The Physics of Free-Space Optics

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Introduction

Several key factors are bringing free-space optical technology (FSOT) into the carrier space as a means of broadband access. The first is a growing and seemingly insatiable bandwidth demand in the marketplace. FSOT technology provides fiber-optic like speeds without significant initial capital expenditures for scarce resources such as spectrum. Deregulation of the telecommunication industry in the US and abroad has introduced a new class of carriers that provide broadband services and require scaleable and affordable infrastructure equipment to bring those services to their customers. While fiber-optic rings are becoming ubiquitous, providing the bandwidth from these rings to customers remains challenging. While FSOT infrastructure sounds inviting, there are many near-term hurdles for FSOT products. Availability is the primary customer concern for FSOT products. Proof of availability needs to be statistically demonstrated with real FSOT systems in the field before there is widespread customer acceptance of the technology. Other concerns are compatibility with existing LEC networks and premise networks, cost, carrier-class hardware, ease of installation, and network management.

This document's primary purpose is to explain and clarify—using real data collected by AirFiber and others—the system design issues of free-space optical technologies. The physics of the atmosphere dictate some very specific performance limitations on free-space systems that can be derived very generally to put an upper bound on carrier-grade range expectations and claims by many vendors in the industry. As a secondary purpose, this paper discusses features associated with a free-space optical system that can be considered performance enhancing. These are aspects of free-space systems that provide added functionality to users, perhaps expanding the market for which free-space technology can be applied. Finally, this paper summarizes the system design discussions into some simple design rules for carrier-class free-space optical systems.

This document is organized as follows:

- **Free Space Optics System Design Issues**
  - **Subsystems**
    Discussions of the various major subsystems that constitute a free-space optical system. Each of the subsystems is discussed in terms of example point designs in the marketplace.
  - **Link Equations**
    High-level discussion of the main factors in the system link equation. Additionally, the relative importance of each of these factors is compared in realistic weather conditions
  - **Comparison Link Budgets**
    Link budgets for point designs that are offered in the marketplace. Most of the data for these designs is available via the vendor's data sheets or from the world wide web. If an assumption is made about a component, that fact is noted.
  - **Availability**
    Actual weather statistics from nephelometers and AirFiber free-space optical communications systems are used to compute link range as a function of availability for carrier-class numbers (99.9% or better).
  - **Theoretical Maximum Range**
    A straw-man design is used to compute the maximum range in 200 dB/km attenuation conditions. Since this is not obtainable, it sets an upper limit on range for free-space systems. The maximum range as a function of availability is also presented for several cities.
  - **Bit Error Rate, Data Rate, and Range**
    Theoretical curves of BER and data rate show that reducing data rate or relaxing BER constraints does not significantly increase the maximum range in realistic weather scenarios.
  - **1550 nm versus 785 nm**
    The debate over propagation characteristics of near infrared (IR) versus 1550 nm light is resolved by curves generated by multiple scattering codes from visible through millimeter waves.
- **Free Space Optics Systems Enhancements**
  - **Tracking**
    The requirements for tracking systems in carrier-class free-space optics systems.
  - **Physics of Scintillation**
    Scintillation effects and techniques for mitigating the detrimental effects of scintillation.
  - **Power Control and Eyesafety**
    The benefits of power control for long-term laser reliability and eyesafety
- **Design Philosophy and Design Rules for Carrier-Grade Free-Space Optics Systems**

Free-Space Optics System Design Issues

Free-Space Optics Subsystems

Figure 1 illustrates the major subsystems in a complete carrier-grade free-space optics communications system. The optical apertures on a free-space system can have an almost infinite variety of forms and some variety of function. They can be refractive, reflective, diffractive, or combinations of these. In figure 1, the transmit, receive, and tracking telescopes are illustrated as separate optical apertures; there are several other configurations possible where, for example, a single optic performs all three functions thereby saving cost, weight, and size. On the transmit side, the important aspects of the optical system are size and quality of the system. Size determines the maximum eye-safe laser flux permitted out of the aperture and may also prevent blockages due to birds. Quality, along with the f-number and wavelength, determine the minimum divergence obtainable with the system. On the receive side, the most important aspects are the aperture size and the f-number. The aperture size determines the amount of light collected on the receiver and the f-number determines the detector's field of view. The tracking system optics' field of view must be wide enough to acquire and maintain link integrity for a given detector and tracking control system.

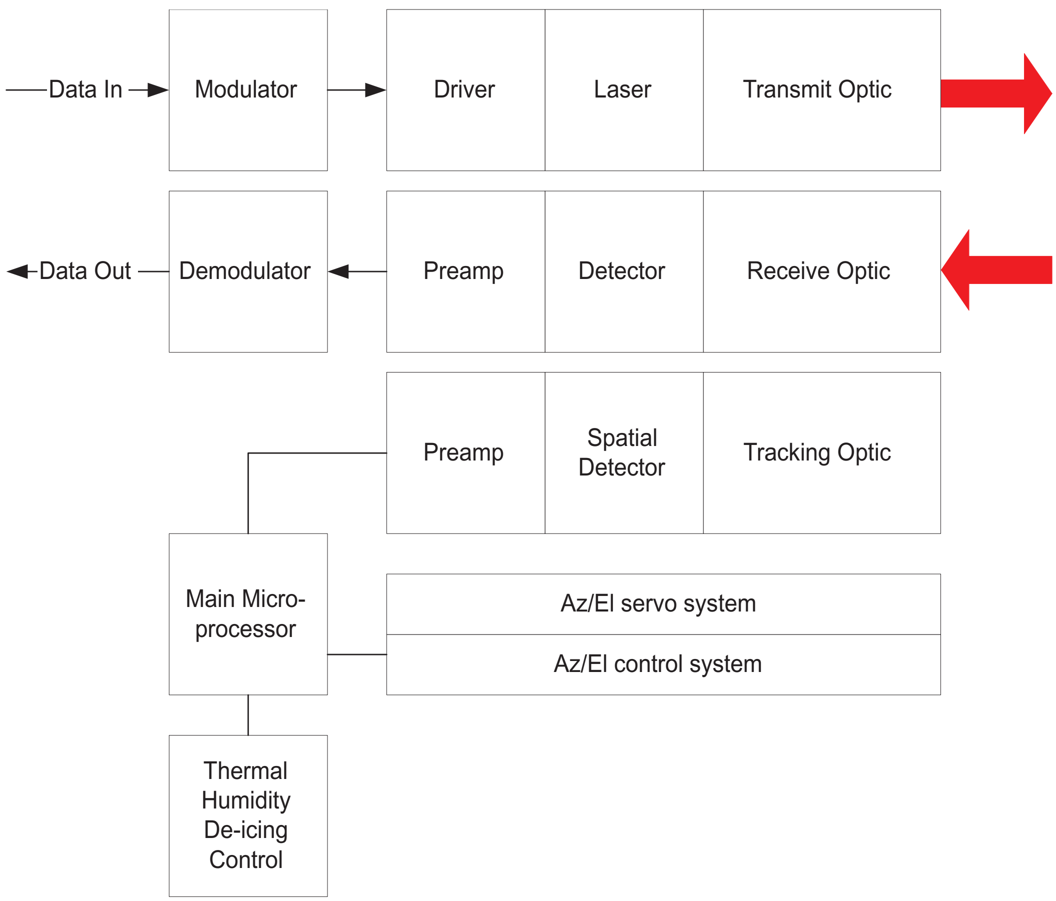


Figure 1. Free-Space Optics Major Subsystems

Several means are available for coupling the laser to the output aperture. If a discrete diode is used, the diode is usually micro-lensed to clean up the astigmatism of the output beam and then is free-space coupled to the output aperture by placing the laser at the focus of the output aperture optical system. The coupling system is very similar for fiber lasers because the core of the fiber laser and the output aperture of a Fabry-Perot laser have similar sizes. The distance from the laser aperture to the output aperture must be maintained such that the system divergence remains in specification over the temperature ranges encountered in an outdoor rooftop environment. This can be accomplished with special materials and/or thermal control.

Diode lasers are driven with a DC bias current to put the devices above threshold, and then, on top of that, are modulated with an AC current to provide, for example, on/off keying (OOK) for data transmission. For lasers with output powers below approximately 50 mW, off-the-shelf current bias and drive chips are available; for higher power lasers, custom circuits or RF amplifiers are generally used.

The receive detector is coupled to the receive aperture through either free-space or fiber. Depending on the data rate and optical design alignment, tolerances can be extremely restrictive. For example, for data rates to 1.25 Gbit/s, detectors with relatively large active areas (500-micron diameter) can be used, making alignment to the receive aperture fairly straightforward. For fiber-optic coupling into multimode fibers, the correct size is about 63 microns in diameter, which makes alignment much tougher. The use of special materials or controls is required in this case, however, coupling is more modular.

