5-2 The Uplink Data Received by OICETS

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This paper shows the results of data analysis obtained by OICETS during international optical communication campaign. Scintillation Index, Probability Density Function, FFT analysis, and Normalized Covariance analysis were carried out using received FPS signal of LUCE onboard OICETS to identify any specific characteristics difference between 4 OGS distributed on the Earth. The analysis of BER characteristics of Uplink was also carried out to investigate the link quality.

Keywords
Atmospheric propagation, Laser beam transmission, Free-space optical communication

1 Introduction

Experiments of optical communications between a ground station and a satellite were conducted using the Optical Inter-orbit Communications Engineering Test Satellite (OICETS), a low earth orbit satellite. An optical detector mounted on OICETS can be commonly used to receive laser beams from two or more ground stations in different locations on the earth. This indicates that it might be possible to clarify the difference in the atmospheric fluctuations in the different locations of ground stations by comparing the characteristics of the signals received from the stations. The optical communications experiments were conducted with OICETS and the optical ground stations (OGS) of the German Aerospace Center (DLR), European Space Agency (ESA), Jet Propulsion Laboratory of the National Aeronautics and Space Administration (JPL/NASA), and National Institute of Information and Communications Technology (NICT). In this paper we show the results of analysis the measurement data obtained by the OICETS in the uplink experiments from the ground stations to the satellite.

2 Locations of ground stations in experiments

Table 1 shows the locations, latitudes, longitudes, and heights above sea level of the ground stations of the agencies that joined the experiments [1]-[4]. Every station is located between the latitudes 28° and 48° in the northern hemisphere. The DLR ground station is located on the European Continent and can be used for experiments at a relatively-low elevation angle (of several degrees). The other stations are all located near the ocean. The ESA and JPL stations are located more than 2,000 m above sea level, where low atmospheric fluctuations are expected. There is in fact an observatory nearby to take advantage of the geography. The elevation angle of the satellite in the experiments, although it varies depend-

Table 1 *Comparison of location conditions of optical ground station*

Organization	Location	Latitude	Longitude	Altitude
DLR	Oberpfaffenhofen	48.08° N	11.27° E	645 m
ESA	Tenerife Island	28.30° N	16.51° W	2,393 m
JPL	Table Mountain	34.38° N	117.66° W	2,200 m
NICT	Koganei	35.71° N	139.49° E	122 m

ing on the orientation at the start of the experiments, was 0° for the DLR and ESA stations, 20° for the JPL station, and 15° for the NICT station.

3 Data analysis

3.1 Data obtained from OICETS

Laser Utilizing Communications Equipment (LUCE) mounted on the OICETS receives optical signals from the ground stations using its three optical detectors: Coarse tracking and pointing sensor (CPS), fine tracking and pointing sensor (FPS), and optical receiver (OPR RX). The FPS uses a relatively high sampling frequency of 1024 Hz, since it can always receive light signals irrespective of the presence/absence of modulation. Therefore the FPS, among the above optical detectors, outputs the most appropriate signals to analyze the influence of atmospheric fluctuations. In this paper we therefore analyze the signal intensity detected by the FPS.

3.2 Analysis method

The reference [5] shows the analysis results from the experimental data obtained in the bidirectional optical communications between the ground station and OICETS conducted by NICT. We also make a similar analysis in this paper to find a difference in the characteristics of various measured data obtained from the different ground stations. In particular we made an analysis of the following five items. In order to prevent functional limitations of the signal processing of the FPS, the analysis was made mostly for data where the output was not saturated.

(1) Scintillation index (SI): SI is a normalized variance of the intensity fluctuation of the received light. Larger SI corresponds to larger intensity fluctuation. We used Equation (1) for 0.5-second data.

$$\sigma_I^2 = \frac{<I^2> - <I>^2}{<I>^2} = \frac{<I^2>}{<I>^2} - 1 \qquad (1)$$

Here I represents the intensity of the received light and $< \; >$ the ensemble average.

