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Abstract

In satellite laser ranging systems, the quality of laser spot characteristics is critical to the success of ranging, with the actual laser spot characteristics after telescope emission being particularly crucial. To accurately characterize the laser spot after telescope emission, a precise method for measuring laser spot characteristics is proposed. The laser is first projected onto a diffuse reflection screen at a specified distance, where a CCD camera captures the diffuse reflection image of the laser spot, while an energy meter mounted on the screen simultaneously records the laser energy in the corresponding spot region. By integrating the CCD image of the laser spot with the energy distribution in the corresponding region, the relevant characteristic parameters of the laser spot are analyzed and calculated. The paper elaborates on the measurement principle, experimental protocol, and data processing methodology, and accurately determines parameters such as the laser spot radius, divergence angle, and average energy density distribution after telescope emission using measured data. Experimental results demonstrate that this measurement method offers high measurement accuracy, rapid response, simple operation, and easy control, indicating significant application prospects in laser spot measurement.

Full Text

Research on Measurement Methods for Laser Spot Characteristics

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Abstract

In satellite laser ranging systems, the quality of the laser spot is a critical factor determining ranging success, and the characteristics of the actual laser spot emitted by the telescope are particularly important. To accurately characterize the laser spot after telescope emission, this paper proposes a precise method for measuring laser spot properties. The approach involves irradiating a diffuse reflection screen at a certain distance with the laser, using a CCD camera to capture the diffusely reflected laser spot image, and simultaneously employing an energy meter mounted on the screen to record the laser energy in the corresponding spot region. By combining the CCD image with the energy distribution data, the relevant characteristic parameters of the laser spot can be analyzed and calculated. This paper presents the measurement principle, experimental scheme, and data processing methodology in detail, and uses measured data to accurately determine parameters including the laser spot radius, divergence angle, and average energy density distribution after telescope emission. Experimental results demonstrate that this measurement method offers high precision, fast response, simple operation, and easy control, indicating significant application prospects for laser spot measurement.

Keywords: Measurement method; Laser spot; CCD imaging; Diffuse reflection; Laser spot radius; Divergence angle

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In satellite laser ranging systems, the characteristics of the emitted laser spot constitute a critical factor that determines ranging success. However, the changes in spot characteristics after the laser beam passes through the transmission system and propagates through the atmosphere remain unknown. Therefore, ground-based spot measurement experiments are necessary to obtain the relevant characteristic parameters of the emitted laser spot. These experimental data enable evaluation of whether the entire laser transmission system operates at optimal conditions and provide technical support for theoretical calculations of the number of return photons that detectors can receive.

Current laser spot measurement methods include ablation, photosensitization, scanning, CCD imaging, and array detector methods [1]. Ablation and photosensitization methods provide only qualitative measurements and cannot quantitatively determine the specific energy magnitude of the laser spot. Scanning methods are generally suitable for spot sizes on the order of micrometers or smaller and cannot accommodate larger apertures. Array detector methods represent a novel approach that can directly and meticulously measure energy values at specific spot locations, offering high signal-to-noise ratios and the ability to respond to high-speed narrow pulses. However, array detectors suffer from small acceptance angles: even slight variations in laser incidence angle cause significant changes in measured energy values, thereby affecting measurement accuracy of the laser spot intensity distribution [2]. In contrast, CCD imaging methods offer advantages of rapid response and high measurement precision for laser spot characteristic parameters. CCD cameras are compact and lightweight, easily integrated with control systems, and simple to operate. Furthermore, continuous advances in CCD technology have expanded dynamic range, improved signal-to-noise ratios, and reduced costs [3]. Considering these factors, this paper designs a laser spot measurement system based on CCD imaging that can accurately measure parameters including the laser spot radius, divergence angle, centroid distribution, and average energy density distribution after transmission through the telescope.

1. CCD Imaging Method Measurement Principle

In the CCD imaging method, materials that approximate ideal Lambertian surfaces are selected as diffuse reflection screens. After light sources undergo diffuse reflection from such materials, the spatial distribution of reflected intensity follows the cosine law. Figure 1 [Figure 1: see original paper] illustrates the diffuse reflection measurement principle for laser spots.

The incident laser irradiates the diffuse reflection screen, producing diffuse reflection. The reflected light passes through an attenuation system composed of filters and neutral density filters before entering the CCD camera for imaging. Through data connections, spot images are transmitted to the computer in real time. Simultaneously, an energy meter installed on the diffuse reflection screen transmits the collected energy from the corresponding spot region to the computer. Finally, by combining the CCD image with the energy distribution data, the laser spot characteristic parameters can be analyzed and calculated.

