Postprint: Distribution Characteristics of Echo Photons in Laser Ranging Systems

Authors: Tang Meirong, He Lijuan, Zhai Dongsheng, Li Yuqiang, Tang Rufeng, Li Zhulian

Date: 2017-09-26T00:00:00+00:00

Abstract

Analysis of echo photon characteristics in laser ranging systems holds significant importance for theoretical research, system design, and performance evaluation of laser ranging. By integrating the principles of laser ranging and comprehensively considering multiple influencing factors—such as atmospheric turbulence, transmission characteristics of the atmosphere and cirrus clouds, and target distance—the ranging equation is theoretically derived to analyze and investigate the distribution characteristics of echo photons. Furthermore, utilizing the Matlab software development platform, dedicated research software for analyzing the distribution characteristics of echo photons in laser ranging systems has been developed. This software enables estimation of echo photon numbers through configuration of relevant system parameters, including the laser, transmitting telescope, receiving telescope, and detector, while simultaneously displaying the corresponding functional relationship curves.

Full Text

Research on the Distribution Characteristics of Echo Photons in Laser Ranging Systems

He Lijuan[1], **Zhai Dongsheng**[1], **Li Yuqiang**[1], **Tang Rufeng**[1], **Li Zhulian**[1],[2] [1]Yunnan Astronomical Observatory, Chinese Academy of Sciences, Kunming, Yunnan 650011, China [2]University of Chinese Academy of Sciences, Beijing 100049, China

Abstract

Analysis of echo photon characteristics in laser ranging systems is of great significance for laser ranging theory, system design, and performance evaluation.

Combining the principles of laser ranging and comprehensively considering various factors affecting laser ranging—such as atmospheric turbulence, transmission characteristics of the atmosphere and cirrus clouds, and target distance—this paper theoretically derives the ranging equation to analyze the distribution characteristics of echo photons. Correspondingly, software for studying the distribution characteristics of echo photons in laser ranging systems is developed using the Matlab platform. By setting relevant parameters of the laser, transmitting telescope, receiving telescope, and detector in the ranging system, the number of echo photons can be estimated, and the corresponding functional relationship curves can be displayed simultaneously.

Keywords: Laser Ranging; Echo Photons; Relevant Parameters; Matlab Research Software

---

1. Introduction

Laser ranging technology is a comprehensive discipline that integrates precision optics, mechanics, and satellite orbit calculation. It obtains the distance R between the observation station and target by precisely measuring the round-trip flight time t of a laser pulse. The actual laser ranging process is extremely complex, influenced by numerous factors including atmospheric transmission characteristics, target characteristics, telescope pointing errors, target distance, and laser beam divergence angle. Any variation in these parameters will cause changes in the number of echo photons in laser ranging. Matlab, as one of the most widely used mathematical software platforms globally, offers powerful numerical computation and symbolic operation capabilities, providing a complete mathematical platform for estimating the influence of these factors on echo photons in laser ranging systems.

2. Theoretical Analysis of Echo Photon Distribution

2.1 Laser Ranging Equation Let the single laser pulse energy emitted by the ranging laser be E, the wavelength be λ, Planck' s constant be h, and the speed of light be c. The laser gain is G, and the emission efficiency of the transmitting system is _t. The number of photons in a single laser pulse emitted from the ground ranging system is given by:

$$n_0 = \frac{E\lambda}{hc}\eta_t$$

The laser beam uniformly illuminates the target with a divergence half-angle . Let the one-way atmospheric transmittance be T_a and the one-way cloud transmittance be T_c. The beam radius at the target is r, forming a spot area of π(R + r)^2. Taking cooperative targets as an example, only photons reaching the effective reflection area σ on the target can be reflected back to the station by the corner reflector. The number of photons reaching the effective reflection area is:

$$n_1 = \frac{E\lambda}{hc}\eta_t G T_a T_c \frac{\sigma}{\pi(R\theta + r)^2}$$

Considering the two-way transmittance through atmosphere and clouds, the average number of echo photons from a single laser pulse that can reach the detector is:

$$n = \frac{E\lambda}{hc}\eta_t G T_a^2 T_c^2 \frac{\rho\sigma}{\pi(R\theta + r)^2} A_r \eta_r$$

where is the target reflectivity, A_r is the effective receiving area of the telescope, and _r is the receiving efficiency of the receiving system.

2.2 Influence of Laser Pointing Deviation and Telescope Tracking Error

Assuming the laser emits a Gaussian beam, the emission gain G can be expressed as:

$$G = \left(\frac{\pi r_0^2}{\lambda R}\right)^2$$

where r_0 is the initial radius of the laser beam.

The influence of pointing deviation and tracking error on echo photon number can be analyzed as follows. Let $\delta\alpha$ and $\delta\beta$ be the azimuth and elevation random pointing errors, respectively, with probability distribution functions p($\delta\alpha$) and p($\delta\beta$), both following Gaussian distributions. When considering pointing errors, the average echo photon number per pulse is:

$$n = \frac{E\lambda}{hc}\eta_t G T_a^2 T_c^2 \frac{\rho\sigma}{\pi(R\theta + r)^2} A_r \eta_r \exp\left(-\frac{2\alpha^2}{\theta^2}\right) \exp\left(-\frac{2\beta^2}{\theta^2}\right)$$

where α and β are the azimuth and elevation pointing deviations, and _α and _β are the azimuth and elevation tracking errors of the telescope, respectively.

