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An Analysis of Optical Propagation Data as a Result in the ETS-VI Laser Communication Experiments

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1. Introduction

For the future high-speed space optical communication systems, the Communications Research Laboratory performed the first ground-to-satellite laser communication experiments from December 1994 to July 1996 to demonstrate relevant key technology [1]. An optical communication package (LCE) onboard the Engineering Test Satellite VI (ETS-VI) and its companion ground optical terminals were developed for constructing the experimental system as shown Fig. 1. A 30-mW laser diode of a wavelength 0.83 µm was implemented for the downlink transmission, and a 10-Watt argon ion laser of a wavelength 0.5145 µm was for the uplink transmission. A bi-directional optical link over 40,000 km was demonstrated successfully along with precise transmission control of narrow laser beams at both onboard and ground terminals under severe path scintillation effects. In the paper, some new aspects on analysis of the optical propagation data are presented.

2. Up-link Received Intensity

At the optical receiver of the LCE, 2 msec-sampled intensity data for 10 seconds can be collected to the onboard memory and downlinked by the S-band telemetry link at 1 sec interval. Nineteen sets of data were obtained during the two-year experiments. The receiver output was always subject to severe random variation of which bandwidth was a hundred hertz or more. Figure 2 shows an example of the optical signal level measured on 27 January 1996. The variance of the intensity normalized by its mean value, that is, the normalized variance, during the 10-sec period is estimated to be 0.92. If the fluctuation is due only to the atmospheric turbulence, this value means that the strong turbulence theory has to be applied and very sophisticated analysis would be required. In general the fluctuations are caused by the atmospheric turbulence, beam-pointing jitter of the ground transmitter, tracking error at the LCE, data quantization error and so forth. Because of these many factors, any theory that can satisfactorily explain the data could not be found and developed at that time. Effort has been continually devoted for explaining the data so far. Recently it illuminated a light to the data on 27 January 1996 with an idea of short-interval data processing. The downlink data taken at the same period was investigated and found that there was less signal fading. This means that tracking works properly at the LCE and almost all of the received light at the LCE is guided to the internal optical receiver. The dominant causes were inferred to be the atmospheric turbulence and the beam pointing jitter.

3. Probability Density Function

The probability density function (PDF) or histogram of the optical signal during the 10 sec is plotted by circles in Fig. 3. It is not like a well-known lognormal distribution that commonly has a single peak. Main feature of the experiment is that use has been made of an extremely narrow laser beam of which beam width is order of 0.001degrees. The satellite direction change speed was about 0.003 degrees per second and the satellite was tracked with angular resolution of about 0.0001 degrees. The data for short-duration, 0.1 sec for example, might be subject to constant pointing error not to random variation of beam-pointing jitter. In fact it was confirmed that the PDFs of the optical signal with the 0.1-sec period were fitted very well to the lognormal distributions with different scintillation indices. This fact also would allow neglecting the loss of the power due to the tracking error at the satellite.

The atmospheric condition can be assumed to be constant because optical path direction does not change largely in 10 seconds. To infer beam pointing characteristics and atmospheric turbulence using the 10-sec data, analytical expressions based on the weak turbulence theory[2] and assuming the Gaussian pointing jitter error can be used, which include some unknown parameters such as the rms value of the beam-pointing jitter error angle(s_j), a bias angle in pointing(j) and a scintillation index at no pointing error(A). The PDF(histogram) for the short-term scintillation index is plotted in Fig. 4. The results are fitted to the analytical expression for the PDF and the above parameters are estimated A=0.20, $j = 0$, and s_j = 3.8 µrad when the beam divergence w_0 = 6 µrad is used as a measured value. This rms value of beam-pointing jitter s_j = 3.8 µrad is consistent with the tracking error of the ground telescope measured in the other experiments using fixed stars

The analytical expression for the PDF of the normalized intensity can be derived as the Eq (A1) in Appendix. The PDF plotted by solid curve agrees very well with the measured histogram if the scintillation index s_I^2 = 0.27 corresponding to the peak of the probability density in Fig. 4. It is noted that the uplink intensity statistics can be explained in terms of both the beam pointing jitter and the atmospheric turbulence. The weak turbulence theory also is applicable to the laser transmission from the ground. These are encouraging for designing and discussing future optical systems.

