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High-Dynamic Transmission Modeling for Laser Inter-Satellite Links (LISLs)

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***Abstract*—Inter-satellite laser communication could achieve the large-capacity, high-reliability, and high-bit-rate transmission, but its terminal is also easily affected by the dynamic space environment. In this paper, we establish a highly dynamic theoretical model for the laser inter-satellite links (LISLs), taking the sun outage, the Doppler frequency shift and the platform vibration as the major noise sources of the free-space laser communication system. Numerical simulations are carried out to quantify the impact of these noises on the transmission system, which provides an effective reference for the further exploration of the satellite industry.**

Keywords-laser inter-satellite link; dynamic transmission modeling; sun outage; Doppler frequency shift; vibration

I. INTRODUCTION

With the advent of the information age and the rapid development of science technology and economy, traditional communication methods can no longer meet people's needs for communication. People are eager to find a convenient, fast and reliable communication method. The emergence of satellite communication technology has greatly changed our traditional way of life, and has gradually been favored by researchers and technicians from all over the world. In recent years, satellite communication technology has been used in office networks, navigational ranging and military fields all have played an irreplaceable role [1]. Inter-satellite laser communication can meet the requirements of platform miniaturization, light weight and low power consumption, and is one of the key technologies for realizing large bandwidth, strong real-time and high reliability transmission of inter-satellite communication.

However, inter-satellite laser communication also faces interference from complex space environment, for example sun outage [3], platform random vibration [4]. In addition, due to the high dynamic characteristics between satellites, the relative motion between satellites in different orbits will inevitably lead to the introduction of Doppler into the system [5]. These factors will seriously affect the communication quality. Therefore, constructing the dynamic model of the laser inter-satellite link (LISL) as well as its noise investigation plays an important supporting role in the development of the entire laser satellite communication.

In this paper, based on our previous modeling works [6], we thoughtfully investigate the high-dynamic operation in the LISL, and evaluate the transmission preformation through optical QPSK simulation system. The results show: 1) The elevation angle varies from 0rad to 1.57rad due to the dynamic nature between two communicating satellites, leading to the received SNR increased by 7.63dB when the input OSNR = 12dB; 2) Comparing the cases between the Doppler shift of 10GHz and 0GHz, the EVM values is increased about 11.67%; 3) The vibration intensity could also degrade the transmission performance, taking the beam divergence angle is 80urad as the example, degradation of 17.47dB obtained when the large vibration intensity applied to the transmission system.

II. DYNAMIC MODEL OF LASER INTER-SATELLITE LINK

Since the real space environment is complex and changeable, based on the static simulation [7], we carry out the dynamic simulation of the LISL, and more realistically restored the dynamic space environment.

A. Sun Outage Dynamic Simulation Model

The huge noise source generated by the sun will interfere with the communication signal, resulting in the degradation of communication quality, and in severe cases, it will also cause link deterioration or even communication interruption.

Since the space environment is a non-vacuum environment, there are interferences from various nuclides such as H, He, and D. Therefore, the solar electromagnetic radiation will decay in the transmission direction. The solar irradiance power at distance L_a from the sun is [8]:

$$E = E_0 \exp(-\mu L_a) \tag{1}$$

where E_0 is the solar constant and u is the decay constant.

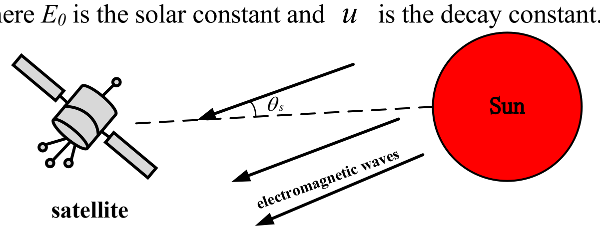


Figure 1. Schematic diagram of satellite interference by solar transit

When the satellite is running in orbit, the relative position to the sun will change. The sunlight incidence angle is different, and the solar elevation angle is also different, as shown in Fig.1, $\theta_s(t)$ represents the elevation angle, and its variation range is 0rad ~ 1.57rad, at this time, the radiation power of the sun shining on the satellite surface can be obtained by [8]:

$$P = \frac{E \bullet A \bullet \left\{ \cos\left[\theta_s(t)\right] + \left|\cos\left[\theta_s(t)\right]\right| \right\}}{2} \tag{2}$$

Among (2), A is the aperture area of the receiving antenna. It can be seen from (2) that when the solar elevation angle changes over time, i.e., $\theta_s(t)$ with the function of the time t, the sun outage power received by the satellite surface would be changed accordingly, and consequently the impact on the system performance is also different. Therefore, the following simulation realizes the dynamic process of the system performance changing from 0rad to 1.57rad in the solar elevation angle.

