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Effects of Antenna Pointing Errors on the Design of Heterodyne Optical Intersatellite Communications

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SUMMARY

In the optical intersatellite communication system using a heterodyne detection, the signal level changes by the pointing error of the receiving antenna on the satellite in addition to the pointing error of the transmitting antenna of another satellite. Further, since these antenna pointing errors cause the unavailable state of the optical channel, the unavailability will become a problem. However, to date, nothing has been reported on link design which reflects the unavailability by considering the pointing errors of both the transmitting and receiving antennas.

In this paper, equations for the burst error rate are derived by means of the probability density function of the pointing error distributions of the transmitting and receiving antennas. With this burst error rate, the unavailability is computed. Hence, a link design reflecting the unavailability can be carried out by taking into consideration the pointing errors of the transmitting and receiving antennas at the same time. Further, a link design example is presented in the case where the facing satellites have identical communication systems.

1. Introduction

Microwave systems and optical systems have been conceived for intersatellite communication. In comparison to the microwave systems, the optical systems are expected to have a large amount of information transmitted with a small and lightweight communication equipment. Further, the optical systems have no interference between systems. Recently, the optical intersatellite communication systems have been studied extensively [1-5].

One of the characteristics of the optical intersatellite communication system is the use of a narrow beam. In the case of transmission of light with a wavelength of 0.8 μm with an antenna of a diameter of 20 cm, the divergence of the optical beam is about 4 μrad in terms of the half-width angle. In this case, the received power degrades by about 3 dB by the pointing error of 2 μrad. Therefore, the signal power level is very sensitive to the pointing error of the transmitting antenna.

In the case of the system with a direct detection, the diameter of the optical detector is much larger than the displacement of the signal light on the detector due to the pointing errors of the receiving antenna. Hence, the only pointing error affecting the communication quality is the one by the transmitting antenna of the facing satellite. On the other hand, in the heterodyne detection system which is more sensitive and more resistant to the background noise than the direct detection system, the pointing error of its own receiving antenna cannot be neglected. For instance, when the light with a wavelength of 0.85 μm is received with an antenna with a diameter of 20 cm, the signal level degrades by almost 2 dB with a pointing error of 2 μrad [6]. This is caused by the reduction of the detection efficiency of the heterodyne detection due to the lowered degree of matching of the electric field distributions of the signal light and the local oscillator light.

As seen in the foregoing, in the heterodyne detection system, the signal level changes by the pointing error of the receiving antenna in addition to the transmitting antenna of the sender, and the bit error rate within a short period of time (in which the antenna pointing error is considered constant) [so-called short-term BER] is not constant. Further, since the period of degraded short-term BER cannot be neglected, the time rate of the unavailable situation is a problem. Therefore, the unavailability of the channel must be reflected in the

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link design by considering the pointing error of the transmitting antenna of the sending satellite and that of the receiving antenna at the same time.

The burst error rate (or the probability of the short-term BER exceeding the desired value) represents the probability of the loss due to the antenna pointing error exceeding the desired level. By means of this burst error rate, the unavailability can be evaluated and the link design reflecting the unavailability becomes possible.

In [7], the burst error rate is derived with the probability density function of the pointing error of the transmitting antenna of the sender in the radial direction. However, in [7] the pointing variation of the receiving antenna on its own satellite is not considered. In [8], although both pointing errors of the transmitting and receiving antennas are considered, only the average value of the short-term BER is evaluated. We have studied the burst error rate in the case where the pointing errors of the transmitting and receiving antennas are taken into consideration [9].

In this paper, a method of link design including both the pointing error of the transmitting antenna of the sending satellite and that of the satellite receiving antenna is presented for the intersatellite heterodyne detection optical communication systems. In Sect. 2, the cause and the effect of the pointing error are described. The formula for the burst error rate is derived by means of the probability density functions of the pointing errors of the transmitting and receiving antennas in the radial direction. In Sect. 3, the burst error rate is computed in the case where both the transmitting and receiving antennas are circular aperture antennas and the radial pointing error distributions are Rayleigh. In Sect. 4, a channel design is carried out with this result by taking into account the pointing variations.

2. Loss and Burst Error Due to Pointing Error

In this section, the cause and the effect of the antenna pointing errors are discussed. Formulas for the burst error rate are derived with the probability density functions of the pointing errors of the transmitting and receiving antennas.

