E. Korevaar et al, in Optical Wireless Communications V., Eric J. Korevaar editor, Proceedings: SPIE Vol. 4873 (2002) p. 155

Debunking the recurring myth of a magic wavelength for free-space optics

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MRV Communications

ABSTRACT

Free-Space Optics (FSO) is a proven, reliable technology for last mile telecommunications applications, used worldwide for both enterprise network building-to-building connections and for wireless access to more traditional land line communications networks. In most mid-latitude coastal cities, link availability at distances above a few hundred meters is primarily affected by fog and low clouds. At longer distances, heavy rain and snow can also affect the link. The most mature technology used in FSO equipment relies on low cost semiconductor lasers or LED's operating in the near infrared at wavelengths of 785 nm or 850 nm. In the past few years, systems operating at 1550 nm have also been developed. At first the vendors of these systems claimed that the 1550 nm wavelength had better propagation characteristics in severe weather than the 785 nm wavelength. With further analysis and research, those claims were withdrawn. Now there are claims that even longer wavelengths near 10 microns will solve the FSO link availability issues associated with severe weather. Hype about such magic wavelengths for FSO is both a disservice to the investors who will lose the money they are investing based on exaggerated claims, and to the rest of the FSO industry which should be creating realistic expectations for the capability of its equipment. In the weather conditions which normally cause the highest attenuation for FSO systems, namely coastal fog and low clouds, 10 microns offers no propagation advantage over shorter wavelengths.

1. INTRODUCTION

"Hot New Beam May Zap Bandwidth Bottleneck" was the title of a short article appearing in Science magazine on December 21, 2001. This article contained the following statements:

"Companies have recently been pursuing an alternative to laying fiber called free-space optics, in which an infrared (IR) laser beams data to a receiver on your rooftop. But the only cheap semiconductor lasers available aren't really up to the job. They work at a relatively short wavelength of about 1.5 micrometers, and the beams typically travel only a few hundred meters before being absorbed by water vapor in the air."

"…new semiconductor IR laser with a wavelength of about 9 micrometers. Because water vapor –and even rain, snow, and smog – absorbs only a tiny amount of light at that wavelength, free-space optical systems built with the new laser should work at distances of 2 kilometers."

"'We're very excited about it,' says Jim Plante, president of Maxima Corp., a San Diego, California, company that is working to develop free-space optics technology. 'With this technology we can conquer the weather.'"

"Plante says the approach could revolutionize free-space optical communications. Although companies specializing in the technology have raked in more than a billion dollars in investments, Plante says, the industry has been struggling to put shorter wavelength lasers to work. 'The use of mid-IR allows you to get the job done,' he says."

On January 22, 2002, one of us (Eric Korevaar) as CTO of Optical Access (formerly AstroTerra and now part of MRV Communications) wrote a joint letter with Scott Bloom (CTO of Air Fiber) to the editors of Science to let them know that they were hyping inaccurate information about atmospheric propagation at different laser wavelengths. That letter follows:

January 22, 2002

Editor
SCIENCE
1200 New York Avenue, NW
Washington, DC 20005
Science_letters@aaas.org

Dear sirs,

We would like to point out a serious error in the News of the Week article "Hot New Beam May Zap Bandwidth Bottleneck" by Robert F. Service appearing in the Dec. 21, 2001 issue of Science Magazine. The article promotes a start-up company's efforts to obtain venture capital funding at the expense of known science by making claims that free space optical communications systems based on 9 micron lasers can "conquer the weather" and "revolutionize free-space optical communications" by propagating through adverse weather conditions better than existing systems based on 850 nm or 1.5 micron lasers. In fact, it is easily shown that the wavelength dependence of laser propagation in fog, clouds, snow and rain is very slight from the visible out to 10 micron wavelengths. For snow and rain, the scattering particles are much larger than the wavelength, and the scattering cross-section is geometrical, going asymptotically as $2\pi r^2$, where r is the particle radius. For fog and clouds, wavelengths and particle sizes are similar, and a full Mie scattering calculation is necessary. The calculation shown in the figure for typical particle size distributions, courtesy of Bob Pierce at Terabeam Corporation, shows that there is no magic wavelength for fog and clouds, which are the worst attenuators for free space optical systems. Fog and clouds are essentially white from the visible out to 10 microns. At wavelengths much longer than 10 microns, molecular absorption becomes a serious problem.

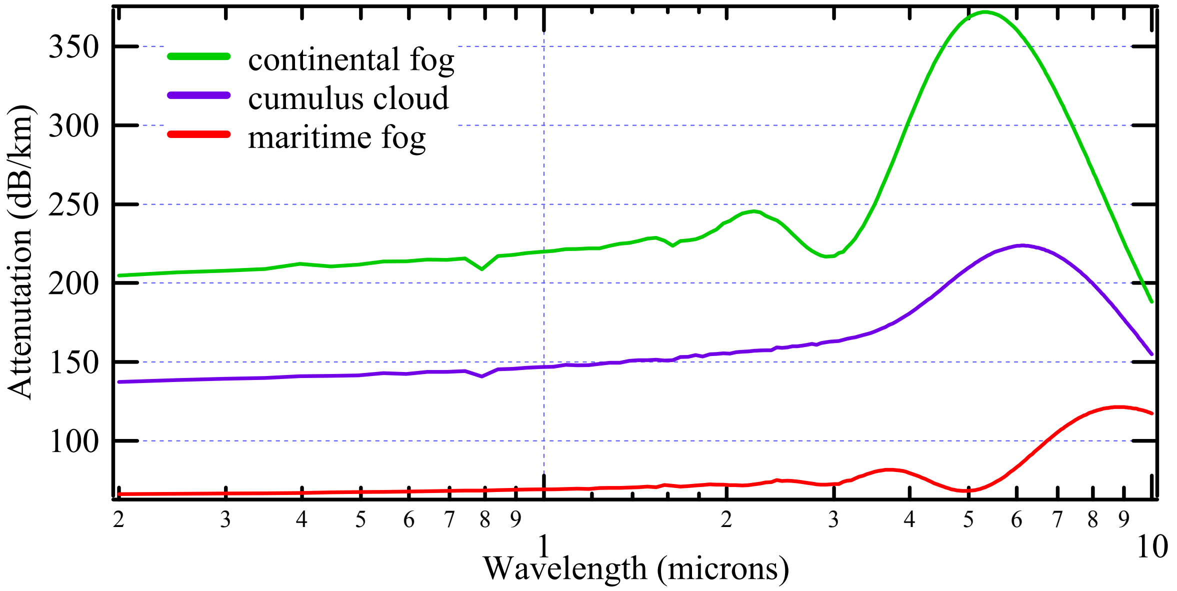

Figure 1. Calculated Mie scattering attenuation in dB/km for the various fog distribution models. Note the general trend for the main resonance is that it occurs at a wavelength roughly equal to the radius of the most common fog droplet. Note also that little fine structure remains. From R.M. Pierce et al, "Optical attenuation in fog and clouds," in *Optical Wireless Communications IV,* Eric J. Korevaar, Editor, Proceedings of SPIE Vol. 4530, 68 (2001).

