

OPTICAL SCINTILLATION NOISE ON LONG ATMOSPHERIC PATHS

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ABSTRACT

Free-space optical communications provide higher security and wider bandwidth than is currently available in the microwave band. However, refractive index fluctuations along the atmospheric path scatter and attenuate the optical beam and introduce intensity noise (“scintillation”) on millisecond time scales. We present new results from the University of Canberra / RMIT / Monash University / Canberra Institute of Technology Free-Space Optical Communications Test Bed obtained over atmospheric paths with lengths between 4 and 26 km. These results include statistical analyses of long-path scintillation in the amplitude, time and frequency domains.

INTRODUCTION

Random fluctuations of temperature due to turbulence in the earth’s atmosphere lead to related fluctuations in the refractive index along the line of sight to both terrestrial and extra-terrestrial sources of light. Atmospheric turbulence gives rise to fluctuations in the phase, amplitude, phase velocity and group velocity of the propagating light [1-4]. In addition, multiple scattering from aerosols and turbulent eddies weakens, broadens and reduces the bandwidth of optical signals and distorts the shape of picosecond scale optical pulses [5,6]. This propagation noise degrades the signal to noise ratio, bit error rate and information capacity of free-space analogue and digital lightwave telecommunications and the accuracy of laser distance measuring systems [7,8].

Although the characteristic time scale for optical intensity noise (“scintillation”) is usually of the order of tens of milliseconds, some of the optical effects due to atmospheric turbulence and scattering only become apparent at high bit rates. For example, clear air refractive index fluctuations limit the bandwidth of ultra broadband digital telecommunications and data communications between the ground and orbiting satellites, to less than 100 Gbps. Multiple scattering by aerosols and strong off-axis turbulent eddies can lower this bandwidth by many orders of magnitude. There is current interest in high bit rate transmission of very weak optical pulses between earth stations and low earth orbit satellites as a means of distributing secret quantum cryptographic keys over global distances [9-12].

In this paper we outline current work on optical bright-beam scintillation noise being undertaken in Australia at the University of Canberra / RMIT Monash University / Canberra Institute of Technology Free-Space Optical Communications Test Bed [9,10,11] over atmospheric paths of length between 4 and 26 km. We shall examine the form of the probability distribution of saturated optical scintillation noise and its intensity level-crossing statistics. We also characterise our scintillation measurements in the time and frequency domains.

BRIGHT BEAM SCINTILLATION NOISE

Long Path Measurements

A typical four minute log of fluctuations in the irradiance of a bright red (635 nm) laser beam over a nocturnal 26 km path just after sunset is shown in Fig. 1 below. This illustrates the general character of saturated long path scintillation noise on a coarse time scale [11]. Fig. 2 is a typical 40 minute sequence of probability density plots of the bright red (635 nm) beam intensity scintillation sampled over 4 minute intervals for the 14.3 km long atmospheric path between Black Mountain telecom tower (altitude 800m) in Canberra and our field station at Wallaroo (altitude 630m).

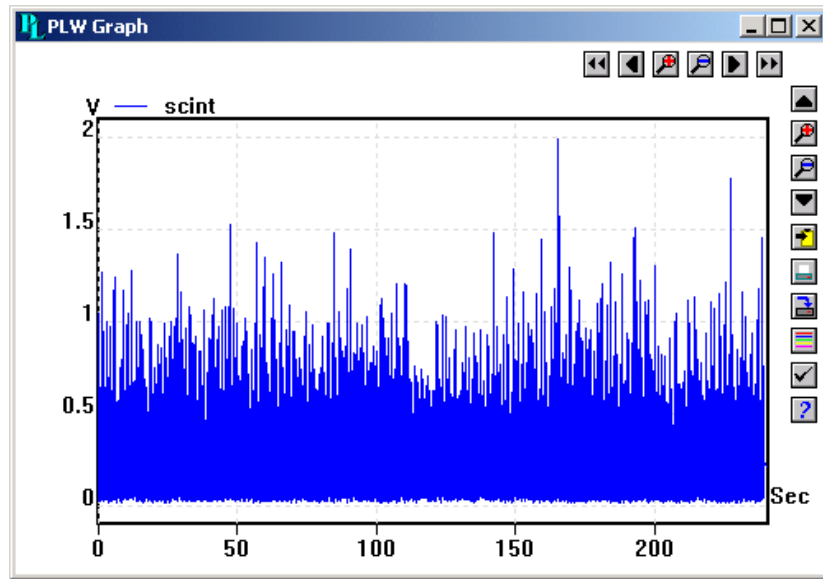


Figure 1. Typical four minute sample log of intensity scintillations in the irradiance of a red (635 nm) laser beam received over a nocturnal 26 km urban path shortly after sunset. Receiving aperture diameter: 250mm; sampling resolution: 4 ms. (from Edwards et alia [11]).