Detectors are generally either PIN diodes or avalanche photodiodes (APD). For carrier-class free-space optics systems, an APD is always advantageous since atmospheric-induced losses can reduce received signals to very low levels where electronics noise dominates the signal-to-noise (SNR) ratio. Of course the APD must be capable of meeting the system bandwidth requirements. Usually a trans-impedance amplifier is used after the detector because in most cases they provide the highest gain at the fastest speed.

If CCD, CMOS, or quad cell detectors are used as tracking detectors, these relatively large area devices are easy to align to the tracking optics. However, care must be taken in manufacture to co-align these optics with the transmit and receive optical axes. For building-mounted free-space optical systems, the tracking bandwidth can be very low—sub-hertz—because the bulk of building motion is due to the building's uneven thermal loading and these effects occur on a time scale of hours. For systems that are to be mounted on towers or tall poles, the tracking bandwidth should be higher—most likely on the order of several hertz at least—to remove wind-induced vibrations.

Acquisition systems can be as crude as aligning a gunsight to very sophisticated GPS-based, high accuracy, fully automated systems. The choice of this subsystem really depends on the application and number of devices to be put into a network.

The Free-Space Optic Link Equation

The link equation for a free-space optical system is actually very simple at a high level (leaving out optical efficiencies, detector noises, etc.). The equation is illustrated in figure 2. The amount of received power is proportional to the amount of power transmitted and the area of the collection aperture. It is inversely proportional to the square of the beam divergence and the square of link range. It is also inversely proportional to the exponential of the product of the atmospheric attenuation coefficient (in units of 1/distance) times the link range.

Receiver area

$$P_{received} = P_{transmit} \cdot \frac{A_{receiver}}{(Div \cdot Range)^2} \cdot \exp(-\alpha \cdot Range)$$

Beam divergence

Atmospheric Attenuation Factor $\left(\frac{1}{km}\right)$

Figure 2. Basic FSO Link Equation

Looking at this equation, the variables that can be controlled are: transmit power, receive aperture size, beam divergence, and link range. The atmospheric attenuation coefficient is uncontrollable in an outdoor environment and is roughly independent of wavelength in heavy attenuation conditions. Unfortunately, the received power is exponentially dependent on the product of the atmospheric attenuation coefficient and the range; in real atmospheric situations, for carrier-class products (i.e., availabilities at 99.9% or better) this term overwhelms everything else in the equation. This means that a system designer can choose to use huge transmit laser powers, design large apertures, and employ very tight beam divergences, but the amount of received power will remain essentially unchanged. Figure 3 illustrates this point. Except for clear air, the atmospheric loss component of the link equation dominates by many orders of magnitude, essentially obviating any system design choices that could affect availability. Designers of free-space systems that are to be carrier class must accept this fact and design the system accordingly. Basically, the only other variable under the designer's control is link range, which must be short enough to ensure that atmospheric attenuation is not the dominant term in the link equation. As discussed in a later section, this implies the link range *must* be less than 500 m. However, efficient designs can be produced that permit economical, reliable operation under this constraint.

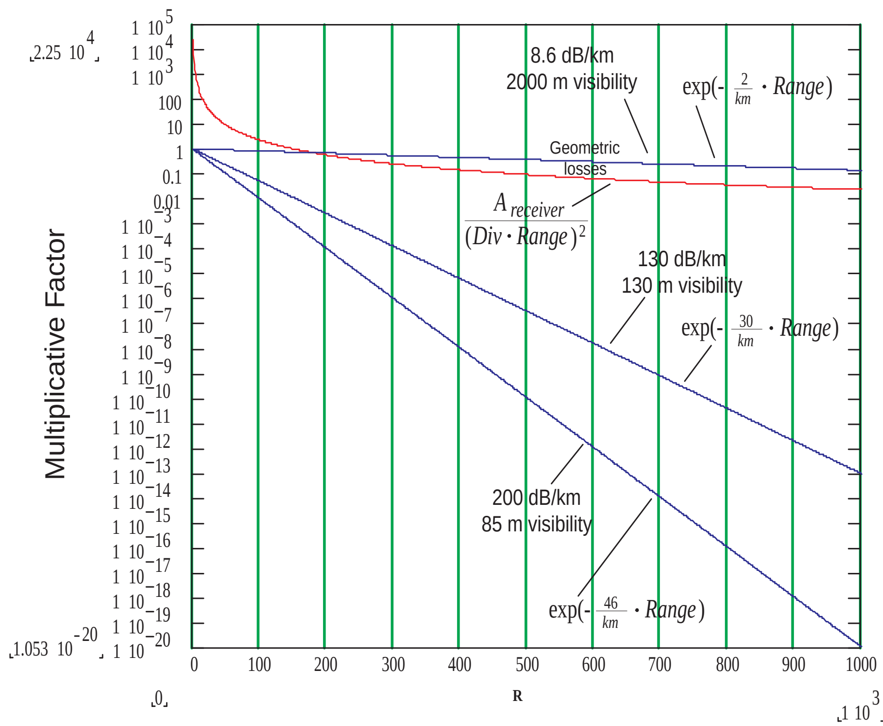


Figure 3. Geometric and Atmospheric Loss Components

Comparison Link Budgets

Figure 4 shows a tabular link budget for the top five free-space optical system manufacturers. Most of the system parameters are freely available from manufacturers data sheets; where a parameter has been assumed it is noted. One of the vendors (highlighted) has a product at 155 Mbit/s and really should not be compared with the others at 1.25 Gbit/s but has been included for informational purposes. The atmospheric attenuation condition is 200 dB/km. The link ranges were adjusted for each system such that the margin came out to approximately zero. It is interesting to note the wide variety of adjustable system parameters (aperture size, wavelengths, transmit divergences, transmit powers) that have been employed in these systems yet, as previously discussed, the maximum link ranges are all about the same (approximately +/– 30 m). This again illustrates the point that system designers do not have a lot of options available to increase link range in realistic carrier-grade atmospheric conditions. Given that all manufacturers have about the same performance in high attenuation conditions, figure 5 plots the maximum range versus atmospheric attenuation (dB/km) for one of the vendors, which is about the same for all of the vendors. It is interesting to note that at longer ranges (about 1 km or so) the maximum attenuation allowable is about 30–40 dB/km. It turns out that heavy rain can produce this range of attenuation values and therefore the long link range issue is going to be widespread throughout the world, and not just limited to foggy coastal areas.

	AirFiber	Vendor A	Vendor B	Vendor C	Vendor D	
AtmosLoss						
dB/km	-200	-200	-200	-200	-200	
Transmitter	AlGaAs					
Modulation Format	NRZ OOK					
Receiver	Si APD					
Wavelength	785	850	1550	1550	850	nm
Range	200	190	215	205	176	m
Data Rate	1250	1250	1250	***155***	1250	Mbit/s
Average Laser Power	18	30	1000	320	15.6	mW
Peak Laser Power	36	60	2000	640	31	mW
Transmit Aperture	5	5	16	2.5	5	cm
Transmit Divergence	0.5	2	2	4.25	2	mrad(1/e^2)
Receive Aperture	7.5	20	40	20	19	cm
Optical Background	0.2	0.2	0.2	0.2	0.2	W/m^2/nm/sr
Receiver FOV	3.25	3.25	3.25	3.25	3.25	mrad(1/e^2)
Receive Filter Width	25	25	25	25	25	nm
Receiver Sensitivity	800	1000	1000	1000	1000	nW
BER	1.00E-12	1.00E-12	1.00E-12	1.00E-12	1.00E-12	
Peak Laser Transmit Power	-14.43697499	-12.2184875	3.010299957	-1.93820026	-15.08638306	dBW
Extinction Ratio Degradation	-0.2	-0.2	-0.2	-0.2	-0.2	dB
Transmit Optics Degradation	0	0	-15	0	0	dBW
Pointing Loss	-1	-1	-1	-1	-1	dB
Geometric Range Loss	-2.498774732	-5.575072019	-0.628169285	-12.78225591	-5.355781251	dB
Atmospheric Loss	-40	-38	-43	-41	-35.2	dB
Atmospheric Scintillation Fade	-1	-1	-1	-1	-1	dB
Receive Optics Attenuation	-1.4	-1.4	-1.4	-1.4	-1.4	dB
Bandpass Filter Loss	-0.7	-0.7	-0.7	-0.7	-0.7	dB
Misc Loss Elements	0	0	0	0	0	dB
Received Peak Power at Detector	-61.23574972	-60.09355952	-59.91786933	-60.02045617	-59.94216431	dBW
Required Peak Power at Detector	-60.96910013	-60	-60	-60	-60	dBW
Link Margin at Range	-0.266649594	-0.093559515	0.082130672	-0.020456169	0.057835688	dB