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On February 21, 2002 we received a response from Science as follows:

From: Brian White
[mailto:bwhite@aaas.org]
Sent: Thursday, February 21, 2002 12:47 PM
To: Eric Korevaar
Subject: Decision on your letter to Science

Dear Mr. Korevaar, Thank you for giving us the opportunity to consider your letter about a news article published in Science. I regret to say that we have decided not to publish it. We receive many more letters than we can accommodate and must reject most of those submitted. Our writer's reply to the concerns that you had mentioned follows. Sincerely, Christine M. Pearce
Associate Letters Editor CMP/bw = = = = = = = = = = = = = = = = = =
I spoke again with my contacts on this story, and they had quite a bit to say about the letter we received. The letter refers to a previous study that claimed to show that the mid infrared laser that the group we covered had developed would do little or no better at penetrating fog (a necessity for transmitting data though the air). But what they failed to note was that this conclusion was not based on any real world data. Rather the graph they sited was a model based on a certain type of fog. One person I spoke with heads a company that is testing the real world performance of mid IR lasers and near IR lasers. He says that the model the letter refers to is simply wrong. It is very rare, he says, to see the type of fog that would render the mid IR laser no better than the near IR lasers. In fact, he says, their side by side comparisons show that the mid IR lasers steadily out perform the near IR lasers, and work better at longer distances. As a result, I don't see much point in us publishing the letter. Its objections are based on an inaccurate model, with no real world data to back it up. The real world data that is out there contradicts their assertion. And the authors of the letter are affiliated with companies that use near IR lasers for free space optics, and thus stand to gain by making this new approach seem no better than their own.

2. UNSENT REBUTTAL

We were somewhat incredulous at this response from Science, which we had heretofore thought was a credible scientific journal. One of us (Korevaar) drafted the following further rebuttal, but in the end decided not to send it, but rather to present these issues in this SPIE talk instead.

