4-5 Fading Simulator for Satellite-to-Ground Optical Communication

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In the satellite-to-ground optical communications, it is well known that communication quality will be deteriorated by the fading by atmospheric turbulence. Atmospheric turbulence is a phenomenon which light is refracted on the boundary surface by change of the refractive-index distribution in the atmosphere. Satellite onboard optical-communications apparatus needs to be tested in advance about this influence. Hence, the fading simulator for satellite-ground optical link was developed based on the actual propagation data obtained by Optical Inter-orbit Communications Engineering Test Satellite (OICETS) experiment. More advanced ground evaluation of satellite onboard optical-communications apparatus will be attained by using this simulator from now on.

Keywords
Communication, Satellite communication, Laser satellite communication, Atmospheric turbulence, OICETS

1 Introduction

One of the important subjects to establish a stable optical link is to study the variations in the received optical signal caused by atmospheric turbulence in ground-to-satellite optical communications. Atmospheric turbulence is a phenomenon of variations in the refractive index of air caused by temperature changes, or variations in an arrival angle and wave-front distortion of light affected by wind, convection flow with the wind or turbulent flow. The atmospheric turbulence makes the received level of light signals change in satellite laser communications, and as a result, the communication quality is degraded. The degradation of the communication quality is up to 20 dB, and moreover, the frequency components in the signal, which are several Hz to 2 kHz, are quite slow compared to the communication speed.

For example, assuming that the communication speed is 100 Mbps, 1 Mbit of data will be lost if burst errors happen for 10 msec. At present, the NICT pursues research on the development of error correction schemes with LDGM (Low Density Generator Matrix) codes into a channel in order to solve the problem of atmospheric turbulence [1]. LDGM codes are a kind of LDPC (Low Density Parity Check) codes which enable high speed encoding/decoding, and which can realize a long code length. In order to determine a proper code length for LDPC codes, a simulator which simulates fading caused by the ground to satellite atmospheric turbulence is demanded.

The purpose of this research is to generate pseudo atmospheric turbulence and to reproduce fading caused by atmospheric paths in the ground-to-satellite communication path. The simulator developed in this research is usable to evaluate the performance of actual space optical communication equipment for satellites, and can evaluate the effectiveness of the communication path when it is encoded. In addition, signals of pseudo atmospheric turbulence used by the simulator are obtained from OICETS experiment data, which has been analyzed by the NICT. Therefore, the simulator can reproduce atmospheric turbulence that is very close to the actual environment generated between an optical ground station and a satellite.

2 Theoretical model of atmospheric turbulence

The power spectrum of atmospheric turbulence is calculated by convoluting a spatial frequency spectrum of speckle patterns in received beams caused by atmospheric turbulence and a spatial spectrum of a window function from the aperture of an antenna [2]. It is assumed that the spatial frequency spectrum of $W_S^2(\kappa)$ of speckle patterns by the atmospheric turbulence can be generally described as Equation (1) of the spectrum of Von Karman-type.

$$W_S^2(\kappa) = \frac{0.033C_n^2 \exp\left(-\kappa^2/\kappa_m^2\right)}{(\kappa^2+\kappa_0^2)^{11/6}} \tag{1}$$

where, $\kappa_m = 5.92/l_0$, $\kappa_0 = 2\pi/L_0$, l_0 is the inner scale of the spatial distribution of atmospheric turbulence, and L_0 is the outer scale. In addition, C_n^2 is a structure function. Equation (2) of the Hufnagel-Valley model is utilized for simulation in the case of ground-to-satellite propagation.

$$\begin{aligned} C_n^2 &= 0.00594\left(\frac{v}{27}\right)^2 (10^{-5}h)^{10}\exp\left(-\frac{h}{1000}\right) \\ &+2.7\times10^{-16}\exp\left(-\frac{h}{1500}\right) \\ &+A\exp(-h/100) \end{aligned} \tag{2}$$