Figure 4. FSO Performance Comparison (I)

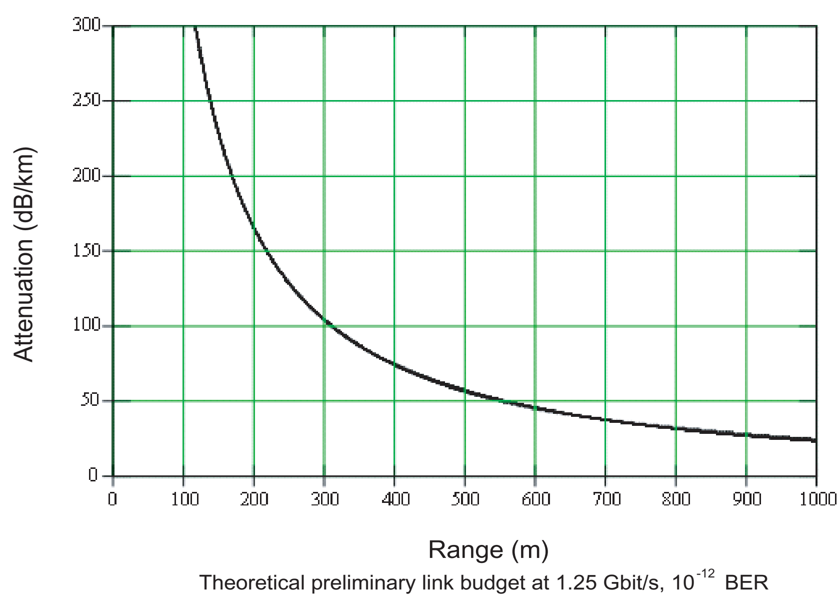


Figure 5. FSO Performance Comparison (II)

Availability

A carrier's key issue in deploying free-space optical systems is system availability. System availability comprises many factors, including equipment reliability and network design (redundancy, for example) but these are well known and fairly quantifiable. The biggest unknown is the statistics of atmospheric attenuation. While almost all major airports around the world keep visibility statistics (which can be converted to attenuation coefficients), the spatial scale of visibility measurements is rough (generally 100 m or so) and the temporal scale is infrequent (hourly in most cases). With the crude spatial and temporal scales, estimates of availability for carrier-grade equipment (99.9% or better) are going to be limited to 99.9% or worse. Therefore, these huge databases are not useful except for estimating the lowest acceptable carrier grade of service. Better data is needed to permit carriers to write reasonable service level agreements. AirFiber has had instruments capable of acquiring this data running continuously for approximately two years. These instruments, which include a nephelometer and an in-house designed and built weather benchmark system, allow the collection of data at the correct spatial and temporal resolution for accurate estimates of availability versus link range.

Figure 6 shows a plot of this data for two cities, Tokyo and San Diego. One line shows the cumulative probability density function for San Diego and the other shows the same information for Tokyo. Also plotted is the link budget equation for an AirFiber product; other vendors' products have about the same link margins. The left vertical axis shows the percentage of time that the attenuation is greater than or equal to a given value. The horizontal axis is attenuation in dB/km, and the vertical axis on the right side is the maximum link range at zero link margin. To use the chart, choose an availability, say 99.9% (as shown by the dotted line), move horizontally to the desired city (say Tokyo in this example), move vertically to the link budget equation, and finally move horizontally to the maximum link range (in the case of Tokyo, about 350 m). It is interesting to note that Tokyo is qualitatively in the top 10% of cities for clarity of the atmosphere and San Diego is in the bottom 10%. Therefore for most deployments, the maximum range will fall somewhere in between these two cities, certainly less than 500 m in most cases.

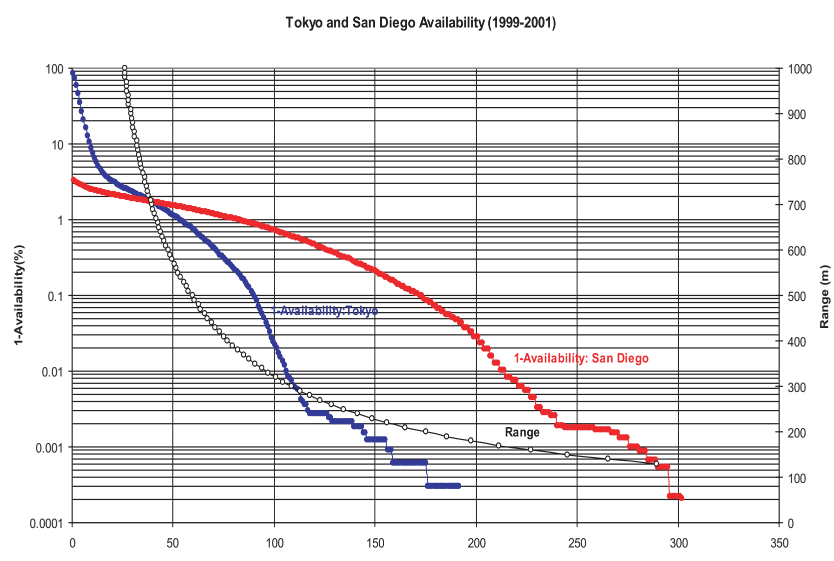


Figure 6. FSO Availability

Theoretical Maximum Range

As a final statement about the performance of free-space optical systems in realistic weather conditions, we perform calculations of maximum link ranges for a strawman theoretically "perfect"—but as yet unobtainable—free-space optical system. Figure 7 illustrates the assumptions and results of this calculation. Under the assumptions it is worthy to note that the detector, electronics, and background noise were set to zero and the collection aperture was assumed to receive *all* transmitted photons; that is, beam divergence was set at zero. In addition, a very large transmit aperture was chosen so that 80 watts of transmit power could be used and still maintain eye-safe levels. Running through the numbers for 200 dB/km and 10^{-12} BER at 1 Gbit/s data rate results in a maximum range of about 500 m. So even in an "unobtainable" system, the maximum range in realistic atmospheric attenuation situations is about 500 m.

Assumptions

- Eye-safe laser
- No detector/electronics or background noise
- **No geometrical loss**
- 1 Gbit/s
- 25.4 cm aperture
- 80 W transmit power
- 200 dB/km Attenuation
- Need SNR=14 for 10^{-12} BER

Results

$$SNR = \frac{1}{2} \frac{\eta P_{signal}}{h\nu B}$$

$$80W \; 10^{-\frac{200\, Range}{10}} = 8.9nW$$

Range = 497 meters

Figure 7. Strawman "Perfect" FSO Link

Figure 8 further illustrates this point and correlates this system with real availability data for several cities around the world. In this figure the 99% line can be as high as several kilometers in some cities as illustrated by the 99% rectangle. As soon as carrier-grade availability of 99.9% is used, the box shrinks significantly as illustrated by the 99.9% rectangle in the figure. The maximum range in this carrier-grade case is about 900 m; if Chicago is taken out of the data set, the maximum range is 600 m.

