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Laser Communications Through the Atmosphere

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Abstract

Atmospheric properties affecting laser propagation with reference to optical communications are reviewed. Some of the optical space network configurations and various diversity techniques that may need be utilized to develop robust bi-directional space-earth laser communication links are explored.

1. Introduction

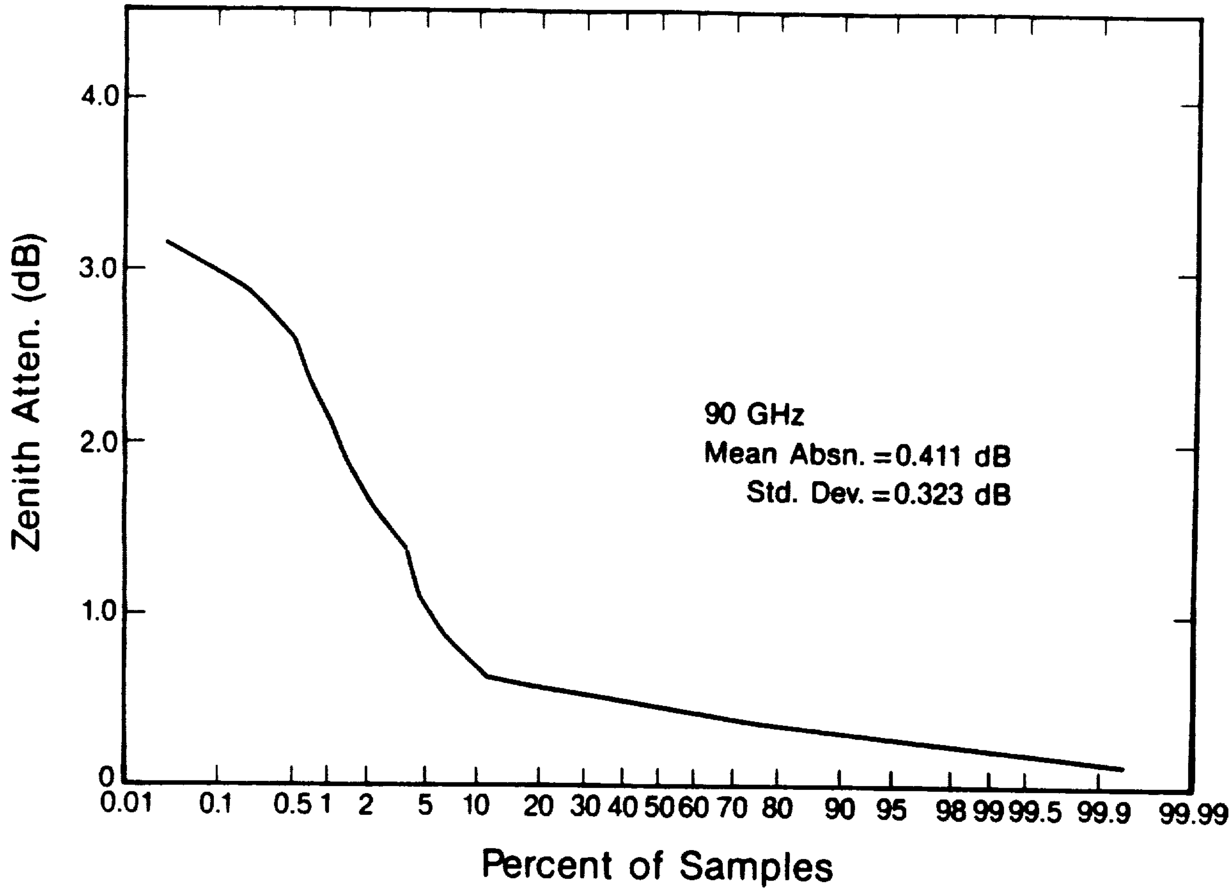
The interest in laser optical communications follows a dominant trend in communications systems research. Communications systems with higher carrier frequencies are inherently capable of operating at higher antenna gain and modulation bandwidth. Optical frequencies ($\approx 10^{14}$ Hz) are several orders of magnitude higher than the operating carrier frequencies of the conventional radio frequency (RF) communication systems ($\approx 10^{10}$ Hz) in use today. The promise of large antenna gain and enormous modulation bandwidth, which become available at optical frequencies, provide basic reasons for the compelling interest shown by commercial, civilian, and military establishments in the development of optical communication systems.

