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Acquisition performance analysis for intersatellite optical communications with vibration influence*

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A stable and accurate pointing, acquisition system is an important part of initially building intersatellite optical communication links. Satellite platform vibration can cause the system instability and reduce the system precision in building and maintenance of a satellite optical communication system. In this paper, vibration influence is consciously discussed by acquisition time for intersatellite optical communications. Analytical expression of acquisition possibility is derived, taking the scan parameters and platform vibration into account, and vibration influence on the multi-scan acquisition time is also presented. The theoretical result calculated by the proposed analytical expression is approximate to the result by the Monte Carlo simulation.

Keywords: optical communication systems, optical communications, acquisition time, vibration influence

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1. Introduction

Free space optical (FSO) communication has many advantages over microwave communications, such as light weight, high speed data capacity and immunity to interference.[1–5] FSO communication has important applications for intersatellite communications with a few successful in-orbit demonstrations in recent years.[6–9] However, compared to the ground terminals, the transmitters of intersatellite optical links (IOLs) are limited by the narrow beam width and low power.[10,11] During the pointing, acquisition and tracking (PAT) phase, inter-satellites using narrow beam width will be severely influenced by pointing errors due to the platform vibration. Pointing errors will be drastically enhanced in long distance communication and IOLs will use more time to build the links and relatively reduce the communication time. Hence, PAT systems meet challenges to design appropriately for particularly high accuracy long distance IOLs.[12,13]

In order to establish stable IOLs, a acquisition system should achieve the communication line of sight (LOS).[13,14] For this purpose, the transmitter scans with the beacon beam under a selected model over a field of uncertainty (FOU) until the receiver is detected and locked by the transmitter during the acquisition process.[15] To realize the acquisition process, different scanning patterns for microsatellite communications are discussed in Ref. [16]. Details of spatial acquisition algorithm have been described in Ref. [16]. Numerous studies have mainly focused on the spatial acquisition system.[17,18]

From the perspective of acquisition system performance analysis, acquisition time and probability are introduced to evaluate the performance of the acquisition system when a certain FOU is given. The FOU is the field where receivers will possibly exist during the pointing and acquisition, and it mainly depends on the attitudes of the satellites and orbits. Larger FOU will increase not only the acquisition probability but also the acquisition time. An appropriate FOU should be firstly considered in the acquisition phase. In addition, for most of the acquisition processes, single scan can not complete the acquisition task. Therefore, multi-scan is required to increase the acquisition probability up to approximate 1. Li *et al.* proposed an analytical expression of multi-scan acquisition time and gave Monte Carlo simulation to prove the validity of the theory. Meanwhile, an optimal FOU was provided and led to the minimal acquisition time.[9] Further discussion in acquisition time of using the narrow divergence beam was presented in Ref. [19]. In addition, vibration influence on hit probability during beaconless spatial acquisition was also mentioned in Ref. [20].

Influences of platform vibration on acquisition possibility will severely increase the acquisition time. However, its effects on IOLs have not been systematically discussed. Meanwhile, scan parameters related to the beacon beam in the acquisition system design also require further discussions in the presence of platform vibrations. Hence, it is significantly interesting to parameterize the vibration influence on acquisition phase for IOLs.

In this paper, we introduce the distribution function of the satellite position and a spiral scan pattern. Considering the transmitter platform vibration, we calculate the acquisition probability in single scan. Finally, the mean acquisition time of multi-scan is derived under the vibration influence and

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Monte Carlo simulations are performed to verify the theoretical calculations.

2. Mathematical models of acquisition probability and acquisition time

2.1. Acquisition probability of single scan

For building IOLs, two satellites need to point to each other based on predicted positions calculated by the known Ephemeris. With respect to pointing and acquisition system, size of FOU in IOLs should consider deviation position of receiver, as shown in Fig. 1. Here $\theta_{\rm v}$ and $\theta_{\rm h}$ are the angels in vertical and horizontal directions in the o–xyz coordinate system, respectively. Line of sight (LOS) of the two satellites is along the z-axis in the non-error situation.