Equation (3) provides v in Equation (2), wherein h is the height of the optical ground station and v is a mean square deviation of wind velocity. A is a coefficient of C_n^2 on the ground. For example, it can be obtained by the method called Differential Image Motion Monitor (DIMM).

$$v = \left[\frac{1}{15\times10^3}\int_{5\times10^3}^{20\times10^3} V_B^2(h)dh\right]^{1/2} \tag{3}$$

Here, $V_B(h)$ is a Bufton wind velocity model, which is obtained by Equation (4).

$$V_B(h) = \omega_g h + v_g + 30\exp\left[-\frac{h-9400}{4800}\right] \tag{4}$$

where, v_g is the wind velocity near the ground and ω_g is a satellite angular motion relative to the telescope in the atmosphere. In addition, the window function for the aperture of the receiving antenna is given by Equation (5).

$$W_a(\kappa) = \frac{\pi D^2}{4}\frac{2J_1(\pi D\kappa)}{(\pi D\kappa)} \tag{5}$$

Therefore, using Equation (1) and Equation (5), the temporal power spectrum of the atmospheric turbulence in the time region is given by Equation (6).

$$\begin{aligned} W_e^2(f) &= \left|\frac{\tau_r}{V}\int_0^\infty W_a\left(\sqrt{\kappa^2+\frac{f^2}{V^2}}\right)W_s^*\left(\sqrt{\kappa^2+\frac{f^2}{V^2}}\right)d\kappa\right|^2 \\ &= \frac{\tau_r^2}{V^2}\int_0^\infty \left(\frac{\pi D^2}{4}\right)^2 \frac{2^2J_1^2\left(\pi D\sqrt{\kappa^2+f^2/V^2}\right)}{\left(\pi D\sqrt{\kappa^2+f^2/V^2}\right)^2} \\ &\times\frac{0.033C_n^2\exp\left[-\frac{(\kappa^2+f^2/V^2)}{\kappa_m^2}\right]}{(\kappa^2+f^2/V^2+\kappa_0^2)^{\frac{11}{6}}}d\kappa \\ &= \frac{0.033C_n^2\tau_r^2D^2}{4V^2}\int_0^\infty \frac{J_1^2\left(\pi D\sqrt{\kappa^2+f^2/V^2}\right)}{(\kappa^2+f^2/V^2)} \\ &\times\frac{\exp\left[-(\kappa^2+f^2/V^2)/\kappa_m^2\right]}{(\kappa^2+f^2/V^2+\kappa_0^2)^{11/6}}d\kappa \end{aligned} \tag{6}$$

where, τ_r is an optical loss and V is the wind velocity in the channel. Next, the frequency in Equation (6) is normalized, and the output probability of each frequency is obtained. The equation for calculating the probability density function $P_W(f)$ is given by Equation (7).

$$P_W(f) = fW_e^2(f)\Big/\int_0^\infty W_e^2(x)dx \tag{7}$$

3 Simulator configuration

The fading simulator newly developed for satellite-to-ground optical communications can reproduce variations in the received optical signal caused by atmospheric turbulence using an optical intensity modulator. Figure 1 shows the simulator configuration. And Figure 2 shows the optical intensity modulator with a lithium niobate (LN) in the experiment. The wavelength of the optical source is 1550 nm, and Photodiode (PD) is used to detect optical signals. First, the simulator generates fading signals caused by the atmospheric turbulence in a personal computer (PC) for generating pseudo atmospheric turbulence. In order to generate the signals, LabVIEW and LabVIEW FPGA from the National Instruments Corporation are used as software, and FPGA boards (PCI-7811R) of the same company installed on PCI slots are used as hardware. These instruments enable the generation of fading signals affected by pseudo atmospheric turbulence in real time.

