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Using top-hat beam to improve the performance of the inter-satellite laser communication

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ABSTRACT

The profile of transmitting beams in inter-satellite optical links significantly impacts communication performance, shaping the general Gaussian transmitting beam into a far field top-hat profile may improve the performance of the inter-satellite laser communication system. The calculations show that this scheme would at least reduce beaconless acquisition time by nearly 63%, and may reduce the outage probability of communication link several orders of magnitude. In addition, the tracking error allowance of communication terminals would at least increase to 1.65 times while keep communication link stable. Use of top-hat beam is quite helpful to build and operate robust inter-satellite optical communication terminals at lower technical risks and cost.

1. Introduction

Several breakthroughs have occurred in the fields of the satellite-borne laser communication in the recent years. In 2001, the first laser link between satellites ARTEMIS and SPOT-4 has been successfully established, the mean bit error probability was under 10^{-9} for data rate of 50 Mbps [1]. And later the inter-satellite laser communication has also been demonstrated between ARTEMIS and Japanese satellite OICETS [2]. In 2008, the 5.6 Gbps bidirectional binary phase shift keying laser communication links have been successfully demonstrated between two low orbit satellites [3], and now the European Data Rely System has been proceeding [4], in which the communication terminals built by German TESAT company reached technology readiness level (TRL) 9. Nowadays, considering the crucial requirement of precision and hardness of maintenance in orbit for deploying affordable commercial satellite-borne laser communication, enhancing the operation reliability of the satellite-borne laser communication system has a lot more neediness than ever after its feasibility is totally validated.

Generally, the optical systems of free space laser communication are designed as Gaussian optical system by using spherical or aspherical optical surfaces, in which a Gaussian laser beam is transmitted and formed a Gaussian far field at the location plane of its receiving terminal. However, it is possible to adopt new type beam as the transmitting beam in satellite-borne laser communication system with the development of beam shaping technology. The top-hat beam, which has a flat intensity within a circular disc, was discussed and it would bring some improvement of communication performance [5]. By using particular optical elements such as diffractive optical element or aspheric lens in the laser communication terminal, the Gaussian beam can be shaped to top-hat beam on far field [6,7]. In this paper, through calculating the improvements of

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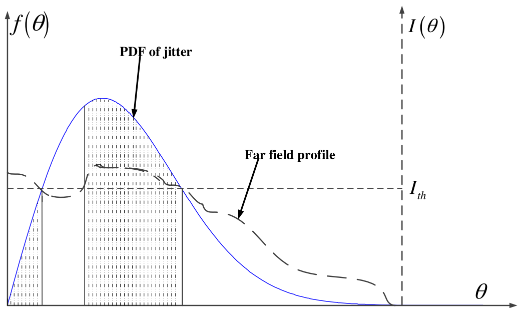

Fig. 1. Calculation of the probability of laser communication link works properly for a centrosymmetric far field profile and Rayleigh distribution jitter.

the beaconless acquisition time, link outage probability and the allowance of tracking error when shaping Gaussian beam to top-hat beam in the scenario of inter-satellite laser communication, we would present the advantages of the application of top-hat beam to optimization the performance of inter-satellite laser communication system.

2. Analysis and results

The performance of inter-satellite laser communication could be evaluated by different parameters in different working stages. Acquisition time and acquisition probability was used for acquisition performance, tracking error is used for tracking performance, and signal to noise ratio or bit error rate are used for communication performance. All of these parameters are directly related with the intensity on the telescope entrance of received terminal, specifically, the received laser power is proportional to the intensity on telescope entrance. Moreover, the intensity randomly variated along with the transmitting beam jitter due to satellite vibration and insufficient closed loop control of pointing/tracking subsystem. Therefore, the aforementioned parameters of communication system evaluation could be calculated through analyzing the probability of the received intensity.

The beam jitter of the laser communication terminal is a random variable satisfying Rayleigh distribution, and for a centrosymmetric far field profile$I\left(\theta\right)$, as shown in Fig. 1, the probability of received intensity could be calculated by the integral of the probability density function (PDF) of jitter. This model could be further simplified as that, if the received intensity is above a threshold I_{th} (which has different values in acquisition and communication stages of laser link), the communication link would work properly, and otherwise the communication link breaks off. As a results of that, the probability of laser communication link works properly is calculated by the integral of the PDF of jitter over the interval of$I\left(\theta\right) > I_{th}$.

$$p = \int_{I(\theta)>I_{th}} f(\theta)d\theta \tag{1}$$

where f(θ) is the PDF of transmitting beam jitter, and

$$f(\theta) = \frac{\theta}{\sigma^2}\exp\left(-\frac{\theta^2}{2\sigma^2}\right) \tag{2}$$

where σ is the scale parameter of Rayleigh distribution, which physically equals to the root mean square of the jitter on X or Y coordinate of transmitting beam direction.