4. Temporal Autocovariance Function

To characterize the light intensity variation by using the 10-sec data, the temporal autocorrelation was taken with a time lag of up to 0.1 sec at 2 msec interval. Correlation value was yielded as an average over about a hundred of sample values in which correlating time is selected to be 0.1-sec. This short interval analysis would bring only small effects of beam pointing error as developed in the previous section. For the temporal autocovariance experienced in the experiments, the mean values and the rms deviations are plotted as circles and error bars, respectively. The tendency of the graph is close to the empirical spatial correlation function of the fluctuations of light intensity shown in the Tartarski's literature [3]. The analytical expression with such tendency was found by a slight modification of the equation developed in [4] as the equation (A2) shown in the Appendix. The equation (A3) is a result from application to the data in Fig.2. Using the equation the time-averaging effects at any integration time or relating parameters such as correlation time can be evaluated. The approximate curve for the mean values is plotted as a solid curve in Fig. 5. The mean $1/e^2$ correlation time of the intensity was 6.3 msec. The correlation time depends on the atmospheric coherence length and the wind velocity in the optical path in the atmosphere, and during the experiments it ranged every measurement between 1.9 and 11.7 ms. In the data on 27 January 1996 the correlation time is 10.5 ms corresponding to about 100 Hz frequency bandwidth.

5. Conclusion

In the paper, analysis and discussions were made in use of optical propagation data acquired in the ETS-VI experiments. The equations for the probability density function and the temporal autocovariance function that can explain satisfactorily the statistical property of real transmission data will be useful to simulate laser transmissions from ground to space in various situations. Optimizing of beam parameters, implementation of multiple laser transmitters, and application of adaptive optics techniques are to be investigated for stable optical communication links.

This paper is a summary of the paper 2000-I-5, "Up-Link Intensity Statistics in ETS-VI Laser Communication Experiments", presented at the 22nd International Symposium on Space Technology and Science held in Morioka, Japan on May 28 - June 6, 2000.

References:

[1] M. Toyoshima and K. Araki, Applied Optics, Vol.37, No.10, pp. 1720-1730, April 1998.
[2] L. C. Andrews *et al.*, Applied Optics, Vol.34, No.33, pp. 7742-7751, Nov.1995.
[3] V. I. Tatarski, *Wave Propagation in a Turbulent Medium* (McGraw-Hill, New York, 1961), p. 213.
[4] P. Stroud, Opt. Eng., Vol. 35, No. 2, pp. 543-548, 1996.

Appendix

In the case of the weak atmospheric turbulence and the Gaussian beam pointing jitter with zero offset angle, the analytical expression of the PDF for the normalized intensity I/I_0 is given by

$$p(I) = \frac{1}{I_0} Erfc\left[\frac{\ln(I/I_0) + s_I^{\,2}(b+1/2)}{\sqrt{2}s_I}\right] \cdot b \exp\left[\frac{s_I^{\,2}}{2} b(b+1)\right](I/I_0)^{b-1} \qquad \text{(A1)}$$

, where *Erfc*( ) is the complementary error function, s_I^2 the scintillation index, s_j the rms beam-pointing jitter,

w_0 the 1/e^2 beam divergence angle of a Gaussian beam (half angle), and $b = w_0^2/(4s_j^2)$.