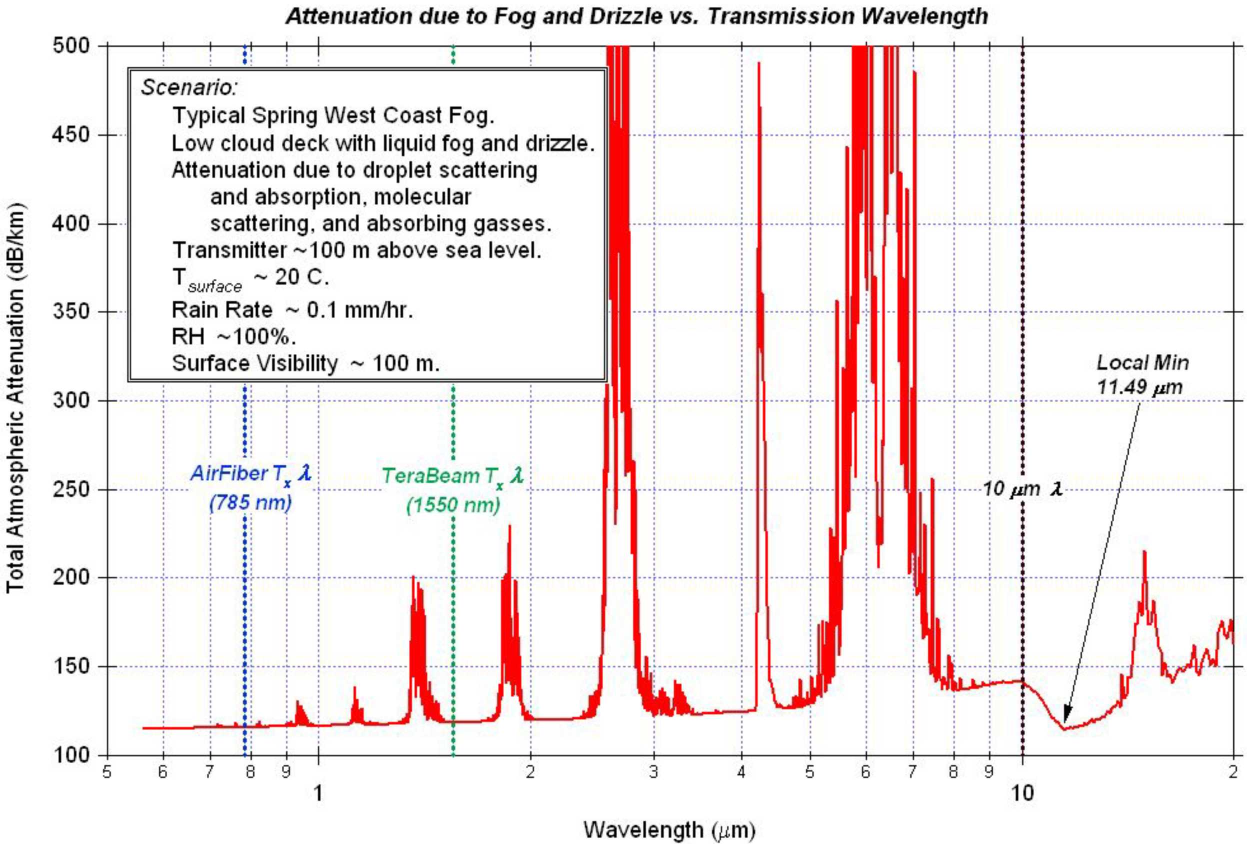
February 21, 2002

Christine Pearce
Associate Letters Editor
Science

Dear Christine,

Thank you for considering our letter to the editor regarding attenuation of various laser wavelengths in fog. It is true that Scott Bloom and I work for companies which use near IR lasers for free space optics, and stand to gain by discrediting the potential advantages of lasers at longer wavelength. But the company which your writer interviewed has a much larger vested interest in propagating the fallacy that there is an advantage to the longer wavelength than we have in discrediting it. We are both PhD scientists. We both have physics bachelors degrees from Caltech. My PhD is from Princeton, and Scott's is from Tufts. Our main concern in writing the letter was for the integrity of scientific fact. The letter writer chooses in his reply to our comments to elevate the unpublished views of one company over standard Mie scattering theory and standard measured fog particle size distributions, which are used in standard atmospheric scattering codes such as ModTran. If there is truth to the measurements of the interviewed company, then they should be published and explained so that the standard established models can be revised. In our letter, we used the published results of a third company which makes FSO equipment, TeraBeam Corp., specifically because 2 years ago when they received VC investment they made a big deal out of the idea that 1.55 micron wavelengths would propagate better through fog than 785 nm wavelengths. After receiving large VC financing and doing their own research, they have now published information showing that they were wrong and that the propagation in fog is no better at 1.55 microns. The same conclusion will hold out to 10 micron wavelengths. By giving credence to the unpublished data your writer uncovered, while ignoring established scientific models, you will lead investors to put their money into hype backed up by voodoo science. I think it is incumbent on your magazine to present a more balanced view.

Here is a graph which gives attenuation results from ModTran for a particular fog distribution and some height above the ground. It is a very usual situation for FSO equipment to be mounted on high buildings, which can be in the clouds. The attenuation is above 100 dB/km at all wavelengths in this graph. There is no laser system which will carry high data rates a distance of 1 km in this kind of weather.



Scenario:
Typical Spring West Coast Fog.
Low cloud deck with liquid fog and drizzle.
Attenuation due to droplet scattering and absorption, molecular scattering, and absorbing gasses.
Transmitter ~100 m above sea level.
$T_{surface}$ ~ 20 C.
Rain Rate ~ 0.1 mm/hr.
RH ~100%.
Surface Visibility ~ 100 m.

Figure 2. Attenuation in West Coast Fog vs. Wavelength. Courtesy of Eric Woodbridge and Scott Bloom, Air Fiber, Inc.. In addition to almost wavelength independent scattering from water droplets, high molecular absorption occurs at some wavelengths. Also, above a 20 micron wavelength, molecular absorption becomes severe.

The Infrared & Electro-Optical Systems Handbook (SPIE Press, Frederick Smith editor, 1993, Bellingham) devotes Volume 2 to Atmospheric Propagation of Radiation. This gives particle size distributions used for various weather conditions. These are used in the propagation codes LOWTRAN, MODTRAN and FASCODE. For a heavy advective fog (which would be found in coastal areas such as the Los Angeles airport or the San Diego airport fairly commonly), the most common particle radius in the distributions is 10 microns. (Table 1.31, page 109). For particle radius >> wavelength, the asymptotic scattering cross section is 2*π*r^2. For wavelength around the radius there are resonances in the Mie scattering cross section which could lead to higher or lower values, but tend to average out over a distribution of particle sizes. Because of the r^2 dependence, the total scattering cross section is heavily dominated by those particles at the large end of the radius distribution. This argues against the existence of a special low attenuation window at any wavelength below 10 microns in fog, rain, snow, hail, clouds, etc. as claimed by your writer.

I just did a quick search on the web for actual data on fog particle size distributions. (Search with Copernic 2000 under fog particle size distribution) I found a very nice thesis by Christos Kontogeorgakis, published 5/9/97 by Virginia Tech entitled "Millimeter Through Visible Frequency Waves Through Aerosols-Particle Modeling, Reflectivity and Attenuation." This thesis contains measured fog particle size distributions as a function of altitude at 5 locations, namely Vandenberg AFB, Ca, Arcata, CA, Santa Maria, CA, Huntington, WV, and Worcester, MA. I did not sort my data search in any way to try to obtain a particular conclusion, this was the first data I found. The Vandenberg particle size distribution appears to peak at 5 micron radius, with significant numbers out to 10 micron radius. The author of the thesis uses the particle size distributions to calculate attenuations at wavelengths of 0.5 micron, 2 micron, 10 micron, 3.2 mm, 6.8 mm and 8.6 mm and in between. The attenuation does not show significant variation between 0.5 and 10 micron wavelengths. The author makes the following statement in particular: "Especially, for the wavelength 10.6 microns, which is of particular interest, the b/M ratio ranges from about 619 to about 661 dB/km/gm^3 for the five sites with average 638 dB/km/gm^3. This is in very close agreement with experimental results found in the literature (610 dB/km [26] and 630 dB/km [14])." The measured distributions gave water contents which varied considerably with altitude, from between 0.02 and 0.08 g/m^3 at the ground up to 0.4 g/m^3 at 100 meter elevation. Using 0.04 g/m^3 and 638 dB/km/gm^3 gives an attenuation of 25 dB/km. Using 0.4 g/m^3 gives an attenuation of 250 dB/km. In cities like Chicago, for instance, it is not unusual for the tops of the buildings to be in the clouds with these kinds of attenuations. These attenuations are essentially independent of wavelength out to 10 microns.

In summary, I think it is scientifically fraudulent to propagate the idea in your magazine that Free Space Optics based on lasers at 9 micron wavelength can "work at distances of 2 km" while also saying that "the only cheap semiconductor lasers available aren't really up to the job. They work at a relatively short wavelength of about 1.5 micrometers, and the beams typically travel only a few hundred meters before being absorbed by water vapor in the air." Mie scattering theory and accepted fog particle size distributions say that propagation is barely wavelength dependent. The type of wavelength comparison measurements that your author sited are incredibly hard to do and prone to error. Shouldn't the burden of proof be on the person presenting evidence which contradicts the standard established theories rather than the other way around?