In CCD diffuse reflection imaging experiments for measuring spot energy spatial distribution, data must be collected for the laser spot emitted by the 1.2 m telescope, including the spot pattern on the diffuse screen and energy values recorded by the energy meter. Using the acquired CCD spot images and corresponding energy data, further analysis can calculate parameters such as laser divergence angle, spot size ω and centroid distribution, spot energy density spatial distribution, and energy transmission efficiency through the 1.2 m telescope system and atmospheric propagation.

To ensure accurate spot data acquisition, the diffuse screen must exhibit ideal or near-ideal diffuse reflection characteristics, with its reflected intensity spatial distribution satisfying the cosine law: when the angle between incident light and the screen normal is not too large, the luminous intensity of diffuse reflected light in any direction from the normal is proportional to cos [4]:

$$I_\theta = I_N \cos\theta$$

where I_N is the luminous intensity along the screen normal direction and I_θ is the luminous intensity in any direction from the normal.

This relationship indicates that the endpoint of the intensity vector traces a sphere tangent to the emitting surface, with its center on the normal line and diameter equal to I_N. The luminous intensity distribution in any cross-section through the normal is shown in Figure 2 [Figure 2: see original paper].

The luminance L_θ in any direction from the normal is:

$$L_\theta = \frac{I_\theta}{dA\cos\theta} = \frac{I_N\cos\theta}{dA\cos\theta} = \frac{I_N}{dA} = L_N = \text{constant}$$

These calculations demonstrate that an ideal diffuse reflector exhibits constant luminance in all directions. When laser light undergoes diffuse reflection from such a surface, the resulting light field distribution is deterministic. By capturing the diffusely reflected spot pattern with a CCD camera and recording the corresponding laser energy with an energy meter, the energy distribution of the emitted laser spot can be accurately measured. Common diffuse reflector materials include barium sulfate coated plates, sandblasted aluminum plates, and polytetrafluoroethylene (PTFE) plates with excellent diffuse reflection properties. After comprehensive evaluation, a custom 1.2 m PTFE-coated diffuse reflection plate with 98% reflectance was selected and verified to exhibit outstanding diffuse reflection characteristics.

For energy calibration design, after disabling the CCD camera's automatic gain control and setting a high signal-to-noise ratio, the grayscale values of captured spot images maintain a linear relationship with laser intensity [5]. Therefore, a hole matching the energy meter size was designed in the diffuse screen to accommodate the energy meter. Through USB data connection, real-time energy collection from the region corresponding to each image frame was implemented.

Additionally, designing the laser incidence at a small angle to the screen normal ensures the diffuse reflection field distribution remains unchanged while allowing the screen to be perpendicular to the CCD camera's optical axis. This configuration minimizes shape distortion and energy distortion of the imaged spot after passing through the camera lens, reducing measurement errors from subsequent image processing and improving measurement accuracy.

2. Diffuse Reflection Measurement System

The laser spot measurement system consists of a laser emission device, spot measurement apparatus, and post-processing image analysis system. The emission device comprises a high-energy solid-state laser, collimating and beam-expanding optics, and a 1.2 m emission telescope. The performance parameters of the solid-state laser and optical parameters of the emission telescope are listed in Table 1 and Table 2 [6].

Table 1. High-energy solid-state laser parameters

Parameter	Value
Wavelength	532 nm
Frequency	10 Hz
Pulse width	10 ns
Power	3.2 J
Divergence angle	0.5 mrad
Spot radius	5 mm

Table 2. Optical parameters of 1.2 m telescope

Parameter	Value
Primary mirror effective diameter	1200 mm
Primary mirror focal length	-7.5×
Secondary mirror effective diameter	400 mm
Secondary mirror focal length	-
Magnification	14.15%
Shielded ratio	-

The laser undergoes primary expansion through the collimating optics, followed by secondary expansion through the telescope's primary and secondary mirrors before emission. The diffuse screen reflects the laser to the CCD camera lens while the energy meter simultaneously collects energy from the corresponding spot region. The complete laser spot measurement apparatus comprises the diffuse reflection screen, energy meter, camera lens, CCD camera, tripod, filters, neutral density filters, and data processing computer. The structural schematic is shown in Figure 3 [Figure 3: see original paper].

The diffuse reflection screen reflects the emitted laser and ensures the diffuse light field approximately satisfies the cosine law. Constructed from PTFE plate as a near-ideal diffuse reflector, it achieves 98% diffuse reflectance. The energy meter collects real-time energy values from corresponding spot regions to calibrate grayscale values in spot images. It operates at wavelengths from 0.19 m to 12 m, measures energies from 12 J to 20 mJ, withstands maximum average power of 4 W, maximum energy density of 500 mJ/cm^2 (10 ns, 532 nm), and features a 10 mm diameter detector surface. The camera lens focuses light onto the CCD sensor for clear spot imaging, using a standard C-mount with manually adjustable focal length from 8 mm to 28 mm. The CCD camera receives focused spot images and transmits them via USB to the computer. The camera used in this experiment features a 2/3" sensor with 1936$×$1456 resolution, 14-bit AD conversion, progressive scanning, and maximum frame rate of 40 fps. The filter is an absorptive type centered at 532 nm with 20 nm bandwidth to remove stray light at other wavelengths. Neutral density filters with different attenuation factors are combined to attenuate the intense laser after filtering, preventing excessive light intensity that would cause CCD saturation.