After the generated fading signals are converted to analog signals by a digital-to-analog converter (DAC), the analog signals are input to the optical intensity modulator. Then we can try to reproduce fading affected by the satellite-to-ground atmospheric turbulence in the optical fiber. The optical intensity modulator can adjust the magnitude of attenuation by input voltage and can also adjust the effectiveness of

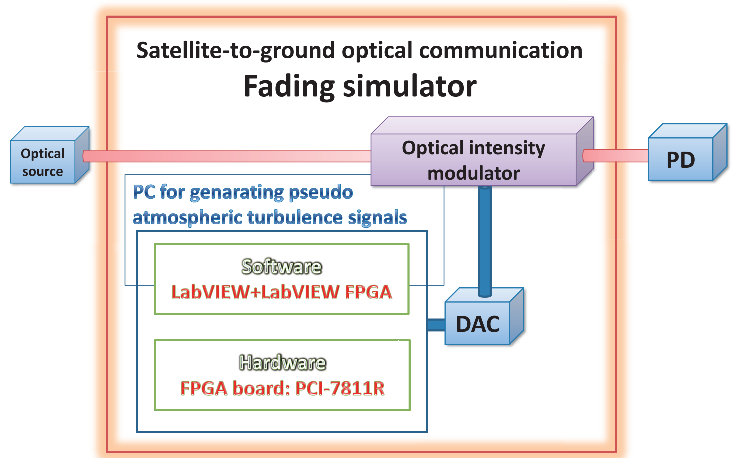

Fig.1 *Configuration of simulator*

Fig.2 *Optical intensity modulator*

pseudo atmospheric turbulence by changing the amplitude of voltage of input signals.

4 Simulation results

First, pseudo atmospheric turbulence is generated in computer simulations using the equation for the power spectrum obtained in **2**. The condition of the simulation is based on the assumption that $l_0 = 4e-3$ [m], $L_0 = 1.6$ [m], $D = 0.05$ [m] and $V = 80$ [m/s]. Figures 3 and 4 show respectively the waveform of generated atmospheric turbulence and its frequency-spectrum. In addition, to compare the simulation results, Fig. 5 shows a graph of the power spectrum of actual atmospheric turbulence