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3. FURTHER HYPE

In the spring of 2002, the San Diego Telecom Council prepared a special advertising section as an insert to Telephony magazine. The purpose of the insert was to highlight San Diego's leadership role in various aspects of telecommunications. The advertising insert contained one page (paid) profiles of a number of San Diego companies, including three dealing with Free Space Optics, namely Air Fiber, LightPointe and Maxima. The profile on Maxima contained the following statements in talking about using the 8-12 micron wavelength band for FSO links. The bold emphasis has been added by us:

"In sharp contrast to other FSO offerings, Maxima's technological enhancement makes its system **virtually impervious** to the bad weather that **cripples** all first-generation wavelength systems. Maxima's ability to deliver up to **200 dB/km less** attenuation in fog results in improved **distances up to 10 times** at "four nines" availability. While most rival FSO systems cannot reliably exceed 200 meters, some 90 percent of buildings are 250 meters to 1,200 meters from any available fiber, which means many times first-generation FSO systems are inappropriate for 90 percent of the access market."

"In addition, Maxima operates at up to **2,000 times higher power**, yielding better link margin, while its signals travel at wavelengths that are **safe to the eye**, hence **avoiding the serious safety concerns** that are inherent in many first-generation FSO products."

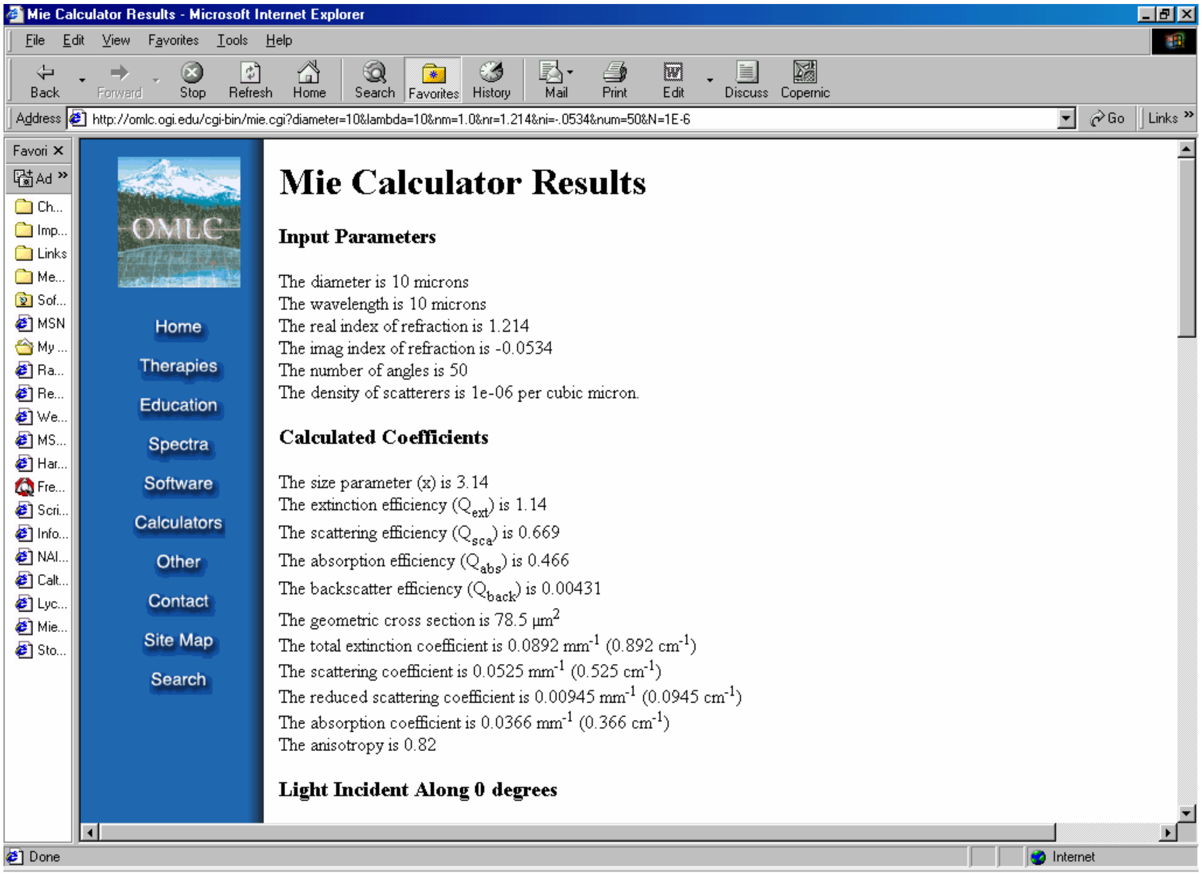
Although these statements by Maxima are both incredible and false, Maxima has recently been able to garner a few million dollars worth of venture capital funding with this kind of hype, even though we are far past the peak of the telecom bubble.

Before moving on to some science, we would like to point out that the Class 1M eye safe laser intensities vary from about 2 mW/cm^2 at 850 nm (based on light focusing onto the retina) to 100 mW/cm^2 for all wavelengths above 1.4 microns (based on surface heating of the eye or skin). Typical near infrared (785 nm) FSO systems transmit about 10 mW per aperture. A power 2,000 times this level would be 20 W. To be eye-safe, this would need to propagate in a beam with a diameter larger than 16 cm. If accidentally focused, 20W of laser power at 10 micron wavelength can easily start a fire.

4. Some Science

For the weather conditions which limit the availability of Free Space Optical systems, atmospheric propagation is governed by Mie Scattering. (This assumes that the system has been designed to avoid one of the many spectral regions of high molecular absorption due to atmospheric gases such as water vapor and carbon dioxide, as seen in Figure 2.) Mie scattering theory is an approximation of atmospheric propagation based on the scattering of light off of spherical particles with a particular index of refraction. In practice, for calculating the expected attenuation of a laser beam over an atmospheric path, the fact that all of the particles are not spherical does not seem to have a large impact on the accuracy of results calculated using Mie scattering theory. Calculations are typically done numerically, since the equations involve summations of combinations of Riccati-Bessel functions and their derivatives. (A good Ph.D. thesis topic would be to devise a simple to use approximation to Mie theory which is accurate to within 10 or 20%, and which is easy to explain). There is a nice Mie Scattering Calculator program at http://omlc.ogi.edu (Figure 3) and that is what we used for the following calculations.