The fit equation suitable for the temporal autocovariance function could be given by

$$B(t) = a\left[1 + (t/\Delta t)^b\right]^{-c} - a + 1 \qquad \text{(A2)}$$

, where t is the time lag, Δt is the sampling period, and a, b, c are constants. The fit equation of Eq. (5) in Ref [4], which is under the conditions of a=1 and c=2 in Eq. (A2), was modified because the autocovariance function has negative values in a time range shown in Fig. 5. For data on 27 January 1996 shown in Fig. 2, the fit autocovariance function was obtained:

$$B(t)\big|_{1/27} = 1.947\left[1 + (t/0.002)^{0.443}\right]^{-1.121} - 0.947\,. \qquad \text{(A3)}$$

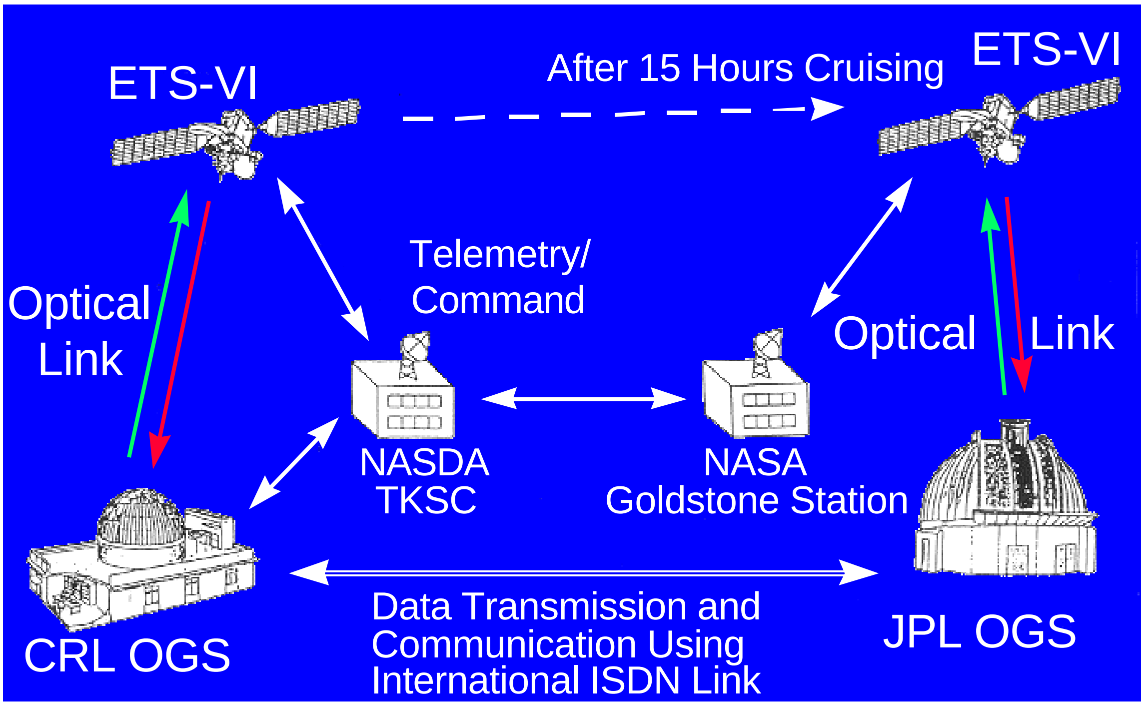

Fig. 1 Configuration of laser communications experiment system using ground stations and the ETS-VI satellite.

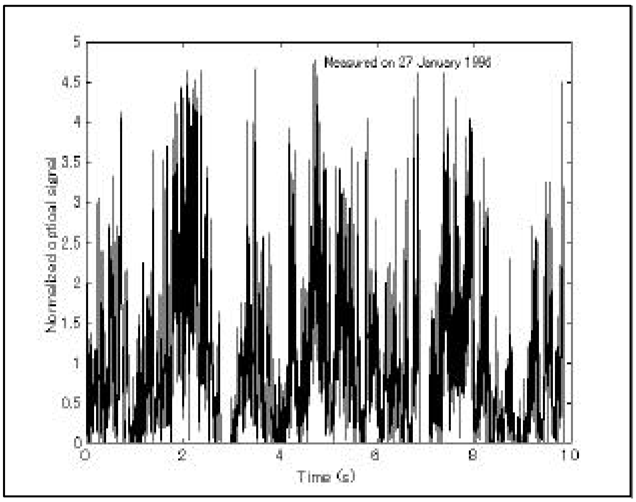

Fig. 2. Normalized uplink optical signal measured on 27 January 1996.