B. Doppler Frequency Shift Dynamic Simulation Model

In a satellite communication system, the relative movement of the receiving and transmitting ends causes a frequency shift, which results in a change in the wavelength of the received light, the phenomenon called the Doppler effect. The generation principle of Doppler frequency shift is shown in Fig.2.

A and B respectively represent two satellites with different orbits. Satellite B receives the signal from satellite A in vertical orbit while moving along the horizontal orbit. Suppose that B moves to B1 and A moves to A1 at the next moment, the angle between the advancing direction of B and the incident wave of A can be obtained by:

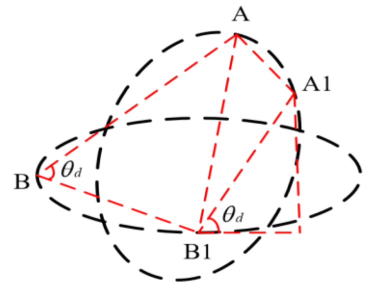


Figure 2. Schematic diagram of satellite interference by Doppler frequency shift

$$\cos\left[\theta_d(t)\right] = \frac{\overrightarrow{BA} \bullet \overrightarrow{BB_1}}{\left|BA\right| \bullet \left|BB_1\right|} \tag{3}$$

$\theta_d(t)$ is the angle between the direction of satellite movement and the received signal, it will change with the relative position of the two satellites. At the same time, the relative motion speed between them is recorded, and the Doppler frequency shift value generated between the satellites A and B can be obtained by [9]:

$$f_d = \frac{1}{2\pi}\frac{\Delta\phi}{\Delta t} = \frac{v(t)}{\lambda}\cos\left[\theta_d(t)\right] = f_c \frac{v(t)\cos\left[\theta_d(t)\right]}{c} \tag{4}$$

Since the Doppler shift is a frequency offset in the original signal phase, so the output signal is equal to the input signal multiplied by a frequency offset. Further, substitute the obtained Doppler shift value into (5) to map into the simulation system [10]:

$$E_{out}(t) = E_{in}(t)e^{j2\pi f_d t} \tag{5}$$

Among (5), E_{in} is the input signal, and E_{out} is the corresponding output after the frequency shift.

C. Vibration Dynamic Simulation Model

Since the divergence angle of the laser beam is small and the directionality is relatively strong in the process of signal acquisition, but the satellite platform will vibrate due to the movement of the satellite platform itself and the influence of the space environment, which will cause the gap between the transmitting antenna and the receiving antenna. There is a certain angle error, it is called the tracking error angle, which will make the directivity of the laser communication worse. The vibration will cause the beam to shift, leading to the fluctuation of the received optical power. The schematic diagram is shown in Fig.3.

As shown in Fig.3, it is assumed that the tracking error angle of the transmitting end is φ, and the tracking error angle of the receiving end is ϕ, θ_b is the beam divergence angle of the signal beam. At this time, the signal power received is [11]:

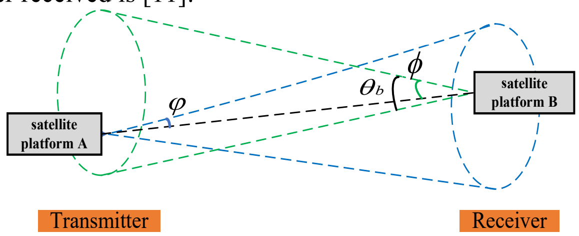


Figure 3. Schematic diagram of satellite interference by vibration

$$P = \cos[\varphi(t)] \bullet \frac{4A_0C_0^2}{L_b^2\theta_b^2}\exp\{-\frac{8[\phi(t)]^2}{\theta_b^2}\} \tag{6}$$

Among them, $\varphi(t)$ and $\phi(t)$ respectively are the tracking error angles of the transmitter and receiver, A_0 is the receiving antenna area, L_b is the inter-satellite distance, and C_0 is a constant factor.