As shown in Figure 4, the scattering cross-section for laser radiation from a single spherical particle of radius r and index of refraction n falls into one of three regions depending on the wavelength λ relative to r. In the geometric region where λ is much smaller than r, the scattering cross-section is approximately 2πr^2, even for particle index of refractions very close to that of the propagation medium. For wavelengths much larger than r, scattering falls into the Rayleigh Region and falls off rapidly with longer wavelengths. In between, where λ and r are similar, there is a resonance region where the wavelength functionality of the scattering is more complicated. Note however, that (for water droplets) the scattering cross-section tends to peak at a value of about 4πr^2 (double the geometrical cross-section) when the wavelength is about equal to the particle radius. Also, because of the r^2 weighting, scattering in a fog or cloud consisting of a distribution of particles of different sizes is heavily dominated by the larger particles. One simplifying assumption used for the calculation in Figure 4 for a 5 micron radius water droplet was that the index of refraction was constant vs. wavelength at n=1.33. As we shall see later, this assumption is not accurate. However, the figure shows the qualitative behavior of scattering vs. wavelength. Of particular note is that rain and snow particles are far, far larger than any of the laser propagation wavelengths (even 10 microns) being considered here, and the scattering in heavy rain or snow will be essentially wavelength independent for all FSO systems.



http://omlc.ogi.edu/cgi-bin/mie.cgi?diameter=10&lambda=10&nm=1.0&nr=1.214&ni=-.0534&num=50&N=1E-6

Mie Calculator Results

Input Parameters

The diameter is 10 microns
The wavelength is 10 microns
The real index of refraction is 1.214
The imag index of refraction is -0.0534
The number of angles is 50
The density of scatterers is 1e-06 per cubic micron.

Calculated Coefficients

The size parameter (x) is 3.14
The extinction efficiency (Q_{ext}) is 1.14
The scattering efficiency (Q_{sca}) is 0.669
The absorption efficiency (Q_{abs}) is 0.466
The backscatter efficiency (Q_{back}) is 0.00431
The geometric cross section is 78.5 μm^2
The total extinction coefficient is 0.0892 mm^{-1} (0.892 cm^{-1})
The scattering coefficient is 0.0525 mm^{-1} (0.525 cm^{-1})
The reduced scattering coefficient is 0.00945 mm^{-1} (0.0945 cm^{-1})
The absorption coefficient is 0.0366 mm^{-1} (0.366 cm^{-1})
The anisotropy is 0.82

Light Incident Along 0 degrees

Figure 3. Mie Scattering Calculator website at http://omlc.ogi.edu/calc/mie_calc.html

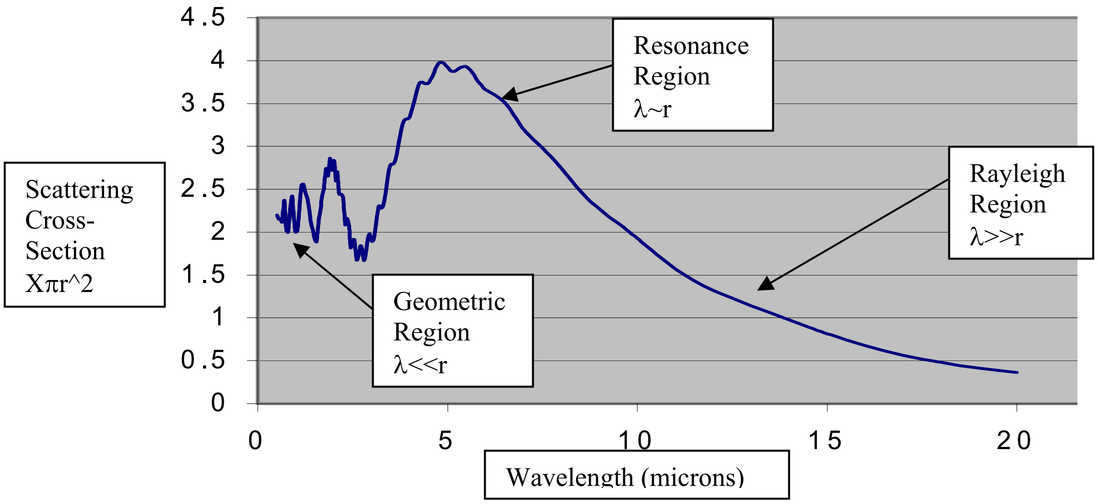


Figure 4. Scattering Cross-Section (x πr^2) vs. wavelength (microns) for a 5 micron radius water droplet, assuming a constant water index of refraction of 1.33.

Since the Mie Scattering of light by spherical water droplets from fog or rain is a well established theory, we need to look at expected particle size distributions to see if there is a reason to expect a magic propagation window at longer wavelengths. The Infrared and Electro-Optical Systems Handbook, Volume 2, Atmospheric Propagation of Radiation, Frederick G. Smith, Editor, SPIE Press 1993 gives parameters for use in size distribution models for different fog and cloud conditions in Tables 1.30 and 1.31. Figure 5 shows the expected particle size distributions for a Moderate Radiative Fog with 200 particles per cubic centimeter and a 34 dB/km attenuation in the visible (tall left peak), a Cumulus Cloud with 100 particles per cubic centimeter and a 68 dB/km attenuation (middle peak), a Cumulus Cloud with 250 particles per cubic centimeter and a 570 dB/km attenuation (right peak) and a Heavy Advective Fog with 20 particles per cubic centimeter and a 125 dB/km attenuation (low broad distribution). The advective fog should be most typical of a coastal fog occurring in mid-latitudes.

