Influence of atmospheric-induced beam extinction and scintillations on a line-of-sight optical link at 8.5-km range

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The limitations imposed by Mie scattering and atmospheric-induced beam scintillations on a direct line-of-sight optical link were investigated at 632.8 nm. The experimental investigations were carried out in Kuwait during the summer season when the local climate is characterized by high daily temperatures and frequent dust storms. Beam attenuation and scintillation data coupled with climatological data indicated that an unacceptably high level of system outages would occur in local climatic conditions for atmospheric optical links longer than 3 km.

I. Introduction

Since 1965 a number of studies have been carried out on line-of-sight optical communication systems. Results of these studies indicate that the limitations imposed by the atmosphere can be attributed primarily to scattering, absorption, and turbulence. Since these limiting processes depend on local climatic conditions, it is desirable, especially for relatively long direct line-of-sight atmospheric optical links, to conduct experimental studies aimed at determining the limitations imposed by the local atmospheric conditions on the general behavior and feasibility of such a link before entering a system design and construction phase. An investigation of this nature was carried out during a recent summer season in Kuwait, where the climate is characterized by hot days with prevalent sandstorms. The major results of the work are reported below.

II. Experimental System

The experimental system utilized for this study is shown schematically in Fig. 1. A He-Ne laser (0.8 mW) with a beam divergence of 1.5 mrad was used as an optical source. After transmission through the atmosphere at a height of 30 m above ground level, the central portion of the laser beam was intercepted and collected by a 100-mm diam reflecting telescope with a 900-mm focal length, followed by a narrowband transmission filter centered at 632.8 nm (6 nm BW). The laser transmitter and its immediate surroundings were imaged in the focal plane of the telescope. Two silicon PIN photodiodes operating in the back to back balance mode (Hewlett-Packard 4207) with sensitivities of 0.5 A/W were aligned along this plane such that the He–Ne laser beam, plus transmitter surrounding, was incident on one diode and the surroundings only on the second diode. This procedure is shown schematically in Fig. 2. This technique was used to eliminate the effect of background illumination. With the filter in front of the telescope focal plane, total background power levels could be reduced to 30 nW at midday. This was almost one hundred times greater than the threshold set by the thermal noise of 250 pW. The system signal-to-noise ratio was dominated by thermal noise in the detector load resistor (22 kΩ).

The outputs of the photodiodes were fed into a summing preamplifier followed by an amplifier with an adjustable gain. The output of this amplifier was either fed directly to a chart recorder or to a transient recorder for signal processing. The latter alternative was employed when scintillation effects were under investigation.

Processing consisted of transferring the digitized output from the transient recorders memory, through an interface, and into a computer. This input was converted into binary numbers representative of the receiver signal amplitudes. The computer was programmed to interrogate the binary representation of the scan from the transient recorder, and the amplitude of each sample (random amplitude because of scintillation) was categorized into one of twenty-five ranges. A frequency distribution of the sample amplitudes was then a representation of the frequency distribution of the laser beam intensity falling on the detector.
Fig. 1. Schematic diagram showing the system used for studying atmospheric, mechanical, and thermal factors influencing a direct line-of-sight laser optical link.

Fig. 2. Location of the double-diode detectors in the focal plane of the receiver. The PIN photodiode detectors were operated in a back-to-back balanced mode. The schematic diagram shows the He-Ne laser beam plus transmitter surroundings imaged on photodiode 1 and the immediate surroundings only on photodiode 2.

tillation details with frequencies up to 200 Hz were thus easily observed using this system. The higher-frequency components in the scintillations were investigated by feeding the output of the detector amplifier directly to an oscilloscope.

III. Results

Three experimental links of 1, 3.5, and 8.5 km were studied. The number of system outages predicted by results for the shorter links (i.e., 1 and 3.5 km) was sufficiently small to enable successful utilization of a low-cost atmospheric optical communication system. Furthermore, the atmospheric scintillation effects were minimal for these ranges and did not introduce any noticeable limitations.

However, the frequent occurrence of poor visibility (<8 km), caused by dust storms and the presence of atmospheric turbulence, imposed severe restrictions on the system when applied to an 8.5-km link. Because of this, results pertaining to this link will be described in detail below.

A. Attenuation Measurements

Signal strength received over the 8.5-km link and reliable visibility range data based on visibility observation were measured from 1 Apr. to 30 June 1979. Using this data the relevant attenuation coefficients $\alpha$ were calculated as a function of visibility range $V$ from Eqs. (1) and (2) below:

$$P = P_0 \frac{I^2}{L^2} \exp(-\alpha R),$$

$$\alpha = 3.91 \left( \frac{\lambda}{V(0.55)} \right)^{0.585^{1/2}},$$

where $P =$ received power, $P_0 =$ transmitted power, $R =$ optical link range, $L =$ the diameter of the laser beam at range $R$, $I =$ the diameter of the receiver telescope objective, and $\alpha$ is given by $\lambda = 632.8$ nm.

Theoretical attenuation factors calculated from Eqs. (1) and (2) and the experimentally measured data are presented in Fig. 3. The experimental data fit the theoretical curve fairly closely, indicating that MIE scattering was the major attenuation mechanism.