The main parameters that determine the communication quality are optical output and wavelength of the laser diode, antenna diameter and pointing accuracy, receiving sensitivity of the receiver, and the distance

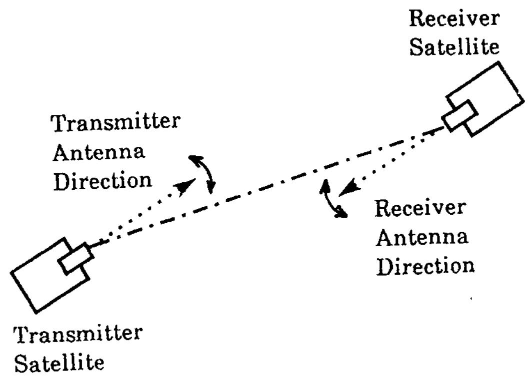


Fig. 1. Fluctuations of antenna pointing direction.

between the satellites. Link design is carried out with these parameters by means of the following transmission equation:

$$P_R = P_T G_T G_R L_T L_R L_P \left(\frac{\lambda}{4\pi R}\right)^2 \quad (1)$$

where P_R is the optical power received by the photodetector, P_T is the optical output of the laser diode, G_T and G_R are the gains of the transmitting and receiving antennas in the antenna-pointing directions, L_T and L_R are the transmitter and receiver optical efficiencies, L_P is the loss due to the antenna-pointing error, λ is the oscillation wavelength of the diode laser, and R is the distance between the satellites. From Eq. (1), the received optical power is studied if the required optical power (the optical power needed for attaining a specified short-term bit error rate) can be secured. The difference between the received optical power and the required optical power is treated as the system margin.

As shown in Fig. 1, the pointing directions of the transmitting antenna of the sender and of the satellite receiving antenna constantly change. Hence, the loss L_P due to the antenna pointing errors is not constant. By these antenna-pointing variations, the short-term BER constantly changes in the optical satellite communication channel.

Next, the loss due to the antenna-pointing error is described. An angular deviation occurs in the antenna-pointing direction if there exists an internal alignment error and point-ahead error in the optical system, and tracking error and residual

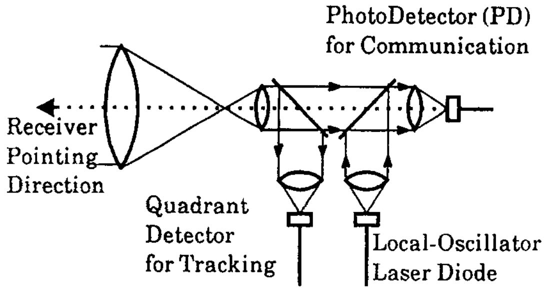


Fig. 2. Basic configuration for receiver optics.

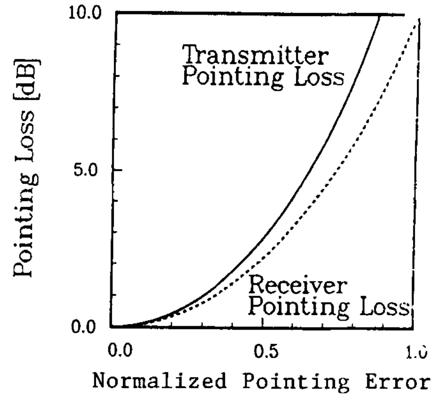


Fig. 4. Antenna pointing loss.

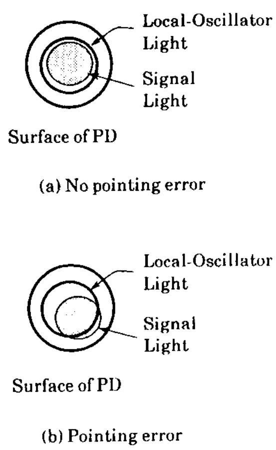


Fig. 3. Signal light and local-oscillator light on PD.

error of the tracking photodetector due to thermal noise. The losses due to this tracking error are made up of the one by the pointing error of the transmitting antenna of the sending satellite and that of the satellite receiving antenna.

The pointing direction of the transmitting antenna is controlled such that the transmitting optical beam is directed to the direction for which the point-ahead angle for optical path difference correction is added. If there is an angular shift between the pointing direction of the transmitting antenna and the direction toward the receiving satellite, the received optical power of the receiving satellite decreases depending on the pointing error and the beam pattern. This is the loss due to the pointing error of the transmitting antenna.