(2) Probability density function PDF: Using 1-second data in the time that corresponds to a given elevation angle, the probability was calculated for the intensity normalized with the average value.

(3) Frequency analysis FFT: Analysis was carried out for a set of 2^{10} data, which was picked up from 1-second data in the time that corresponds to each elevation angle.

(4) Autocovariance function: Analysis was made with 0.1-second data for each elevation angle. The following calculation formula was used.

$$\begin{aligned} \mathrm{K}(t,s) &= E[(I_t - \mu_t)(I_s - \mu_s)] \\ &= E[I_t \cdot I_s] - \mu_t \cdot \mu_s \end{aligned} \qquad (2)$$

Here, E is an expectation operator, and μ_t and μ_s are averaged values. The above equation was then normalized with the dispersion σ^2 and presented in a graph as autocorrelation coefficients. The time difference t-s of the two data sets is 0.1 seconds.

In addition to the above, the following item was also analyzed for the communication link quality evaluation.

(5) Bit error rate BER: The pseudo noise (PN) codes sent from the ground stations were received at the optical detector. The BER was then calculated from the error count of the demodulated PN signals. The BER was evaluated using the data of the error rate in 1 second.

3.3 Extraction of FPS and BER data for analysis

Table 2 shows the established optical links in the campaign. The table shows the agencies, experiment dates, experiment period (planned period), minimum/maximum satellite elevation angles during the experiment, time rates of unsaturated effective FPR data, and FPS and BER data analysis ("Y" if analysis was conducted). Since the experiment with the DLR ground station used unmodulated uplink signals, BER analysis was not conducted for this case. For the same reason, BER analysis was not carried out for the experiment using the ESA ground station.

Table 2 List of established optical links

OGS	Date	Duration [m:ss]	EL. Angle Min/Max [deg]	Effective FPS Data	FPS Data Ana.	BER
DLR	2009/07/01	4:14	11/57	80%	Y	
	2009/08/19	4:27	3/35	50%	Y	
	2009/08/21	5:43	10/27	25%	Y	
	2009/08/28	4:43	4/49	25%	Y	
ESA	2009/07/08	8:06	0/23	3%	Y	
	2009/07/10	8:48	0/39	6%	Y	
	2009/07/15	3:15	0/52	0%		
	2009/07/22	6:19	0/53	5%		
	2009/07/29	7:13	0/19	42%	Y	
	2009/07/31	4:17	0/31	12%		
	2009/09/11	7:23	0/20	0%		
	2009/09/16	4:41	0/79	0%		
JPL	2009/05/21	2:29	20/61	14%		
	2009/06/02	1:39	20/60	100%	Y	
	2009/06/04	2:16	20/83	60%	Y	
	2009/06/11	2:15	20/51	75%	Y	Y
NICT	2008/11/13	5:38	15/56	34%	Y	
	2008/11/18	5:04	15/38	40%		
	2008/11/20	4:04	15/24	80%		
	2008/12/02	5:30	18/34	60%		
	2008/12/04	5:30	22/58	5%	Y	
	2008/12/11	4:36	15/24	15%		Y
	2008/12/16	2:30	23/89	30%		
	2008/12/18	5:56	20/54	8%		
	2008/12/23	5:36	18/26	25%		
	2009/01/13	5:49	18/36	20%		
	2009/01/15	6:35	22/62	18%		
	2009/01/20	5:46	14/24	80%		Y
	2009/04/23	2:05	24/87	100%	Y	

4 Analysis results

4.1 Scintillation index (SI)

Figure 1 shows an example of the analysis results, obtained from the analysis of the data measured with the DLR station on September 1, 2009 in Table 2. The upper figure shows the time variation of the power of the light re-