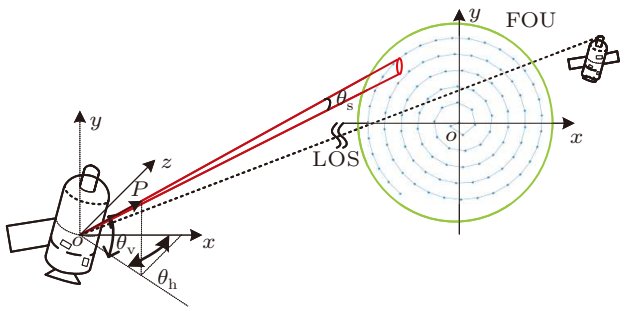


Fig. 1. The scan geometry of inter-satellite link.

The probability distribution function is related to the deviation of the satellite position. The probability density function (PDF) is given by[2,17,21]

$$f(\theta_{\rm R}) = \frac{\theta_{\rm R}}{{\sigma_\theta}^2} \exp\left(-\frac{{\theta_{\rm R}}^2}{2{\sigma_\theta}^2}\right), \tag{1}$$

where $\theta_{\rm R}$ is the deviation of the satellite position, σ_θ^2 is the variance of satellite position. The PDF of the deviation obeys the Rayleigh distribution.

Considering the limited size of FOU, the probability of the satellite presenting in the FOU can be expressed as[17,18]

$$P_{\rm FOU}(\theta_{\rm U}) = \int_0^{\theta_{\rm U}} f(\theta_{\rm R})\,{\rm d}\theta_{\rm R} = 1 - \exp\left(\frac{\theta_{\rm U}^2}{2{\sigma_\theta}^2}\right), \tag{2}$$

where $\theta_{\rm U}$ is half width of the FOU.

For all of the positions of satellites, $\theta_{\rm U} = 3\sigma_\theta$ is large enough to ensure acquisition with a high probability, which is approximately 98.9% for a single scan.[19,21,22]

The spiral scan starts from the center of FOU, where the highest possibility of target terminal presents. It moves towards the edge of FOU with a linear velocity. The spiral scan is illustrated in Fig. 2.

In polar coordinates, the trace equation of spiral scan is given by

$$r_{\rm p} = \frac{d}{2\pi}\theta_{\rm p}, \tag{3}$$

$(r_{\rm p}, \theta_{\rm p})$ is one point in polar coordinates for spiral scan.

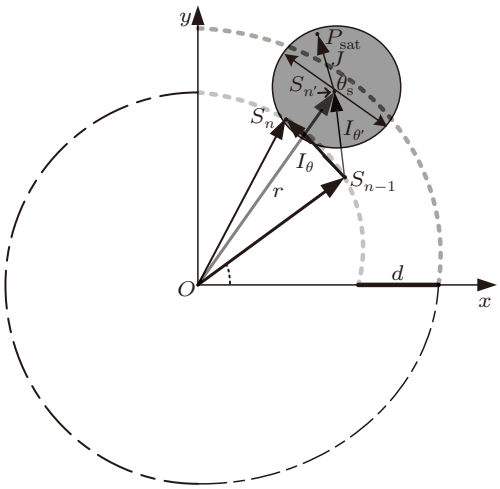


Fig. 2. Scan geometry. I_θ is the step length, $\theta_{\rm s}$ is the width of scanning beam, d is the spiral pitch. $I_{\theta'}$ is the actual step length influenced by vibration, S_n is the n-th center of the scanning beam. $S_{n'}$ is the actual beam center with the vibration. $P_{\rm sat}$ is the receiver position in the FOU. J is the vector from the nth center with vibration to receiver point.

The width of the scanning beam and the step length are given by

$$\theta_{\rm s} = \alpha d, \tag{4}$$

$$I_\theta = \beta d, \tag{5}$$

where α is the width parameter, β is the step length parameter, $\theta_{\rm s}$ is determined by divergence of the beacon beam and I_θ depends on the parameter initializing set of scan driver unit.

Despite the vibration influence, these parameters should satisfy covering of the area of FOU,[21]

$$\begin{cases} \alpha > 1.065, \\ \beta^2 \le \alpha^2 - 1. \end{cases} \tag{6}$$

From initial point $(0,0)$ to the final scan point $(r_{\rm U}, \theta_{\rm U})$, the total scan time is expressed as[9]

$$T_{\rm Full} \approx \frac{\pi\beta\theta_{\rm U}^2}{I_\theta^2}\Delta t, \tag{7}$$

where $\Delta t = 2L/c$ is the dwell time between the two adjacent points, L is the link length, and c is the speed of light.