2.1. Optimal shape of top-hat beam

The intensity of top-hat beam should satisfies the requirements of communication system, specifically larger than the required threshold I_{th}.Without loss of generality, the top-hat beam may be doughnut shape with inner angle radius θ_0 and outer angle radius $\theta_0+\theta_t$ as shown in Fig. 2, and moreover, according to the principles of energy conservation, the area of the beam is

$$\left[\pi(\theta_0+\theta_t)^2 - \pi\theta_0^2\right] = \frac{P_s}{L^2 I_{th}} \tag{3}$$

where P_s is the power of transmitting laser, L is the link distance, hence the probability of the received intensity equals to the integral over the interval of $\left[\theta_0, \theta_0+\theta_t\right]$,

$$p = \int_{\theta_0}^{\theta_0+\theta_t} f\left(\theta\right) d\theta$$

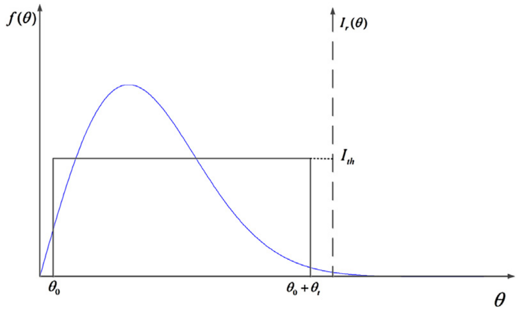

Fig. 2. Calculation of the probability of the received intensity for a top-hat beam, the top-hat beam may be hollow because of $f(\theta) = 0$ at the zeros point $\theta = 0$.

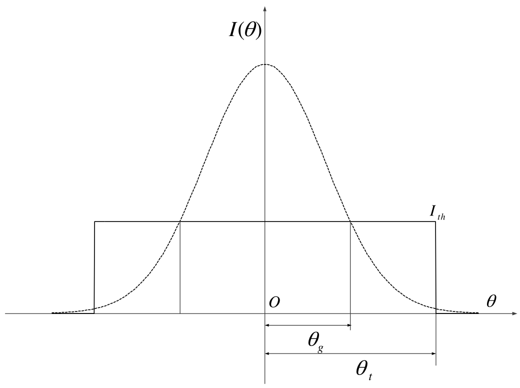

Fig. 3. Shaping a Gaussian beam into top-hat beam, the effective beam radius is increased from θ_g to θ_t for an given intensity threshold I_{th}.

$$= \exp\left(-\frac{\theta_0^2}{2\sigma^2}\right) - \exp\left(-\frac{\left(\theta_0+\theta_t\right)^2}{2\sigma^2}\right) \tag{4}$$

Substitute Eq. (3) into Eq. (4), then it could be found that probability p in Eq. (4) takes its maximum value $p_{\max}$ when $\theta_0 = 0$, and we have

$$p_{\max} = 1 - \exp\left(- \frac{P_s}{2\sigma^2 \pi L^2 I_{th}}\right) \tag{5}$$

Therefore the optimal top-hat beam is a disc but not a donut shape, the angular radius of top hat beam is

$$\theta_t = \left(\frac{P_s}{\pi I_{th} L^2}\right)^{1/2} \tag{6}$$

2.2. Link performance improvement

As shown in Fig. 3, if I_{th} represents the decision threshold of acquisition sensor which corresponding to a beam jitter of θ_g for a Gaussian beam, which means the terminal acquisition succeed only if the beam jitter is less than θ_g. Obviously I_{th} is determined by

$$I_{th} = \frac{2P_s}{\pi(\omega L)^2} \exp\left(- \frac{2{\theta_g}^2}{\omega^2}\right) \tag{7}$$

where ω is the half 1/e divergence angle of Gaussian beam.

If the Gaussian beam is shaped into top-hat beam with intensity of I_{th}, according to Eqs. (6)–(7), the angle radius of top-hat beam is

$$\theta_t = \frac{\omega}{\sqrt{2}} \exp\left(\frac{\theta_g^2}{\omega^2}\right) \tag{8}$$

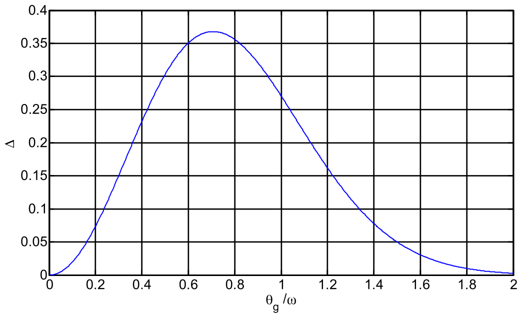

Fig. 4. Beaconless acquisition time decrease after shaping transmitting beam of inter-satellite laser communication system from Gaussian beam to far field top-hat beam, the beaconless acquisition time at least decreases 63%.

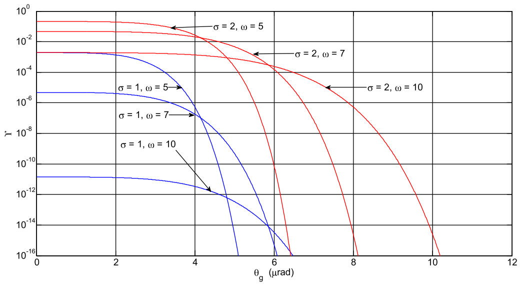

Fig. 5. Change of link outage probability by shaping Gaussian transmitting beam into top-hat beam.