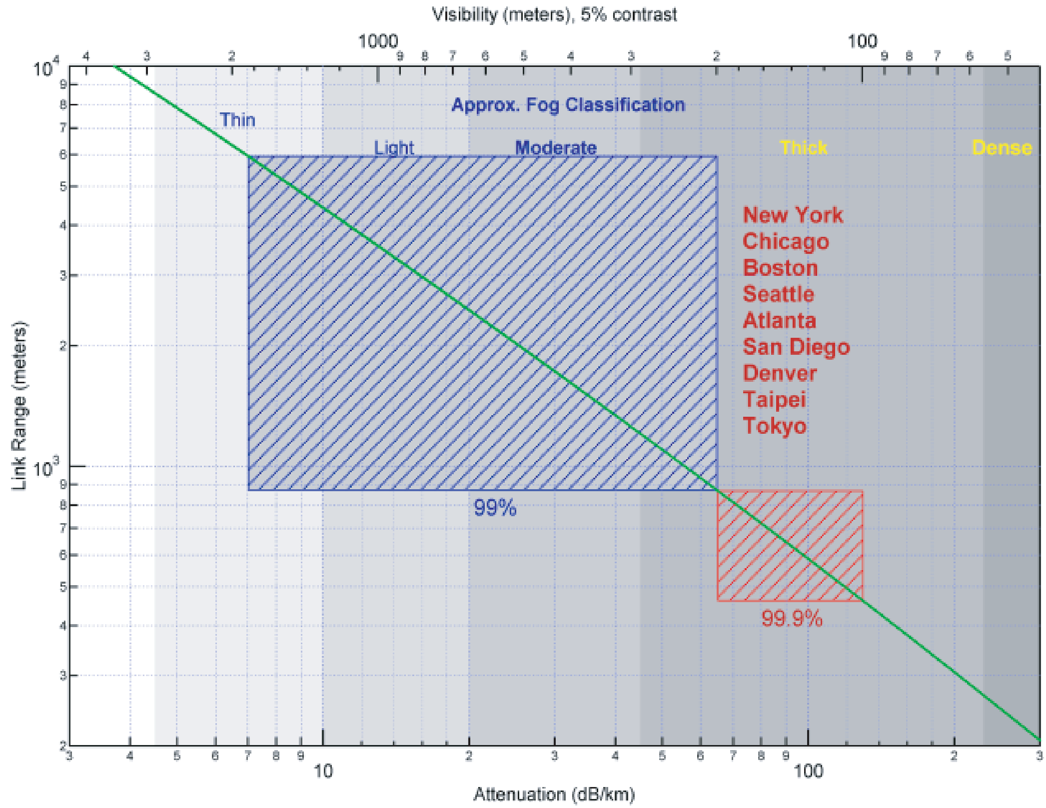


Figure 8. Theoretical Link with 63 dB Margin

Bit Error Rate, Data Rates, and Range

In figure 9, which depicts a set of buildings in Denver, Colorado, we illustrate the effects of fog on visibility range. The tall building in the foreground is about 300 m from the photographer. The left photo shows clear air, at 6.5 dB/km (2000 m visibility range), as measured with a nephelometer mounted at the photographer's site. Note that the distant mountain ranges are easily visible at many miles distance. During a fog which measured about 150 dB/km (visibility range of about 113 m), as shown in the middle photo, the building is still visible at 300 m, but the scenery is washed out beyond this range. As shown in the right photo, at 225 dB/km (visibility range of about 75 m) the building is completely obscured.

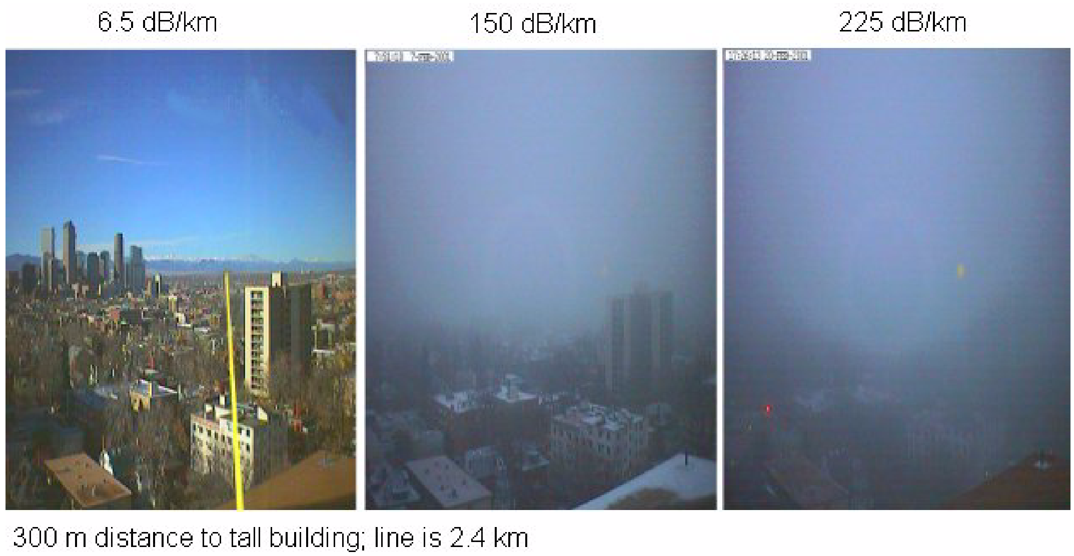


Figure 9. Denver, Colorado Fog/Snowstorm Conditions

For free-space optical systems, the questions of bit error rate (BER) versus range and data rate versus range frequently arise. Unlike fiber-optic systems where the channel is well known and characterized, free-space systems have severe atmospheric attenuation propagation conditions that cause the BER to behave in an almost binary manner. This is illustrated in figure 10, showing the BER versus range for a Gigabit Ethernet system in 200 dB/km attenuation conditions. The graph clearly illustrates that relaxing the BER requirement from, for example, 10^{-12} to 10^{-6} results in a range gain of only 10–15 m. Because free-space systems in general, under carrier-grade conditions, are either error free or fully errored when severe atmospheric attenuation is encountered, it does not make sense to design for moderate bit error rates. The same is true for data rate as shown in figure 11, where the data rate for the same system was reduced to 100 Mbit/s. In this case, the gain in range is only 30 m at 10^{-12} BER. In carrier-grade conditions, the best design for free-space optical systems is to push the components to their limits in terms of speed and BER performance, reducing these factors does not buy a significant increase in range performance.

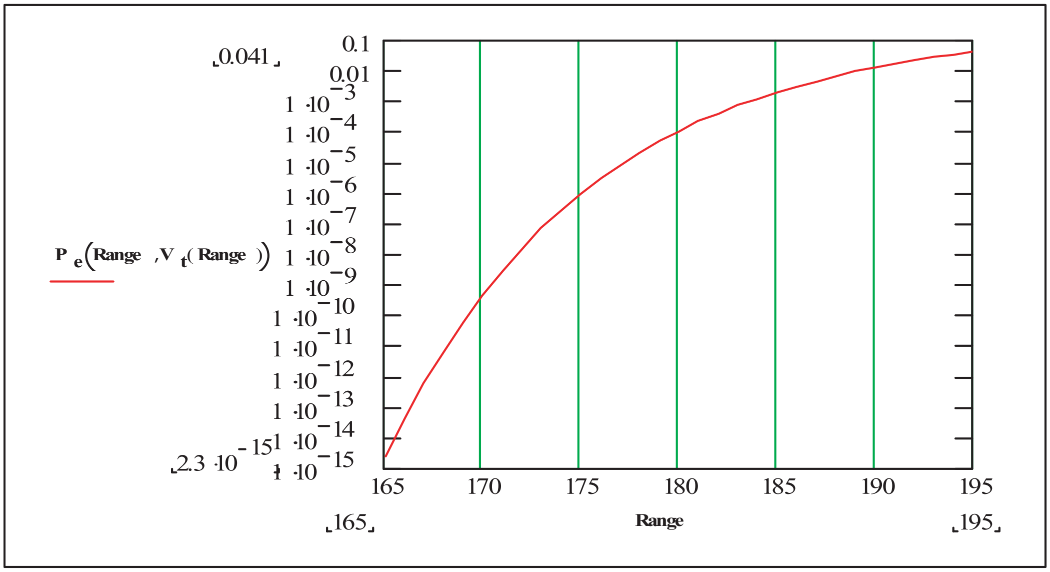
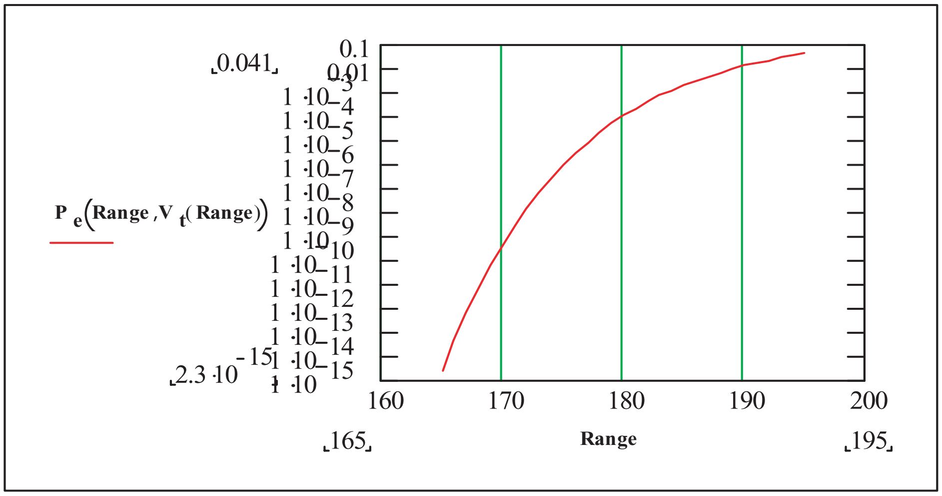


Figure 10. BER versus Range at 1.25 Gbit/s

1550 nm Versus 785 nm

Another topic frequently discussed concerning the performance of free-space optical systems is the issue of atmospheric propagation and wavelength. One generally held belief is that a system operating at longer wavelengths has better range performance than systems at shorter wavelengths. Figure 12 shows several calculations performed using MODTRAN for a 1 km path length for which the x-axis is wavelength. The visibility range was 200 m, typical of an advection fog. The y-axis in the top panel is transmission from a minimum of 0 to a maximum of 1. The top panel shows the amount of absorption due to water only in the atmosphere. Here many wavelengths propagate very poorly due to absorption by water vapor, particularly near 1.3–1.4 microns. The second panel from the top shows absorption due to oxygen and carbon dioxide, which are relatively narrow lines and are easily avoided.