B. Scintillation Measurements

If a receiver with a small aperture is placed normal to a wave front, the laser beam will be swept tangentially across this aperture due to atmospheric fluctuations. As a consequence of this, a time scan of the intensity falling on the aperture is a representation of the spatial intensity distribution across the wave front.

Figure 4(a) shows a typical unmodulated 8-sec scan irradiance scintillation pattern for midday in the months of May and June. Figure 4(b) shows a typical scintillation pattern for the modulated signal at 1.2 kHz, highlighting the implications of the random scintillation noise superimposed on the modulated signal. It is clear that the scintillation depth of modulation is almost 100% at random intervals, causing missing pulses. Because of the limited capability of the data processing system and the limited time available, it was not possible to measure accurately missing pulse rates as a function of pulse modulation frequency. However,
Attempts were made to make semiquantitative estimates by using the following data: scintillation irradiance distributions; scintillation frequency distributions; the electronic circuitry threshold level, which was measured to be 16 mV for an amplifier gain of 5000.

Scintillation frequency distributions ranged from a fraction of a Hz up to ~1 kHz, with the predominant frequencies in the 5–100-Hz region. These frequencies were established from scintillation signals captured in the recorder operating at full bandwidth (2 MHz) and also from a large number of oscilloscope traces. The bandwidth of the diode–amplifier system was measured to be 0.5 MHz.

Missing pulses were estimated as follows. In Fig. 4(a) the threshold level (denoted by the upper solid line) was set to 16 mV. The percentage of the total time was recorded, during which the scintillation signal amplitude fell below this threshold. During this period it is reasonable to assume that the missing pulses would have occurred if the transmitted laser beam was pulsed. A set of typical results based on the procedure above is presented in Table I. In all cases the missing pulse rate was much higher than the $10^{-8}$–$10^{-9}$ error rate required for reliable operation.

Table I. Data from Typical 8-sec Scans Indicating the Percentage of Time During Which Scintillations Caused the Signal Level to Drop Below the Threshold Level of 16 mV Set by Electronic Noise in the Receiver

<table>
<thead>
<tr>
<th>Date</th>
<th>Time</th>
<th>Visibility (km)</th>
<th>Mean signal level (mV)</th>
<th>Percentage of 8-sec scan time during which signal level was &lt;16 mV</th>
</tr>
</thead>
<tbody>
<tr>
<td>5-29-79</td>
<td>9:15</td>
<td>8</td>
<td>162</td>
<td>1.75</td>
</tr>
<tr>
<td>5-29-79</td>
<td>9:00</td>
<td>6</td>
<td>149</td>
<td>1.75</td>
</tr>
<tr>
<td>5-29-79</td>
<td>18:00</td>
<td>6</td>
<td>114</td>
<td>12.0</td>
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<tr>
<td>5-29-79</td>
<td>17:20</td>
<td>6</td>
<td>130</td>
<td>7.0</td>
</tr>
<tr>
<td>5-29-79</td>
<td>17:00</td>
<td>8</td>
<td>142</td>
<td>6.5</td>
</tr>
<tr>
<td>5-29-79</td>
<td>6:35</td>
<td>8</td>
<td>156</td>
<td>2.1</td>
</tr>
<tr>
<td>5-29-79</td>
<td>14:45</td>
<td>8</td>
<td>110</td>
<td>7.5</td>
</tr>
<tr>
<td>5-29-79</td>
<td>14:20</td>
<td>8</td>
<td>144</td>
<td>2.2</td>
</tr>
<tr>
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<td>9</td>
<td>200</td>
<td>3.25</td>
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<tr>
<td>5-30-79</td>
<td>12:50</td>
<td>8</td>
<td>225</td>
<td>2.2</td>
</tr>
<tr>
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<td>14:20</td>
<td>7</td>
<td>188</td>
<td>0.3</td>
</tr>
<tr>
<td>5-30-79</td>
<td>14:45</td>
<td>7</td>
<td>172</td>
<td>0.9</td>
</tr>
<tr>
<td>5-30-79</td>
<td>3:05</td>
<td>6</td>
<td>172</td>
<td>0.9</td>
</tr>
<tr>
<td>5-30-79</td>
<td>3:50</td>
<td>7</td>
<td>180</td>
<td>1.0</td>
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<tr>
<td>5-30-79</td>
<td>4:15</td>
<td>7</td>
<td>168</td>
<td>1.5</td>
</tr>
<tr>
<td>5-30-79</td>
<td>4:45</td>
<td>7–8</td>
<td>170</td>
<td>3.0</td>
</tr>
</tbody>
</table>
Theoretical investigations and experimental observations of atmospheric-induced scintillations indicate that a wave front distorted by scintillations has a spatial intensity distribution that is lognormally distributed. It is customary to define the strength of scintillations in terms of the log-intensity variance \( \sigma^2 \), which is predicted to follow Eqs. (3) and (4) for plane wave and spherical wave propagation, respectively:

\[
\begin{align*}
\sigma^2 &= 1.23 C_n^2 K^7/6R^{11/6} \text{ for } l_0 < \sqrt{\lambda R}, \\
\sigma^2 &= 0.5 C_n^2 K^7/6R^{11/6} \text{ for } l_0 < \sqrt{\lambda R},
\end{align*}
\]

where \( K = 2\pi/\lambda \), \( C_n \) is a parameter related to the turbulence strength, and \( l_0 \) is the magnitude of the smallest-scale eddies involved in the scintillation mechanism.

