Measurements of the Refractive Index Structure Constant and Studies on Beam wander

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***Abstract*—A setup of a simplified optical ground station is studied for receiving laser stably in the space optical communications. We study the reception system that takes into account the beam wander that is a matter of peculiar atmospheric propagation.**

Keywords*— *free space laser communications, optical ground station, structure parameter, atmospheic turbulence

I. Introduction

In the space optical communication between ground and satellites, it is important to consider the effects of the break by the cloud and the atmosphere, and to employ the mechanism to reduce their effects. Especially, the interception of the laser by the cloud and the fog, etc. is the problem that should be avoided. It is considered to evade this by a site diversity in which plural earth stations are located away[1].

Generally, the wave surface of the laser that propagates the atmosphere is distorted, and the change of receiving power strength and the arrival angle is observed in the aperture plane of the receiving optical system. These changes cause the movement and scattering of the light focus. In the space optical communication, the transmitted laser is detected at the photodetector in the receiving optical system. For stable communication, it must have a mechanism to receive the light efficiently. One of the ways is to install mirrors that can control the angle at high speed in the receiving optical system, and to adjust the angle of mirrors corresponding to the arrival angle of laser. On the other hand, the adoption of a photodetector having a large diameter to cover an irradiation range of laser that spreads under the influence of the atmosphere is considered.

When it is assumed to make earth station portable and to set up plural earth stations for site of diversity, the simplification of the receiving optical system is an important task. To simplify the receiving optical system, it is thought that the measure to use a large photodetector is better than the measure to install mirrors.

In this paper, we consider a simple optical ground station for irradiating a laser directly. The system has not installing high speed driving mirror. Firstly we conducted the horizontal laser transmission experiment to consider the effect of the atmosphere to the laser propagation by measuring the received power of the laser. The atmospheric refractive index structure constant that expresses the size of the atmospheric turbulence is calculated by use of the experimental results of received power. From the atmospheric refractive index structure constant, the beam wander, which is related to a range to irradiate in the focal plane of the reception optical system, is calculated. Finally, an appropriate diameter of the photo-detector to cover beam wonder in consideration of atmospheric influence is estimated.

II. Constitution of the Simple Optical Communication System

An example of the receiving optical system in the optical ground station that is used in the space laser communication between ground and satellites is shown in Figure.1[2]. The optical system is composed of the optical equipment such as telescope, gimbal, sensor for coarse tracking, beam splitter, sensor for fine tracking, fine pursuit drive mirror, and photodetector. Two stage tracking mechanism is used to control the wavefront error of the laser that propagates from the satellite in the atmosphere and to achieve highly accurate tracking as a result. The Coarse tracking mechanism is the first stage and it is given by the gimbal that can control the direction of the telescope from side to side and up and down. The Fine tracking mechanism is the second stage and it corrects a minute angle variation of laser led in the receiving system. The focus of a laser beam squeezed with the telescope lens is controlled as being at the center of the photodetector. Figure.2 shows the suppressed focus scattering at the photodetector.

We propose the receiving optical system that has only the coarse tracking mechanism and fine tracking mechanism is reduced for the simplification of the optical ground station, as shown in Figure 3. When this receiving system is used, focus scattering at the photodetector is observed as shown in Figure 4 according to the time variance of the arrival angle of the laser.

It is necessary to adopt the photodetector that covers the range of focus scattering in the receiving optical system that has only the coarse tracking mechanism for a stable reception, whereas the range of focus scattering is smaller in the receiving optical system shown in Figure 1 because the error of arrival angle is decreased by fine tracking mechanism. On the other hand, the response speed of the photodetector that is related to transmission speed is decreased as the diameter of the photodetector is increased. So it is necessary to adopt the photodetector of an appropriate size to cover the irradiation range of a laser affected by the atmosphere.

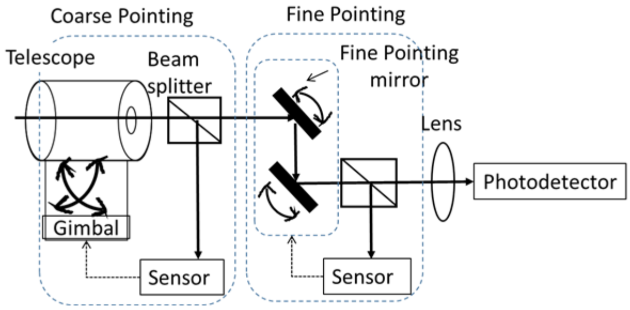

Fig.1 Receiving optical system with two tracking mechanism

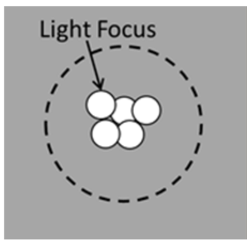

Fig.2 Suppressed focus scattering at the photodetector in the receiving optical system with two tracking mechanism

