Influence of Coaxiality Deviation on Double-aperture Transmitter System in Wireless Laser Communication

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Abstract. In order to study the influence of the coaxiality deviation on the received energy of the double-aperture transmission system in weak turbulence. The models of single and double-aperture transmission system are introduced, and the received energy of each link is calculated. Based on the interval of the link received energy, the coaxial deviation range and the angle variation of the double-aperture transmission system are calculated, and the effect factors of the different link distance and aperture spacing on coaxial deviation are also analyzed.

Keyword: Wireless Laser Communication, Double-Aperture Transmission System, Coaxial Deviation

1. Introduction
Wireless Laser communication systems have received extensive attention in recent years based on their free spectral license and excellent information security. Many companies at home and abroad are developing wireless laser communication system products, and multi-aperture emission system-based. It can be seen that the multi-aperture transmitting system has become the main direction of development in wireless laser communication. At present, the related scholars at home and abroad have carried on the different aspect research to the porous transmission system [1]. N. Letzepis constructs a Gaussian attenuation channel model to verify the suppression of scintillation using the porous transmission technique [2].Zhao Yingjun et Al have studied the effect of atmospheric turbulence on the bit error rate (Ber) of the multi-beam transmitting system in a ship laser system [3]. Farid and other integrated atmospheric attenuation and misalignment factors, according to the probability of communication interruption to study the performance of multi-aperture launch system [4]. Using CCD imaging technology, Zhao Qi and others analyzed the drift of signal beam after atmospheric turbulence [5].Zhang Yafei and others analyzed the influence factors of alignment error, and introduced alignment error into MIMO wireless optical communication channel quantitatively, and analyzed the outage probability and diversity gain asymptotic expression [6]. Yang et Al established the pointing error model and analyzed the bit error rate performance under the model [7]. In this paper, the error rate models of optical wireless communication, which only consider the influence of atmospheric turbulence and pointing error, are compared and analyzed in the offshore environment by Wang Hongxing et Al. [8].
2. Research On Single Aperture Launch System

2.1. Link Model Analysis
Wireless Laser Communications, unlike Fiber-optic communication, require no fibre link, modulate the information to be transmitted to a laser signal, which is transmitted through an atmospheric channel to the receiving end for transmission. A simple near-earth single-aperture wireless laser communication system is a one-transmit-one-receive communication, as shown in figure 1.

![Schematic diagram of wireless laser communication](image)

The wireless laser communication system consists of transmitter and receiver, and the transmitter consists of signal source, optical modulator, laser and collimator. The receiving end comprises a focusing lens, a detector, a decoder and a signal display. The main working process is as follows: at the transmitting end, the signal source provides the needed information, the light modulator modulates the information to the laser, the laser outputs the optical signal of the specified wavelength, and the collimating Lens Group transmits the optical signal to the atmospheric channel; At the receiving end, the focusing lens focuses the signal light onto the detector surface, the detector converts the optical signal into an electrical signal, the decoder decodes the electrical signal, and finally the signal display displays the information transmitted by the transmitter.

2.2. Single Aperture Energy Analysis
The wireless laser communication system uses the atmosphere as the medium to transmit signals. Because the density and temperature of the atmosphere are not uniform, turbulence vortices of different sizes are formed, which are called atmospheric turbulence, it scatters, diffracts and reflects the signal light passing by, which causes the signal light intensity to fluctuate randomly at the receiving end. According to the Davis inequality, atmospheric turbulence is generally divided into three levels: weak, neutral and strong turbulence according to the magnitude of the structural constant of atmospheric refractive index [9]. In weak turbulence, the energy reaching the receiving end is gauss distributed. At this point, the gas turbulence scintillation is expressed in terms of the variance of the intensity [10].

\[
\sigma^2 = 1.23 \cdot C_n^2 \left( \frac{2\pi}{\lambda} \right)^{7/6} \cdot Z^{11/6}
\]  

(1)

\[C_n^2\] is the atmospheric refractive index structure constant, \(Z\) is the link distance, \(\lambda\) is the signal wavelength.