The number of the spot in FOU can be given as

$$K = \frac{\pi\beta{\theta_{\rm U}}^2}{I_\theta^2} + 1. \tag{8}$$

The coordinates of point S_n in Cartesian coordinates are given by

$$S_n = (r_n\cos\theta_n, r_n\sin\theta_n), \quad n = 1,2,\ldots,K, \tag{9}$$

where

$$r_n = d\sqrt{\frac{(n-1)\beta}{\pi}}, \tag{10}$$

$$\theta_n = \sqrt{4\pi(n-1)\beta}. \tag{11}$$

The vector component of J satisfies the normal distribution and can be given as follows:

$$f(J_x) = \frac{J_x}{\sqrt{2\pi}\sigma_x}\exp\left[-\frac{(J_x - r_n\cos\theta_n)^2}{2{\sigma_x}^2}\right], \tag{12}$$

$$f(J_y) = \frac{J_y}{\sqrt{2\pi}\sigma_y}\exp\left[-\frac{(J_y - r_n\sin\theta_n)^2}{2{\sigma_y}^2}\right], \tag{13}$$

where ${\sigma_x}^2 = {\sigma_y}^2 = \sigma^2 = \sigma_{\rm N}^2/2$, $\sigma_{\rm N}^2$ is variance of the platform vibration.

Considering $J = \sqrt{J_x^2 + J_y^2}$, we can deduce J satisfying the Rice distribution as follows:

$$f_n(J) = \frac{J}{\sigma^2}\exp\left(-\frac{J^2 + {r_n}^2}{2\sigma^2}\right) I_0\left(\frac{Jr_n}{\sigma^2}\right), \tag{14}$$

where $I_0(\cdot)$ is the zero-order Bessel function of the first kind.

When the receiver position $P_{\rm sat}$ in the area of the n-th point of scanning beam width, we can obtain the acquisition probability in the n-th point as follows:

$$P_n\left(J \le \frac{\theta_{\rm s}}{2}\right) = \int_0^{\frac{\theta_{\rm s}}{2}} \frac{J}{\sigma^2}\exp\left(-\frac{J^2 + {r_n}^2}{2\sigma^2}\right) I_0\left(\frac{Jr_n}{\sigma^2}\right) {\rm d}J. \tag{15}$$

According to Eq. (15), we can reach

$$P_n(\sigma,\alpha,d) = Q_1\left(\frac{r_n}{\sigma},0\right) - Q_1\left(\frac{r_n}{\sigma},\frac{\theta_{\rm s}}{2\sigma}\right), \tag{16}$$

where $Q_1(\cdot,\cdot)$ is the first-order Marcum-Q function

$$Q_1(a,b) = \int_b^{\infty} x\exp\left(-\frac{x^2 + a^2}{2}\right) I_0(xa)\,{\rm d}x, \tag{17}$$

and its numerical calculation can be given by software.

As we know from the probability theory, the probability of acquisition only in the n-th point during scan process is

$$P_{o,n} = P_n\prod_{i=1}^{n-1}(1 - P_i). \tag{18}$$

Then the acquisition probability of single scan in FOU can be given as

$$P_{\rm Acq}(\sigma,\alpha,\beta,d) = \left[1 - \prod_{n=0}^{K-1}(1 - P_{o,n})\right] P_{\rm FOU}. \tag{19}$$

2.2. Acquisition time of multi-scan

In practice, the acquisition process adopts multi-scan to ensure the acquisition probability to be approximately to 1. Combining the single scan time with vibration and scan parameters, acquisition time of multi-scan will be further derived.

Scan time of the n-th point can be given as

$$T_n = n\Delta t. \tag{20}$$

The acquisition time of the single scan can be given as

$$T_{\rm s} = (1 - P_{\rm FOU})T_{\rm Full} + \sum_{n=0}^{K-1} P_{\rm FOU}P_{o,n}n\Delta t. \tag{21}$$

Due to the vibration influence, the single scan possibly cannot accomplish the acquisition task. To increase the acquisition probability, the multi-scan is introduced in the acquisition process. More importantly, we can achieve relatively high acquisition probability which could be approximate to 1.