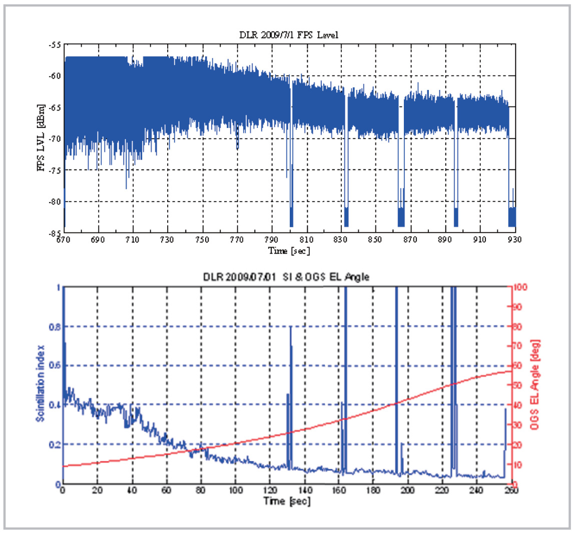

Fig.1 Analysis example of Scintillation index

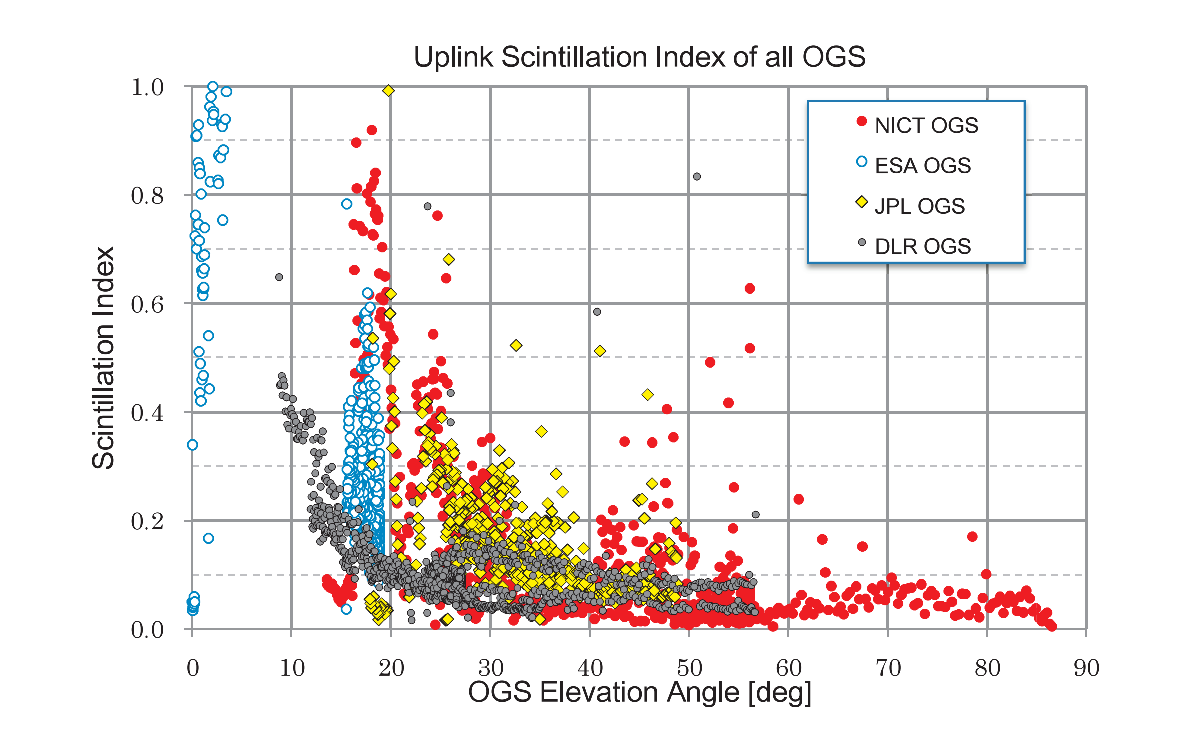

Fig.2 Relationship between scintillation index and elevation angle at each ground station

ceived at the FPS. The power was saturated above –57 dBm. The lower shows the SI, which is calculated from the FPS output data. The red line in the figure shows the satellite elevation angle at the OGS. As seen in Fig. 1, the SI decreases as the elevation angle increases for any OGS.