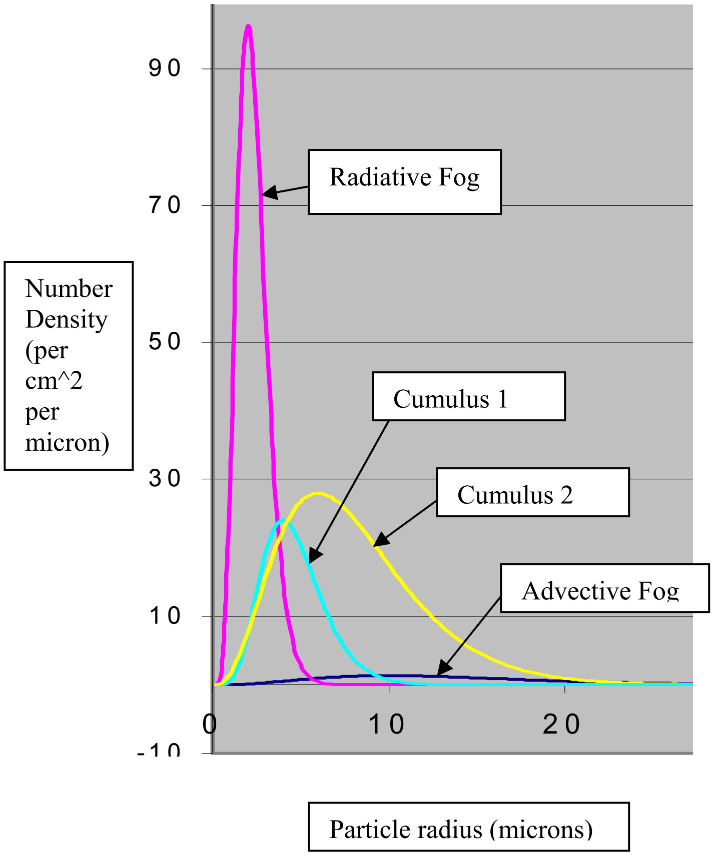


Figure 5. Particle Size Distributions for Two types of Fog and Cumulus Clouds (calculated from tables 1.30 and 1.31 in IR/EO handbook Volume 2).

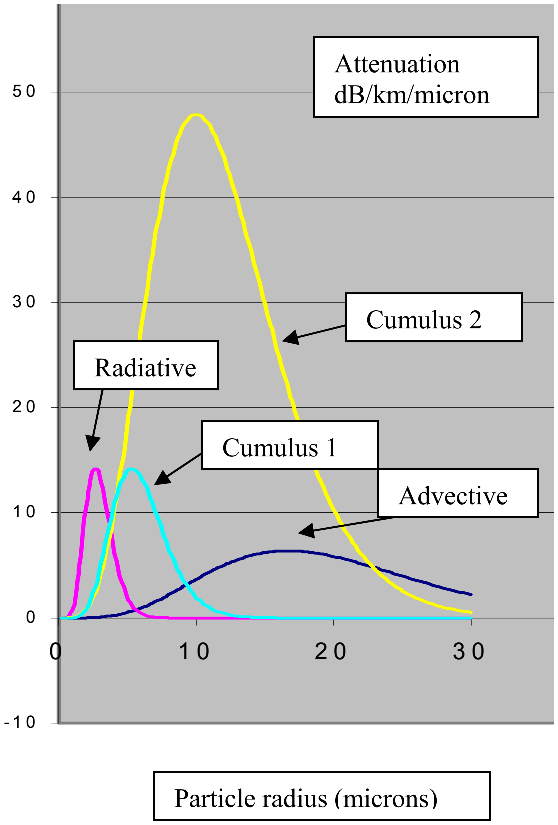


Figure 6. Contribution of particles to total attenuation for fog and cloud distributions of Figure 5. Note r^2 weighting to large radius.

In figure 6, the contribution of different particles in the distributions of figure 5 to the total attenuation (dB/km/micron) is shown. Because of the r^2 weighting in the scattering cross-section, we see that the particles with large radius contribute much more to the attenuation than those with small radius. For this reason, even a small fraction of particles having a radius larger than the highest propagation wavelength of interest will lead to the attenuation being essentially wavelength independent. (Clouds are white, even far into the infrared). Also, to a fair degree of accuracy the attenuation can be calculated using the geometrical scattering cross-section of 2πr^2 for each particle and integrating over the particle size distribution, ignoring the more complicated Mie scattering resonance behaviors. As we can see from figure 6, even though the radiative fog (which occurs due to overnight cooling in low valleys) has a larger number of particles per volume than the advective fog (which occurs in coastal areas), the advective fog leads to much higher attenuation (because the particles are larger) and the attenuation will be fairly wavelength independent up to ten microns.

To simplify calculations (basically allowing them to be done in an Excel spreadsheet), we fit a simplified parametrized curve to the scattering cross-section curve of figure 4. The rationalization for this is that the oscillating cross-section behavior in the resonance region will basically average out when the cross-section curve is integrated over the particle size distribution. The same curve can be used for all wavelengths and radii since the scattering cross-section in this approximation is only a function of the ratio λ/r. (This approximation should work as long as the index of refraction of the scattering particle is wavelength independent. Some effects of using the correct wavelength dependent index of refraction are addressed at the end of the paper). Figure 7 shows the parametrized curve we used for further calculations, compared to the Mie scattering cross-section. The curve falls off as (r/λ)^4 for long wavelengths as it should. The parametrized equation we used was as follows. (No scientific significance should be given to the form of the equation).

Scattering Cross-Section Q = exp(-9*(r/λ)^2) * 175 * (r/λ)^4 + exp(-1.25 * (λ/r)^2) * (2 + (λ/r)^3 * 11.7).

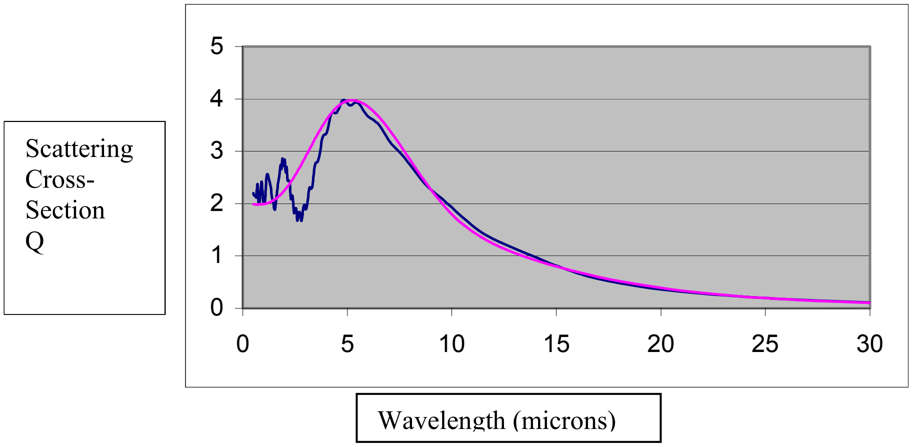


Figure 7. Parametrized curve fit for Mie scattering cross-section of 5 micron radius particle, and constant n=1.33.