3. Laser Spot Data Acquisition and Analysis Processing

The designed laser spot measurement system was used to collect data for the laser spot emitted by the 1.2 m telescope. Through corresponding image processing software, relevant characteristic parameters were obtained, including laser spot size ω, energy density distribution, divergence angle, and energy transmission efficiency.

Since laser beams are affected by atmospheric turbulence during propagation, particularly noticeable near the ground, phenomena such as beam expansion, spot jitter, and centroid separation occur, resulting in irregular spot shapes with distinct bright and dark regions. These effects significantly impact measurement of laser spot characteristic information [7]. Therefore, preprocessing of collected spot data is required before analysis, including removal of image background noise, to ensure accurate reflection of spot characteristic parameters [8].

3.1 Measurement Data Processing Methods

(1) Spot intensity spatial distribution

The spatial distribution of spot intensity is determined by the light intensity corresponding to all pixel grayscale values. Let the spot intensity corresponding to the grayscale value of the nth detection region at time t be:

$$I_n(r) = K[G_n(r) - \langle G_n \rangle]$$

where $G_n(r)$ is the instantaneous grayscale value corresponding to the spot intensity in the nth region of frame r, $\langle G_n \rangle$ is the average background grayscale value of the nth region, $G_n(m)$ is the instantaneous grayscale value of frame m without laser illumination, and K is the calibration coefficient converting real-time energy values recorded by the energy meter to pixel grayscale values.

(2) Spot centroid position

Due to atmospheric turbulence effects, actual spots experience expansion, beam jitter, and centroid separation. The geometric center is not the intensity center (centroid) of the spot, requiring centroid calculation. The entire spot image is divided into coordinate regions corresponding to the energy meter size, with grayscale values in each region accumulated accordingly. The centroid is then:

$$X = \frac{\sum_i I_i \cdot x_i}{\sum_i I_i}, \quad Y = \frac{\sum_i I_i \cdot y_i}{\sum_i I_i}$$

where (X, Y) is the spot centroid, (x_i, y_i) are coordinates of corresponding regions, and I_i are grayscale values of corresponding regions.

(3) Spot radius ω

Assuming a circular spot shape, the spot radius ω is defined using isointensity contours to partition the intensity distribution plane. The radius ω corresponds to the spot size when intensity decreases to $1/e^2$ of the central intensity. For a spot with radius ω, let the encircled power be P_ω and the total power on the image plane be P. Through calculation [5]:

$$\frac{P_\omega}{P} = 1 - e^{-2\omega^2/\omega_0^2} = 0.865$$

The spot radius ω is then:

$$\omega = \sqrt{\frac{\sum_i I_i[(x_i - X)^2 + (y_i - Y)^2]}{\sum_i I_i}}$$

where (x_i, y_i) are coordinates of corresponding regions, (X, Y) is the spot centroid, and I_i are grayscale values of corresponding regions.

(4) Laser divergence angle

$$\theta_{\text{mea}} = \frac{\omega - \omega_{\text{telescope}}}{L}$$

where ω is the measured spot radius, $\omega_{\text{telescope}}$ is the spot radius at the telescope aperture, and L is the laser propagation distance.

Due to atmospheric turbulence, the actual spot experiences expansion and beam jitter. From a microscopic perspective, atmospheric turbulence can be modeled as numerous prisms with coherence length r_0 along the propagation path, causing beam diffraction and expansion. The angular radius of beam expansion is [5]:

$$\sigma = \frac{2.1\lambda}{r_0}$$

where λ is the laser wavelength and r_0 is the atmospheric coherence length. At the Yunnan Observatory site, the atmospheric coherence length is approximately 10 cm. Considering near-ground slant propagation where turbulence is more severe due to temperature effects than vertical transmission, the coherence length is approximately 8 cm [9][10].

Therefore, the theoretical divergence angle measured during atmospheric propagation is:

$$\theta_{\text{theo}} = \sqrt{\theta_{\text{emit}}^2 + \sigma^2}$$

where θ_{theo} is the theoretical divergence angle after atmospheric turbulence and θ_{emit} is the divergence angle emitted by the telescope.

(5) Average power density

$$I_{\text{ave}} = \frac{P_\omega}{\pi\omega^2}$$

where P_ω is the actual energy enclosed within spot radius ω.