It can be seen from (6) that the main causes of optical power loss are the tracking error angle. Further, we assume $G(\phi)$ and $G'(\varphi)$ respectively is the signal optical power loss coefficient caused by the tracking error of the transmitter and receiver [11]:

$$G(\phi) = \exp(-\frac{8[\phi]_t^2}{\theta_b^2}) \tag{7}$$

$$G'(\varphi) = \cos[\varphi]_t \tag{8}$$

Their values are between 0 and 1, 1 means no power loss, and 0 means the maximum loss.

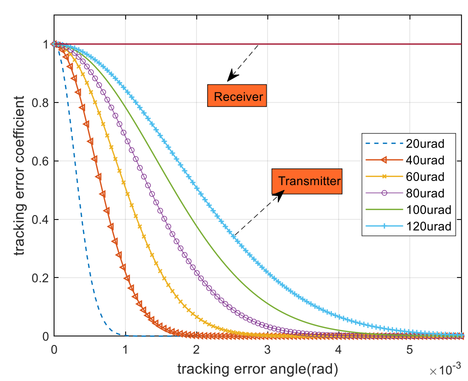


Figure 4. The relationship between the tracking error angle and the tracking error coefficient

By simulating the relationship between the tracking error coefficient and the tracking error angle, as shown in Fig.4: 1)With the increase of the tracking error of the receiving end, the optical power loss coefficient remains unchanged, which means that the influence of the tracking error on the receiving end can be ignored; 2)With the increase of the tracking error of the transmitting end, the signal optical power of the sending end changes drastically, so the following work mainly discusses the influence of the tracking error angle of the transmitting end on the system performance; 3)The size of the laser beam divergence also affects the power received. With the increase of the beam divergence, the effect of the tracking error angle on the power becomes slower. Therefore, increasing the beam divergence is a method to compensate for vibration.

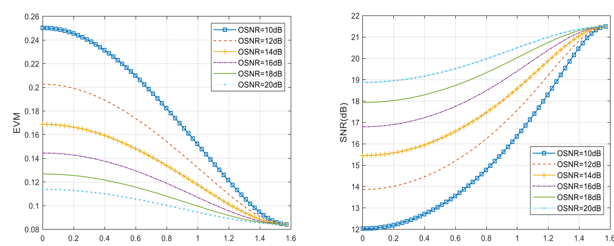
III. Simulation Investigation

On the basis of the previous dynamic transmission modeling of the LISL, we carry out the simulation investigation on the impact of the three dynamic parameters, i.e., the sun outage, the Doppler frequency shift and the vibration on the transmission performance.

A. *Analysis of the Dynamic Change of the Sun*

The dynamic characteristics of the sun outage are reflected in the fact that the $\theta_s(t)$ changes with the incident angle of the sun light, so we simulated the dynamic process of the $\theta_s(t)$ changing from 0rad to 1.57rad.

It can be seen from Fig.5 that: 1) under different OSNR, the system performance gradually changes from poor to better when the solar elevation angle changes from 0rad to 1.57rad. When $\theta_s(t)$ = 1.57rad, this means that the incident direction of the sun's rays is exactly tangent to the terminal of the satellite system, at this time, the signal is almost not affected by the sun, and the signal performance is optimal; 2) Taking OSNR = 16dB as an example, when $\theta_s(t)$ = 1.57rad vs $\theta_s(t)$ = 0rad, the EVM decreases by 6%, and the SNR increases by 4.7dB.



(a) (b)

Figure 5. The influence of the elevation angle on the performance of the system under different OSNR (a) EVM; (b) SNR