For similar modulation depths, the gain in the available bandwidth will be about 10^4-fold for optical communication systems. Also, for a given transmitter antenna size, the angular beamwidth is inversely proportional to the carrier frequency and the spatial power density at the receiver corresponds to the square of the frequency. This implies, for example, that the power density at the receiving aperture will be 10^6 times larger for an optical system with a 0.1 m antenna operating at 10^{14} Hz than for a system with 10 m antenna operating at 10^9 Hz. Optical systems with bit rates higher than a Gbit/s without multiplexing have been achieved; with various types of multiplexing 10^5 Gbit/s data rate is possible [1].

Optical systems also promise to be smaller in size and weight and have lower power consumption as compared to RF systems with similar performance characteristics. A decrease in the equipment size is very desirable as it will result in lower costs to put communication satellites in space. In the case of other space missions, the advantage of size and weight will leave more room for scientific payloads and allow for more flexibility in spacecraft design.

Since optical transmitters experience relatively much lower diffractive spreading, optical communications provide excellent means for the design of secure systems with low probability of intercept and, intentional or unintentional, jamming. Tight laser beams also provide extensive opportunities for frequency reuse.

In short, laser communication technology has the potential to provide (i) an enormous data bandwidth



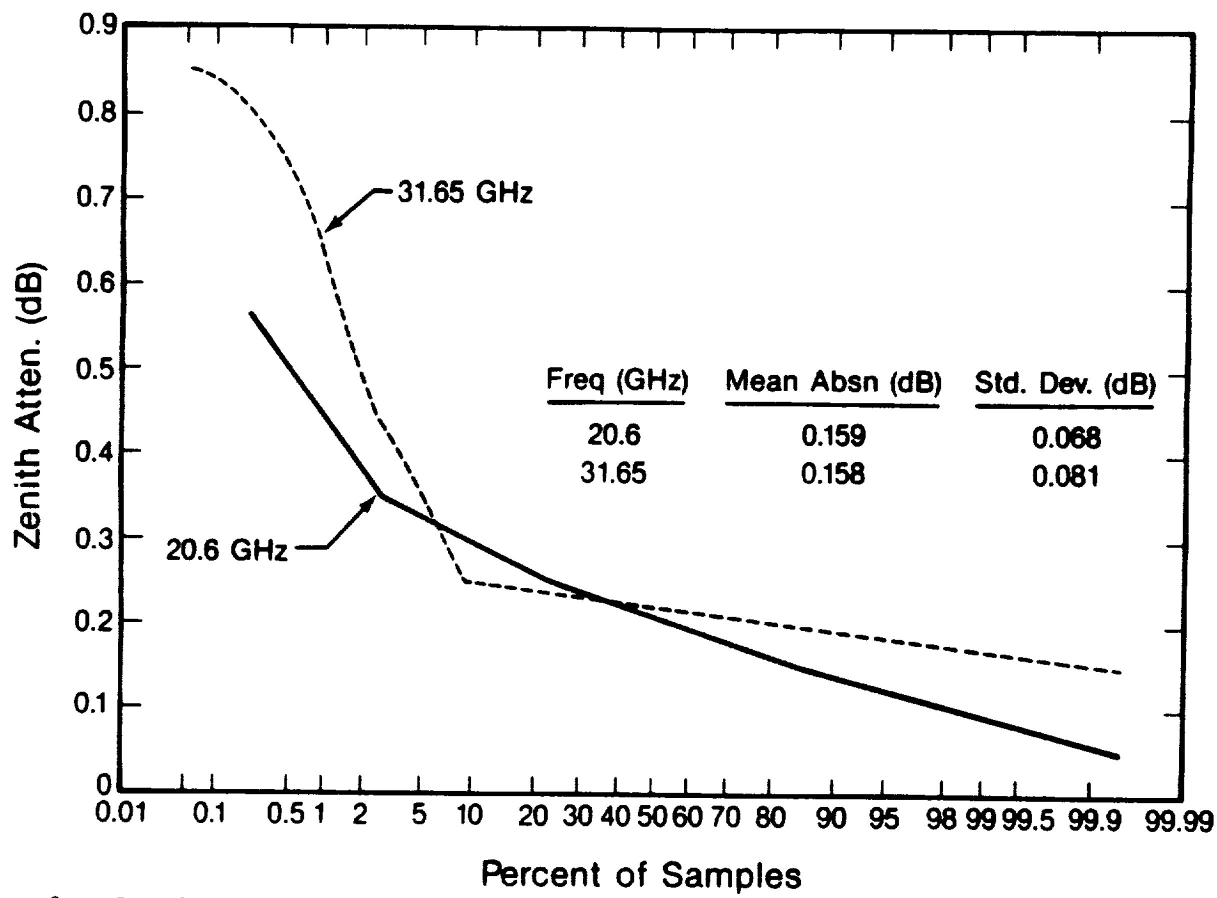


Fig. 3. Cumulative distribution of zenith attenuation measured by 3 channel radiometer at Denver, Colorado, December 1987. 14181 two-minute averages.

for significantly improved channel performance, (ii) a significant advantage in weight, size, and power consumption over RF systems, and (iii) non-interacting multiple access link geometries that are amenable to extensive frequency reuse, and secure systems with low probability of interception and jamming.