The multi acquisition probability of the n-th scan can be written as

$$P_{\rm M} = \sum_{i=1}^{M} P_{\rm Acq}\left(1 - P_{\rm Acq}\right)^{i-1}. \tag{22}$$

The multi acquisition time can be written as

$$\begin{aligned} T_{\rm M} = {} & T_{\rm s}P_{\rm Acq} + (T_{\rm Full} + T_{\rm s})\left(1 - P_{\rm Acq}\right)P_{\rm Acq} + \ldots \\ & + \left[(i-1)T_{\rm Full} + T_{\rm s}\right]\left(1 - P_{\rm Acq}\right)^{i-1}P_{\rm Acq} + \ldots, \end{aligned} \tag{23}$$

which can be simplified to

$$T_{\rm M} = T_{\rm s} + \left(\frac{1 - P_{\rm Acq}}{P_{\rm Acq}}\right) T_{\rm Full}. \tag{24}$$

Substituting Eqs. (7), (21) and (23) into Eq. (24), we can reach

$$\begin{aligned} T_{\rm M} = {} & P_{\rm FOU}\sum_{n=0}^{K-1} nP_{o,n}\Delta t + (1 - P_{\rm FOU})(K-1)\Delta t \\ & + \frac{1 - \left[1 - \prod_{n=0}^{K-1}(1 - P_n)\right]P_{\rm FOU}}{\left[1 - \prod_{n=0}^{K-1}(1 - P_n)\right]P_{\rm FOU}}(K-1)\Delta t. \end{aligned} \tag{25}$$

3. Numerical results and discussion

In this section, numerical calculations are conducted to analyze the influence of scan parameters, and the optimum FOU should satisfy $\theta_{\rm U\,opt} = 1.3\sigma_\theta$.[9] Data are calculated under the condition that $\alpha = 1.3,\ 1.4,\ 1,5$ and $\beta = 0.8,\ 0.9,\ 1.0$ in accordance with Eq. (6) limitation and all parameters used in the process of scanning are listed in Table 1.

Link length 36000–45000 km is a range of typical value for long distance inter-satellite communication systems in engineering. Considering that the narrow beam width is about 10–50 μrad and standard deviation of the satellite position is about 100–3000 μrad, we select all scan parameters in this range. According to the spectrum characteristic of the satellite platform vibration model used by ESA in the SILEX program,[23] we appropriately choose the range of the vibration deviation as 0–100 μrad.

Table 1. Scan parameters of the intersatellite links.

Variable	Parameter	Simulation value
L	link length	45000 km
I_θ	step length	26 μrad, 28 μrad, 30 μrad
$\theta_{\rm s}$	beacon beam width	16 μrad, 18 μrad, 20 μrad
d	spiral pitch	20 μrad, 25 μrad, 30 μrad
σ_θ	standard deviation of satellite position	100 μrad, 150 μrad, 200 μrad
$\sigma_{\rm N}$	standard deviation of vibration	0–100 μrad

