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Analysis of influential factors on a space target's laser radar cross-section

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ABSTRACT

This paper utilises the idea of theoretical analysis to introduce a fast and visual laser radar cross-section (LRCS) calculation method for space targets that is implemented with OpenGL. We chose the cube, cylinder and cone as targets based on the general characteristics of satellite shapes. The four-parameter mono-station BRDF is used, and we assume the surface materials are either purely diffuse, purely specular or mixed. The degree of influence on a target's total LRCS of the target's shape and size and the surface materials' BRDF are described. We describe the general laws governing influential factors by comparing simulated results. These conclusions can provide a reference for new research directions and methods to determine a target's laser scattering characteristics.

1. Introduction

Laser scattering characteristics are one of the most important optical scattering properties of space targets. These properties have played an important role in the design, demonstration and performance evaluation of ground-based or space-based laser active detection systems [1]. Calculations of LRCS (laser radar cross-section) can synthetically reflect a target's laser scattering characteristics, which are produced by such factors as the surface material and coarseness, the geometrical structure, and the shape. LRCS is one of the most important indices to measure laser scattering characteristics for quantitative analysis, and it directly impacts the maximum operational range of detection systems such as laser rangefinders, laser guidance systems, laser radar and laser active imaging systems [2–4]. LRCS embodies the target's scattering characteristics at the given laser wavelength and incident direction, and it has no relationship to the specific laser measurement system in use. An estimation of a space target's LRCS and an analysis of influential factors are also very important for the design and realisation of a target's laser stealth capability [5]. This paper is geared only toward the instance of single-station detection, namely, it considers only the laser backscattering condition, and the use of the word “LRCS” refers to single-station LRCS and is denoted by σ in equations with units of m^2.

Actual space targets are complicated due to factors such as complex geometrical structures, the variety of target surface materials, and the different scattering characteristics of various materials. In previous studies, researchers have usually regarded a satellite's surface materials as diffuse Lambert surfaces [6]. This method is simple and convenient, but it is quite different from the actual situation. Subsequent researchers have gradually begun to utilise the bi-directional reflectance distribution function (BRDF), which is more accurate than the diffuse reflectance method [7–9]. The BRDF is a fundamental radiometric concept, and it captures all the detailed scattering physics for how light interacts with a surface. The method gives the reflectance of a target as a function of illumination geometry and viewing geometry. The BRDF is determined by the structural and optical properties of the surface such as shadow-casting, multiple scattering, mutual shadowing, transmission, reflection by surface elements, facet orientation distribution and facet density. Accordingly, BRDF is used widely in remote sensing, computer graphics (for photorealistic rendering of synthetic scenes), and signature simulations to accurately characterise the optical effects of surface treatments on targets.

Some agencies and companies were early developers of deep research into optical scattering characteristics of space targets. These works are outstanding and helpful, but the calculation method is far from convenient and the calculation time is long. In addition, it is difficult to quickly and accurately uncover the factors that influence different targets' LRCS and how widely they can vary.

OpenGL is one of the best development environments for 2D and 3D graphics applications. It has a large number of applications in the fields of visual simulation and computing.

In this work, we deduce the LRCS expression and utilise OpenGL to accomplish complicated calculation work, including

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geometry transformations, shading judgments and the display of complex targets; this approach greatly improves the calculation speed. The time to calculate a complex target's LRCS once is less than 0.05 s, and the simulation results have been verified as credible and accurate. The quantitative conclusions about which factors influence a space targets' LRCS, which were obtained by the validated method, will be helpful both to realise laser stealth in targets and to identify space targets.

2. LRCS calculation method based on OpenGL

2.1. Fast calculation method

The geometry relationship of single-station detection is shown in Fig. 1. We assume that the target surfaces are composed of a large number of tiny plate surfaces. The BRDF of the surface element dA is defined as f_r, and $\vec{n}$ is the unit normal vector of dA. The direction of the incident laser $\vec{I}$ is collinear with the detector direction $\vec{S}$. The angle between $\vec{n}$ and $\vec{S}$ is the laser incidence angle θ.

This paper gives consideration to both engineering applications and scientific research, and based on the existing information about types, features and characteristics of satellite surface materials, we at last adopted the following expression for the four-parameter mono-station BRDF, which was put forward by Ove Steinvall [10]:

$$f_r = f_{spec} + f_{diff} = [A/\cos^6(\theta)]\exp(-\tan^2(\theta)/s^2) + B\cos^m(\theta) \quad (1)$$

This model contains both specular and diffuse components. In the expression, m represents the diffusivity coefficient, s is the surface slope, and the relation A/B indicates the ratio of surface glint to diffuse behaviour. It has been shown that many different types of surfaces can be fitted by the above expression [11].