B. *Analysis of Doppler Frequency Shift Dynamic Changes*

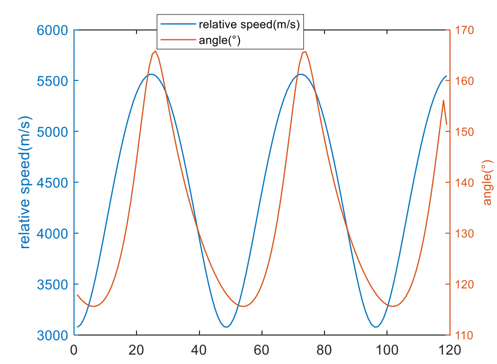


Figure 6. Relative angle and relative motion speed between two satellites

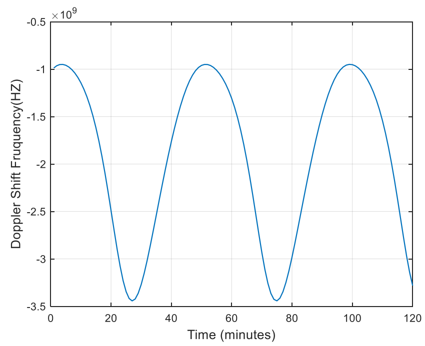


Figure 7. Doppler shift between satellites in different orbits

It can be known from (4) that the Doppler frequency shift value can be calculated as long as the relative motion velocity and angle between any two satellites are known, and it can be mapped into the simulation system by (5). Therefore, we dynamically simulate the motion between the two orbiting satellites, as shown in Fig.2.

In Fig.6, the calculated $\theta_d(t)$ is shown in the right ordinate, and the left ordinate represents the relative motion speed between the two satellites at this time. Substitute the time dependent results of Fig.6 into (4) to obtain the Doppler frequency shift between the two satellites, as shown in Fig.7.

By mapping the conclusion of Fig.7 into the system simulation platform, the effect of Doppler shift can be obtained, as shown in Fig.8. It can be seen from Fig.8 that with the increase of Doppler frequency shift, the system performance decreases accordingly. Taking the input OSNR = 15dB as an example, comparing the cases between f_d = 10GHz and f_d = 0GHz, EVM increases by 12%, proving the impact of the dynamic Doppler frequency shift in the LISL.

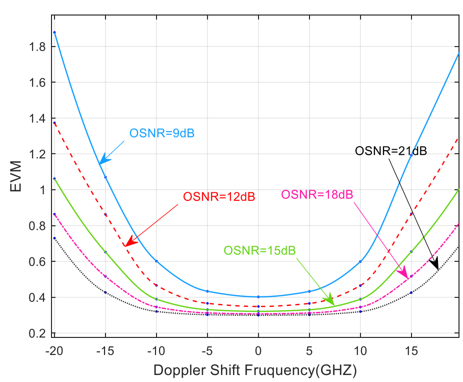


Figure 8. Influence of Doppler shift on system performance under different signal-to-noise ratios

C. Analysis of Dynamic Changes of Vibration

The dynamic characteristics of vibration are reflected in the different intensity of the random vibration of the system, and the resulting angle of tracking error is also different.

We randomly take a signal that is affected by vibration over an arbitrary period of time, and the obtained signal can simulate the random vibration on the star more realistically and effectively. The simulated vibration signal is shown in Fig.9.

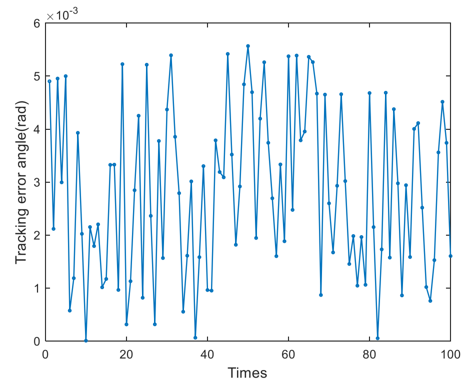


Figure 9. The tracking error angle caused by vibration at any time

It can be seen from the above theoretical analysis that the impact of vibration on the system performance is not only affected by the tracking error angle, but also by the beam divergence angle. Therefore, we simulated the impact of vibration on the signal performance under different beam divergence angles.

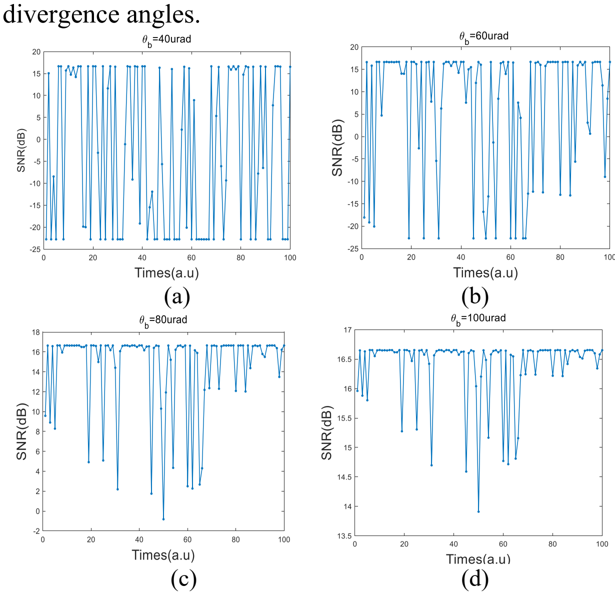
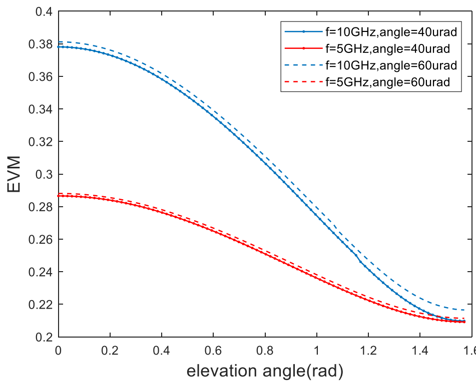