(6) Transmission efficiency

$$\eta = \frac{P_\omega}{P_{\text{laser}}}$$

where P_ω is the actual energy enclosed within spot radius ω and P_{laser} is the laser output energy.

3.2 Energy Coefficient Calibration

After disabling the CCD camera's automatic gain control and setting the γ correction to 1, the measured spot image grayscale values maintain a linear relationship with spot intensity [11]. An energy meter with 10 mm aperture was installed on the diffuse screen to collect real-time energy from the image region corresponding to the energy meter. Based on the imaging relationship, the image of the 10 mm aperture consists of multiple pixels. Using the energy meter's pixel count as a reference, the entire spot image is divided into pixel regions. Since all pixels in the energy meter's image region appear completely black, the sum of grayscale values from pixels with equal encircled area is equated to the sum of grayscale values from the energy meter region [12], as shown in Figure 4 [Figure 4: see original paper].

$$n = \frac{l_{\text{aper}}^2}{l_{\text{pic}}^2} = \frac{l_{\text{aper}}^2}{(\beta d)^2} = \frac{l_{\text{aper}}^2 {f'}^2}{d^2 L^2}$$

where f' is the CCD camera focal length, L is the object distance from diffuse screen to camera, d is the pixel size, and l_{aper} is the energy meter aperture.

By selecting appropriate f' and object distance L, and knowing pixel size d and energy meter aperture l_{aper}, the number of pixels n corresponding to the 10 mm energy meter aperture can be determined. This serves as the reference for dividing the spot image into N regions. Using the sum of grayscale values from equal-area pixels to represent the energy meter region's grayscale sum enables energy calibration for the other N-1 regions.

Twenty sets of energy meter readings and corresponding equivalent grayscale sums from the energy meter image region were collected and averaged to obtain the calibration coefficient K.

3.3 Experimental Data Processing

The designed laser spot measurement system was used to characterize the spot emitted by the 1.2 m telescope. With telescope aperture D = 1.2 m (parameters in Table 1), propagation distance L = 202 m, maximum laser pulse energy = 3.2 J (parameters in Table 2), CCD exposure time = 50 ms, acquisition frequency = 20 Hz, and acquisition duration = 125 s, 2500 frames were collected. The raw image is shown in Figure 5 [Figure 5: see original paper].

Using equations (3)-(13), the collected spot images were analyzed with software. Figure 6 [Figure 6: see original paper] shows the processed spot image, Figure 7 [Figure 7: see original paper] displays the successfully processed spot data, Figure 8 [Figure 8: see original paper] presents the three-dimensional energy density distribution from telescope center to edge, and Figure 9 [Figure 9: see original paper] shows the normalized grayscale value map of energy density distribution with the image's upper-left corner as the origin.

Figure 5 shows the original emitted laser spot image. Due to obstruction by the telescope's secondary mirror and trees during propagation, the central region and partial edges of the laser spot are missing. The black dot above the central region in Figure 5 indicates the energy meter installation position. Figure 6 shows grayscale images before and after background noise removal in MATLAB. Figure 7 displays the spot centroid processed according to equations (5)-(6). Using equations (7)-(14) in MATLAB, the spot diameter was calculated as 974 mm with total spot energy of 12.506 J. This yields a spot radius ω of 487 mm, theoretical divergence angle θ_{theo} of approximately 3.96“, measured divergence angle θ_{mea} of about 3.12”, average energy density distribution I_{ave} of 1.6796 mJ/cm^2, average power density distribution of 11.0467 W/cm^2, and laser energy transmission efficiency of 37.6%. Figure 8 shows the three-dimensional energy density distribution from spot center to edge, where the central portion is nearly zero due to secondary mirror obstruction. Figure 9 shows the normalized grayscale map of energy density distribution from the image origin (upper-left corner) to the spot edge. The grayscale curve changes steeply around 500 mm from the origin because this region corresponds to the telescope secondary mirror obstruction, making grayscale values nearly black.

Throughout the measurement process, various experimental errors affect final accuracy. Error sources include: measurement apparatus errors, insufficient measurement precision of atmospheric coherence length r_0 due to poor seeing conditions during field tests, and errors from digital image processing including background light filtering and grayscale value classification.

The experimental results demonstrate that the diffuse reflection CCD imaging method for measuring laser spot characteristic parameters is feasible, offering high measurement precision and fast response. This method accurately measured the spot characteristics of the laser emitted by the 1.2 m telescope at Yunnan Observatory, including energy density spatial distribution, spot size ω, divergence angle, energy transmission efficiency , and average power density distribution. The measured spot data confirm normal operation of the laser ranging system, providing a technical foundation for successful lunar laser ranging experiments at Yunnan Observatory. Additionally, this laser spot characterization method offers detection technical support for subsequent improvements to the laser transmission system or divergence angle compression, enabling the laser ranging system to detect space targets at greater distances and smaller sizes.

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