According to the generalized Huygens–Fresnel principle [11], the formula of the one dimensional received optical power after the laser transmits the distance \(Z\) in the atmosphere is derived

\[
P(r,z) = \frac{2B^2 P_0 G^2 \omega_0^2}{\pi G^2 \omega_0^2} \cdot \exp \left( \frac{-2B^2 r^2}{G^2 \omega_0^2} \right) \cdot \exp (-cz)
\]  

(2)
Where $w_0$ is the waist radius of the gauss beam, proportional to its wavelength and inversely proportional to its divergence angle \[12\]. $\bar{\sigma}$ is the atmospheric attenuation coefficient \[13\], as shown in formulas \[3\] and \[4\].

$$\bar{\sigma} = \frac{3.91}{V} \left[ \frac{\lambda}{550\text{nm}} \right]^q$$ \hspace{1cm} (3)

\[
q = \begin{cases} 
1.6 & V \geq 50\text{Km} \\
1.3 & 6\text{Km} < V < 50\text{Km} \\
0.16V + 0.3 & 1\text{Km} < V \leq 6\text{Km} \\
V - 0.5 & 500\text{m} < V < 1\text{Km} \\
0 & V < 500\text{m}
\end{cases}
\] \hspace{1cm} (4)

In the formula, $Z$ is the link distance, $q$ is the correction factor, and $V$ is the visibility. Figure 2 shows a schematic diagram of a single-aperture launch system. The emission aperture $T_x$ is coaxial with the focusing Lens $R$ and the distance $Z$. The diameter of the focusing Lens is $d$, $\theta$ is the beam divergence angle of the signal light, and $A$ and $B$ are the coordinate points of the upper and lower edges of the focusing lens respectively.

![Figure 2. Schematic diagram of single-aperture transmission system](image)

The single-aperture Transmitting System Receives Energy $P_{\text{single}}$ at the focusing Lens $R$, as shown in formula \[5\].

$$P_{\text{single}} = \int_A^{B} \int_{\theta}^{r,z} P(r,z) dr = \int_A^{B} \left( \frac{2B^2 P_o}{\pi G^2 \omega_0^2} \exp \left( \frac{-2B^2r^2}{G^2 \omega_0^2} \right) \exp (-\bar{\sigma}z) \right) dr$$ \hspace{1cm} (5)

Before calculating the received energy of a single-aperture transmission system, the parameters of the system should be determined, including the link distance, the signal wavelength, the transmitting power, the beam divergence angle and the focusing lens diameter. The parameters of the communication system link used in this experiment are shown in table 1 below.

**Table 1.** The parameter of single-aperture transmission system

| No. | parameter                     | value     |
|-----|-------------------------------|-----------|
| 1   | wavelength $\lambda$/nm       | 980       |
| 2   | emission energy $P_o$/mW       | 54        |
| 3   | focal lens diameter $d$/mm     | 50.8      |
| 4   | link distance $z$/m            | 1000      |
| 5   | atmospheric visibility $V$/km  | 4         |
| 6   | beam divergence angle $\theta$/\micro rad | 450      |
| 6   | atmospheric refractive index structure constant $C_n^2$ | $1 \times 10^{-18}$ |

### 3. Research On Dual-Aperture Launch System
Theoretically, the two emission apertures of the two-aperture emission system are parallel to each other, but the optical terminal system installed on the building will be subject to external interference, if the thermal gradient of the building causes the structure to bend, the strong wind causes the building to swing and the equipment to sway, these factors will cause the two launch aperture angle deviation, namely coaxial deviation.

3.1. Dual-Aperture Link Energy Calculation

The principle of the two-aperture transmitting system is shown in figure 3. The aperture spacing of the transmitting aperture TX1 and TX2 is $s$, and the focusing Lens R is coaxial with the transmitting aperture Tx2. The spot diameter of the two signal beams increases with the propagation distance when the two signal beams send out from the transmitting end at a certain divergence angle. Region I is the effective region for receiving TX1 signal from the focusing lens R, because the transmitting aperture is different from the focusing Lens, the focusing lens can only receive part of the signal. Region II is the effective region for receiving TX2 signal light with a focusing Lens R.