The commercial interest in laser communications is focused on the development of a high quality multiplexed voice, video, and data transmission network. The commercial sector envisions a network of satellites and ground stations to move information efficiently on a global scale. However, there is strong competition from the relatively mature fiber optic technology for point-to-point communications. Since the terrestrial and under-sea fiber links between the continents are being under-utilized at present, the commercial sector, at least for the short term, has lost some of its enthusiasm for the development of a global satellite communications network.

The civilian interests are based on the need to develop high throughput real time data transfer mechanisms for remote sensing or earth resource satellites in low earth orbits. The data from low earth orbiting satellites will, perhaps, be first transmitted to strategically placed geosynchronous satellites for subsequent transfer to appropriate ground station. Other applications include communication links to science probes in deep space for planetary and extra-planetary exploration.

2. Optical Communications in Atmosphere

The atmospheric channel for optical communication is characterized by (i) attenuation due to scattering and absorption by molecules and other particulate matter, (ii) diffractive and turbulent beam spreading, (iii) log-normal fading due to scintillation, (iv) a coherence bandwidth of 10^{10} Hz or greater, (v) a long coherence time ($\sim$ 1 msec), (vi) a significant wavefront distortion, which, among other things, limits the power collecting capability of a diffraction limited receiver, and (vii) background noise from stellar and earth-based light sources [1-4].

Shapiro and Harney [5] have developed an expression for the received power, $P_R(t)$, in terms of the transmitted power, $P_T(t)$, and relevant atmospheric propagation effects. Neglecting the propagation delay and background noise effects, we have

$$P_R(t) = P_T(t)(D_R^2/\pi\theta_T^2 Z^2)\ \epsilon\ \exp[-\tau]\ \exp[2u(t)], \tag{2.1}$$

where $(D_R^2/\pi\theta_T^2 Z^2)$ represents free space propagation loss in terms of receiver diameter D_R, transmitter beam divergence θ_T, and path length Z. ϵ is the efficiency of the optical system, τ is the optical depth for the propagation path due to scattering and absorption, and $u(t)$ is the time varying aperture-averaged log-amplitude fluctuation due to turbulence. Exp$[2u(t)]$ is, then, the time varying aperture-averaged irradiance fluctuation at the receiver.

The only noticeable effect of scattering and absorption due to gas molecules, aerosols, and other particulate matter in the atmosphere is signal attenuation. The optical depth τ in eq. (2.1) expresses this attenuation loss (Bouguer's law). If $\gamma_t(z)$ at position z is the total scattering and absorption coefficient due to various atmospheric constituents, the optical depth is given by

$$\tau = \int_0^Z \gamma_t(z)\ dz, \tag{2.2}$$

where Z is the distance over which the laser light travels through the atmosphere.

Eq.(2.1) disregards the effect of fluctuations in the angle of arrival at the receiver. In heterodyne systems this leads to a loss in the mixing efficiency. For direct detection schemes, the focused signal moves randomly in the image plane affecting energy collection capabilities of the system at the detector. It has been shown that incorporation of tilt correction techniques into the receiver system can result in improvements as high as 8 dB [6].

Scintillation and loss of communication link due to opaque clouds are two of the most important problems, and will be discussed in the following paragraphs. We will also look at some of the possible optical space network (OSN) configurations and explore various diversity techniques.

2.1 Scintillation

Scintillation causes fades and surges in received signal power. These fades may be as long as 10 msec, which is long enough to wipe out an entire message packet. The fade level, F in dB, is defined as [7]

$$F = -10 \log[I(t)/I_m], \tag{2.3}$$

where I_m is the mean and $I(t)$ is the instantaneous irradiance observed. Yura and McKinley [7] have developed various results to compute the fraction of time that a fade exceeds some given value. For the worst case scintillation, fades exceeding 3 dB occur more than 50% of the time and fades exceeding 10 dB occur more than 10% of the time. For more reasonable values of scintillation strength, fades exceeding 10 dB occur only 1% of the time.