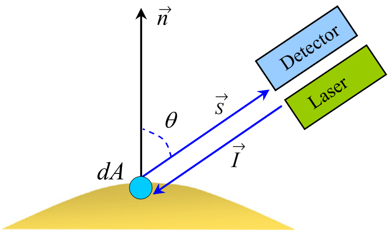

Fig. 1. The geometric relationship between laser radar and the target surface element dA.

In practical applications, the BRDF data of typical satellite materials vs. laser wavelength can be gained through experimental measurement [12,13], and the BRDF model parameters can then be detailed by empirical or semi-empirical statistical methods and the variation laws of a target's LRCS can be analysed and investigated.

The general relationship between the target's mono-station LRCS and its BRDF [14] is

$$\sigma = \int_A d\sigma = 4\pi \int_A f_r(\theta)\cos^2\theta dA \quad (2)$$

where dA represents a facet element of the target surface and θ represents the laser incidence angle of the facet dA. In principle, the LRCS for various shapes and sizes of targets can be calculated based on a BRDF database of detailed target surface materials.

This paper puts forward a fast and visual calculation method to determine a complex space target's LRCS based on OpenGL and 3ds target model files; the calculation process is shown in Fig. 2. OpenGL is one of the best development environments for the development of 2D and 3D graphics applications and has a large number of applications in the field of visual simulation and computation [15].

The calculation process is described in detail in what follows.

We utilise 3D modelling software to establish the 3ds files of target 3D models, which contain materials information, and we use different combinations of RGB colours to represent different materials. Through a programme, we read and draw the 3ds model file into OpenGL.

To facilitate the description and calculation of the target's attitude, we establish the coordinate systems as shown in Fig. 3. Fig. 3(a) shows the initial state of the satellite. The observation coordinate system o-xyz is initially coincident with the target body's coordinate system o-$x'y'z'$; the z-axis points to the laser and detector, the x-axis is coincident with the rotation axis of the solar

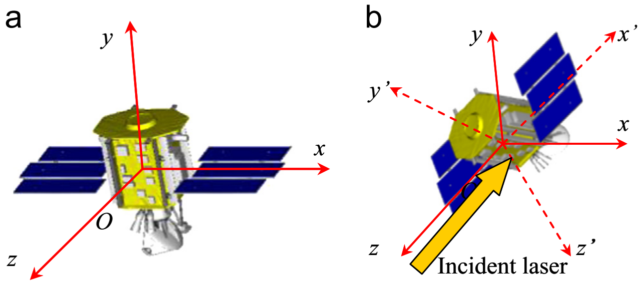

Fig. 3. Illustration of the coordinate systems and corresponding angles.

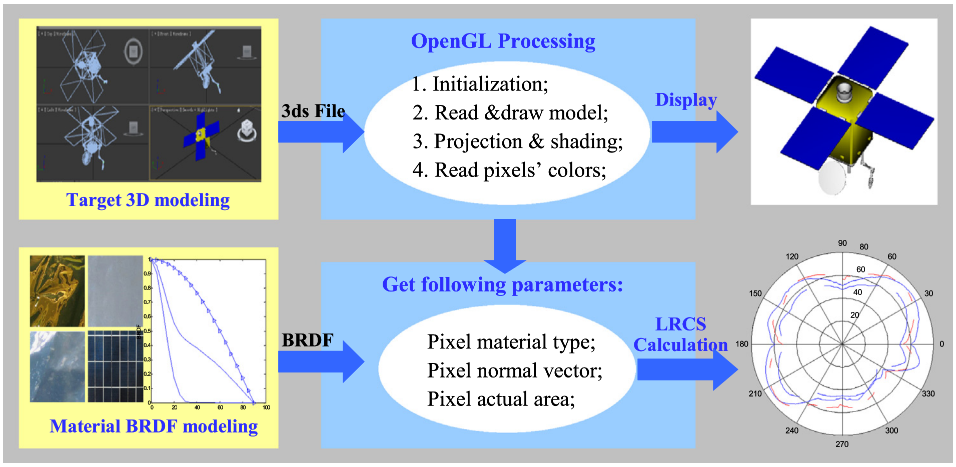

Fig. 2. Illustration of the process of calculating the complex space target's LRCS.