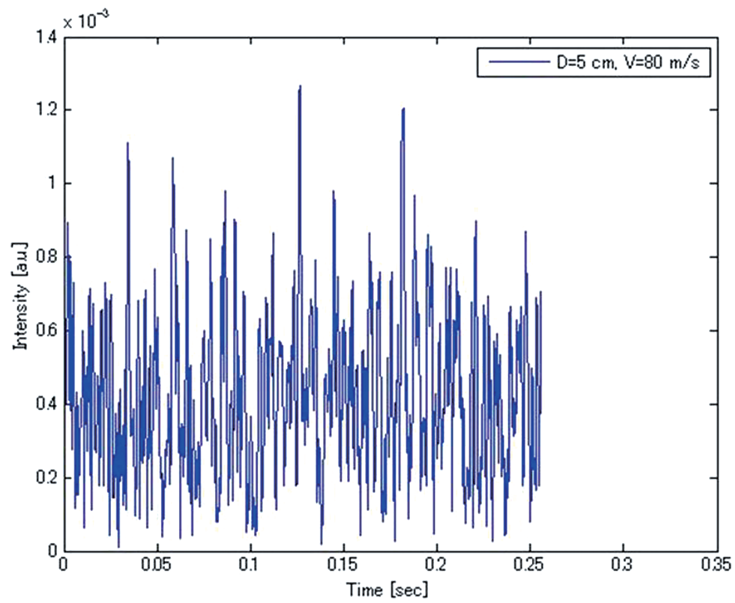

Fig.3 Simulation results on PC

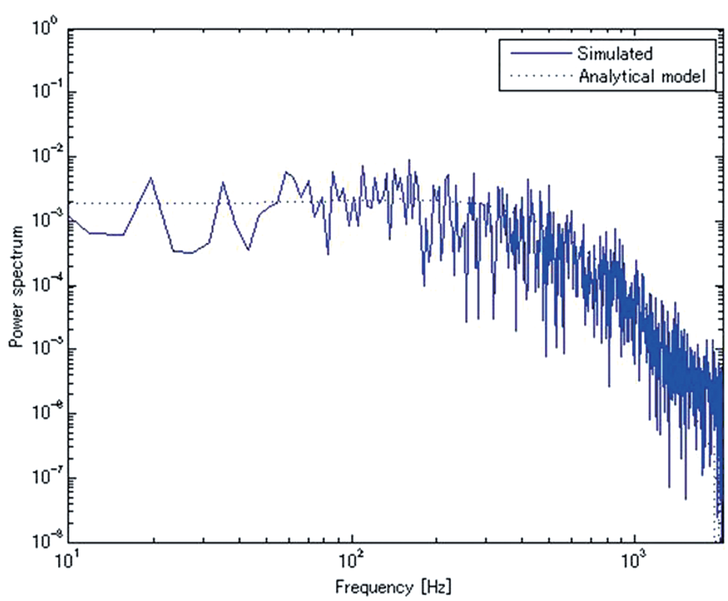

Fig.4 Result of Fourier transformed waveforms simulated on PC

measured in satellite-to-ground optical satellite communications. This is the data obtained using the OICETS satellite. Referring to Fig. 5, dominant frequency-components indicate frequencies from several Hz to several hundred Hz. Because this characteristic is also verified in Fig. 4, it is clear from the results of the simulation that the simulator reproduces the characteristics of the atmospheric turbulence.

In addition, atmospheric turbulence has another characteristic where the frequency spectrum in the latter part of the 100 Hz-range drops dramatically. When the frequency spectra in Figs. 4 and 5 are compared with respect to this characteristic, the frequency spectrum starts to drop from around 400 Hz in both graphs. Therefore, we consider that the simulator can reproduce another characteristic with respect to atmospheric turbulence.

For these reasons, by using this newly developed simulation program, the simulator can reproduce the power spectrum of fading caused by the satellite-to-ground atmospheric turbulence.

5 Measurement results

5.1 Measurement results using the simulator

Using the fading simulator for satellite-to-ground optical communications, atmospheric turbulence was actually generated in an optical fiber. First, we performed the measurement using the configuration shown in Fig. 1. Figures 6 and 7 show waveforms and Fourier spectra, which were recorded at that measurement. When Figs. 3 and 6 are with compared each other, the graphs show that the pseudo atmospheric turbulence generated in the optical fiber has a larger attenuation than that obtained by the simulator. We plan to adjust the LN modulator to compensate for the pseudo atmospheric turbulence.

On the other hand, referring to Fig. 7, we confirm that the characteristic of atmospheric turbulence is reproduced in some degree because dominant frequency components of the recorded waveforms are from several Hz to several 100 Hz and the spectrum drops from