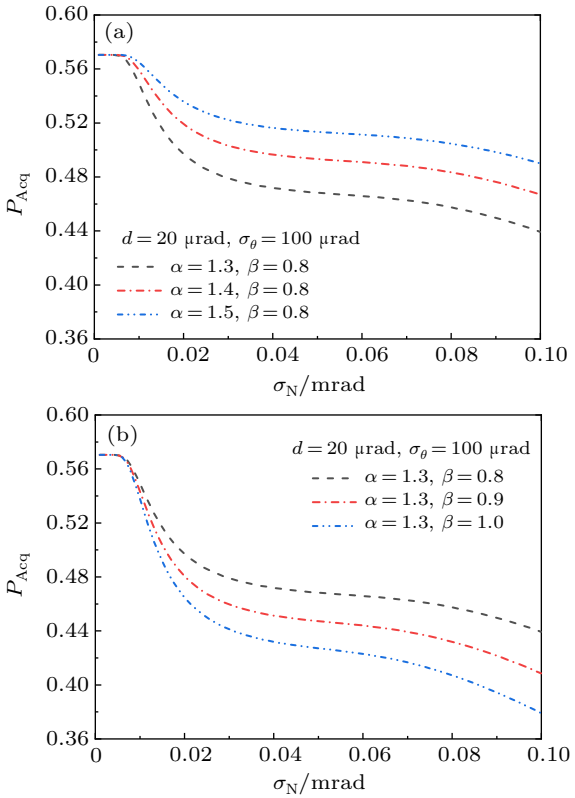


Fig. 3. Single scan acquisition probability as a function of the vibration deviation $\sigma_{\rm N}$ with different parameters of (a) scan beam width α and (b) scan step length β for $\theta_{\rm Uopt} = 1.3\sigma_\theta$.

The acquisition probability could be numerically evaluated for vibration levels up to 100 μrad with a series of scan parameters from Eq. (19). The calculated probability is plotted as a function of vibration deviation with different scan parameters, as shown in Fig. 3. It is found that acquisition probability decreases approximately linearly with the increasing vibration deviation in the range from 5 μrad to 20 μrad. When the vibration deviation <5 μrad, vibration influence on acquisition probability could hardly be observed for all scan parameters. When the vibration deviation >20 μrad, acquisition probability could slowly decrease with the increasing vibration deviation. The smaller scan beam width and larger step length parameter will relatively decrease acquisition probability under the same vibration deviation as shown in Figs. 3(a) and 3(b).

The vibration influences on multi-scan time by vibration deviation, scan parameter and spiral pitch are illustrated in Figs. 4(a), 4(b) and 4(c), respectively. According to Eq. (25), when $\theta_{\rm Uopt} = 1.3\sigma_\theta$, for a specific spiral pitch and FOU deviation, multi-scan time will decrease with the increasing scan beam width parameter and step length parameter as shown in Figs. 4(a) and 4(b), respectively. Although the larger step length parameter will relatively decrease acquisition probability as shown, it will reduce multi-scan time, compared Figs. 3(b) and 4(b). For fixed scan parameters, multi-scan time will decrease with the increasing spiral pitch as shown in Fig. 4(c). For the deviation of the satellite position, the larger FOU can drastically increase multi acquisition time in Fig. 4(d).

