BEACONLESS APPROACH TO MAINTAIN OPTICAL LINK FOR FREE- SPACE LASER COMMUNICATION

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ABSTRACT

In the existing free-space laser communication system between a satellite and the ground, the beacon laser had been used to acquire the position of optical ground station(OGS)s from the satellite besides the laser for communication. However, it is desirable to have an alternative measure to acquire the position of OGSs because the output power of the beacon laser is very high and it makes limitation to set OGSs. We propose a novel system that uses GPS information for initial acquisition of the position of OGSs instead of the beacon laser. To implement this system, it is necessary to estimate the pointing error at the ground station when the information of GPS and the satellite's orbit is used instead of beacon laser. From the results of examination, we confirm that the satellite can point at the ground station by the same accuracy with the case of using beacon laser in our proposed system. Then, to irradiate the ground station accurately, a laser divergence angle by considering the estimated error margin is calculated. Furthermore, an attitude control error of low-orbit satellites that orbit the Earth is estimated, and the accuracy required for the gimbal to correct the attitude control error of the satellite is derived from this error margin. Finally, the beam wander effect that is caused by the atmospheric turbulence and the aberration of light in laser downlink from the satellite to ground is calculated. By considering all these errors, we evaluated the feasibility of the beacon-less space laser communication system between the low orbit satellite and the ground.

1. INTRODUCTION

The demand for high data rate transmissions from space-borne observation platforms is steadily increasing. The advantages of a laser communication system compared with a usual radio communication system are wider bandwidth, larger capacity, lower power consumption, compactness of equipment, greater security against eavesdropping, and protection against interference[1]. However, in this satellite laser communication system, laser beam is blocked easily by the clouds. The application of the site diversity is one of the solutions for this problem. In the site diversity, plural OGSs are set up apart respectively, and they are operated concurrently[2]. When plural OGSs are used, the simplification of configuration in each OGS is one of the important items that should be examined.

In the existing satellite laser communication system, an OGS emits high power beacon laser, and a satellite receives it for initial acquisition of the OGS. It is necessary to make sure the OGS does not harm human body and the environment because output power of the beacon laser is very high. The simplification of the OGS configuration promotes the portability, and enables more flexible operation of the site diversity. However, the place where OGS can be set up is restricted in consideration of safety because output power of beacon laser is very high. Therefore, the beaconless initial acquisition scheme has advantages in both of the relaxation of setting portable OGS and the simplification of OGS configuration[3]. We have been proposed the new system which can acquire the position information of the OGS without using a beacon laser and establish a downlink by pointing a laser to that position[4][5]. According to the past study, the satellite can acquire the position of OGS by using GPS information and can point laser there without using the beacon to establish a downlink channel from the satellite to the OGS. However, requirement for the OGS has not been studied yet. If the performance requirement for OGS in the case of beaconless is higher than the case of using beacon, it will no longer be said that simplification and portability of OGS is propelled by beaconless.

In this paper, the specifications required for the telescope in the case of the beaconless system and using a beacon laser is compared and examined. In the conventional space laser communication system, beacon laser is emitted from the transmitter of OGS to satellite. The satellite emits a laser for communication to the arrival direction of the beacon laser. At this time, the beacon laser emitted from OGS is diffused by the strong atmospheric turbulence. Therefore, a significant arrival angle error occurs in the satellite side, and the satellite cannot irradiate a communication laser to the correct direction of the OGS. However in order to transmit the communication laser in the direction of arrival of the beacon laser, it is possible to correct the error in the attitude control of the satellite. Divergence angle of the transmission laser must be enough to cover the effects of beam wander. In addition, divergence angle of the transmission laser must be enlarged to cover OGS location error and satellite attitude control error in the case of beaconless system. First, the mechanism of the initial acquisition by use of the beacon laser in the satellite laser communication system is described. Then, the arrival angle error of the beacon laser which is caused by atmosphere turbulence is calculated. After that, the permissible error of GPS in the proposed system is estimated. Finally, the specifications necessary for telescope in the OGS to achieve the same transmission rate with the case of using beacon is proposed.

2.INITIAL ACQUISITION USING BEACON LASER

A high power and wide-angle beacon laser is used for the typical acquisition process of optical link in the satellite laser communication system. The satellite detects incoming beacon laser and locks on the OGS. Then the downlink is established by using a low power and narrow-angle communication laser.