Since the beaconless acquisition time is inversely proportional to the beam area, the deduce of beaconless acquisition time described by the ratio between the acquisition times of top-hat and Gaussian beams is given by

$$\Delta = \frac{\theta_g^2}{\theta_t^2} = 2\frac{\theta_g^2}{\omega^2}\exp\left(-2\frac{\theta_g^2}{\omega^2}\right) \tag{9}$$

From Eq. (9), the ratio of acquisition time decrease is determined the value of θ_g, or it varies along with the required intensity threshold of acquisition sensor I_{th} considering that I_{th} connects with θ_g as in Eq. (7). The relationship between Δ and θ_g/ω is illustrated in. (4)

The results in Fig. 4 shows that when $\theta_g/\omega = \sqrt{2}/2$, Δ takes its maximum value $1/e$, which means that the beaconless acquisition time would at least reduce 63% if the Gaussian beam is shaped to a top-hat beam for an inter-satellite laser communication link.

In the same way, if I_{th} represents the decision threshold of link outage, then the change of outage probability described by ratio between the link outage probabilities of top-hat beam and Gaussian beam is calculated by

$$\Upsilon = \frac{\int_{\theta_t}^{\infty} f(\theta)d\theta}{\int_{\theta_g}^{\infty} f(\theta)d\theta} = \exp\left(\frac{\theta_g^2-\theta_t^2}{2\sigma^2}\right) = \exp\left(\frac{\theta_g^2}{2\sigma^2} - \frac{\omega^2}{4\sigma^2}e^{\frac{2\theta_g^2}{\omega^2}}\right) \tag{10}$$

For some typical parameters of σ and ω with unit of μrad, the value of Υ is calculated and shown in Fig. 5, the value of Υ decrease along with the increase of θ_g for any given σ and ω, and the link outage probability would at least reduce by $\exp\left(-\omega^2/4\sigma^2\right)$ after shaping the Gaussian beam to top-hat beam.

On the other hand, shaping the Gaussian transmitting beam into top-hat beam expands the effective beam area in which the laser communication terminal still can receive sufficient power for tracking or communication, which means the tracking error would be relaxed while maintains the same availability of the communication link. We assume that the

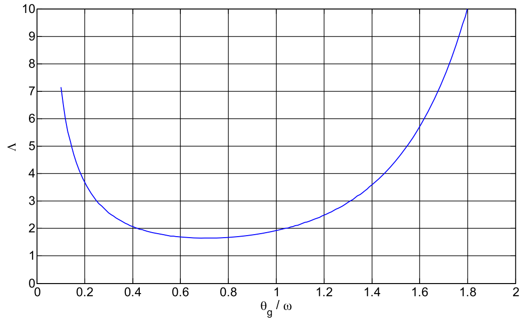

Fig. 6. Increase of tracking error allowance by shaping Gaussian beam to top-hat beam for different intensity threshold while keep the communication link stable.

required tracking errors for Gaussian beam and top-hat beam are σ_g and σ_t respectively for the same availability, it infers that

$$\int_0^{\theta_g} \frac{\theta}{\sigma_g^2} \exp\left(-\frac{\theta^2}{2\sigma_g^2}\right) d\theta = \int_0^{\theta_t} \frac{\theta}{\sigma_t^2} \exp\left(-\frac{\theta^2}{2\sigma_t^2}\right) d\theta \tag{11}$$

From Eq. (11) and Eq. (9), the increase of tracking error allowance could be calculated as

$$\Lambda = \frac{\sigma_t}{\sigma_g} = \frac{\omega}{\sqrt{2}\theta_g} \exp\left(\frac{\theta_g^2}{\omega^2}\right) \tag{12}$$

As the results shown in Fig. 6, Λ gets its minimum value of 1.65 when $\theta_g/\omega = \sqrt{2}/2$, which means the allowance of tracking error would at least increase to 1.65 times.

Considering that the tracking error is dependent upon many parameters such as satellite vibration, tracking sensor noise, signal timing errors, mechanical misalignments, microprocessor computational errors et.al, and even on the heat control and functional deterioration of devices in the whole life time of laser communication terminal, therefore the increase of tracking error allowance may relax the precision requirements of terminal devices and increase the reliability and lifetime of satellite-borne laser communication system, that is helpful to promote the commercialization process of satellite-borne laser communication.

3. Conclusions

In conclusion, it is not necessary to adopt a Gaussian transmitting beam in inter-satellite optical communication, shaping the transmitting beam into a top-hat beam is likely to be more advantageous in inter-satellite communication systems without changing the other configuration of laser communication terminal. The beaconless acquisition time can reduce at least over 63%, the outage probability may reduce several order magnitude depends on the jitter variance and beam divergence angle, and the allowance of tracking error can increase 1.65 times while the communication performance would not be deteriorated. These effects help to improve the reliability of the inter-satellite laser communication system with lower cost and technical risks, furthermore, to promote the commercial operation process of laser communication in free space.

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