Figure 10. Influence of vibration on system performance under different beam divergence angles(a) θ_b = 40urad; (b) θ_b = 60urad; (c) θ_b = 80urad; (d) θ_b = 100urad

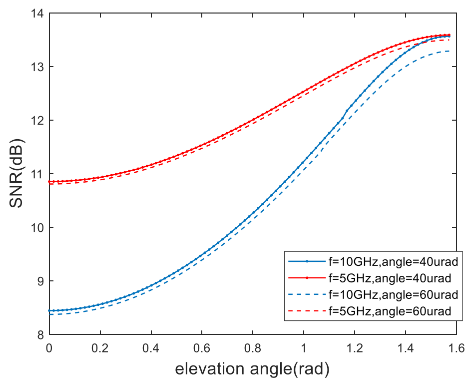
It can be seen from Fig.10 that the degree of influence of the system varies with the intensity of the vibration, and as the divergence angle of the beam increases, the influence of the vibration on the system is effectively slowed down.

D. Comprehensive Analysis of Three Factors Including Solar Transit, Doppler Frequency Shift and Vibration

Fig.11 is a comprehensive simulation of the influence of three factors: sun outage, Doppler frequency shift and vibration on the system. The f_d and $\varphi(t)$ were changed to measure the change of the system performance in the range of $\theta_s(t)$ = 0 ~ 1.57rad. We found that form Fig.11: 1)When the $\varphi(t)$ is constant, the performance of the system with f_d = 5GHz is better than that of the system with f_d = 10GHz; 2)



(a)



(b)

Figure 11. The influence of sun outage, Doppler frequency shift and vibration on system performance, (a)EVM results; (b) SNR results

when the f_d is the same, the performance of the system with $\varphi(t)$ = 40urad is better than that $\varphi(t)$ = 60urad. Taking $\theta_s(t)$ =1rad as an example, when f_d = 10GHz, $\varphi(t)$ = 40urad vs $\varphi(t)$ = 60urad, the EVM decreases by about 2%, and the SNR increases by 0.2dB. Similarly, taking $\theta_s(t)$ = 1rad as an example, when $\varphi(t)$ =40urad, f_d =5GHz is compared with f_d =10GHz, the EVM decreases by about 4%, and the SNR increases by about 1.4dB.

IV. Conclusion

Based on the physical modeling and noise research of the inter-satellite laser channel, this paper explores the complex environmental interference. Study these variable space environments and fully understand their impact on inter-satellite laser communication from a "dynamic point of view": 1) The solar elevation angle changes with the incident angle of the sun's rays. Taking OSNR =12dB as an example, when $\theta_s(t)$ = 1.57rad vs $\theta_s(t)$ = 0rad, the EVM decreases by 11.85%, and the SNR increases by about 7.63dB; 2) The Doppler frequency shift will change with the relative movement speed and relative position between the two satellites. Similarly, OSNR=12dB as an example, when f_d =10GHz vs f_d = 0GHz, and the EVM decreases by 11.67%; 3) The dynamic characteristics of vibration are reflected in the tracking error of the beam shift as the intensity of the system vibration is different, and the degree of influence varies with different systems. Taking the beam divergence angle θ_b =80urad as an example, compared with $\varphi(t)$ = 5.56urad and $\varphi(t)$ = 0.3urad, the SNR decreased by about 17.47dB. To sum up, this paper demonstrates the dynamic simulation of solar interruption, Doppler frequency shift and vibration for inter-satellite laser communication, which plays an important supporting role for the practical application of network on-orbit operation.

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