The wavefront of the beacon laser which is irradiated from OGS is distorted by the influence of an atmospheric fluctuation, and the direction of propagation is changed at the satellite. This phenomenon is called "beam wander". Arrival angle error θ_{BW} of the beacon laser is observed at the satellite. This error causes lock on error. An example of the beam wander that is observed at the satellite is shown in figure 1, where the solid circle represents the illuminated range of the beacon laser at each moment of t_1-t_4. Note that $\langle r_c^2 \rangle$ in figure 1 is a variance of the distance between the ideal center of the beacon illumination area with no atmospheric influences and the center of the illumination area affected by atmosphere[6]. A typical positional relationship between satellite and OGS are shown in figure 2. The altitudes of the satellite and the OGS are given as H and h_0, respectively. The zenith angle is ζ. $\langle r_c^2 \rangle$ is derived from

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

where W_0 is the radius of the transmission laser, and $C_n^2(h)$ is the refractive index structure constant that represents strength of atmospheric turbulence [7][8]. To calculate $C_n^2(h)$, Hufnagel-Valley (H-V) model is used and it is given as

$$C_n^2(h) = 0.00594\left(\frac{v}{27}\right)^2 (10^{-5}h)^{10} exp\left(-\frac{h}{1000}\right) \times 2.7 \times 10^{-16} exp\left(-\frac{h}{1500}\right) + C_n^2(0) exp\left(-\frac{h}{100}\right) \quad (2)$$

where v is the wind velocity at ground (m/s), and $C_n^2(0)$ is a scaling factor that expresses fluctuation properties of the surface of the earth[12]. When v is set to 20m/s, and $C_n^2(0)$ is set to 9.0×10^{-14} which is measured by using the DIMM method, the $C_n^2(h)$ becomes $2.68 \times 10^{-14} m^{-2/3}$ at an altitude of NICT optical ground station (h = 122m).

The variance of fluctuation of the beam arrival angle $\langle {\theta_{BW}}^2 \rangle$ is given as

$$\langle {\theta_{BW}}^2 \rangle = \langle r_c^2 \rangle / L^2 \quad (3).$$

The arrival angle error of the beacon laser that is observed in the satellite side is calculated as a function of elevation angle, and it is shown in Figure 3. From this figure, it is observed that the arrival angle error of the beacon laser is decreased as the increase of the elevation angle. It is also confirmed that the smaller arrival angle error is derived by larger OGS transmission radius of emitted beacon beam at the same elevation angle. For example, when the transmission laser radius is 0.1m, the arrival angle error of 3.9μrad is derived at the elevation angle is 80deg, and arrival angle error of 7.6μrad is derived at the elevation angle is 30deg. Satellite emits a communication laser to the arrival direction of the beacon. So arrival angle error of the communication laser is occurred by this arrival angle error.