![Figure 3. Schematic diagram of double-aperture transmission system](image)

The EMISSION APERTURE Tx1 receives energy $P_{tx1}$ at the focusing Lens, as shown in formula 6.

$$P_{tx1} = \int_{A}^{B} P(r, z) dr = \int_{\frac{d}{2}}^{d} \left( \frac{2B^2}{\pi G^2 \omega_0^2} \cdot \exp \left( \frac{-2B^2 r^2}{G^2 \omega_0^2} \right) \cdot \exp \left( -\frac{z}{\omega_0} \right) \right) dr$$

(6)

The focusing Lens receives the total energy $P_{double}$, as shown in formula 7.

$$P_{double} = P_{tx1} + P_{tx2}$$

(7)

The result of the calculation is shown in table 2. The emission aperture a receives energy $P_{tx1}$ of 0.385 mw at the focusing lens Tx1. The receiving energy $P_{tx2}$ of TX2 at the focusing lens is 0.774 MW, and the total receiving energy $P_{double}$ is 1.159 MW.

| No. | parameter                     | value |
|-----|-------------------------------|-------|
| 1   | received energy from emission aperture TX1 $P_{tx1}/mW$ | 0.385 |
| 2   | received energy from emission aperture TX1 $P_{tx2}/mW$ | 0.774 |
| 3   | total energy $P_{double}/mW$  | 1.159 |

Table 2. The received energy of double-aperture transmission system

As can be seen from table 4, the total energy $P_{double}$ of the two-aperture launch system is about 0.390 MW less than the received energy $P_{single}$ of the single-aperture launch system. This is because the transmitting aperture TX1 is not the same axis as the focusing lens, so the energy at the receiving end is reduced and the total receiving energy is reduced. If the transmitting angle of the transmitting aperture TX1 is deflected properly, the optical axis can be shifted to the focusing Lens, and the
deflection angle is within a certain range, the receiving energy can be increased, but if the deflection angle is too large, the focusing lens can not receive the signal light of the transmitting aperture TX1.

3.2. Coaxiality Impact Analysis
As shown in figure 4, the relation between the relative position of the signal light emitted by TX1 and the focusing lens can be divided into three cases. In the first case, as shown in figure 4(a), the transmit aperture TX1 deflects β1, and the center axis of the signal OH deflects to the center point of the focusing Lens L2, where the overlap of the Facula is the largest. In the second case, as shown in figure 4(b), the transmitting aperture TX1 deflects β2, the center axis of the signal light is located below the focusing lens, and the upper edge beam OM of the signal light reaches the upper edge point A of the focusing Lens, when the spot is at the critical position of the full-coverage focusing Lens. In the third case, as shown in figure 4(c), the emission aperture TX1 deflects the β3, and the signal beam Om reaches the lower edge point B of the focusing Lens, when the spot is separated from the focusing lens.

![Figure 4](image-url)

Figure 4. Schematic diagram of the relative position between signal light and focusing lens
In the process of angle deflection of TX1, the Focus Lens and TX2 are in the same axis, and the position and angle of the focus lens remain unchanged, so does the beam divergence angle θ. The received energy values at each critical point deflection angle are obtained by calculation. The deflection angle β varies from 201 Rad to 450 Rad in the range of deflection angle β1 to β3 with a sampling interval of 1.7 Rad per deflection. The energy simulation results under different deflection angles β are shown in figure 5.

![Figure 5](image-url)

Figure 5. The variation curve of deflection angle and total energy
When TX1 deflects β1 to 201 µrad, the maximum energy is obtained and the total received energy is 1.548 mW. The optical axis of the transmitting aperture Tx 1 and the transmitting axis of the transmitting aperture Tx 2 intersect the focusing Lens.

When β3 is deflected to 450 µrad, the minimum energy $P_{\text{double}}$ is 0.774 MW. At this time, the signal light energy of the transmitting aperture TX1 can not enter the focusing lens, and the received energy only contains the signal light energy of the transmitting aperture $P_{\text{tx2}}$. 
As can be seen from the diagram, the receiving energy decreases gradually when the transmitting aperture \(tx_1\) deflects \(\beta_1 \sim \beta_2\). When the deflection angle is from \(\beta_2 \sim \beta_3\), only part of the signal light can cover the focusing lens, and the rate of receiving energy decrease is obviously accelerated.

4. Conclusion.
This paper summarizes the research status of multi-aperture transmitting system in wireless laser communication, introduces the link model of single-aperture and double-aperture transmitting system, and calculates the link receiving energy of single-aperture transmitting system and double-aperture transmitting system, the influence of coaxiality deviation on the performance of two-aperture transmission system is verified according to the change of received energy. When the link distance is 1000m and the aperture distance is 20cm, the allowable coaxiality deviation angle range is \(201 \sim 450\,\mu\text{rad}\), the link receiving energy range is \(1.549 \sim 0.774\,\text{mW}\), the angle variation is \(249\,\mu\text{rad}\). This paper is of practical significance to determine the allowable coaxiality deviation range, clear debugging range, for the initial debugging stage to provide a theoretical basis.

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