This parametrized curve was combined with the particle size distributions of Cumulus Cloud 1 and of the heavy advective fog to calculate attenuation vs. wavelength. In figures 8 (cloud) and 10 (fog) the contributions from different particle size bins are shown, using 1 micron bins for the cloud and 2 micron bins for the fog. In figures 9 (cloud) and 11 (fog) the resulting total attenuation vs. wavelength is shown.

For the cumulus cloud example, we chose the cloud with the lower attenuation from the typical particle size distributions given above. This cloud does have some fall off in attenuation with longer wavelengths at 10 microns compared with that around 5 microns. However, there is no propagation advantage when compared to the near IR wavelengths close to 1 micron.

For the advective fog, which has a significant number density of particles with large radius, the attenuation is significantly worse at 10 microns than at 1 micron. This fog particle size distribution would be typical of what we would expect when the visibility falls below 100 meters or so. At some locations, such as the Los Angeles airport, the visibility falls below 100 meters about 0.04% of the time. This is significant for a carrier class system which is expected to have an availability of 99.99% or better. (Often 99.999%). The Free Space Optics system must work at the specified range in attenuations higher than 100 dB/km to come close to these availabilities in the most populous North American cities. Using a wavelength around 10 microns does not help in solving this issue for such a fog.

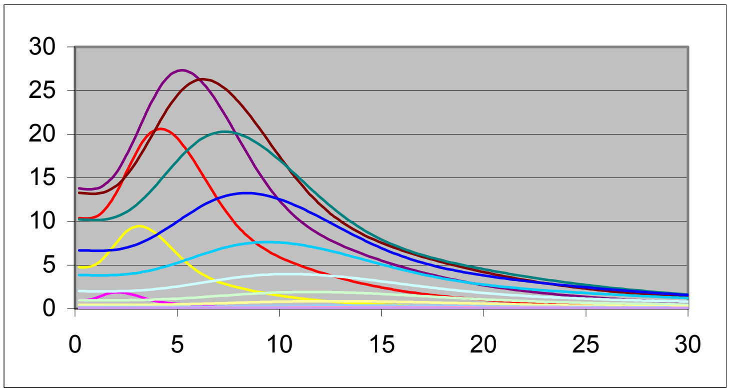


Figure 8. Contributions of particles in one micron bins from 1 micron to 15 microns to attenuation vs. wavelength for Cumulus Cloud 1. The vertical axis is attenuation in dB/km, and the horizontal axis is wavelength in microns. The largest contributors for this cloud are the particles with 5 and 6 micron radii.

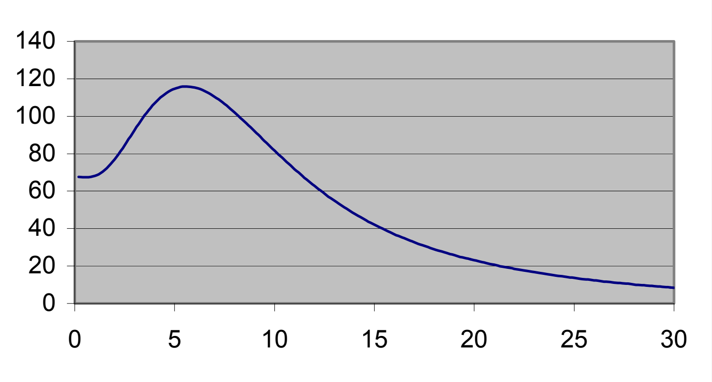


Figure 9. Total calculated attenuation vs. wavelength for Cumulus Cloud 1. (This is a fairly light cumulus cloud). The vertical axis is attenuation in dB/km and the horizontal axis is wavelength in microns.

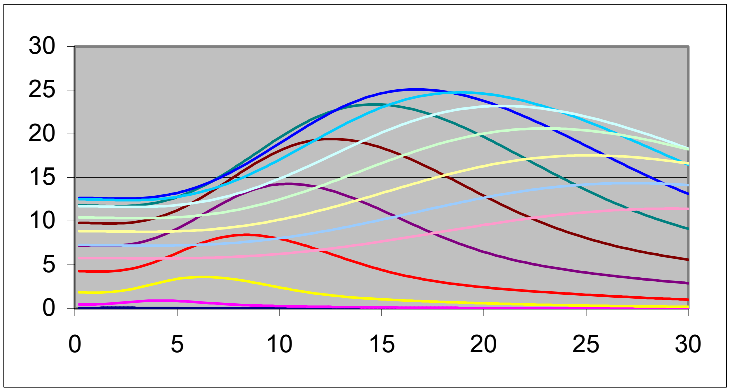


Figure 10. Contributions of particles in two micron bins from 2 to 28 microns to attenuation vs. wavelength for the Advective Fog. The vertical axis is attenuation in dB/km and the horizontal axis is wavelength in microns. The largest contributors for this fog are the particles with 16 and 18 micron radii.

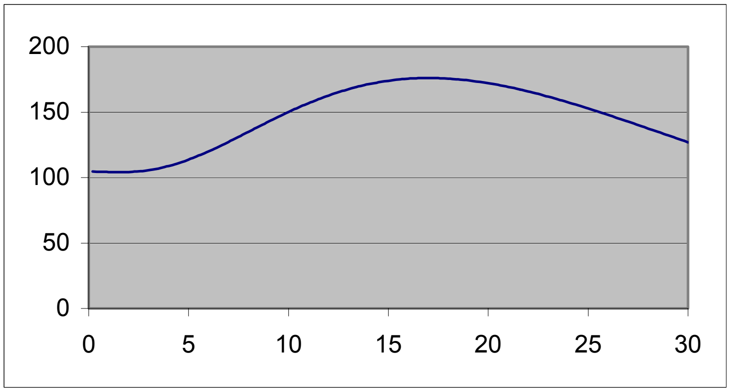


Figure 11. Total calculated attenuation vs. wavelength for heavy advective fog. The vertical axis is attenuation in dB/km and the horizontal axis is wavelength in microns. Note that for this fog, typical of heavy mid-latitude coastal fogs, the attenuation is high across the whole range of wavelengths which might be considered for Free Space Optics.