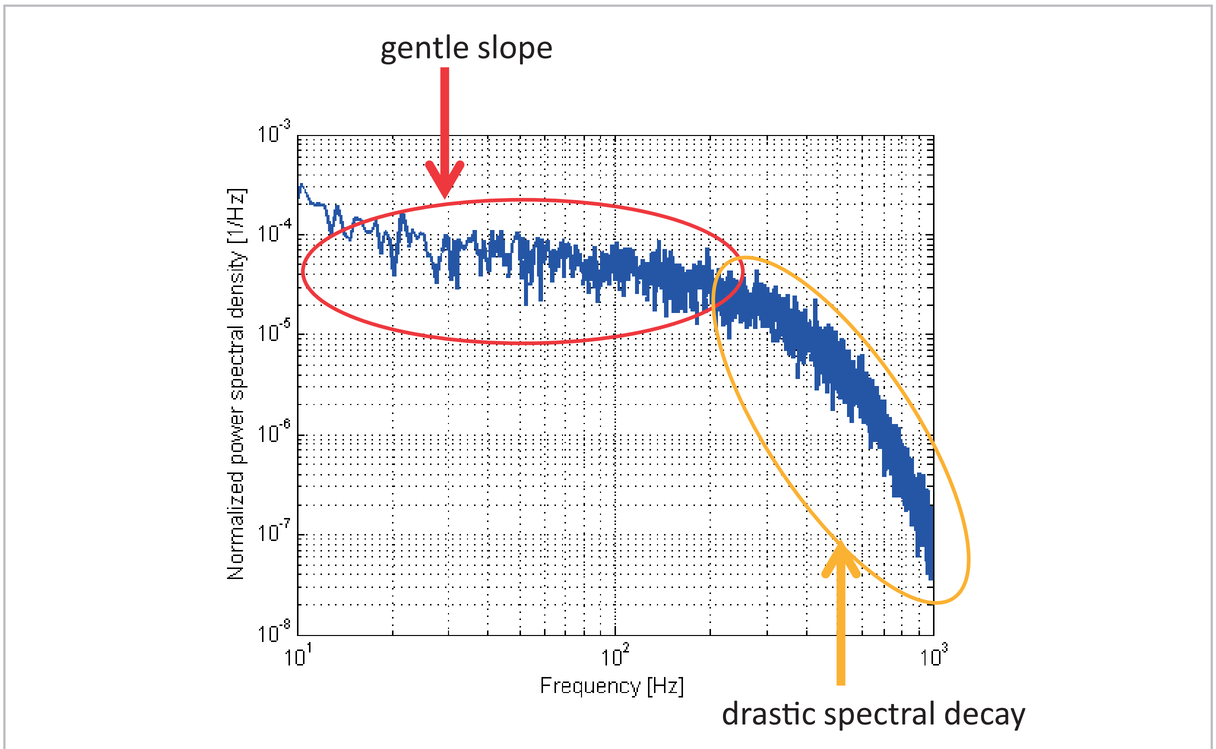

Fig.5 *Results of Fourier transformed waveforms of optical signals under atmospheric turbulence measured at OICETS experiment*

the latter part of the 100 Hz range. However, it was found that the way of a spectrum's drop is different when comparing Fig. 4 and Fig. 5. Therefore, this might happen because of the LN modulator. The LN modulator used to generate the atmospheric turbulence does not operate linearly corresponding to the input voltage. Therefore, we tried to compensate this characteristic by integrating an inverse function of this optical modulation-characteristic into the newly developed simulation program. Although intending on approximating the modulation characteristic, we have the above results because the compensation may not have been perfect.

5.2 Measurement results using the communication system

The communication experiment system was established as shown in Fig. 8. We per-

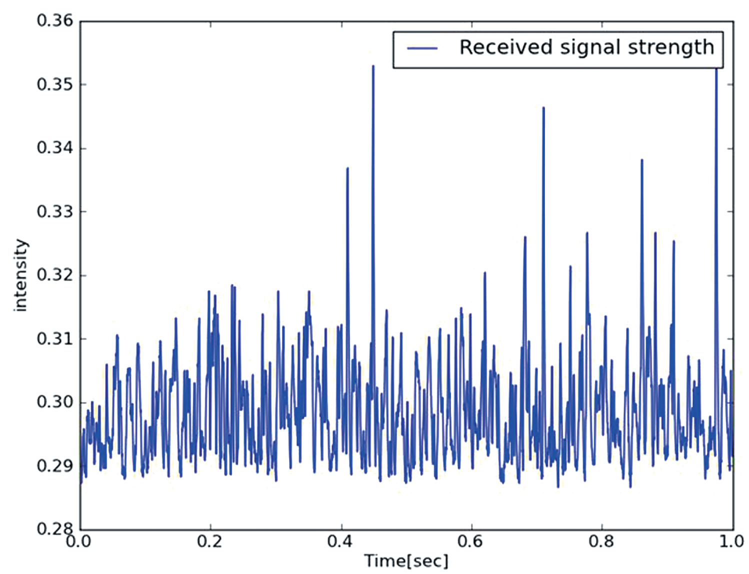

Fig.6 Variations in the received signal level caused by pseudo atmospheric turbulence generated in the optical fiber