The third panel shows the effects of Mie scattering by water droplets in the fog. Clearly this is the dominant loss mechanism under these conditions and is basically independent of wavelength (for example, it is actually a little *worse* at 1.5 microns than at 785 nm). Finally, the bottom panel shows the combined effects of all three loss mechanisms. Again the result is basically independent of wavelength. There is no advantage in propagation range by using longer wavelengths. Taking this one step further, the calculations were performed at even longer wavelengths as illustrated in figure 13. Here the x-axis is again wavelength, the y-axis is the combined loss over a 1 km path. In these illustrations the vertical axis is attenuation in dB/km. For all wavelengths up to about 12 microns the result is the same. There are no "spectral holes" in which it is very advantageous to propagate; the attenuation is basically flat over these wavelengths. Finally the same calculations were carried out all the way to millimeter waves, as illustrated in figure 14. This was done for completeness and to make sure that at RF frequencies the attenuation reduced to generally accepted values. Not until the wavelength is at sub-millimeter size (RF) is attenuation markedly reduced.



Decreasing the data rate from 1.25 Gbit/s to 100 Mbit/s increases the range for 10^{-12} BER by only about 30 meters in 200 dB/km attentuation

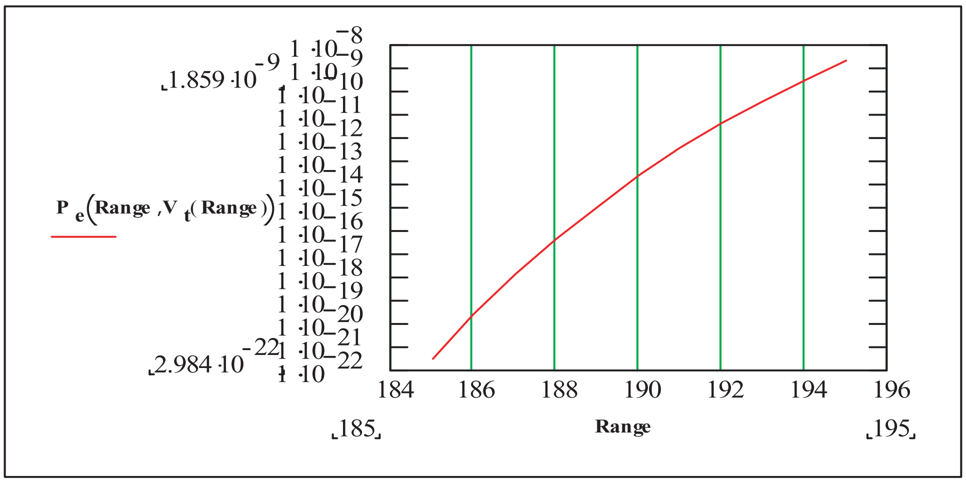


Figure 11. BER and Range versus Data Rate

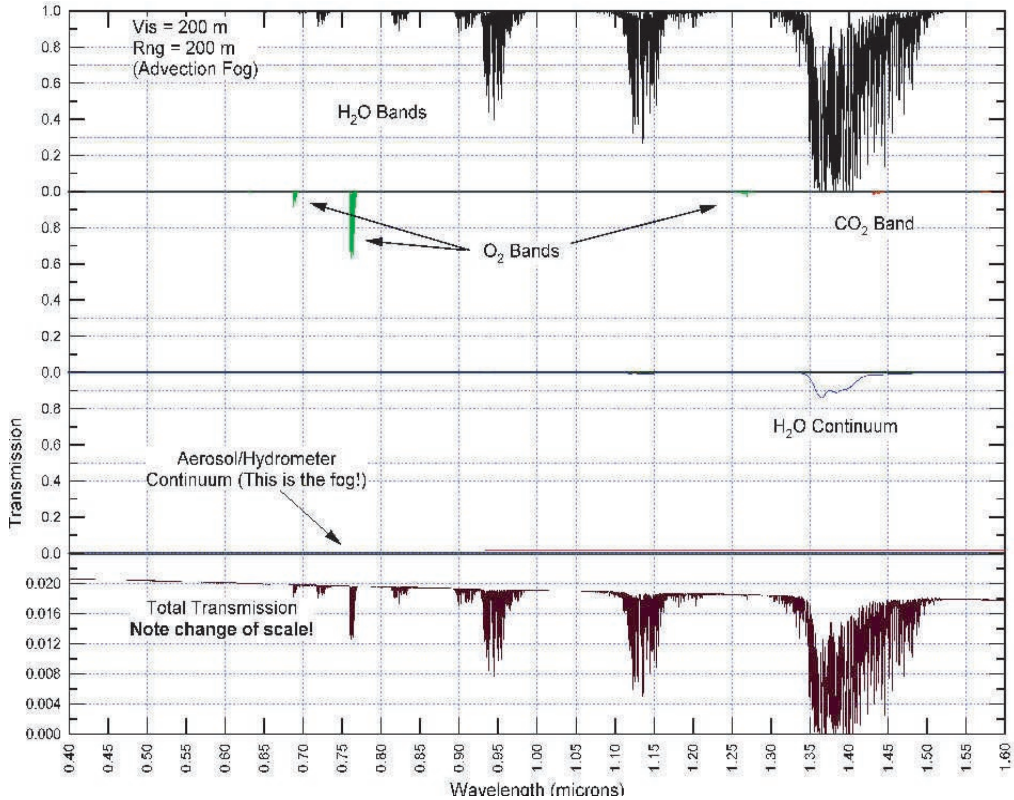


Figure 12. 1550 nm versus 780 nm Atmospheric Propagation

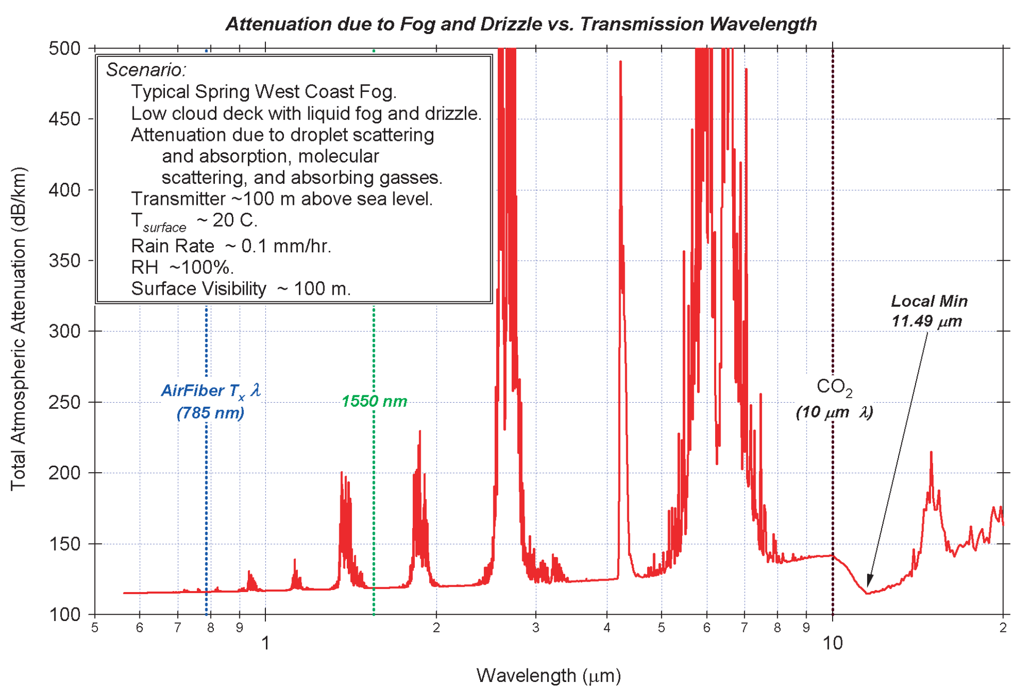


Figure 13. Wavelength versus Attenuation—Near Infrared

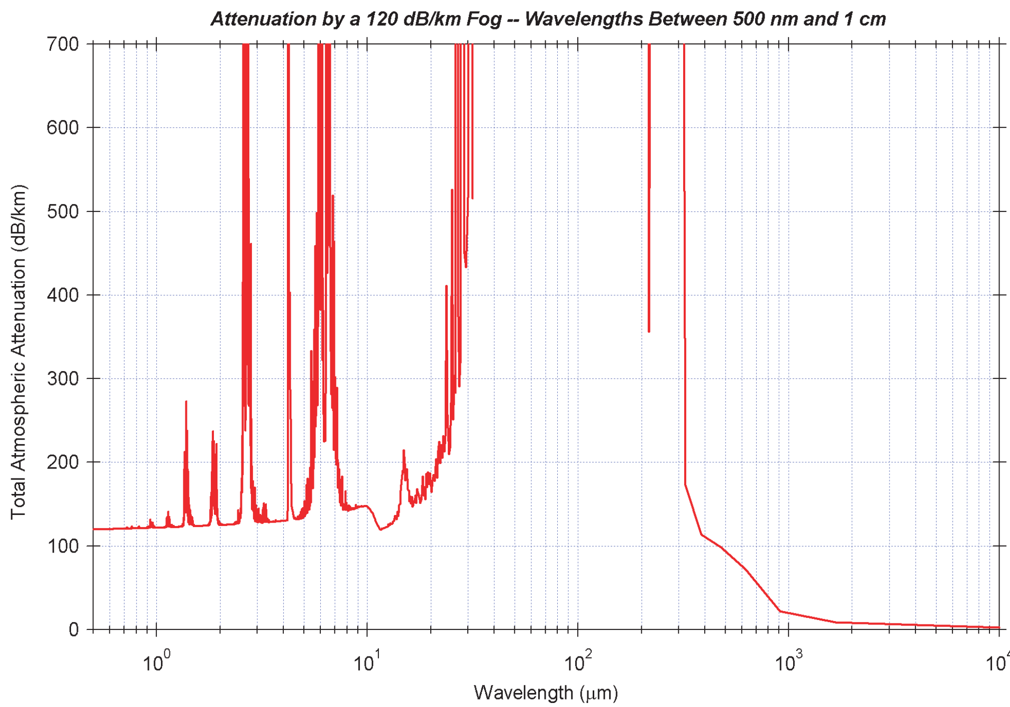


Figure 14. Wavelength versus Attentuation—through Millimeter Waves

In summary we can clearly state that for the majority of cities around the world, the carrier-class distance (as defined by 99.9% availability or better) is less than 500 m. In addition, despite numerous claims, all free-space optics vendors have about the same range performance in carrier-grade conditions (99.9% or better) due to complete domination of the link budget equation by the atmospheric attenuation factor in high attenuation situations. Finally, wavelength has absolutely no effect on propagation range under carrier-grade conditions for wavelengths from visible all the way up to millimeter wave (RF) scales.

Free-Space Optics Systems Enhancements

Tracking

One issue that is debated among free-space optics vendors is the necessity of having a *tracking system*. The question is whether the hardware needs to compensate for small amplitude, low frequency, building motion—usually thermally induced—to maintain link integrity or is it sufficient to spread the divergence of the transmitter beam large enough to encompass all foreseeable building movement amplitudes? Going back to the link equation, it is easy to see that spreading the beam divergence impacts the link margin by the inverse square of the spread. In other words, every doubling of the beam divergence negatively impacts the link margin by 6 dB. In addition, even if the beam is spread broadly enough to accommodate building motion, the overall system link margin will fluctuate negatively and/or degrade since, by design, precise alignment of free-space optical systems will not always be achieved over time and temperature.