5. Index of Refraction Adjustment

As mentioned previously, the approximations used above to calculate attenuation vs. wavelength for different particle size distributions should be fairly accurate if the index of refraction of water is constant at n=1.33. However, these calculations did not show any advantage in laser propagation for wavelengths near 10 microns, even though we have no reason to doubt the published cloud and advective fog particle size distributions. Therefore, we wondered if the explanation for a claimed advantageous propagation window could be found by looking at the index of refraction. The reason this could provide an explanation is that the scattering is related to the change in index of refraction at the air/water interface. The less the index of refraction difference, the less scattering (just as for reflection of light at the surface of a piece of glass). Figure 12 gives measured values of the index of refraction of water vs. wavelength. This data contains both the real part of the index (related to the scattering) and the imaginary part (related to absorption by the water droplets).

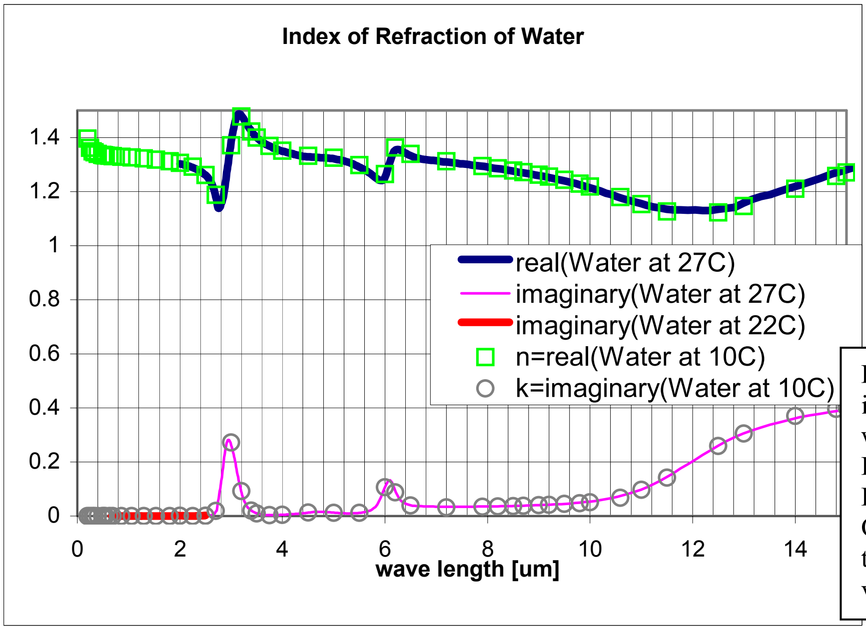


Figure 12. Real and imaginary index of refraction of water vs. wavelength. Data from HITRAN CD ROM, H.D. Downing and D. Williams, Optical constants of water in the Infrared, J. Geophys. Res., vol. 80, pgs. 1656-1661, 1975.

This index of refraction data is interesting, in that it shows a significant dip in the real part of the index of refraction at a wavelength of 12 microns. If the decrease in scattering is not compensated by a concurrent increase in absorption at those wavelengths, this could lead to a propagation advantage for weather conditions which aren't dominated by larger particles. To test this idea out, we did a comparison of the attenuation we would expect for the Cumulus Cloud 1 (where attenuation was dominated by the 5-6 micron particles) assuming n=1.33 as in the previous calculations, and the actual values of the index of refraction from the HITRAN CD ROM. (HITRAN is a standard high resolution atmospheric propagation code). This comparison is given in Figure 13.

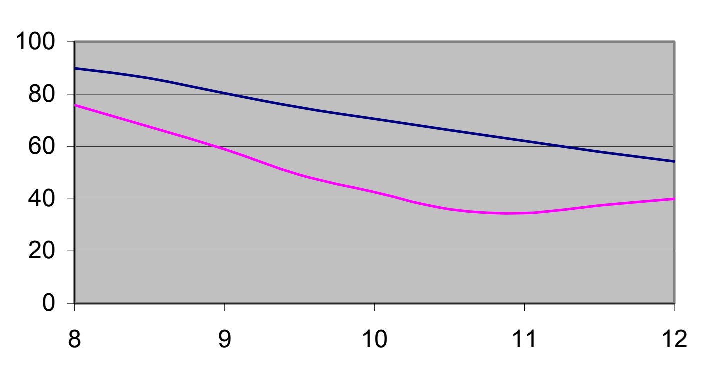


Figure 13. Comparison of attenuation vs. wavelength for Cumulus Cloud 1 using water index of refraction n=1.33 (top curve) and the actual real and imaginary index of refraction (bottom curve). The vertical axis is attenuation in dB/km and the horizontal axis is wavelength in microns.

From this chart, we can see that there is some propagation advantage (about 30 dB/km) at the 9-11 micron wavelength region in this particular kind of cloud. This advantage would also occur in the radiative fog distribution discussed above. However, for the higher attenuation conditions of the Cumulus Cloud 2 and the Advective fog (which is of the most concern), this advantage would disappear because in that case there are significant numbers of particles with larger radii than the wavelength. As a final comment on Figure 13, although the real part of the index of refraction has a minimum at 12 microns, the attenuation minimum is closer to 11 microns because of the increase in absorption at longer wavelengths. Note that this attenuation minimum also showed up in Figure 2.

6. Conclusions

We have provided evidence based on standard, well established Mie Scattering Theory, along with standard, accepted particle size distributions for water droplets in clouds and fog, to show that there is no significant propagation window that gives significant advantage to long wavelengths near 10 microns compared to short wavelengths near 1 microns with regard to laser propagation for Free-Space Optics systems. In weather conditions such as rain and snow, the propagation characteristics will be insensitive to wavelength because of the large particle sizes and geometrical scattering. In heavy cumulus clouds and heavy coastal fog, which are the main availability limiting weather conditions for FSO in the large coastal cities of the United States, there appears to be a slight propagation advantage for the shorter wavelengths because of resonances with particles of radius close to 10 microns. For radiative fog, some light cumulus clouds (and also haze) there will be some advantage for propagation at 10 microns. However, in no case do those advantages come close to matching the hype surrounding the design of some FSO systems at the longer wavelengths. For the unfortunate investors, CAVEAT EMPTOR.