If the telescope’ s azimuth and elevation tracking error probability distributions are identical (_α = _β), the equation can be simplified to:

$$n = \frac{E\lambda}{hc}\eta_t G T_a^2 T_c^2 \frac{\rho\sigma}{\pi(R\theta + r)^2} A_r \eta_r \exp\left(-\frac{2(\alpha^2 + \beta^2)}{\theta^2 + \theta_\alpha^2}\right)$$

2.3 Influence of Atmospheric Turbulence When laser beams propagate through atmospheric turbulence, random fluctuations in atmospheric refractive index cause wavefront phase distortion, resulting in beam expansion, intensity scintillation, and other phenomena. For a Gaussian beam propagating along the Z-axis, taking a very short exposure image of the spot on a plane perpendicular to the Z-axis at distance R, the short-term drift _d and expansion _e cause the spot to shift from the original center O and expand. For long observation times, the combined effect manifests as long-term expansion _L.

The initial Gaussian field distribution u(’) at the plane is:

$$u(\rho') = \exp\left(-\frac{\rho o'^2}{r_0^2} - i\frac{k\rho o'^2}{2F}\right)$$

where F is the curvature radius. Using the second-order moment formula for field distribution, the long-term expansion radius is:

$$\rho_L = \sqrt{\rho_e^2 + \rho_d^2} = \sqrt{17.6\left(\frac{R}{k^2 r_0^{5/3}}\right)^{6/5}}$$

Since short-term drift and expansion represent real-time atmospheric turbulence effects, while long-term expansion includes the combined effect of both, this paper uses long-term expansion to analyze echo photon numbers in laser ranging. The resulting equation for average echo photons per pulse at the detector photosensitive surface is:

$$n = \frac{E\lambda}{hc}\eta_t G T_a^2 T_c^2 \frac{\rho\sigma}{\pi(R\theta + r + \rho_L)^2} A_r \eta_r$$

2.4 Influence of Atmosphere and Clouds Visibility is measured by meteorological visual range—the maximum horizontal distance at which a person with normal vision can see and identify a target from the sky background under prevailing weather conditions. The atmospheric attenuation coefficient is determined empirically by:

$$\mu = \frac{3.91}{V}\left(\frac{0.55}{\lambda}\right)^q$$

where V is visibility in km, λ is wavelength in m, and q = 1.3 for V > 80 km, q = 1.6 for 6 km < V < 80 km, and q = 0.585 V^(1/3) for V < 6 km. The atmospheric transmittance is then T_a = exp(- R).

For cirrus clouds with total optical thickness less than 0.14, the cirrus transmittance in the wavelength range 0.317-1.064 m is:

$$T_c = \exp(-0.28\tau)$$

where τ is the average cirrus thickness. The final equation for average echo photons per pulse becomes:

$$n = \frac{E\lambda}{hc}\eta_t G \exp\left(-\frac{7.82}{V}\left(\frac{0.55}{\lambda}\right)^q R\right)\exp(-0.56\tau)\frac{\rho\sigma}{\pi(R\theta + r + \rho_L)^2}A_r\eta_r$$

3. Software Development and Implementation

Given the complexity of actual laser ranging processes and the numerous factors affecting echo photon distribution, we developed a comprehensive analysis software for laser ranging echo photon distribution characteristics using Matlab' s Graphical User Interface (GUI). The software interface includes parameter input modules (laser energy, wavelength, beam divergence angle, telescope tracking errors, target effective optical diameter, corner reflector beam divergence, telescope effective aperture, atmospheric and cloud transmittance, turbulence factors, etc.), calculation modules, and graphical result display modules.

The software can conveniently adjust each parameter for different ranging systems and intuitively analyze the overall relationship between system parameters and echo photon numbers through relationship curves. For example, [Figure 2: see original paper] shows the relationship between echo photon number and distance, while [Figure 3: see original paper] illustrates this relationship under different zenith angles.

Analysis Results: The detected echo photon number decreases with increasing target distance when other parameters remain constant. Modifying any parameter causes corresponding changes in echo photon number. The interface allows convenient selection and output of different relationship curves.

For different zenith angles, atmospheric attenuation coefficient decreases with altitude. In ground-based laser ranging, the detection distance along the vertical direction is much greater than along the horizontal direction. The difference in average echo photons between vertical and horizontal directions decreases with increasing distance. Under the same atmospheric conditions and at the same detection distance, echo photon numbers decrease more slowly with increasing zenith angle when the zenith angle is small, but decrease more rapidly when the zenith angle is large, primarily due to aerosol absorption and scattering effects.