As in Fig. 1, the experiments that have “Y” in the FPS analysis field of Table 2 were analyzed. The results are summarized in Fig. 2, where, for each OGS, the same symbols are used for experiments conducted on different dates.

The characteristics of the data were compared between the ground stations using the results of Fig. 2. Although the number of experiments of each OGS were limited and the experiment dates were different, it could be found that, for small elevation angles (20°–30°), the experiment result for the DLR station showed a smaller SI than those for the other stations. It was difficult to find a characteristic difference in the experiment results for the other optical ground stations.

4.2 Probability density function (PDF)

The 7/1/2009 data for the DLR station was analyzed at every 10° of the elevation angle from 15° to 55° and the results are shown in Fig. 3. The analysis of the data for the other stations showed the same results as that for the DLR station and no characteristic difference between stations was found.

With an assumption of a lognormal distribution, a theoretical formula [6] for the PDF in the presence of weak disturbance was applied to the SI data for each elevation angle. The calculation results are shown in Fig. 4. The curves in Figs. 3 and 4 have similar shapes.

$$p(I) = \frac{1}{I\sigma_I^2\sqrt{2\pi}} exp\left\{-\frac{\left[ln\left(\frac{I}{<I>}\right)+\frac{1}{2}\sigma_I^2\right]^2}{2\sigma_I^2}\right\},\ I > 0 \quad (3)$$

Here, σ_I^2 is the scintillation index and $<I>$ is the average irradiance.

4.3 Frequency analysis

As an example of frequency analysis, the 7/1/2009 data for the DLR station was analyzed in every 10° of the elevation angle from 15° to 55° and the result is shown in Fig. 3. The data was obtained for up to 514 Hz due to the limitation of the sampling frequency. The spectrum shows a clear decrease at high frequencies for the low elevation angle of 15°, while the decrease disappears as the elevation angle becomes larger. This tendency was also seen in the experiments with the other stations.

4.4 Autocovariance function

In order to understand the characteristic time variations of the signals received at the FPS, the 7/1/2009 data for the DLR station was used to obtain an autocovariance function of the normalized intensity for the time difference

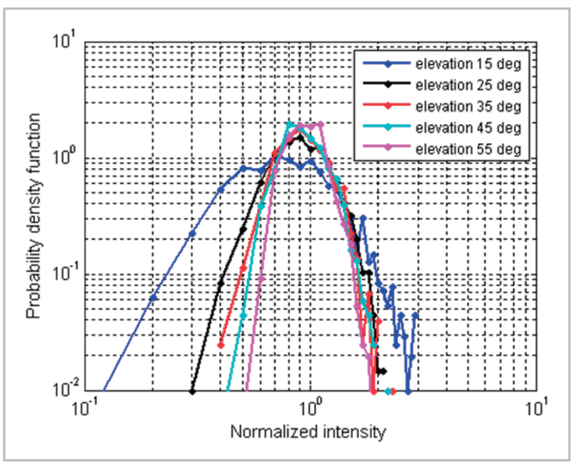

Fig.3 PDF analysis results for DLR station (7/1/2009)