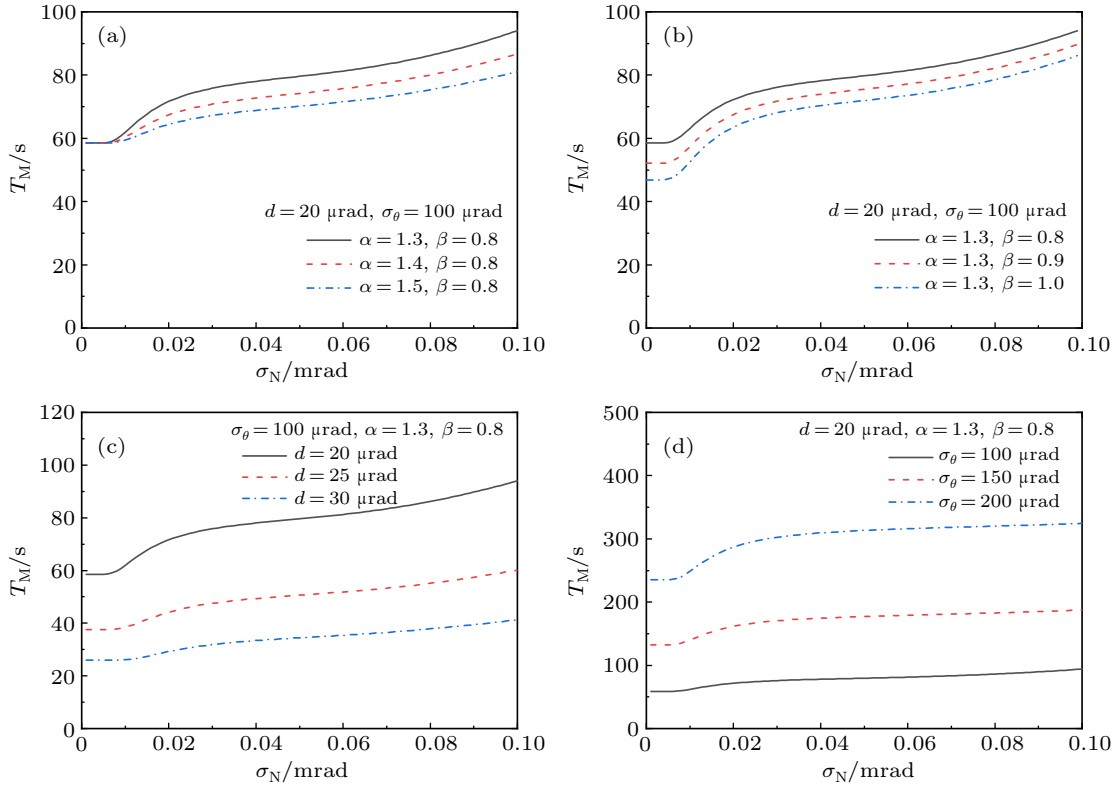


Fig. 4. Multi-scan time as a function of vibration deviation $\sigma_{\rm N}$ for different parameters of (a) beam width α, (b) scan step length parameter β, (c) spiral pitch d, and (d) deviation of the satellite position σ_θ, for $\theta_{\rm Uopt} = 1.3\sigma_\theta$.

It should be noted that multi-scan time has no obvious change at small vibration deviation < 5 μrad, as shown in Fig. 4. Multi-scan time would rapidly increase in the range of 5–20 μrad, then slowly increase with the increasing vibration deviation > 20 μrad.

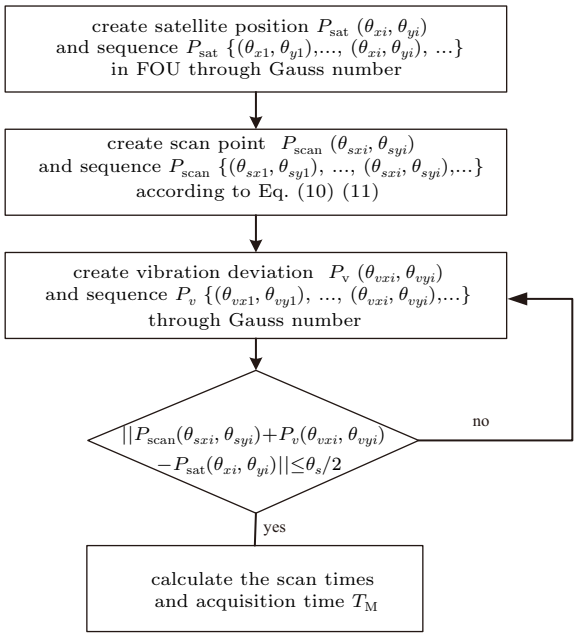


Fig. 5. The process of Monto Carlo simulation.

The simulation process is shown in Fig. 5 and multi-scan time simulated by Monte Carlo, using 10000 different satellite positions on each vibration deviation, is also included (the error bar) in Fig. 6. The details of the Monte Carlo simulation are as follows: (a) Generate random 10000 different positions of the satellite $P_{\text{sat}}\left(\theta_{xi}, \theta_{y_i}\right)$ of Gauss number using Matlab. Here $\theta_x = (\theta_{x1}, \theta_{x2}, \ldots, \theta_{x10000})$ and $\theta_y = \left(\theta_{y_1}, \theta_{y_2}, \ldots, \theta_{y_{10000}}\right)$ are the position array. They satisfy the distribution $\theta_x \sim N\left(0, \sigma_\theta^2\right)$ and $\theta_y \sim N\left(0, \sigma_\theta^2\right)$, respectively. (b) Generate the position of the scan point $P_{\text{scan}}(\theta_{sxi}, \theta_{syi})$, according to Eqs. (10) and (11). (c) Generate random $N = 10K$ different vibration deviations of Gauss numbers on each scan point $P_{\text{v}}(\theta_{vx}, \theta_{vy})$. The number of the scan point of single scan, K, is given in Eq. (8). Here $\theta_{vx} = (\theta_{vx1}, \theta_{vx2}, \ldots, \theta_{vx\text{N}})$ and $\theta_{vy} = \left(\theta_{vy1}, \theta_{vy_2}, \ldots, \theta_{vyN}\right)$ are the random deviation array. They satisfy the distribution $\theta_{vx} \sim N\left(0, \sigma_{\text{N}}^2/2\right)$ and $\theta_{vy} \sim N\left(0, \sigma_{\text{N}}^2/2\right)$, respectively. (d) From the central point $(0,0)$ to the point $(r_{\text{U}}, \theta_{\text{U}})$, we can judge if these points satisfy the criterion of a successful acquisition. The criterion of the successful acquisition can be given as $\left\|P_{\text{scan}}(\theta_{sxi}, \theta_{syi}) + P_{\text{v}}(\theta_{vxi}, \theta_{vyi}) - P_{\text{sat}}(\theta_{xi}, \theta_{yi})\right\| \leq \theta_{\text{s}}/2$, which means that the distance between the current scan point S_i' and satellite position point P_{sat} is less than the half beam width with random vibration. (e) If all the points of single scan do not satisfy the criterion, we add a number of the scan times and then go to the step (c). (f) If the current scan point satisfies the criterion, then we calculate the acquisition time and scan times. Otherwise, go to the next scan point to judge the criterion until it meets the condition.

