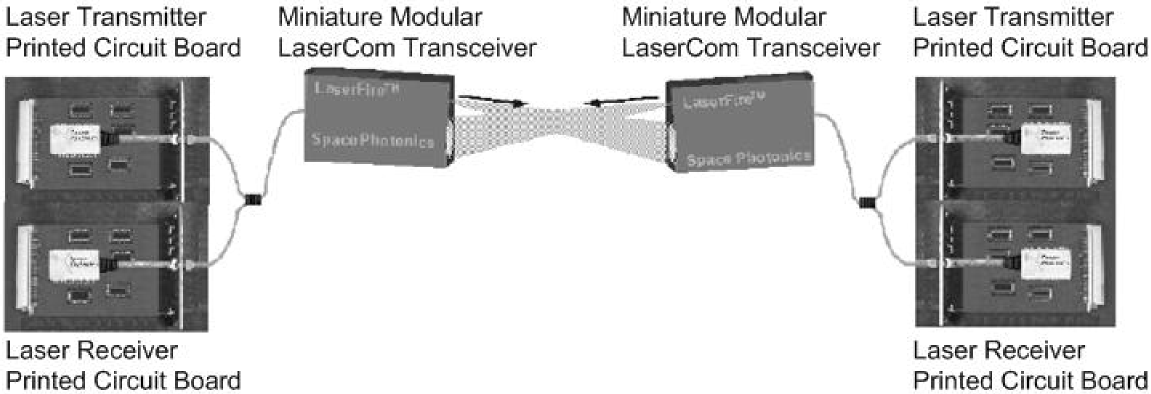

Figure 51. AFRL's Gimballess Pointing and Tracking Prototype (After: [Chalfant 2002])

D. MODULATING RETRO-REFLECTORS

As seen from the earlier sections of this chapter, the tasks of pointing and tracking are more challenging than that of acquisition because of the narrow communication beam. Modulating Retro-Reflectors (MRR) alleviate this problem by making use of corner cube reflectors.

Figure 52. Concept of a Modulating Retro-Reflector (After: [NRL 2001])

Figure 52 shows a modulator coupled in front of a corner cube reflector. When the modulator is off, light cannot pass, and there is no return beam. When the modulator is on, the beam will be allowed through. Data can be encoded into the retro-reflected beam by allowing data to drive the modulator.

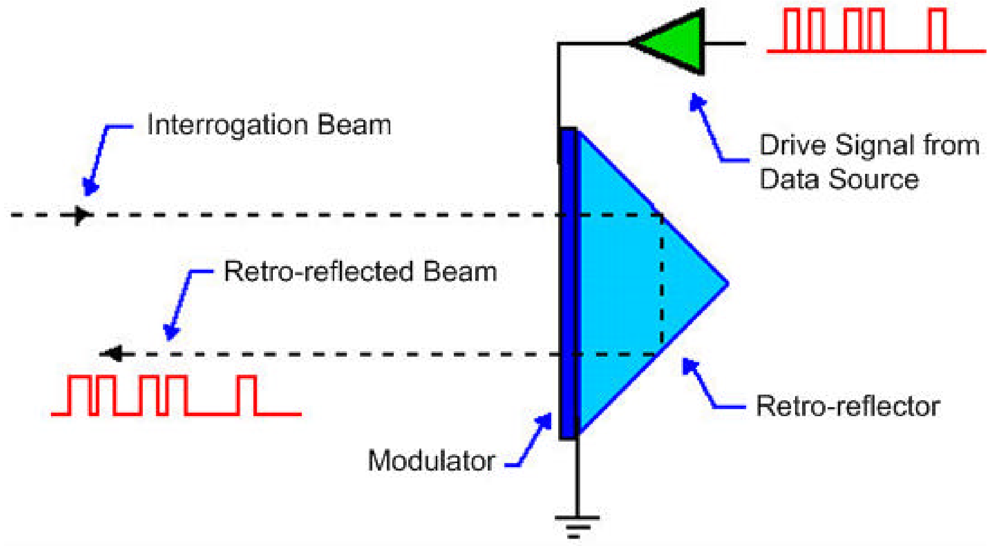

Figure 53. Feeding a Data Source to a Modulating Retro-Reflector (After: [NRL 2001])

The Multiple Quantum Well (MQW) modulator is one such modulator patented by the U.S. Navy Research Laboratory (NRL) [NRL 2001]. NRL claims that the MQW Modulator is robust, operates at low voltages (less than 20V) and low power (tens of milliWatts), and is capable of very high switching speeds. Currently, MQW modulators have been demonstrated at 10 Mbps. NRL claims that Gbps data rates can be supported.