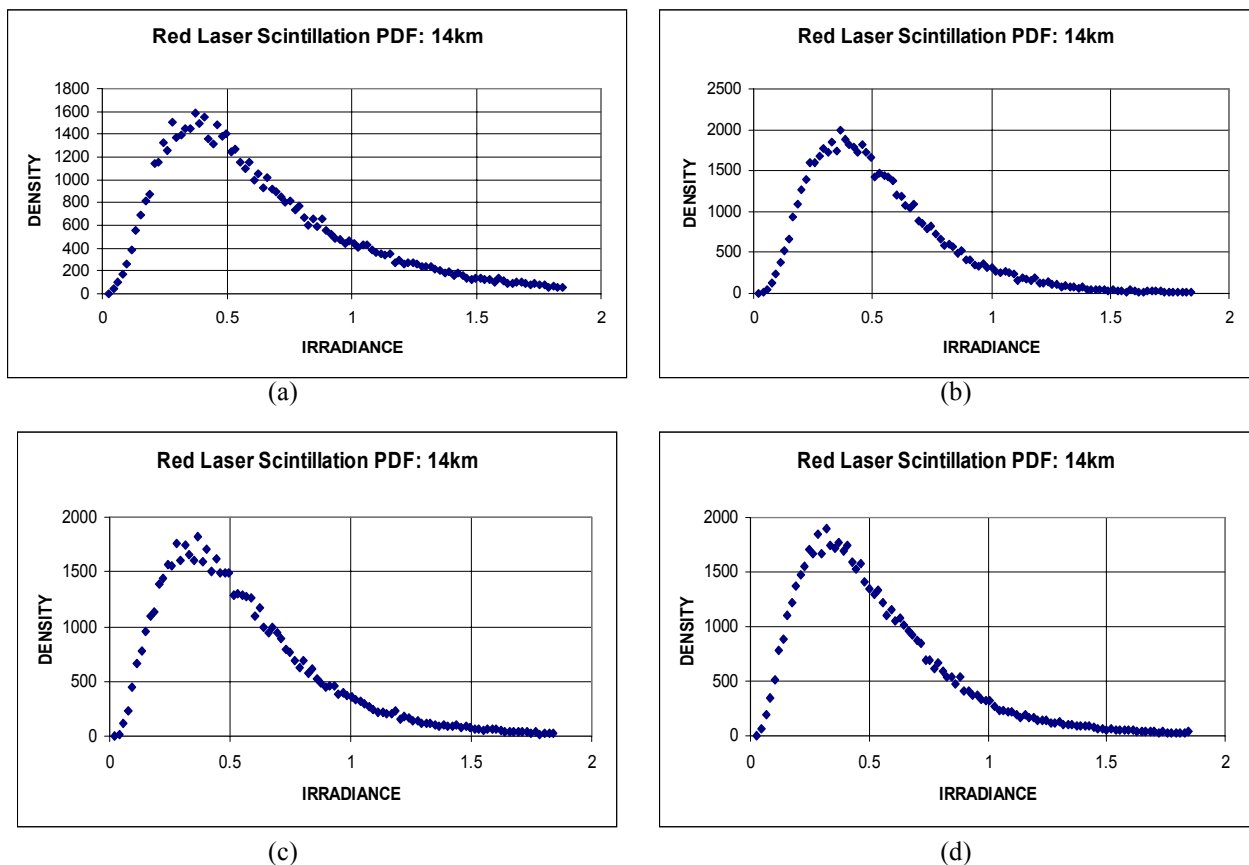


Figure 2 (a)-(d): Consecutive four-minute sample estimates (separated by one-minute) of the red irradiance scintillation probability density functions logged at Wallaroo on 5 December, 2003. Normalised variances: (a) 0.41; (b) 0.31; (c) 0.37; (d) 0.40.