When analyzed carefully, the scintillation pattern shown in Fig. 4(a) is seen to have a small dc component above which scintillation noise exists. A large number of oscilloscope measurements of these scintillation signals indicated that the dc component was 5–10% of the mean signal level. A statistical analysis was carried out to estimate the variance \( \sigma^2 \) of the lognormal irradiance distribution. The variance gave a measure of the scintillation strength and consequently a measure of the relative magnitude of the dc component. The analysis also indicated that the distribution was probably lognormal as predicted by theory.

To test for the lognormal distribution, the cumulative probability of the normalized variable \((\ln I - \langle \ln I \rangle)/\sigma\) was plotted in Fig. 5. A normal distribution lies on a straight line passing through the origin (the solid line). Three sets of scintillation data corresponding to measurements taken at three different times of a typical day are plotted in Fig. 5. The data fit a straight line fairly closely. The straight line is slightly displaced from the origin, which is caused by a small negative dc offset voltage superimposed on the scintillation signals originating in the transient digitizer. The variance of these lognormal distributions always lies in the range \( \sigma^2 = 0.15–0.35 \), indicating medium-strength turbulence.

IV. Discussion and Conclusion

The results presented above emphasize the limitations imposed by Mie scattering and atmospheric-induced beam scintillations on a line-of-sight optical link. The attenuation data presented in Fig. 3 in conjunction with the climatological data shown in Fig. 6 (compiled...
and averaged over the period 1962–1973 by the Meteorological and Climatological Sections of Kuwait’s Civil Aviation Service), indicate that an unacceptable high level of system outages will occur for optical links longer than 3 km. A considerably more reliable system can be realized by utilizing a transmitter power of 1 W or more. An LED or laser diode operating in the pulsed mode might be the best choice as a transmitter for such a communications link.

The data reported here predict poor performance for the 8.5-km optical link. However, if the transmitted power is increased to 1 W, a drastic improvement will occur, since the magnitude of the dc component (i.e., unrandomized signal component) would increase by a factor of 1000. Techniques are also available for partially overcoming beam scintillation problems. Unfortunately these techniques generally limit the data transmission rate, reduce the usable bandwidth, and increase system cost.

Our statistical analysis of the spatial irradiance distribution or scintillation indicated a lognormal distribution as predicted by theory. When the calculated variances are substituted into Eqs. (3) and (4), the calculated structure constants \( C_n \) indicate medium-strength turbulence. We did not attempt to establish the effects of moving our propagation path closer to the ground. Results of other work indicate drastic increases in the turbulence strength as the propagation path is taken closer to the ground.

We wish to acknowledge Aram Mooradian as the original instigator of this work and also thank him for his appraisal of its final outcome. We wish to thank Mohammad Farhat, Joseph D’Souza, and Othman Mohammad for their technical assistance during the entire project and the Kuwait Institute for Scientific Research for providing the necessary support.

References
6. A. A. Al-Kulaib, Weather and Climate of Kuwait (Kuwait Meteorological Service, Climatological Section, Kuwait, 1975).

Glow Discharge Processes: Sputtering and Plasma Etching.

This book is the outgrowth of a series of seminars presented by Chapman in 1978–79. No doubt due to this oral origin an informal and generally refreshing style is maintained throughout. The subject of the book, accurately reflected in its title, is glow discharge processes. The emphasis is on those related to the semiconductor industry. After two introductory chapters on gases and gas phase collisions Chapman presents an elementary discussion on concepts of plasma physics. These chapters would be understandable to a college sophomore, which may be a disappointment to a more advanced reader. Chapters on dc glow discharges and rf glow discharges follow. These are more illuminating than the previous. Magnetic fields, essential to the study of most plasmas, are not covered in any detail until p. 270. They clearly should be discussed earlier in the book.

In addition I feel that Chapman could have introduced a broader range of references. For example, the literature in fusion physics and astrophysics is full of review articles of major utility to the designers and users of process plasmas. The last two chapters deal with the plasma surface interactions of sputtering and etching. Again the collection of references is limited to those from the semiconductor industry. There have now been five international conferences (organized in the fusion community) on plasma surface interactions. Not a reference to any of the nearly 500 papers is in Chapman’s book.

In general this book makes an excellent introduction to process plasmas. The organization is well planned. Each chapter gives the important results both in the introductory and concluding paragraphs. The presentation of the complexity of plasma processing is correct and should stimulate many heated discussions and new experiments. The prospective reader should take warning. This book is not a manual. It gives little explicit detail such as how to make a particular sputtering system or etch a particular set of samples, though answers to these questions may lie in the references.

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