Figure 15 illustrates this effect with actual data from a fielded system (distance of 500 m) running live customer traffic in Phoenix, Arizona. The upper graph shows the change in azimuthal position as a function of time. The x-axis units are arbitrary; however, the pattern of peaks and valleys is due to diurnal thermal changes at the site. The same is true of the bottom graph but for the elevation axis. One tick on either vertical axis corresponds to about 100 microradians of motion, so the maximum azimuthal variation (building twist) is about 1.5 milliradians, and the maximum elevation variation is about 2.5 milliradians. In fact we have observed elevation variations of 8 milliradians on this same link under different thermal conditions. Another interesting point to note is that a competitor's non-tracking units were removed from this link because they consistently lost link during diurnal thermal cycles. To illustrate the importance of tracking, loss of link margin due to building motion was calculated for non-tracking units. If the $1/e^2$ beam divergence is 2 milliradians and the links are perfectly aligned at installation, a 1 milliradian building motion would incur a loss of link margin of about 8.6 dB. Even if the link stayed up during this excursion, system performance would be degraded by 8.6 dB from the initially specified margin. This means that for a typical carrier-grade link of 200 m, in the absence of tracking the system can withstand about 43 dB/km *less* atmospheric attenuation than the initial design. For calibration, heavy rain can induce about 17–40 dB/km of attenuation, so a system that is designed to handle heavy rain could be down in a severe storm.

Data from customer running live traffic, 500 m range

AirFiber units replaced competitor's non-tracking units

Non-tracking multi-laser units regularly lost communications during diurnal cycle; maximum 8 mrad excursion measured

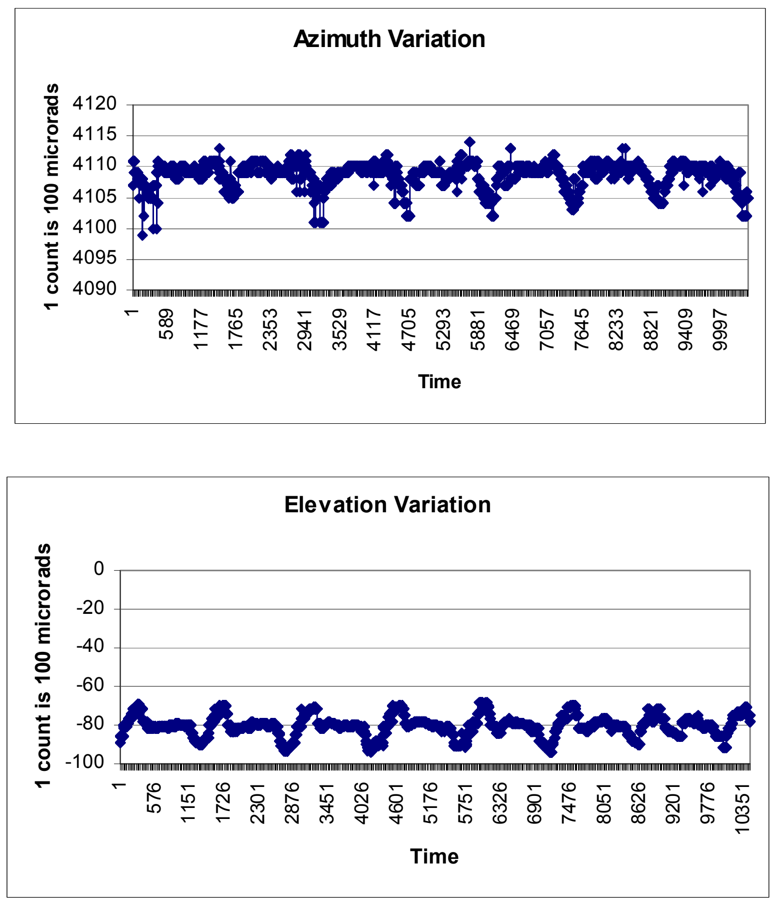


Figure 15. Tracking Example—Customer Network in Phoenix, AZ

Physics of Scintillation

Atmospheric scintillation, as used in this document, can be thought of as changing light intensities in time and space at the plane of a receiver detecting the signal from a transmitter at a distance. The received signal level at the detector fluctuates due to thermally induced changes in the index of refraction of the air along the transmit path. The index changes cause the atmosphere to act like a collection of small prisms and lenses that deflect the light beam into and out of the transmit path. The time scale of these fluctuations is about the time it takes a volume of air the size of the beam to move across the path and therefore is related to wind speed. There are many theoretical papers written on this effect, primarily for ground-to-space applications, and in general, are very complicated. It has been observed that for weak fluctuations, the distribution of received intensities is close to a log normal distribution. For the case of free-space optics, which implies horizontal path propagation and therefore stronger scintillation, the distribution tends to be more exponential.