An obvious strategy to counter scintillation effects is to incorporate sufficient excess margin into the optical link. With this approach for an earth-space link, a margin of 20 dB will be necessary for the system to work properly 99.9% of the time under worst case scintillation. However, this costly solution to the problem can be avoided by employing temporal diversity. These methods include simple repetition of the message, coding, and interleaving. If coding is used, a careful matching of coding schemes to the channel can provide substantial improvement in performance [8].

2.2 Opaque Clouds

Another aspect of the problem that is not readily apparent from eq.(2.1) is the non-zero probability of opaque cloud cover. Presence of thick clouds, in general, will have a catastrophic effect on the availability of an optical communication link. Though scattered laser light is available for communication, the system has to be designed to have (i) a wide field of view to collect enough power, which greatly increases the background noise and (ii) a low data rate to avoid inter-symbol interference due to pulse spreading. Also, polarization coding of the signal can not be used as the scattered light is depolarized. An optical communication system designed to employ the scattered beam, then, quickly loses its advantages over the conventional systems.

An OSN for optical communications can be designed to avoid the clouds by employing spatial and temporal diversity. We need to identify sites for the installation of optical receiver/transmitter stations where the clouds have a low probability of occurrence. Several such sites with uncorrelated weather patterns may need be operated simultaneously to obtain desired link availability.

Cloud cover exhibits a number of cycles, nocturnal, diurnal, seasonal, and long range. A large number of databases, statistical studies, and computer models are available in the literature which describe and simulate cloud behavior. However, it is not clear how much of it is useful or relevant to optical communications. A concrete view of the OSN is essential to help identify available information that may be worthwhile for our purposes. We will discuss two representative configurations of an OSN and see how spatial diversity can be employed to develop robust communication links.

2.2.1 Dispersed Direct Link

The network may be designed to have 6-9 receiving stations roughly equidistant from each other, and placed around the globe near the equatorial region. The inter-station distance would be roughly 5000 km and the individual sites will be chosen for their high probability of having clear weather. Since the characteristic scale of a weather pattern or a climatic zone is of the order of a few hundred kilometers, the adjacent stations would lie in different climatic regions and thus have uncorrelated cloud cover statistics. For satellite-earth links with tight laser beams, the pointing capability of the spacecraft telescope may be employed to hand-off the communication channel to appropriate ground station. We will need to work out joint cloud cover statistics for two or more consecutive sites for link availability. In cases where the spacecraft is several light-hours away, it would be necessary to develop models with the ability to predict future cloud cover statistics. The probability of an outage for this configuration will be low because (i) several stations are monitoring the signal jointly or the spacecraft has the ability to point to one of several stations by choosing the optimum site for cloud-free optical communication, and (ii) the stations lie in different climatic zones and hence their weather patterns are uncorrelated. Since the receiving sites are far apart, there is no initial need to obtain high resolution data on cloud cover. Later, to examine and validate a short list of likely sites high resolution site specific data will be required. The temporal resolution of the data has to be high to compute short-term outage statistics accurately. For validation purposes we will need to do a cloud-free line of sight (CFLOS) and cloud-free arc (CFARC) analysis to compute outage probabilities for single sites as well as jointly for two or more sites. (discussed below).

2.2.2 Clustered Direct Link

For economical, geophysical, or geo-political reasons, the OSN may consist of only 3-4 locations around the globe, chosen for their optimally cloud-free skies. In this configuration, one may build a cluster of two or more autonomous receiving stations on each of these locations. Note that this geometry also includes the case where a single geosynchronous satellite, which accepts messages from other satellites, planes, and ground stations, is linked to a single cluster of receiving stations. Let us consider an extreme situation where the receiving stations are only a few tens of kilometers apart from each other at each of the selected regions. For a major portion of the time the spacecraft can point to only one of these clusters, handing-off the signal beam to the next cluster as it rises above the horizon.

We will need to do most of the studies listed in the preceding section to determine the suitability of sites for ground stations. However, spatial resolution on sky cover in this case needs to be very high (about an order of magnitude better than the distance between the ground sites). The stations would all be in the same climatic zone, and hence their weather patterns will be correlated. An ultra-high temporal resolution may be necessary to extract meaningful statistics. The outage times when all the ground stations are unable to receive will happen more often, and will be of longer duration when compared to the dispersed configuration discussed in sec. 2.2.1 above for the same number of receivers on ground.