With MRR's, only one terminal requires an onboard laser and tracker, thereby significantly reducing the payload on the other terminal. The NRL had demonstrated in the winter of 2000 the use of a tiny 0.5 cm diameter MQW MRR on a small rotary-wing Unmanned Aerial Vehicle (UAV). Bit rates ranged from 400 Kbps to 2 Mbps and the UAV was flown 35 to 65 meters from the transmit/receive laser. The Modulating Retro-Reflector (MRR) represents a unique solution to the problem of pointing and tracking for mobile FSO platforms.

Figure 54. Small UAV Used in the NRL Field Tests (From: [NRL 2001])

VI. CONCLUSION

Deciding whether it is appropriate to equip a particular mobile military platform with an FSO terminal requires substantial understanding of the technology. It is helpful to have some understanding of various fields like computer science, physics (optics), electrical engineering (EMR), mechanical engineering (gimbals & trackers), and even ophthalmology (the human eye). From the earlier discussions in this report, it should be clear that it is not a simple question of whether FSO is a good technology. Instead, careful thought should be given to the various issues in order to decide whether FSO is suitable for a target mobile military platform.

This final chapter attempts to assist such an analysis through a series of questions and discussions. These questions relate to the bandwidth requirement, communications security, the atmospheric conditions, and the requirements of acquisition, positioning, and tracking. Finally, to illustrate, a case study will be discussed.

A. BANDWIDTH

One of the best-known features of FSO technology is the high bandwidth. The lure of Gigabits-per-second (Gbps) transmissions is great. However, achieving Gbps data rates on mobile platforms has not matured, with practical deployments only achieving up to 50 Mbps. One of the highest data rates achieved in research is that done by the Air Force Research Laboratory Sensors Directorate (AFRL/SN), which achieved a 1.1 Gbps data rate on a simulated mobile platform [Gill 1997]. It is not known whether any operational aircraft have been fitted with the AFRL's FSO terminal.

Therefore, immediate deployments on mobile platforms may only be looking at data rates of around 50 Mbps. If this is acceptable, coupled with the promise of scalability, then the decision to deploy FSO terminals may be justified.

Of course, the question needs to be asked as to whether there is indeed a requirement for Gbps bandwidth. Data rates of up to 50 Mbps can be achieved by current RF radios. If the higher bandwidth is only a "nice-to-have," and the other issues discussed in this chapter are not supportive of deploying FSO, then it should be considered whether other RF technologies are more suitable.

Whether or not an FSO terminal can achieve high bandwidth largely depends on whether a high-powered laser can be used. This is because more power in the signal gives it a higher signal-to-noise ratio. If the deployment scenario is such that it can be ensured that humans will not be exposed to the laser, then higher data rates can be achieved through the use of more powerful lasers. The AFRL's FSO terminals were designed for communication between aircraft. Evidently, the requirement should be for the two aircraft to be at least 1.5 km apart as this is the eye-safe distance of the laser used. More powerful lasers also mean a higher signal-to-noise ratio and hence a lower bit error rate. Consideration should also be given as to whether the target platform will be able to provide the necessary power. Fortuitously, the low free-space loss and the use of power-efficient semiconductor lasers can alleviate this problem.

B. COMMUNICATIONS SECURITY

Another main feature of FSO is the security of communications. As should be inferred from the earlier discussions on this topic, FSO systems are indeed very much more secure than the other wireless options. However, a low probability of detection, interception, and exploitation does not mean that there is no chance of compromise. Various means of detecting, intercepting, and exploiting laser transmissions have been discussed. Therefore, one should still be mindful of avenues of compromise and whether these are likely in the intended deployment scenarios.

C. ATMOSPHERIC CONDITIONS

It has been discussed that FSO systems can be designed for maximum atmospheric transmittance by selecting the appropriate wavelength of laser. Furthermore, the use of adaptive optics, wavelength variation techniques, and redundant links help combat the adverse atmospheric effects.

Deciding whether to deploy FSO should take into account the atmospheric environment of the deployment scenario. For example, a new requirement may be for warships to receive their orders through wireless transmission from the base headquarters at the harbor. However, more often than not, the harbor is covered with fog. It should be clear that FSO is not an ideal solution for this wireless link because fog greatly attenuates the laser power. However, if rather than fog, it often rains at the harbor, then FSO may be a better option, since the alternative of microwave radios would be greatly disrupted by rain.

The brute-force method of combating the effects of the atmosphere is to use more power. Once again, the feasibility of doing this depends on whether there are any laser safety issues, and whether the target platform can provide sufficient power.

D. ACQUISITION, POINTING, AND TRACKING

Pertaining to mobile platforms, the acquisition, pointing, and tracking (APT) system should be suitable for the target platform.