The parameters used in the Monto Carlo simulation are as follows: the deviation of FOU σ_θ is 100 μrad, the FOU satisfies $\theta_{\text{U}} = 1.3\sigma_{\text{s}}$, the dwell time Δt is 0.30 s, spiral pitch d is 20 μrad, beam width θ_{s} is 26 μrad ($\alpha = 1.3$), step length I_θ is 20 μrad ($\beta = 1$). It is found that the Monte Carlo simulation is consistent with the calculation results according to Eq. (25). As the trend shown in Fig. 6, multi-scan time has no obvious change at small vibration deviation < 5 μrad. Multi-scan time would rapidly increase in the range of 5–20 μrad, then slowly increase with the increasing vibration deviation > 20 μrad. When the vibration deviation > 80 μrad, there is a little difference between the theoretical results and the Monto Carlo simulation. However, the large vibration deviation (> 80 μrad) means the severe situation, which rarely appears in the platform. The correlation coefficient between the simulation and the theory results is 0.991.

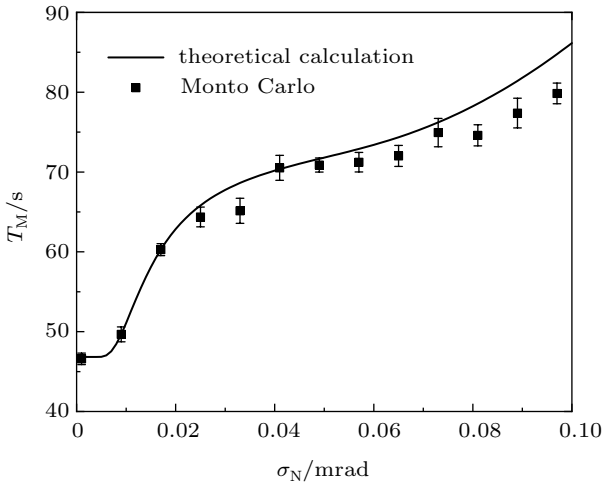


Fig. 6. Theory calculation and Monto Carlo simulation of multi acquisition time versus vibration deviation.

Acquisition probability of scan times with different standard variance for the given Monto Carlo simulation parameters is also shown in Fig. 7. The probability of scan times gradually decreases with the increasing scan times, and the total acquisition is approximately 90% in the first four scan times. When the scan times are more than 4, the further increase of the total acquisition probability cannot be significantly improved. Therefore, we can select four scan times for inter-satellite links to satisfy the acquisition system. When the vibration deviation is 0 μrad, 20 μrad, 50 μrad, and 100 μrad, the acquisition probability of the first scan is 57.2%, 45.8%, 42.8%, and 39.9%, respectively. The acquisition probability of the first scan gradually decreases with the vibration deviation and the acquisition probability of the first scan are also consistent with the theory result given by Eq. (19).