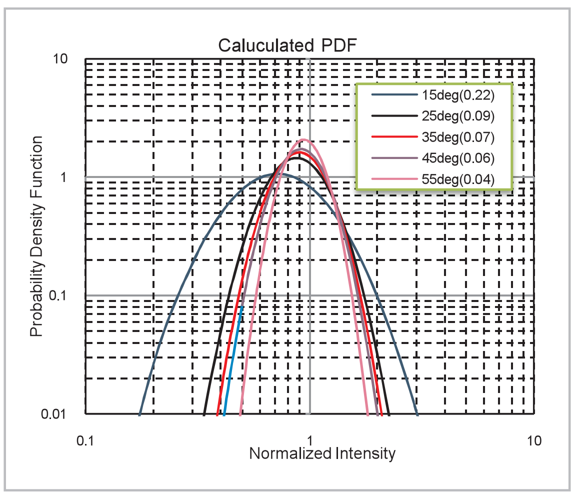

Fig.4 PDF calculated from SI

up to 0.1 second at a given elevation angle. The result is shown in Fig. 6. The correlation time during which the correlation value becomes $1/e^2$ was about 2 ms for an elevation angle 15° and about 7 ms for 55°. Since the correlation time was below 10 ms in most of the experiments, no characteristic tendency was found for any of the optical ground stations.

4.5 Bit error rate, BER

The uplink quality can be evaluated by the bit error count detection function of the LUCE. The LUCE receives from the ground stations the signals that are modulated with PN codes, and demodulates them. The LUCE then compares them with the PN codes which is generated internaly, and distinguishes insertion errors from other signal loss errors. The insertion error is an error where a signal is detected in a place where it is not supposed to be present. The BER is calculated from the total number of errors of each type. Figure 7 shows the experimental data for the NICT station (1/20/2009). The upper figure shows the FPS signal intensity and the lower the occurrence of insertion errors in the demodulated signals. The signal loss errors showed the same tendency. The bit errors occurred when the received signal level was below the threshold of the receiver (–67 dBm of the FPS level in this case) or when the level was higher but the level fluctuation was large. Since the optical detector of the LUCE was designed to suppress the level fluctuation for the use for inter-orbit communications, the fluctuation was actually small if compared with the level fluctuation in the upper figure in Fig. 1. The SI was below 0.05 in the time period from 683 sec to 718 sec and the BER was of the order of 10^{-1} to 10^{-3}.

Figure 8 shows the relationship between the BER and FPS received signal level per second obtained in the experiments using the NICT station and the JPL station. The figure also shows the data of the characteristics of the optical detector obtained in the ground experiments in the reference [7], where the data is converted in the FPS received signal level. The reference [7] indicates that the BER char-