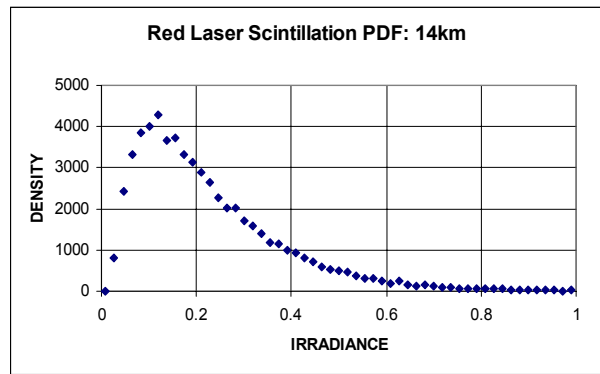
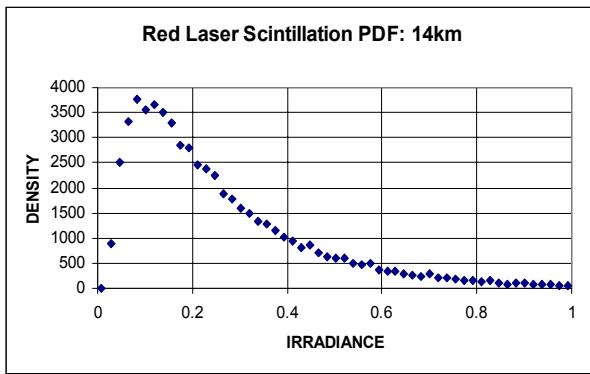
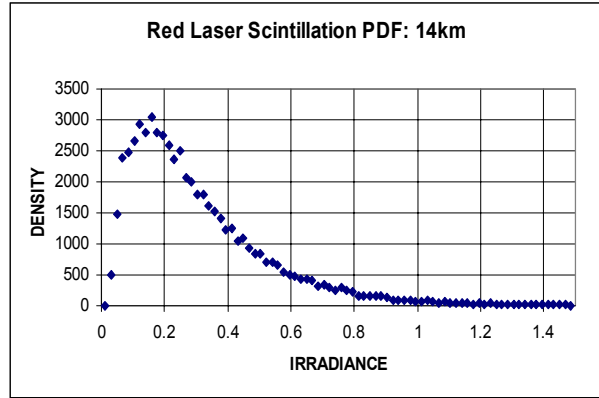
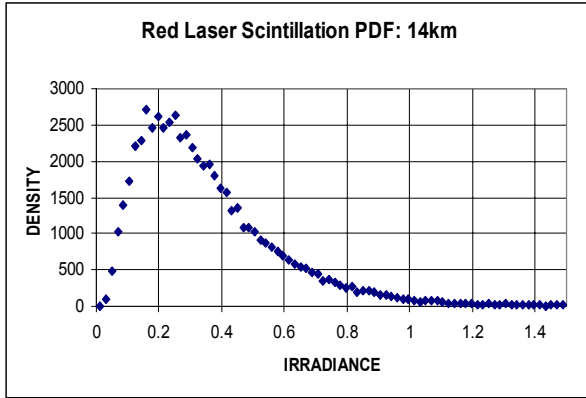


Fig. 2 (e)-(h): Consecutive 4 minute sample estimates of the red irradiance scintillation probability density functions following those of Fig. 2 (a)-(d). Normalised variances (e) 0.43; (f) 0.60; (g) 0.70; (h) 0.53.