One parameter that is often used as a measure of the scintillation strength is the atmospheric structure parameter or C_n^2. This parameter, which is directly related to wind speed, roughly measures how turbulent the atmosphere is. Figure 16 illustrates some measurements of this parameter taken at the AirFiber facility in San Diego, CA. The most interesting feature of the data is the fact that the parameter changes by over an order of magnitude over the course of a day, with the worst—or most scintillated—measurements occuring during midday when the temperature is the greatest.

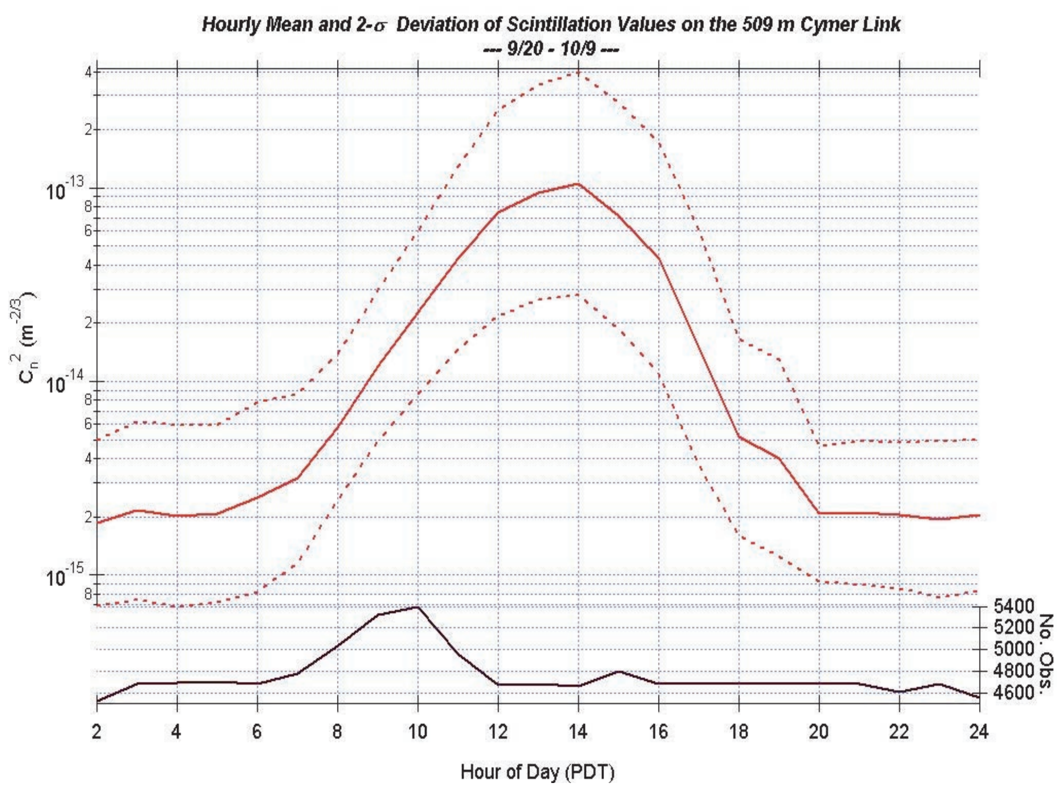


Figure 16. Scintillation and Measured C_n^2 in San Diego, California

The variation in C_n^2 is interesting because C_n^2 can be used to predict the variance in intensity fluctuations at the receiver using the formula displayed at the top of figure 17. The variance is linearly proportional to C_n^2, nearly linearly proportional to 1/wavelength, and nearly proportional to the square of the link distance. Two interesting facts can be inferred from this. First, shorter wavelength systems have proportionally larger variance in the scintillation intensity. For example a system operating at 780 nm has about twice the variance as a system operating at 1550 nm. Second, the effect increases severely with range. At twice the range, the variance is four times greater. The graphs represent the variance as a function of range for the minimum, median, and maximum values of C_n^2 measured in figure 16.

$$\sigma_\chi^2\left(C_{nsq}, k, L\right) := 0.31 \cdot C_{nsq} \cdot k^{\frac{7}{6}} \cdot L^{\frac{11}{6}}$$

Variance in intensity fluctuation is derived from atmospheric structure constant

Scintillation effects scale (become worse) like Range^2

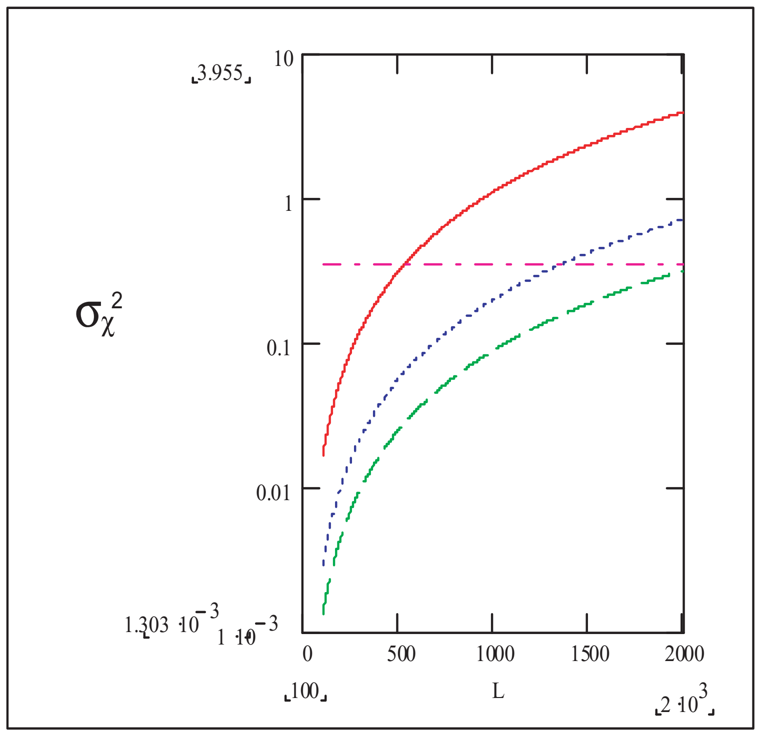


Figure 17. σ_χ^2 **from** C_n^2

The effects of scintillation are graphically illustrated in figure 18. The figure depicts a receiver aperture with dark and light "speckles" distributed randomly over the aperture. The size of these speckles scales like $(\lambda R)^{1/2}$. Again there are two interesting features to note about this scaling. First, the longer the wavelength, the larger the speckle. This is not good for system performance because the smaller the number of speckles at the receiver aperture, the less aperture-averaging over the various intensities of each speckle can occur. If the receive aperture is collecting only one speckle, for example, then a very large increase in system transmit power is required to ensure that the BER is maintained even for a "dark" speckle. Second, the size scales like the square root of the link distance; longer links imply larger speckles, which impacts system performance as previously described.