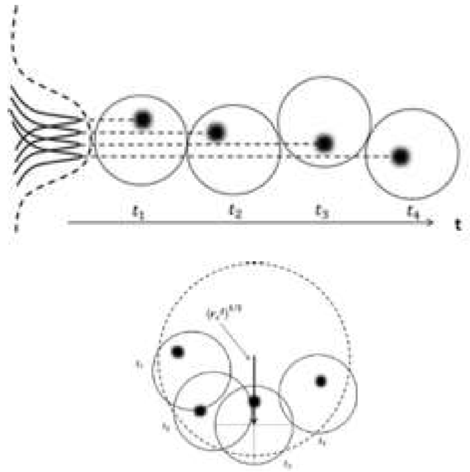

Figure.1 An example of beam wander effect

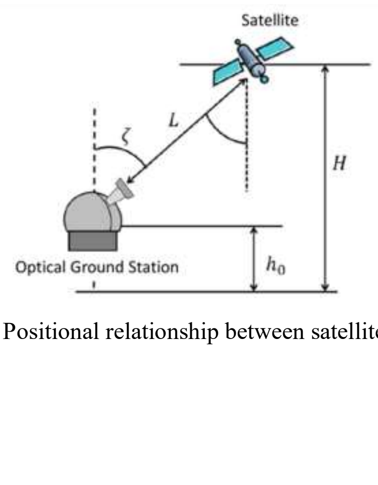

Figure.2 Positional relationship between satellite and OGS

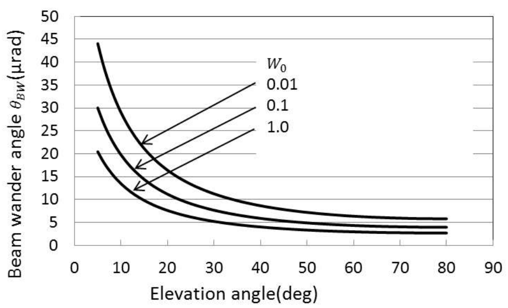

Figure.3 Arrival angle error cause by Beam wander

3. INITIAL ACQUISITION BY USING GPS INFORMATION

3.1 ERROR OF GPS INFORMATION

Recently in most of low earth orbit satellites, the reverse mirror(Corner-Cube Retroreflector; CCR) and GPS receiver for SLR observation are equipped. The observation method of the position of low earth orbit satellite by using GPS is called High-Low Satellite-to-Satellite Tracking (HL SST), because the distance between the medium earth orbit satellite (GPS satellite) and low earth orbit satellite is measured. When GPS is used on the earth, the location of the receiver is determined by measuring the distance from three satellites in the maximum. On the other hand, in the measurement at the low earth orbit satellite, the distance can be observed by using four or more GPS satellites because position of the low orbit satellite is high compared with the ground. Therefore, the position information can be acquired in the accuracy of 15m even if small general GPS receiver is used[10]. Generally, GPS accuracy on the ground is 10m [11]. So the sum of these two error is 25m, and it is necessary to have irradiation area of 25m beam spot radius in order to receive reliably at the receiver. When the propagation distance is L, the divergence angle which includes the total error x[m] of the position information of the transmitter and receiver can be calculated by the following formula.

$$\theta = tan^{-1}\frac{x}{L} \tag{4}$$

When the propagation distance L = 600km, the divergence angle θ = 80μrad to cover the error area of 25m radius. When L = 1200km, θ = 40μrad.

3.2 ANGLE ERROR BY POSTURE CONTROL

In the laser communication between ground and satellite, highly accurate posture control system is required to turn the posture of the satellite in a prescribed direction with high stability because the divergence angle of the laser is very narrow. The accuracy of the roll angle and the pitch angle is less than 0.05deg to stabilize posture in a standard with a gyro in the recent geostationary satellite. When the posture error of the satellite at the OGS is 0.05deg, pointing direction error of communication laser is about 870μrad. This error is larger than the error that is caused by GPS, and the error that is caused by atmospheric fluctuation. So it is unreal to diffuse communication laser so as to cover this error. Therefore in our proposal system, it is assumed to apply the mechanism in which the laser keep pointing OGS by using gimbal on the telescope of the satellite, and the posture control error is ignored. When performing initial acquisition using a beacon laser, it is possible to correct the transmission angle relative to the direction of arrival of the beacon laser, the transmission direction error due posture control does not occur.

4. DESIGN OF THE OGS

When the elevation angle is set to 30 degrees, divergence angle required in the case of using beacon laser is 7.6μrad from section 2, and it is 40μrad in the case of beaconless from section 3. If transmission power of the satellite is constant, the energy density on the ground decreases as the divergence angle becomes large. Therefore, to collect the same power with the system which uses beacon laser at the ground station, larger telescopes aperture is needed in the beaconless system. The receiving power P_r at the aperture of OGS is the product of energy density F and the area of aperture S. F is the ratio of transmission laser power P_t and irradiation area I_a.

The distance of the satellite and OGS is 1200km, and the satellite transmission power is set to 500mW. The relationship between the diameter of OGS telescope aperture and OGS receiving power is shown in Figure 4. From this figure, it can be observed that the reception power in the case of divergence angle is 7.6μrad is larger than the case of 40μrad even in the same aperture diameter. For example, in order to achieve 1Gbps of communication speed, it is necessary to use the detector that has the response frequency 1Gbps and detection limit -48dbm (16nW). In the case of using beacon laser, the lens should have 7cm or more of aperture radius to collect a minimum reception power required for communication. In the case of beaconless, the lens should have 12cm or more of aperture radius.

If attitude control errors of the satellite which transmits the communication laser is not corrected, maximum direction error is 870μrad. By combining this error with the divergence angle and posture control error, the angle error observed in the OGS is 910μrad. In this case, it is impossible to receive the laser even if huge telescopes are used.

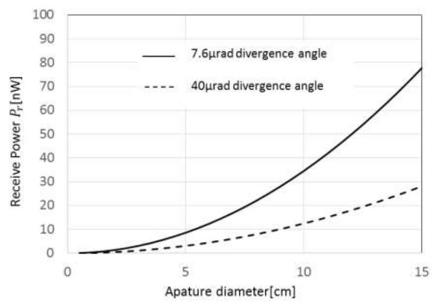

Figure.4 The relationship between the aperture diameter and receive power

5. CONCLUSION

From the viewpoint of realization of portable OGS, the initial acquisition system without a beacon laser is proposed. The requirement to the OGS when using the proposed system is examined. In our proposed beaconless laser system, it is necessary to consider divergence angle of the laser emitted from the satellites to cover the error in the GPS information. In order to achieve the same received power as in the case of using a beacon, it is necessary to use the telescope which has larger aperture. Therefore, as the configuration of the OGS, small telescope with beacon laser, or large telescope without beacon can be considered. However, if the beaconless system is used, it is necessary to consider the attitude control error of the satellite. In the future, we will investigate about tolerance of the attitude control error to realize beaconless OGS.

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