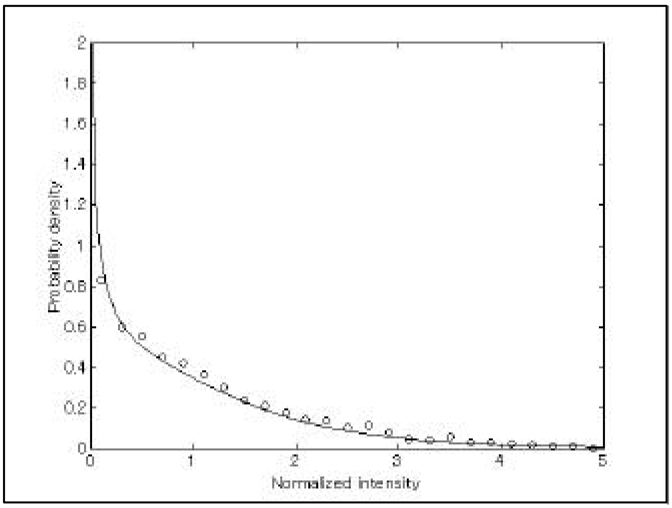

Fig. 3 PDFs of optical signal in the presence of both atmospheric turbulence and beam pointing jitter.

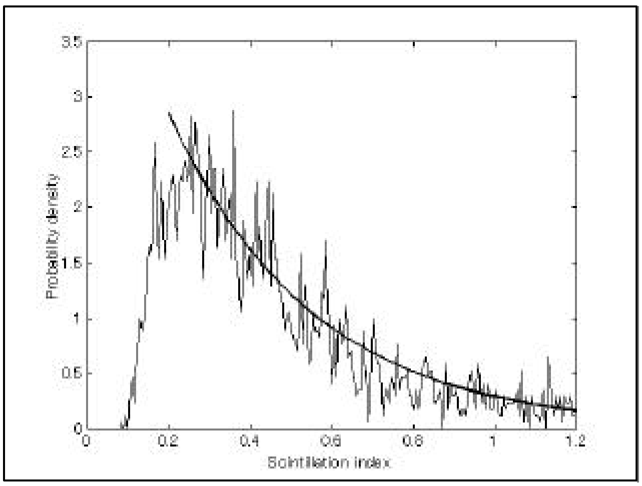

Fig. 4 Probability density function of the scintillation index.

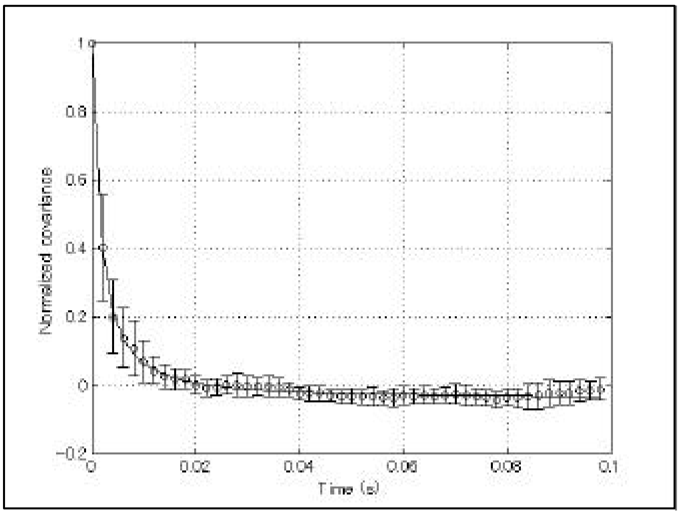

Fig. 5 Normalized temporal autocovariance function of the fluctuation of light intensity.