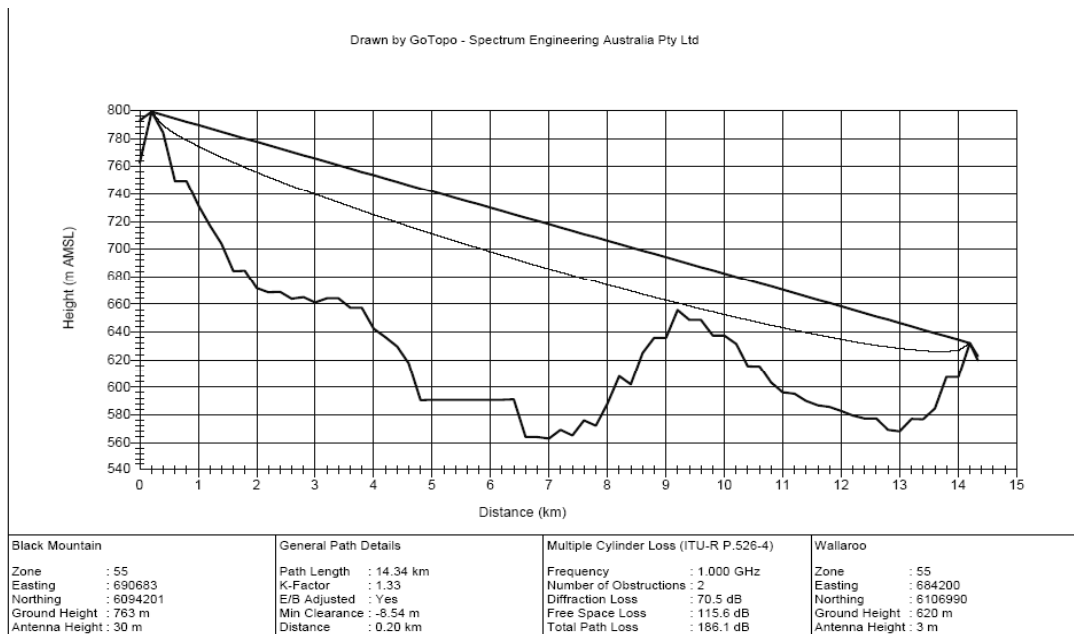


Fig.3. Terrain profile for the 14.3 km propagation path from Telstra Tower on Black Mountain in Canberra to the Wallaroo field station (Courtesy P. Hilly, Spectrum Engineering Australia PL).

These data were obtained during night-time under “quiet” atmospheric conditions over the path profiled in Fig.3. Comparison of the 14.3 km data with data obtained over the 4.2 km optical free-space communications test bed path between Black Mountain Tower and the University of Canberra campus and data from a 43 km path between Mt Tennent (altitude 1000 m) and the Wallaroo field station, all obtained under similar conditions, reveal that the scintillation is saturated [13]. In all cases the normalized variance (the “scintillation index”) $\sigma_I^2 = (\langle I^2 \rangle - \langle I \rangle^2) / \langle I \rangle^2$ is similar, with values between 0.3 and 0.7, with little dependence on path length. This behaviour appears to be typical of aperture-averaged saturated scintillations due to strong turbulence [14]. However it is evident that both the shape of the distribution and the scintillation index vary considerably on a time scale of minutes. When the logarithms of the irradiances are taken, the distributions assume an approximate Gaussian form, indicating the approximate lognormal form of the irradiance distribution.

Scintillation Theory

The non-stationarity of optical turbulence makes comparison with theory difficult. The approximate lognormal form of scintillation intensity distributions due to weak turbulence is that expected from very general considerations. If the many irradiance perturbations due to turbulence and scattering along the path are independent and multiplicative then the logarithm of the irradiance fluctuation can be expressed as the sum of the logarithms of many independent perturbations, thus leading, via the central limit theorem, to the Gaussian form.

Many candidate probability density functions besides the lognormal have been proposed for specific conditions of optical turbulence [4,15]. Although the moderate values of the scintillation indices measured on these long paths might at first appear to indicate weak turbulence for which the lognormal distribution is favoured, this is not so. For sufficiently large aperture diameters, $D > (\lambda L)^{1/2}$, the weak scintillation theory is believed to hold up well into the saturation regime [13,14]. For a path length of $L = 10$ km, strong spatial filtering of near infrared Fresnel zone scale (100 mm) scintillation patterns by the 250 mm diameter aperture used in our study occurs, leading to almost an order of magnitude reduction in the normalized variance [1,2,13]. Churnside and Hill [14] and others have suggested lognormal statistics for this situation also. Other candidates being examined in our study include the K, lognormal-Rician and gamma-gamma distributions [4].

Insofar as optical communications systems are concerned the important issues arising from intensity scintillation are clearly the signal to noise ratios, bit error statistics, the threshold-crossing statistics and the photon counting statistics (for weak signals). Concerning the latter, if the propagation is characterised by a fixed path loss, as it would be in the absence of turbulence, we would expect to encounter Poissonian photon counting noise at an ideal OOK receiver. For such a system, as is well known, the normalized variance $\sigma_I^2 = 1 / \langle n \rangle$, vanishes in the limit of high photon number. The typical photocurrent scintillation plots of Fig. 2 may thus be regarded as the high photon number limits of the corresponding photon count distributions. They provide a basis for calculating photon-counting statistics in the presence of turbulence using the Poisson transform [16,17].

CONCLUSIONS

Although the optical effects of atmospheric turbulence have been extensively modeled and measured over many decades, their influence on optical communication systems is still a matter of conjecture in a number of situations. The lognormal distribution appears well entrenched in the literature but precise experimental confirmation still appears to be lacking, presumably because of non-stationarity. Other optical free-space propagation issues related to scintillation noise include:

1. The characteristics of pico-second scale fluctuations in long path pulse propagation times.
2. The bandwidth limiting effects of multiple scattering by clear air turbulence and aerosols on long path ultra broadband communications.
3. The fading (level-crossing) statistics relevant to bit error statistics and coding.
4. The photon counting statistics of pulsed terrestrial, uplink and downlink beams

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