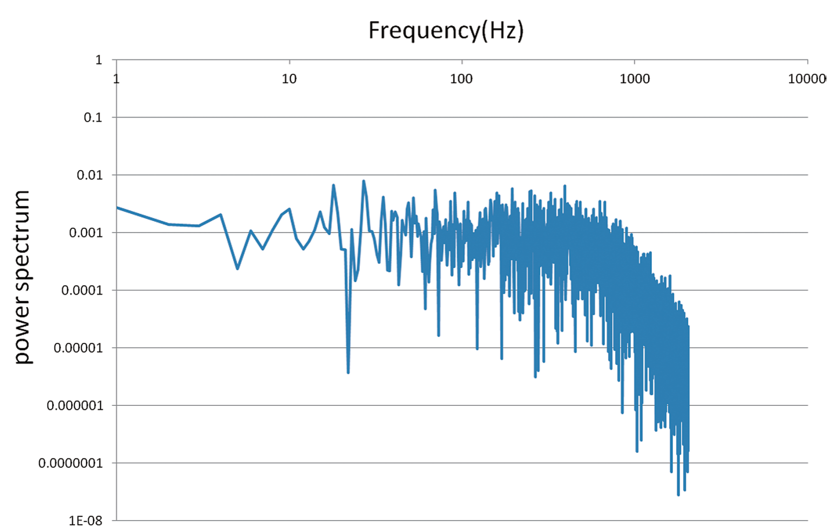

Fig.7 Result of Fourier transformed waveforms recorded (ref. Fig.6)

formed the propagation experiment under atmospheric turbulence using actual communication signals in an intensity modulation scheme and confirmed the signal's degradation. The communication speed was 150 Mbps. The example of communication waveforms was shown in Fig. 9. Here, the amplitude on the vertical axis indicated a voltage from a data recorder. Variations in weak pseudo atmospheric turbulence were compensated by using a limiting amplifier (LMT AMP). However, the graph clearly shows the region where the burst errors were reproduced by large variations. By this, we confirmed that the simulator is able to produce not only the power spectrum of atmospheric turbulence but also burst errors.

6 Conclusions

The fading simulator of satellite-to-ground optical communications has been newly developed and its evaluation has been described. The fading simulator is able to reproduce the power spectrum of atmospheric turbulence and can also generate burst errors. Therefore, from now on, on the ground it makes it possible to accurately evaluate satellite onboard optical communication apparatus, and to verify the effect on the communication quality of encod-