The basic configuration of the receiving optical system is shown in Fig. 2. As the communication optical detector, usually a PD (photodetector) is used while a four-quadrant optical detector is used for tracking. The dotted line is the pointing direction of the receiving antenna. The alignment of the local oscillator light is carried out such that the direction of arrival of the local oscillator light seen from the PD coincides with the pointing direction of the receiving antenna, and the center of the spot of the local oscillator light coincides with the center of the PD. Further, when the pointing direction of the receiving antenna coincides with the direction of arrival of the optical beam, the center of the PD and the center of the spot of the receiving light coincide.

As shown in Fig. 3(a), the pointing direction of the receiving antenna in this case is controlled in such a way that the center of the spot of the local oscillator light and that of the signal light coincide on the photodetector. If there is an angular deviation between the pointing direction of the receiving antenna and the direction of arrival of the optical beam, the spot of the signal light is deviated from that of the local oscillator light as shown in Fig. 3(b) so that the signal power decreases according to the pointing error and the electric field distribution of the local oscillator light. This loss is due to the pointing error of the receiving antenna.

When the losses due to the pointing errors of the transmitting antenna and the receiving antenna are treated, they can be investigated based on [10] and [11]. The results are shown in Fig. 4. The transmitting and receiving antennas are circular aperture antennas with diameters of d_T and d_R, while the electric field distribution of the local oscillator light is assumed to be Gaussian. The spot diameter of the local oscillator light has been chosen as the value which maximizes the detection efficiency of the heterodyne detection when the centers of the spots of the signal light and the local oscillator light coincide [11]. The pointing errors of the transmitting antenna and the receiving antenna are normalized by (λ/d_T) and (λ/d_R), respectively, where λ is the wavelength of the signal light. For instance, if the pointing errors of the transmitting antenna and the receiving antenna with diameters of 20 cm change from 0 to 2 μrad in the case where the signal light wavelength is 0.8 μm and the short-term BER is 10^{-6}, the loss due to the pointing error changes by about 5 dB and the short-term BER changes to 10^{-1}.

The duration of the short-term BER degradation due to the antenna pointing error is usually 0.5 - 1 ms. Therefore, bit errors occur in a burst fashion and the channel is down. The frequency of occurrence of this unavailable condition is related to the divergence angle of the optical beam and the antenna pointing accuracy. If the antenna pointing accuracy is extremely high and the antenna pointing error is much smaller than the optical beam divergence angle, the frequency of occurrence of the unavailable condition is small and the time rate of the unavailable state is not a problem. However, with the antenna-pointing accuracy of the submicroradian order considered possible at the present time, it is necessary to determine the unavailability of the channel due to the antenna-pointing accuracy and to reflect the findings on the link design. In the following, a computation method for the burst error rate to be used for evaluation of the unavailability will be presented.

The burst error rate is defined as the time rate in which the specified short-term BER is guaranteed if the loss due to the antenna pointing error is less than the specified level L_P^* [dB] and the loss by the pointing error is larger than L_P^*. In the case where only the pointing error of the transmitting antenna of the sending satellite is considered, the burst error rate is the probability of the pointing error ε_T being larger than ε_T^* if the loss $L_T(\varepsilon_T^*)$ [dB] by the pointing error ε_T^* is equal to L_P^* [dB]. Hence, the burst error rate P_b is given in terms of the probability density function $P_T(\varepsilon_T)$ of the pointing error of the transmitting antenna in the radial direction [7]

$$P_b=\int_{\varepsilon_T^*}^{\infty} p_T(\varepsilon_T)d\varepsilon_T \tag{2}$$

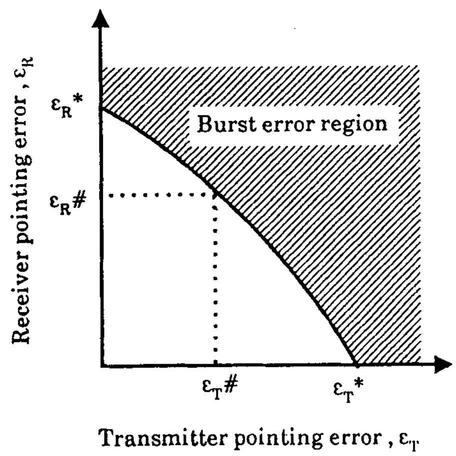


Fig. 5. Burst error region induced by pointing errors.