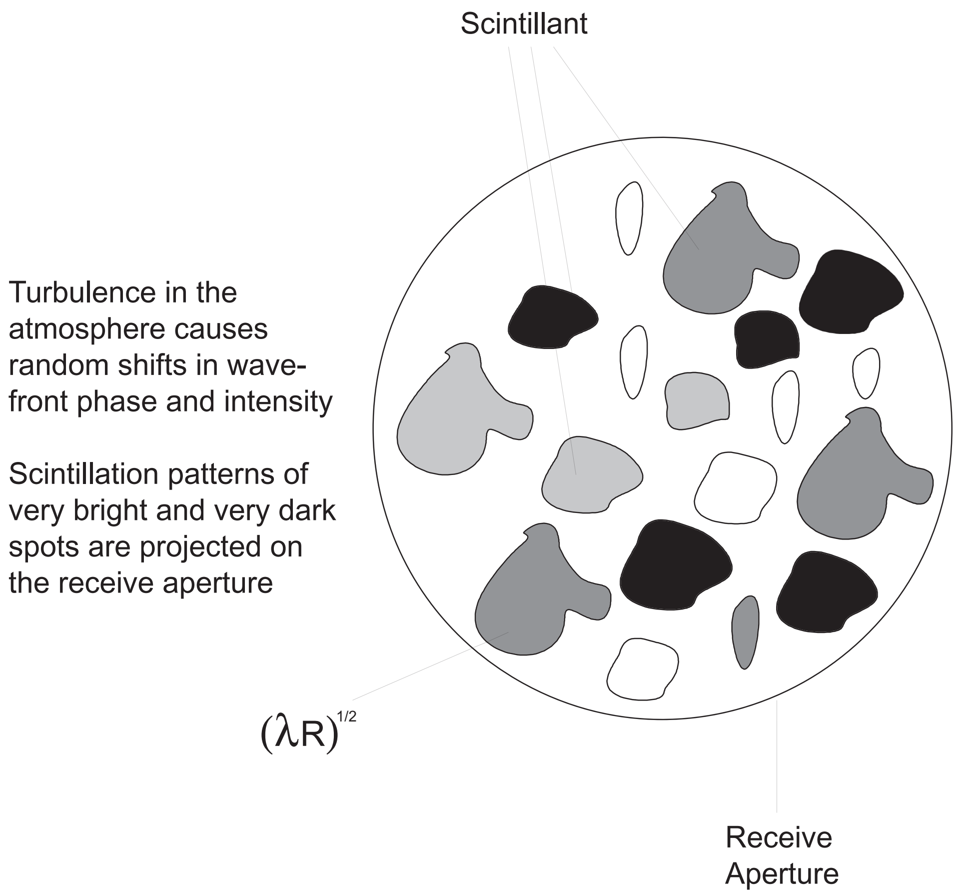


Figure 18. Scintillation Spots and Aperture Averaging

Figure 19 shows the effects of aperture averaging on the required link margin for a 3-inch aperture. The plots are for a 100-m link and a 1000-m link. The 100-m link shows a received intensity distribution that is nearly Gaussian, centered about the mean transmit intensity of 1. Here, scintillation plays no role; in fact for nearly *all* carrier-grade links (ranges of less than 500 m) scintillation effects are a few dB at most. At 1 km, the intensity distribution is more skewed and requires about 13 dB more power for the same BER as the 100-m link (to overcome scintillation, not geometrical effects). The point of this is that for *carrier-grade* links, scintillation is not an issue and therefore does not need to be addressed in the system design. System designs can include features such as multiple laser transmitters to substantially reduce scintillation effects for long links; however, as mentioned previously, this is not necessary on a carrier-grade system since the link ranges are generally less than 500 m. Additionally, for carrier-grade systems, link margins are engineered to accommodate severe attenuation conditions like fog, and therefore already have enough margin to take care of any scintillation conditions since the air is always clear when it is highly scintillated.

$$\mathrm{prob}(I,R) := \left(\frac{1}{2\cdot\sqrt{2\cdot\pi}\cdot I\cdot\sigma_{\chi}(R)\cdot\sqrt{A(R)}}\right)\cdot\exp\left[-\frac{\left[\ln(I)+2\cdot\left(\sigma_{\chi}(R)\cdot\sqrt{A(R)}\right)^{2}\right]^{2}}{8\cdot\left(\sigma_{\chi}(R)\cdot\sqrt{A(R)}\right)^{2}}\right]$$

Aperture-averaging reduces margin at distance

For a 75-mm aperture, the increase in margin due to scintillation for a
1 km link is about 13 dB when aperture-averaging is taken into account (fully saturated atmosphere)

Scintillant size scales like ($\lambda R^{1/2}$ at λ=785 nm, R=1 km
(this is about 2.8 cm)

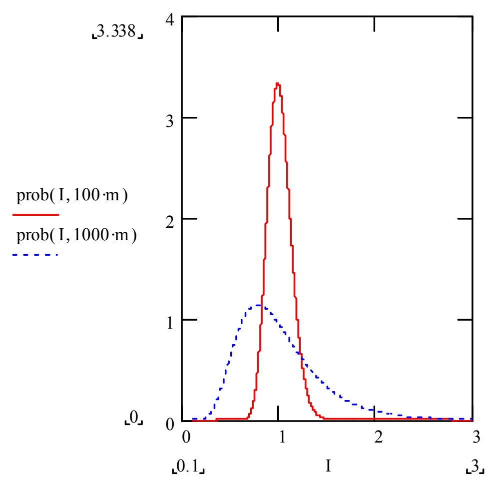
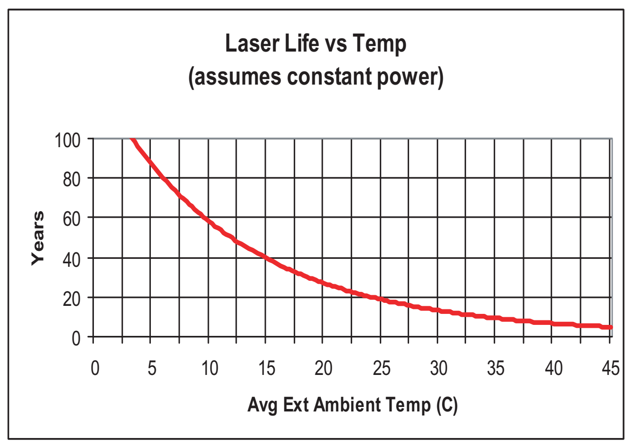


Figure 19. Aperture-Averaging

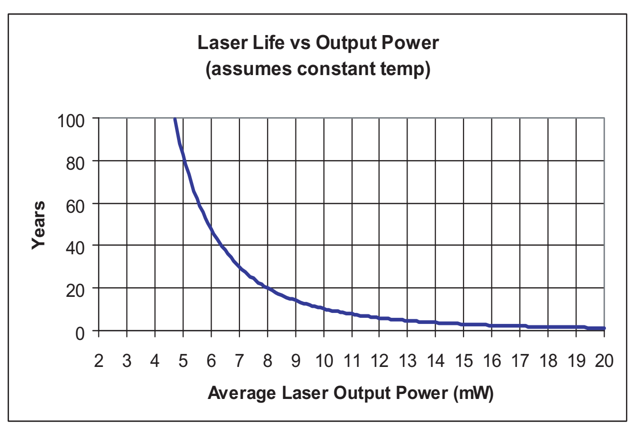
Power Control and Eye Safety

Laser reliability is an issue for carrier-grade free-space optical systems that need to have mean-time between failures (MTBF) of 8 years or more. There are basically two factors that influence the lifetime of a semiconductor diode laser—the average operating temperature of the case of the diode, and the average operating output optical power of the diode. For AlGaAs diode lasers, the activation energy is about 0.65 eV, which implies that the lifetime of the diode increases by about a factor of two for every 10°C decrease in the average operating temperature of the diode case. The top graph of figure 20 shows how the lifetime increases as a function of case temperature. For outdoor equipment a general rule of thumb for most locations in the world is that an average temperature of 25–30°C can be used to predict thermal effects on lifetime.

More important than thermal effects is the average output power of the laser. In this case the lifetime scales inversely with the cube of the power, as illustrated in the bottom graph of figure 20. This means that significant lifetime increases can be obtained by systems that automatically control the output laser power since most of the time a given link transmits through clear air and the output power can be reduced substantially. Note that a distinction is made between automatic control of the output laser power and attenuation of power using a filter, which does not provide the same laser lifetime advantages. Systems that do not employ power control will probably have a very difficult time meeting carrier MTBF expectations.



Laser lifetime approximately doubles for every 10°C decrease in case temperature (activation energy 0.65 eV)



Laser lifetime scales approximately as $1/P^3$. For example, a diode rated at 40 mW maximum output power gets a lifetime boost of 64x if run at 10 mW

Figure 20. Laser Reliability

Eye safety is also a concern among large service providers. There are primarily two classes of eye safety that free-space vendors build to—Class 1 and Class 1M. Basically, Class 1 certifies that the beam can be viewed under any condition without causing damage to the eye. Class 1M certifies that the beam can be viewed under any condition *except* by means of an aided viewing device, such as a binocular or other optical instrument. In terms of wavelength, the IEC60825 rulings permit 1550 nm devices to output about 50 times the flux level of near IR devices such as 780 nm lasers. While this can be an advantage, the detectors at 1550 nm are noisier; therefore, on a system level, although there is a slight advantage for link margin, it is usually at a *substantial* increase in cost, especially for carrier-grade systems where the atmosphere is the limiting variable in the link equation as discussed previously. The subject of eye safety is fairly arcane; for a good discussion see *Eye Safety and Wireless Optical Networks (WONs)* by Jim Alwan, AirFiber Inc.

SUMMARY

In summary, free-space optical systems can be enhanced to carrier-grade (99.9% or better) by following the simple design rules below, which apply for the vast majority of cities on the planet:

- Atmospheric physics fundamentally limit range to less than 500 m. Accept and design the hardware to meet this limit.
- The equipment must be hardened to withstand the rigors of an outdoor environment. It *must* meet Telcordia GR-63, GR-487, and NEBS Level 3 product integrity standards.
- Carrier grade systems *must* include tracking. This is the *only* way to guarantee link margin.
- Carrier grade systems *must* have a carrier-class EMS.
- Carrier grade systems *must* meet Class 1M or Class 1 laser eye-safety standards as defined in IEC 60825 rulings.
- Carrier grade systems should include an in-band management channel. This permits the carrier to avoid building an overlay network to manage the free-space optical units.