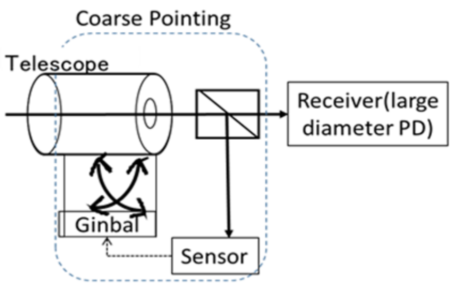

Fig.3 Simplified receiving optical system

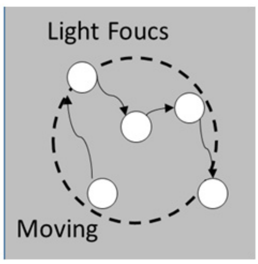

Fig.4 Focus scattering at the photodetector in the simplified receiving optical system

III. Beam Wander

When the laser propagates through the atmosphere, a phenomenon called beam wander occurs [3]. Error of the arrival angle of the laser generated by the beam wander is observed in the receiving system, and movement of the optical focal point occurs in the photodetector of the receiving system. The state that a light focus moves by the error of the arrival angle is shown in figure 5.

The range where an optical focus moves can be calculated from the focal length and the error of arrival angle. Variance of the angle-of-arrival error$\langle {\theta_{BW}}^2 \rangle$ is represented by the following formula.

$$\langle {\theta_{BW}}^2 \rangle = \langle r_c^2 \rangle / L^2 \tag{1}$$

Where, L is the transmission distance of the laser. $\langle r_c^2 \rangle$ is the deviation of the irradiation area obtained when under the influence of beam wander observed in the lens as shown in Figure 5.

Figure 6 shows the state of the irradiated area changed by the beam wander, and Figure 7 is the overlapped irradiated area of Figure 6 [4]. In Figure.6 and Fig.7, t1, t2, t3 and t4 are the time, solid circles stand for the region of the laser irradiation, and the small shaded circles stand for the area where the light is strongly observed [5].

$\langle r_c^2 \rangle$ is the beam wander displacement variance and defined in the following formula in the optical communication between satellite and ground station as shown in Figure 8.

$$\langle r_c^2 \rangle = 7.25 (H - h_0)^2 sec^3(\zeta) W_0^{-1/3} \times \int_{h_0}^{H} C_n^2(h) \left(1 - \frac{h - h_0}{H - h_0}\right)^2 dh \tag{2}$$

Where, h_0 represents the altitude of the optical ground station, H is the altitude of the satellite, and ζ is the elevation angle. We can rewrite $\langle r_c^2 \rangle$ in the case of horizontal propagation.

$$\langle r_c^2 \rangle = 7.25 L^2 W_0^{-1/3} \int_0^L C_n^2(z) \left(1 - \frac{z}{L}\right)^2 dz \tag{3}$$

Where W_0 is the 1/e field radius of the beam and called the beam waist. The structure parameter C_n^2 is a measure of turbulence strength. C_n^2 is defined by

$$C_n^2 = \frac{\ln\left[1 + \frac{\sigma}{\langle I \rangle^2}\right]}{0.5 k^{7/6} L^{11/6}} \tag{4}$$

Where, σ is called the scintillation index, and is the fluctuations in the irradiance of an optical wave caused by small random index-of-refraction σ^2 is defined by the following formula [6].

$$\sigma^2 = \frac{\langle I^2\rangle - \langle I\rangle^2}{\langle I\rangle^2} \quad (5)$$

Where, I denotes irradiance of the optical wave and angle brackets <> denote an ensemble average or, equivalently, a long-time average

By measuring the intensity of the atmospheric propagated laser, it is possible to calculate the beam wander displacement variance.