4. Case Study: Echo Photon Estimation for Yunnan Observatory System

Taking the 1.2m telescope laser ranging system at Yunnan Observatory as an example, we estimate the system echo photon numbers. The system parameters are: single pulse energy E = 0.15 J, wavelength λ = 532 nm, beam divergence half-angle = 1.06 mrad, initial beam radius r_0 = 30 cm, laser pointing error = 1.2 mrad, transmitting system efficiency _t = 0.5, target reflectivity = 0.5, effective target optical diameter D = 10 cm, corner reflector beam divergence half-angle = 30 cm, telescope effective aperture D_r = 1.2 m, receiving system efficiency _r = 0.84, atmospheric coherence length r_0 = 10 cm, one-way atmospheric transmittance T_a = 0.8, one-way cloud transmittance T_c = 0.8, and target distance range R = 400-1000 km. The calculated average echo photon number is approximately 2.1×10^{-3}. [Figure 4: see original paper] shows the relationship between echo photon number and distance.

5. Conclusion

This paper comprehensively considers various factors affecting laser ranging, provides detailed derivation and expressions of the ranging equation, and theoretically analyzes and estimates echo photon numbers in laser ranging. A universal analysis software for laser ranging system echo photon distribution characteristics was developed using the Matlab platform. The software allows convenient adjustment of each relevant parameter for different ranging systems through the interface and enables more intuitive overall analysis of system parameters and echo photon numbers through relationship curves, providing a theoretical basis for detector selection and ranging system design. Future work will involve further analysis and research on detectors and ranging systems, optimization of the system, and deeper exploration of software parameters due to the complexity of the laser ranging process.

References

[1] Ye Shuhua, Huang Cheng. *Astrogeodynamics* [M]. Shandong: Shandong Science and Technology Press.

[2] Fu Qiang, Jiang Huilin, Wang Xiaoman. Study of laser transmission characteristics in atmosphere by simulation [J]. *Journal of Air Force Engineering University: Natural Science Edition*, 57-61.

[3] Yan Wei, Zhang Riwei, Dai Dengpo, et al. Simulation research on atmospheric transmission characteristics and return signal for laser [J]. *Chinese Journal of Radio Science*, 564-571.

[4] Zhang Leihong, Yang Yan, Zang Huaguo, et al. Influence of target reflective characteristics on laser ranging [J]. *Chinese Journal of Lasers*, 1001-1004.

[5] Qu Feng, Wei Zhibin, Cheng Bohui, et al. Telescope pointing correction for stellar tracking and satellite laser ranging [J]. *Science of Surveying and Mapping*, 55-56.

[6] Huang Baoli, Han Xingwei, Zhang Nan, et al. Pointing deviation correction for satellite laser ranging system [J]. *Laser & Infrared*, 715-719.

[7] Li Yuqiang, Li Rongwang, Li Zhulian, et al. Determination of distance to non-cooperative target in laser ranging with separate optical paths [J]. *Publications of National Astronomical Observatories of China*, 137-142.

[8] Song Min, Wang Jiang, Yang Xiangdong, et al. Design of laser ranging parameter analysis software [J]. *Laser Journal*, 55-56.

[9] Degnan J J. Millimeter accuracy satellite laser ranging: a review [C]//Contributions of Space Geodesy to Geodynamics: Technology. 133-162.

[10] Degnan J J. Theoretical performance of NASA's SLR2000 system [C]//ILRS Technical Workshop. 2015.

[11] Ndlouv S C, Combrinck L, Exertier P, et al. An estimation of the number of expected returned photons for the HartRAO Lunar Laser Ranger system [C]//19th International Workshop on Laser Ranging. 2011.

[12] Ke Xizheng, Wang Wanting. Intensity and expansion of partially coherent beam propagating in slant and horizontal atmospheric turbulence [J]. *Journal of Applied Sciences*, 142-154.

[13] Li Jingzhen, Su Shixue, Zhao Junmin. *Handbook of Optics* [M]. Beijing: Tsinghua University Press.

[14] Dai Yang, Cheng Xuewu, Li Faquan, et al. Study on new technical methods for lunar laser ranging [J]. *Publications of the Yunnan Observatory*, 83-84.

[15] Fante R L. Electromagnetic beam propagation in turbulent media [J]. *Proceedings of the IEEE*, 1669-1692.

[16] Wang Haixian, Ye Ai. The influence of the coefficient of atmospheric attenuation to the capability of laser ranging [J]. *Ship Science and Technology*, 116-119.

[17] Guo Hao, Qiu Qi, Ma Na, et al. Numerical algorithm for maximum range of laser rangefinder in different visibility [J]. *Infrared and Laser Engineering*, 3330-3334.

[18] Zhao Shaoqing, Zhang Chu. Simulation on atmospheric transmission characteristic of laser and its impact on laser ranging [J]. *Laser & Optoelectronics Progress*, 55-60.

[19] Li Zhulian, Xiong Yaoheng, He Miaochang, et al. Principle of the 1.2m telescope satellite laser ranging system at Yunnan Observatory [J]. *Astronomical Research & Technology*, 248-252.

Note: Figure translations are in progress. See original paper for figures.