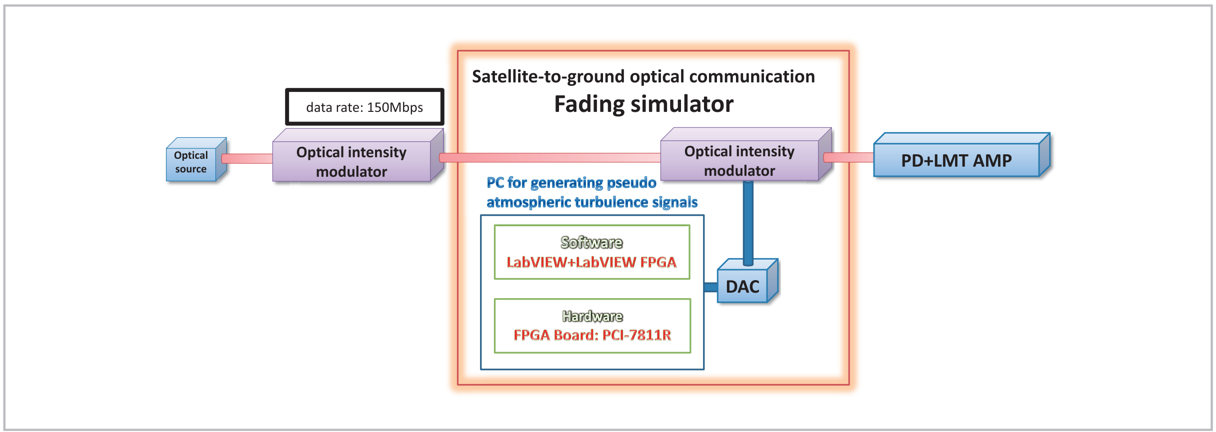

Fig.8 *Configuration of the communication experiment system using the simulator*

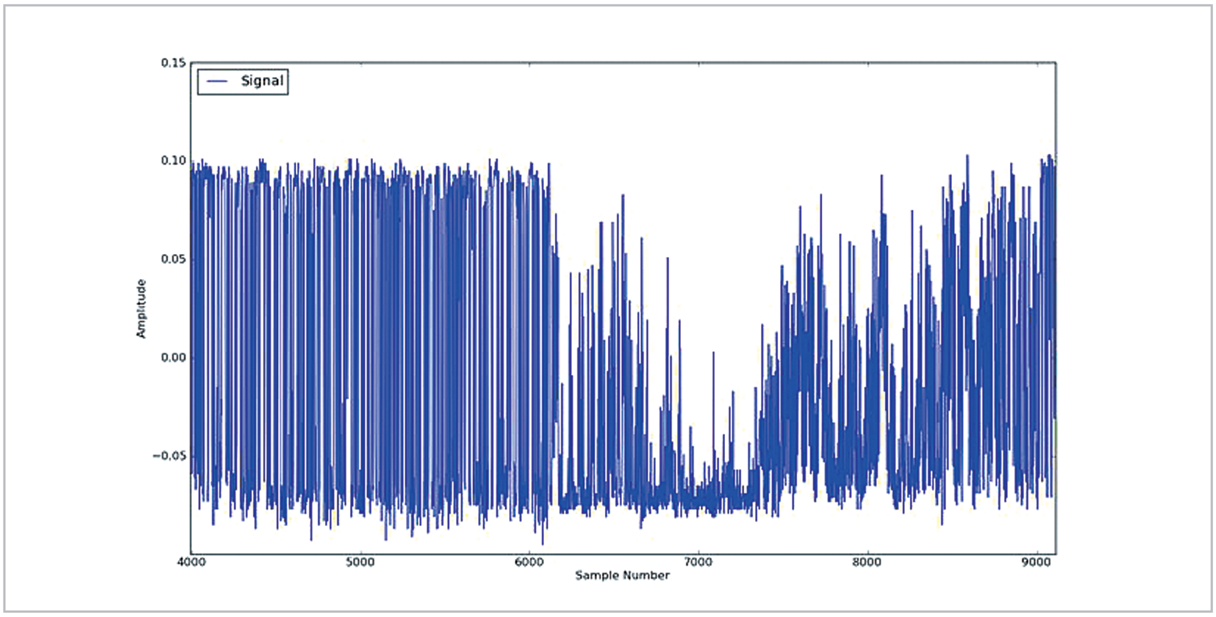

Fig.9 *Received signal level propagated through pseudo atmospheric turbulence*

ing, decoding and others.

We have one future subject to evaluate the communication quality when burst errors happen. Even if the evaluation is made using a general instrument such as a Bit Error Rate Tester (BERT), the number of errors cannot be accurately counted because signal synchronization collapses when burst errors happen intermittently.

In addition, we plan to make the simulator adapt to a coherent scheme as another subject. The configuration of the present simulator is only applied to the evaluation of an IM-DD (Intensity Modulation-Direct Detection) scheme. This is caused by the optical intensity modulator that affects phases. Therefore, the present simulator cannot be applied to a coherent scheme using phase modulation. However, we place expectations on the coherent scheme having tolerance for atmospheric turbulence or strength variations because this scheme has high receiving sensitivity and uses phase modulation. Therefore, we would improve the simulator from now, and show the effectiveness of the coherent scheme for satellite laser communications comparing it to the IM-DD scheme.

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