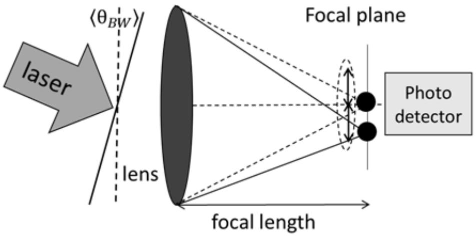

Fig.5 The state that a light focus moves by angle-of-arrival error

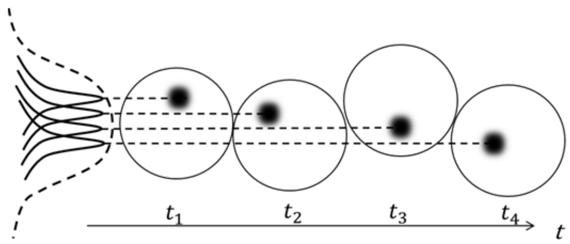

Fig.6 Time variance of the irradiation area at the focal plane in Fig. 5

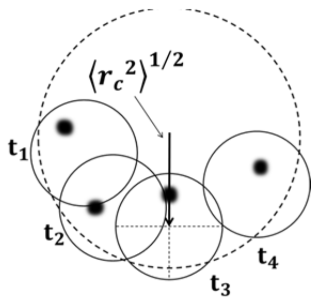

Fig.7 Overlapped irradiation area of Fig.6

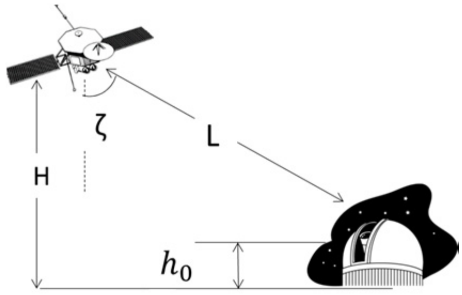

Fig.8 Satellite and ground station in the space laser communications

IV. HORIZONTAL PROPAGATION EXPERIMENT

The horizontal propagation experiment of the laser in propagation distance 7,800m was conducted in 2013. 1.55μm wavelength of the laser is used, and spread angle is 1 mrad. The structure of the optical receiving system is shown in figure 8. In this system, firstly the laser enters into the mirror lens and it becomes the parallel beam and passed to the latter part. The parallel beam is focused on the first convex lens, and the angle is adjusted with three two-axis mirrors that can be adjusted manually. Thereafter, the beam enters from the front to the second convex lens through the beam splitter. The laser collected by the lens enter to the detector, and is converted to electric signal and recorded. Figure 9 shows the structure of the optical receiving system. The samples of measured time change of the received power strength are shown in figure 10 and 11. The received power strength is recorded by a 20 kHz sampling.

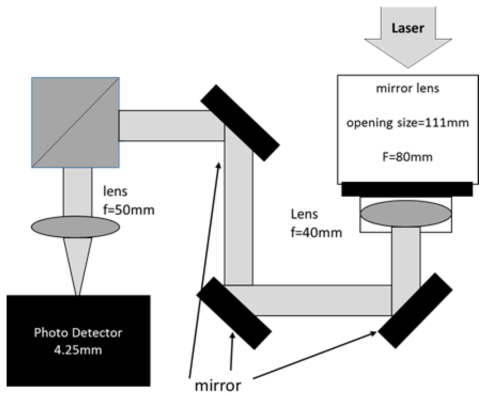

Fig.9 The structure of the optical receiving system

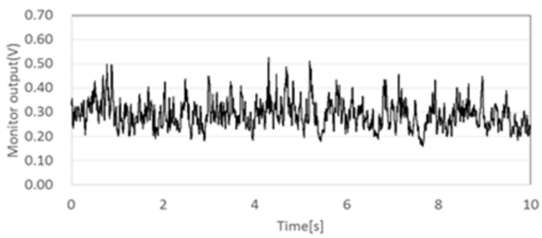

Fig.10 Time change of received power strength (sample 1)

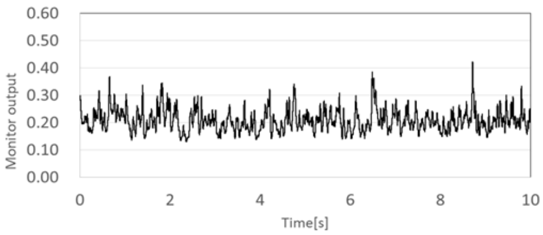

Fig.11 Time change of received power strength (sample 2)

V. MEASUREMENT RESULT

From the measured intensity fluctuations, the scintillation indexes σ are calculated according to equation (5). Then the refractive index structure constants of air C_n^2 are calculated according to the equation (4), and are shown in Figure 12 and 13.

Then the variation of the arrival angle of the beam is calculated by using the formula (1) and (3). In this case, the transmission distance L is 7800m, and the beam waist W_o is 0.2m. The refractive index structure constant of the atmosphere C_n^2 is estimated 3.15E-15 from the measurement results. So the derived arrival angle change is 115μrad. As the focal length of this receiving optical system is 0.1m, Radius of the moving optical focus is 115μm, and it is estimated that the scattered light focus is in the circle of 230μm diameter at this time.

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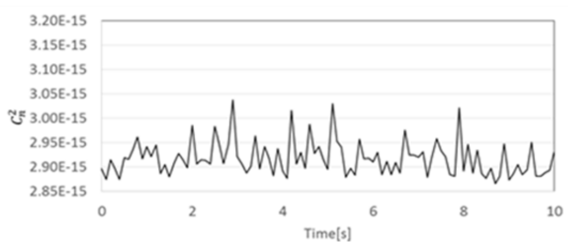

Fig.12 Time change of C_n^2 (sample 1)

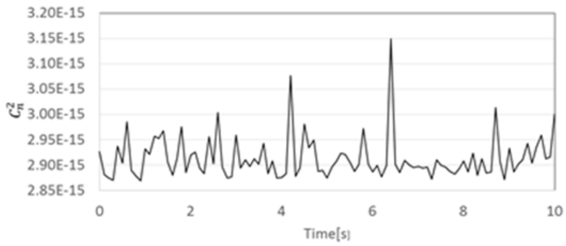

Fig.13 Time change of C_n^2 (sample 2)

VI. CONCLUSION

In this paper, we considered a simple optical ground station for irradiating a laser directly, assuming to operate the plural ground stations by site diversity in the optical communication between satellites and ground. Horizontal propagation experiments laser was performed, and from the results, refractive index structure constant that represents the magnitude of atmospheric turbulence was calculated. Then we discussed the error caused by the receiving system by beam wander, which is a specific matter of space optical communication. The required size of the photodetector was estimated when the simple optical receiving system is designed.

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