2.3 Weather Models and Simulations

Almost all data and statistics currently available on cloud cover is not readily amenable to the study of optical communications through the atmosphere. The next best thing to do is to use available weather data, which is incomplete and insufficient, as a guide to develop computer models and simulations that mimic real time dynamic behavior of clouds. An early model for cloud cover was developed by scientists at SRI International. Work at AFGL, which is based on the SRI model, has produced considerably sophisticated computer simulations of cloud dynamics. The computer programs developed by AFGL may be used to compute cloud-free line of sight (CFLOS) or cloud-free arc (CFARC) probabilities for any site. It is also possible to compute joint CFLOS and CFARC probabilities for two or more sites. These statistics, needless to say, are of great importance to the development of an OSN.

Shaik [9] has proposed a preliminary weather model that may be used to compute link availability statistics. The model may be used to predict joint probability for the percentage time for which weather is such that the extinction loss through the atmosphere is less than some threshold for at least one of the ground stations. If $\omega_n(\tau)$ is the cumulative distribution function (CDF) giving percentage weather for n sites for which at least one of the sites has an optical depth of the atmosphere less than or equal to τ, then the model states that

$$\omega_n(\tau) = 1 - [q \exp[-b(\tau - \tau_0)]]^n, \quad (\tau \geq \tau_0), \tag{2.4}$$

where τ_0 is an empirical constant representing the minimum possible optical depth of the atmosphere associated with an average clear day, b is a site-dependent parameter to model the slope of the CDF curve, and q is the probability of non-clear skies and is assumed, for simplicity, to be the same for all sites. The probability of non-clear skies, for example, in the southwestern US are less than 0.4 and the worst case value for the parameter b is 0.03 [10]. Hence, for a single site in the southwestern U.S. with $q = 0.4$, $\tau_0 = 0.6$, and $b = 0.03$, the probability that the optical depth $\tau \leq 1.0$ (-4.3 dB) is $\omega_1(\tau = 1) = 0.61$. If there are three such independent and identically distributed sites, we have $\omega_3(\tau = 1) = 0.94$. In other words, if a system is designed to absorb extinction loss of 4.3 dB, a three-site receiving network will be functional 94% of the time. However, it is not very clear how the independence of weather patterns at various sites can be insured. It is known, as noted earlier, that the scale size of weather patterns is of the order of a few hundred kilometers, and this measure may be used to find sites with uncorrelated weather. Joint observation of weather parameters for the probable sites will be necessary to make a more accurate determination.

2.4 Other Diversity Techniques

We have discussed path or site diversity in some detail in the sec. 2.3 as it appears to be one of the most important techniques for the design of robust optical communication links. We have also touched on temporal diversity to overcome short-term turbulence induced fades. Brandinger [11] and Engelbrecht [12] have suggested a number of other diversity techniques. Some of these are (i) frequency diversity, (ii) transmitter power diversity, and (iii) transmission delay or temporary data storage diversity.

Apart from strong molecular scattering and absorption lines, the effect of the atmosphere on optical frequencies does not change much over the entire range. For example, the refractive index of the atmosphere changes by 10% and the effect of changing humidity is quite small for all optical frequencies. It may be concluded that the use of frequency diversity can not provide acceptable engineering gain in system design.

The use of transmitter power diversity can be a feasible solution to counter the loss through the atmosphere, especially for the uplink configuration. The power output of ground lasers may be adjusted so as to maintain a constant power level at the spacecraft receiver. However, the transmitter configurations on spacecraft at present must use maximum attainable laser power leaving little room for the use of power diversity.

Temporary storage diversity is an attractive alternative, but only when real time operation is not necessary.

3. Conclusion

We have discussed some of the pressing problems that need to be investigated in depth to acquire necessary know-how for the development and design of an optical communication link through the atmosphere.

Scattering and absorption attenuate the signal. It is therefore necessary to use higher transmitter power to maintain a given irradiance level at the receiver when the laser beam must travel through the atmosphere rather than free space.

Refractive turbulence causes log-normal fading of the signal. This problem can be handled by increased signal power or by the use of temporal diversity. Refractive turbulence also degrades spatial phase front of the signal. Coherent detection methods, which depend on the integrity of the phase front, are relatively more sensitive to this type of degradation than the direct detection systems. Other effects of atmospheric turbulence like pulse broadening and signal depolarization are quite small and can be neglected.

The most effective strategy to counter the problem of opaque clouds is to employ spatial diversity. For three well-chosen sites it is possible to get 94% link availability. However, we note that there is a dearth of quantitative results and directly applicable data in the field. Development of reliable weather models is contingent upon the acquisition of useful data and site-specific statistics.

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