In this paper, the burst error rate is obtained while the pointing variations of both the transmitting and receiving antennas are considered. Let $L_T(\varepsilon_T)$ [dB] be the loss of the signal power when the pointing error of the transmitting antenna of the sending satellite is ε_R and $L_R(\varepsilon_R)$ be the loss when the pointing error of the receiving antenna is ε_R. Then the loss $L_P(\varepsilon_T, \varepsilon_R)$ [dB] due to the antenna pointing errors is

$$L_P(\varepsilon_T, \varepsilon_R)=L_T(\varepsilon_T)+L_R(\varepsilon_R) \tag{3}$$

The burst error region is where the loss $L_P(\varepsilon_T, \varepsilon_R)$ is larger than L_P^*. If it is assumed that $L_P(\varepsilon_T^\#, \varepsilon_R^\#)$ is L_P^*, then $L_P(\varepsilon_T^\#, \varepsilon_R)$ becomes larger than L_P^* when the pointing error of the receiving antenna is larger than $\varepsilon_R^\#$ for a pointing error of the transmitting antenna of $\varepsilon_T^\#$ as shown in Fig. 5. Hence, the burst error rate P_b can be given by the following expression in terms of the probability density function $P_T(\varepsilon_T)$ of the pointing error of the transmitting antenna in the radial direction and $P_R(\varepsilon_R)$ of the receiving antenna:

$$P_b=\int_0^{\infty} p_T(\varepsilon_T^\#)\int_{\varepsilon_R^\#(\varepsilon_T^\#)}^{\infty} p_R(\varepsilon_R)d\varepsilon_R d\varepsilon_T^\# \tag{4}$$

When Eq. (4) is used, the relationship between the loss caused by the antenna-pointing error and the antenna-pointing accuracy is derived for a specified burst error rate. By means of this expression, a flexible design is possible such as the one in which the requirement on the antenna-pointing accuracy is relaxed if there is a margin in the receiving signal power.

3. Required Antenna-Pointing Accuracy

In this section, the formula for the burst error rate derived in Sect. 2 is used and the burst error rate characteristics are investigated in the case where both the transmitting and receiving antenna are circular aperture antennas and the radial distribution of the antenna pointing error is Rayleigh. From the results, the antenna-pointing accuracy needed for attaining the specified burst error rate.

For the tracking of the optical beam, a quadrant detector was used as the tracking optical detector such as in the cases in [2] and [5]. The controls in the elevation angle and in the azimuthal angle are carried out independently. It is assumed that there is no axial deviation due to the internal alignment error and that the antenna-pointing error is due to the tracking error and the residual tracking error by the thermal noise in the tracking optical detector. Then the radial distribution of the pointing error usually is approximated by a Rayleigh distribution [7]. The probability density functions $p_T(\varepsilon_T)$ and $p_R(\varepsilon_R)$ of the pointing error of the transmitting and receiving antennas in the radial direction are given in terms of the rms pointing errors σ_T and σ_R

$$p_T(\varepsilon_T)=\frac{\varepsilon_T}{\sigma_T^2}\exp\left[-\frac{1}{2}\left(\frac{\varepsilon_T}{\sigma_T}\right)^2\right] \tag{5}$$

$$p_R(\varepsilon_R)=\frac{\varepsilon_R}{\sigma_R^2}\exp\left[-\frac{1}{2}\left(\frac{\varepsilon_R}{\sigma_R}\right)^2\right] \tag{6}$$

First, let us study the burst error rate using Eqs. (3) to (6). The loss due to the transmitting antenna-pointing error and that due to the receiving antenna-pointing error are derived according to [10] and [11]. It is assumed that the specified short-term BER, e.g., 10^{-6}, can be guaranteed if the loss due to the antenna-pointing error is less than L_P* (which is used as the loss due to the pointing error at the time of channel design). This L_P* is called the maximum allowable pointing error loss.