The acquisition should be reliable and take place within a reasonable amount of time. This system is likely to be different from that used for pointing and tracking. If a Global Positioning System / Inertial Navigation System (GPS/INS) system is used, the exchange of coordinates may be accomplished through some other RF system. If the acquisition is through the use of beacon beam, this beam is usually sent by a separate laser. Failure of the acquisition system means that communication cannot take place even if the communication lasers are in good functioning order.

Being a line-of-sight communications link, the pointing of the laser beam and the tracking of the opposite terminal cannot allow the line-of-sight to be blocked. Two aspects of the deployment scenario have to be considered. Firstly, the line-of-sight between the two communicating platforms should be maintained throughout operation. Secondly, it must be possible to mount the FSO terminal on the platform such that no part of the platform itself would block the line-of-sight. Examples are the tail fins and wings of planes and UAV's, and the solar panels of satellites.

The tracking frequency of the FSO system has been analyzed as the speed in which the tracking system must sense and react to a change in relative position of the opposite terminal. Different mobile platforms move at different speeds. Therefore, an analysis should be conducted as to whether the tracking frequency of the system is sufficient to track the worst case rate of change of angular position of the opposite terminal.

E. CASE STUDY

In early 1999, Lucent Technologies demonstrated a ship-to-pier FSO link between the USS John C. Stennis (CVN 74) moored pierside, and the Port Operations Building at the U.S. Navy North Island Facility in San Diego, California [Nykolak 1999]. The details of this demonstration will be discussed to determine whether or not the FSO system demonstrated was suitable for this requirement.

The FSO terminals by AstroTerra Corporation provided an OC-3 (155 Mbps) link between the USS Stennis and the Port Operations Building. For the trial, a 10 Mbps NIPRNET (Non-Secure Internet Protocol Router Network) connection and 4 voice-pairs were multiplexed onto the FSO link. These requirements, together with the network management traffic never exceeded 7% of the OC-3 link capacity. If these were the only requirements for this link, then the OC-3 provided was an overkill. If an FSO terminal of lower capacity was used (e.g. 50 Mbps), the tests would probably have attained much better availability figures than the 99.92% to 99.96% reported. This corresponds to a bit error rate of 4×10^{-4} to 8×10^{-4} which is considered high for an FSO link. Furthermore, with a 50 Mbps link, the utilization figure would only have stood at about 21%, which is still a low figure.

The NIPRNET and voice information did not seem to be sensitive. If so, then communications security may not be an issue. Because of this, there is little concern that the reported beam divergence of 1 mrad is slightly larger than a typical 0.5 mrad figure. Furthermore, the link was only 183 yards long (~167 m). At this distance, the laser would only have a width of about 17 cm.

Fog is quite a problem at the North Island Facility in San Diego. The trials conducted attributed 25 to 35 dB attenuation (300 to 3,000 times) primarily due to fog. As mentioned earlier, one way to transmit an FSO signal through fog is to increase its power. The wavelengths used by the FSO system on board the ship are 750 and 850 nm for the transmit and receive beams, respectively. These wavelengths are not suitable for high-power lasers.

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

Table 5 ANSI Maximum Permissible Exposure Limit for Unaided Viewing [Nykolak 1999]

As can be seen from Table 5, according to ANSI regulations, the Maximum Permissible Exposure (MPE) for a 1550 nm laser is 50 to 100 times greater than the MPE's for 750 and 850 nm respectively. In terms of practical implications, a 1550 nm wavelength can safely transmit at almost 100 times more optical power than a 750 nm wavelength, and still be considered eye-safe for unaided viewing. One of the main reasons why 750 and 850 nm lasers are popular is because they are low cost.

Although the USS Stennis was moored at pier, waves caused by passing ships would cause it to have some roll and yaw. Furthermore, as crane activity was very high at the pier, it was necessary to place the FSO terminal very high on the ship superstructure. This accentuated the ship's roll and pitch motion. The tide levels at the North Island Facility vary by up to 8 feet. This also contributed to a change in the relative positions of the FSO terminals.

Two different sets of FSO terminals were considered and tested for the Ship-to-Pier Demonstration; a simple, completely passive design and a more sophisticated design that includes autotracking. Attempts to compensate for ship motion utilizing the passive optical terminals requires increasing the transmission divergence of the laser beam to cover a larger area at the receiver which envelopes the anticipated beam wander resulting from the motion. It was decided that autotracking was necessary to compensate for the ship motion of the USS Stennis.

In summary, the bit error rates attained by the AstroTerra Corporation FSO terminals are too high. Using a lower-bandwidth link should give better bit error rates without causing congestion in the link. The North Island Facility in San Diego tends to have too much fog, and is therefore not friendly to FSO terminals. The wavelengths used by the AstroTerra terminals are not suitable for high-power use as they would pose a danger for the people working on the pier. Autotracking terminals should be used because of the constant movement of the ship even at pier.

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