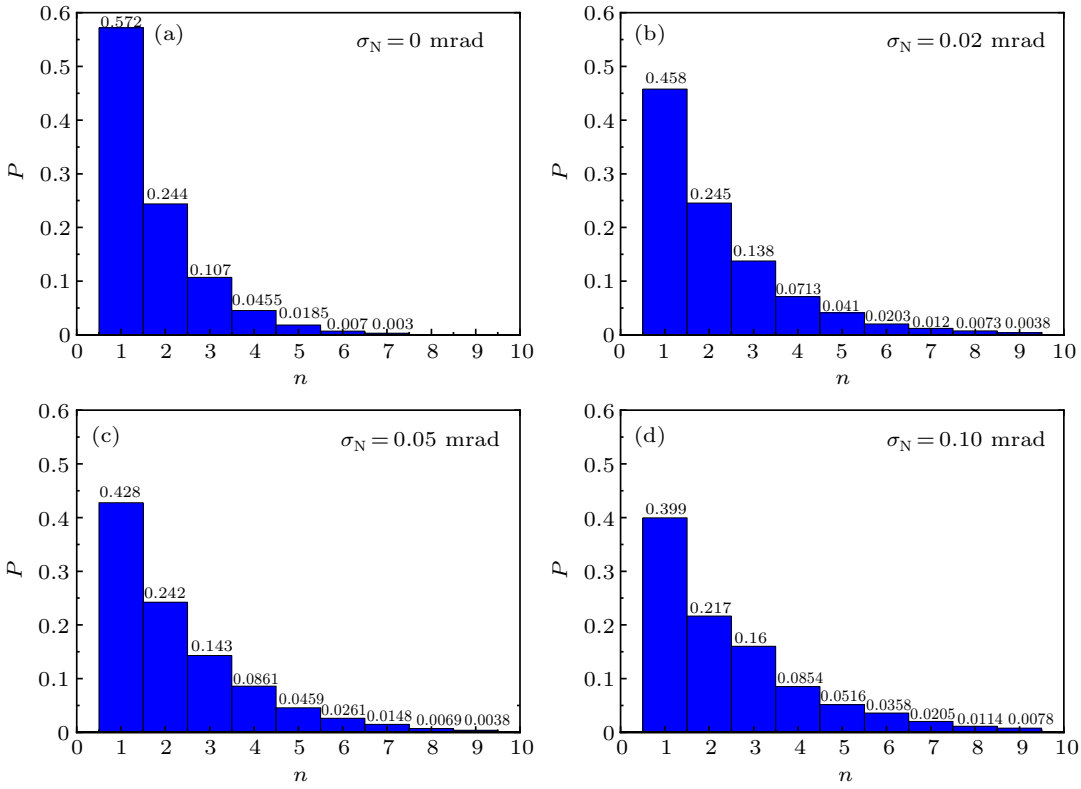


Fig. 7. Acquisition probability of scan times with different standard variances: (a) 0 μrad, (b) 20 μrad, (c) 50 μrad, and (d) 100 μrad.

4. Conclusion

In summary, we have proposed a new approach of using an analytical expression of vibration deviation and scan parameters to calculate vibration influence on an acquisition system for intersatellite optical communications. This analytical model accounts for the scan parameters, dwell time, initial pointing error and platform vibration. The acquisition possibility of the system is attained by using Rice distribution in the spiral scanning model. Taking the FOU into account, we present the corresponding acquisition time of multi-scan.

The scan time increases with the increasing vibration deviation. Meanwhile, the acquisition probability decreases with the increasing deviation. Under the same vibration deviation, the multi-scan time decreases with the increasing scan parameters, such as beam width, step length and the spiral pitch. The FOU determined by the deviation of the satellite position can also influence the scan time. The larger the deviation of the satellite position, the greater the acquisition probability. Also, the scan time increases rapidly with the increasing deviation of the satellite position.

Multi scan can improve the acquisition probability. Monto Carlo simulation gives the multi-scan time and the probability of scan times. The comparison of theoretical and simulation results shows consistence. When the scan times is 4, the acquisition probability is approximately 90% under different vibration deviation. It can be selected as an optimum scan times of the acquisition system design for the intersatellite communication.

This methodology is possible for applications in IOLs with a relatively narrow beacon beam particularly for acquisition. These findings provide further insight into understanding how performance of intersatellite acquisition systems is affected by vibration, and will be useful in parameterizing design for optical communication and future discussion in atmospheric channel.

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