Figure 6 shows the relationship between the rms pointing error of the receiving antenna and the burst error rate with the maximum allowable pointing error loss L_P*. The spot diameter of the local oscillator light is chosen such that the detection efficiency is maximized if the center of the signal light spot and that of the local oscillator light coincide with each other if there is no receiving antenna-pointing error. The rms pointing errors of the transmitting

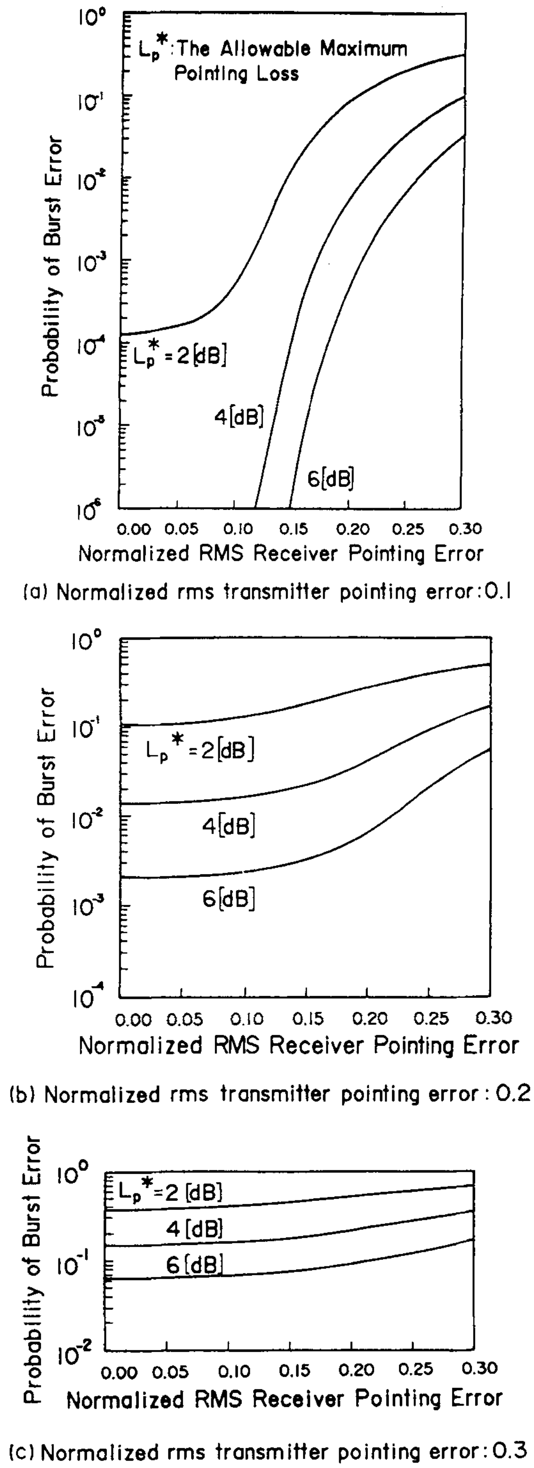
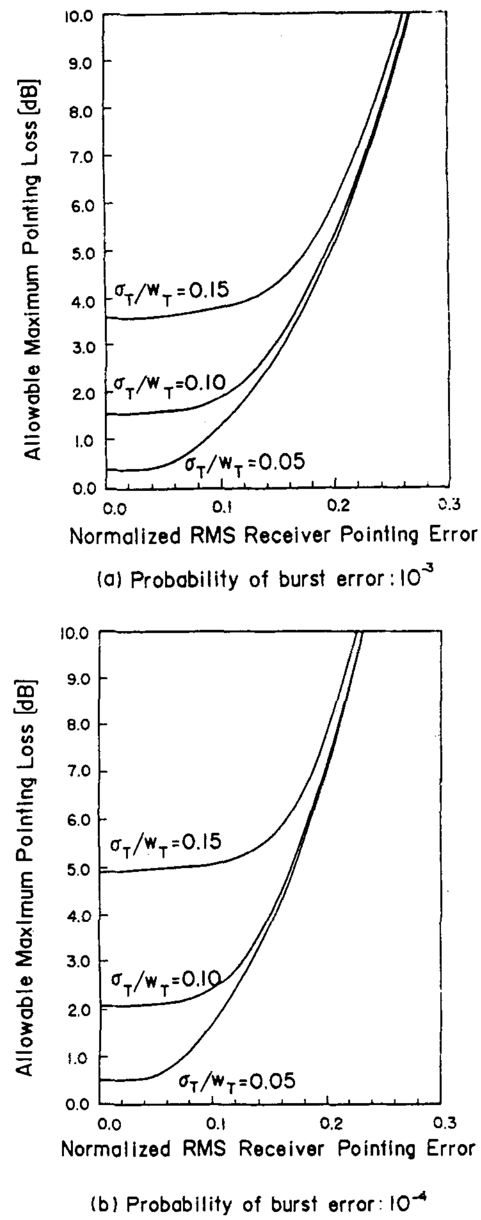


Fig. 6. Probability of burst error as a function of normalized receiver pointing error.