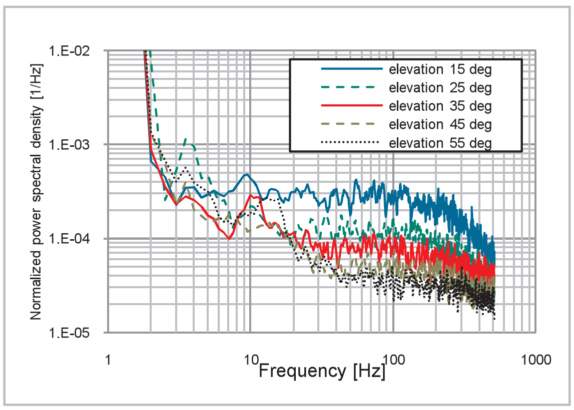

Fig.5 *FFT analysis results for DLR station (7/1/2009)*

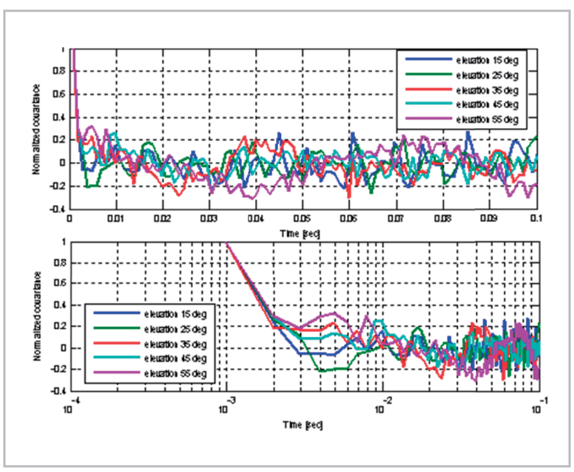

Fig.6 *Analysis results of autocovariance function for DLR station (7/1/2009)*

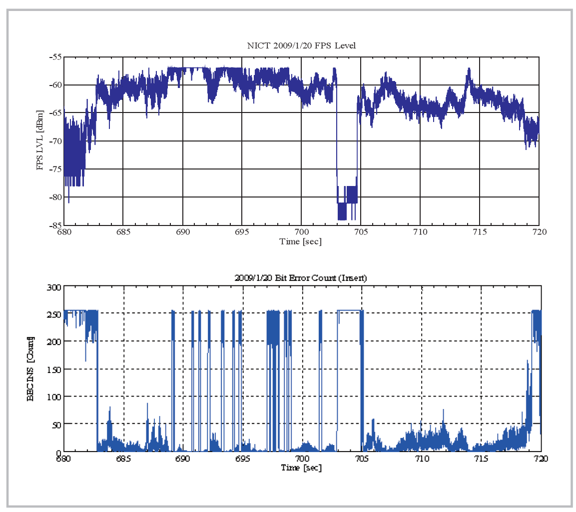

Fig.7 *FPS received signal level and number of insertion errors in experiments with NICT station*

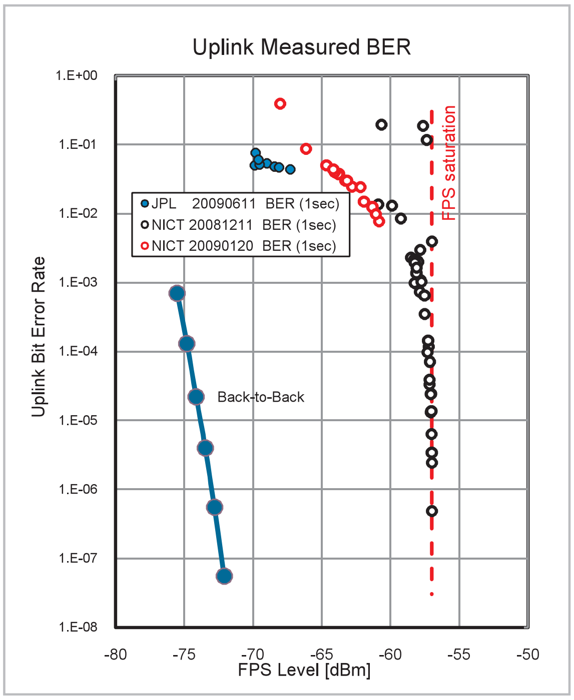

Fig.8 *BER characteristics obtained in NICT and JPL experiments*

acteristics measured in the optical inter-orbit communications experiments showed about 2 dB degradation in comparison with the data obtained in the ground experiments. However in the ground-to-satellite link, the degradation was more than 15 dB due to additional effects from atmospheric fluctuations. Since the output of the FPS level is saturated at –57 dBm, the precise received level is not clear when the BER is smaller than 10^{-3}. But in some cases the BER was about 10^{-7} and even a BER of about 10^{-3} would cause no practical problems if error corrections are adopted.

5 Conclusions

The data that OICETS obtained in the uplink experiments made between the satellite and different ground stations in different places was analyzed to find differences in the signal characteristics. It was difficult to find clear differences since the amount of data that could be used for analysis was limited and the experiment dates were different. However a comparison of the analyzed data indicates that the characteristics obtained in the experiment using the DLR station showed a smaller SI at a low elevation angle than those obtained for the other stations. No significant difference was found in the other analysis results. The optical communications between the four optical ground stations and the satellite using the same optical detector were the world's first such experiment, and the data obtained in the experiments with these stations would be useful to identify the parameters of a model of atmospheric fluctuations at each station and to establish the model. We could expect more data available through a series of this kind of campaigns.

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