σ_T : RMS transmitter pointing error.
w_T: Beamwidth (FWHM).

Fig. 7. The allowable maximum pointing loss as a function of normalized rms receiver pointing error.

Table 1. System parameters

Propagation distance	40,000 km
Bit rate	240 Mbit/s
Bit error rate	10^{-6}
Burst error rate	10^{-4}

and receiving antennas are normalized by $W_T(=\lambda/d_T)$ and $W_R(=\lambda/d_R)$.

When the normalized rms pointing error of the receiving antenna is increased, the burst error rate converges to a constant determined by the maximum allowable pointing error loss and the receiving antenna-pointing accuracy, regardless of the transmitting antenna-pointing accuracy. When the normalized rms pointing error of the receiving antenna approaches zero, the burst error rate converges to a constant value determined by the maximum allowable pointing error loss and the transmission antenna-pointing accuracy. This indicates that the pointing accuracies of both the transmitting and receiving antenna must be increased for better burst error rate. For instance, if a burst error rate exceeding 10^{-3} must be attained at the maximum allowable pointing error loss of less than 6 dB, the normalized rms of the pointing errors of both the transmitting and receiving antennas must be made less than 0.2. Also, the burst error rate is improved more for an increased maximum allowable pointing error loss if the pointing accuracies of both the transmitting and receiving antennas are higher.

Next, the normalized rms receiving antenna-pointing error and the maximum allowable pointing error loss for a burst error rate of 10^{-3} and 10^{-4} are derived from Eqs. (3) to (6) and their relationship is plotted in Fig. 7. By means of this figure, the value of the loss L_P* due to the pointing error used in the channel design can be studied. For instance, to attain the burst error rate of 10^{-4}, L_P* is 2.3 dB if the rms pointing errors of both the transmitting and receiving antennas are 0.1.

4. Link Design

In this section, a link design method including the antenna-pointing variation is presented. The fact that the communication quality is regulated by the burst error rate distinguishes it from the conventional design.

The case studied here is the case in which the facing satellites have identical communication systems. In the case where the system in Table 1 uses the optical devices listed in Table 2, the link budget is

Table 2. Optical device characteristics

LD	Wavelength	0.85 m
	Optical output	17 dBm (50 mW)
	Line width	10 MHz
PIN-PD	Quantum efficiency	88%

Table 3. Link budget

Normalized RMS pointing error of transmitting antenna	0.15	0.10
Normalized RMS pointing error of receiving antenna	0.15	0.10
Beamwidth [μrad]	4.25	4.25
LD optical output	17.0	17.0
Pointing error loss [dB]	5.5	2.3
Transmission loss [dB]	60.7	60.7
Optics loss [dB]	5.0	5.0
Received optical power [dBm]	-54.2	-51.0
Required optical power [dBm]	-54.8	-54.8
System margin [dB]	+0.6	+3.8

shown in Table 3 when the solar light is received. It is assumed that both the transmitting and receiving antennas on the two satellites are circular aperture antennas with a diameter of 20 cm. The modulation and demodulation method is the binary FSK envelope detection. As the noise, the shot noise due to the local oscillator light, background noise and phase noise are considered. The power penalty of the laser diode by the phase noise is 1.6 dB [12] and the power penalty by the solar light is assumed to be 0.5 dB. The heterodyne efficiency in the absence of the receiving antenna pointing error is 81 percent (-0.9 dB). When the normalized rms pointing error is 0.10, the system margin obtain is 3.8 dB.

5. Conclusions

In this paper, a method for link design was introduced in which the pointing variations of the transmitting antenna of the sending satellite and the receiving antenna of the receiving satellite are taken into consideration at the same time in the optical satellite communication system using a heterodyne detection system.

By means of the probability density functions of the pointing error distributions of the receiving and transmitting antennas, the relationship between the burst rate and the antenna pointing error was derived. By using the equation for the burst error rate, a link design including the unavailability due to the antenna-pointing error can be carried out. In the case of a circular aperture antenna, the relationship between the loss due to the pointing error used in the channel installation and the antenna-pointing accuracy for a given burst error rate has been obtained. Based on these findings, a link design example taking into consideration the pointing variation has been presented in the case where the facing satellites have identical communication systems.

In the future, the relationship between the antenna-pointing accuracy and the burst error rate must be confirmed experimentally.

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