Research on Starlight Simulation Technology in Near Space

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ABSTRACT

Near space is currently a popular area for space research. The study of scientific laws in this region, especially environmental changes and their impact on nearby spacecraft, has become the focus of national attention. Although there are more and more studies on near space, there are few studies on the simulation of ambient light environment in near space. Near-space starlight simulation technology is a technology to simulate and study the observation characteristics and background light radiation characteristics of starlight targets, which is of great significance for the astronomical navigation and control of near-space vehicles. Therefore, this paper proposes the technical research of near-space starlight target simulation, and proposes a feasible starlight simulation scheme and an off-axis three-mirror optical system suitable for starlight simulation system. Based on the principle of spectral aliasing, the characteristics of starlight light source and background light source with different color temperatures are simulated by superimposing a continuum base light source and different color LED light sources, and then the spectrum to be simulated is generated through the combination of various systems. The system includes a starlight source and a multispectral light source simulation system (used to simulate stellar light and atmospheric background light respectively); off-axis triple inverted collimator (simulating starlight from infinity); and beam combiners (which inject starlight and background beams into the system under test).

Keywords: Near space, starlight simulation, off-axis triple reflection, spectral simulation.

1. INTRODUCTION

Near-space is also known as "near-space", "suborbital", and "space-space transition zone". In the United States, it is called the "transverse zone", while in China, it is called "middle atmosphere", "subspace", "ultra-high altitude", "high altitude" and other names [1][2], which refers to the Earth's atmosphere at an altitude of 20 to 100 km above the ground. As shown in Figure.1, it straddles the non-ionosphere and the ionosphere, the air is thin, there are special environments such as ozone, ultraviolet, and radiation, and the temperature changes with altitude, and there are special phenomena such as gravitational waves, planetary waves, and atmospheric discharges [3]. Because of its unique space environment, it has become a new field for human beings to understand the earth's space.

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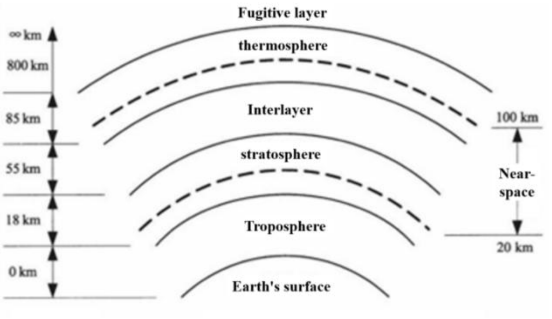

Figure.1 Concept map of near-space

Although there are more and more studies on near-space, most of the studies only study the atmospheric environment of near-space and simulate the atmospheric environment data of near-space based on existing software, and there are few studies on the simulation of near-space light environment. The near-space starlight target simulation technology proposed in this paper refers to the technology for simulating and studying the observation characteristics of starlight targets (such as stars, atmospheric radiation starlight, etc.) in the upper layer of the Earth's atmosphere, that is, near space (usually the area between 20 km and 100 km above the ground). This technology is of great significance in the fields of astronomical observation, satellite navigation, space weather forecasting, spacecraft navigation and control. Environmental simulation is a state in which the specific environmental conditions in the cabin are changed to achieve the corresponding test purpose, and the common environmental conditions mainly include temperature, pressure, and humidity, in addition to some special types of equipment, it is also necessary to simulate extreme environments such as solar radiation, rain, dust, and salt spray [4]. This article discusses the simulation of the light environment, including the brightness of the background, spectral characteristics, starlight radiation characteristics, etc.

Spectral simulation technology is the core of starlight simulation technology. At the beginning of the 20th century, the US National Bureau of Standards and Metrology developed a DMD-based spectrally tunable light source, the structure of which is shown in Figure.2 [5]. The light source uses an integrating rod for light leveling, and the output irradiation uniformity is good, which can realize the accurate spectral simulation of multi-dimensional radiation scenes. Immediately afterwards, foreign scholars have proposed light source simulation systems such as LED spectral tunable light source. However, the research on spectral simulation technology in China is relatively late. It was not until 2008 that Chen Feng et al., Anhui Institute of Optics and Fine Mechanics, Chinese Academy of Sciences, proposed a design scheme for a spectrally tunable light source [6], the composition of which is shown in Figure.3. In 2015, Li Xiaoni from the Xi'an Institute of Optics and Mechanics of the Chinese Academy of Sciences designed an automatic calibration spectral tunable star simulator light source system, as shown in Figure.4 [7]. The system uses white LEDs as the base light source and uses a variety of narrow-band LEDs with different peak wavelengths to compensate for the target spectrum. The spectral simulation range is 400nm-900nm, the color temperature simulation range is 3900K-6500K, and the color temperature simulation error is better than 15%. Subsequently, the spectral simulation technology proposed by Chinese scholars began to be applied to light source simulators such as star simulators.

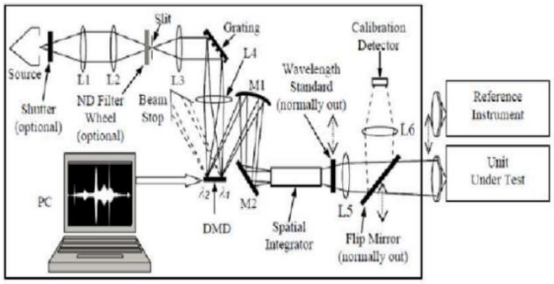

Figure.2 Spectrally tunable light source structure diagram [5]

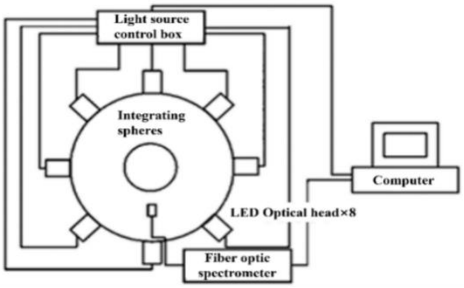

Figure.3 Composition structure diagram of LED spectral distribution adjustable light source[6]

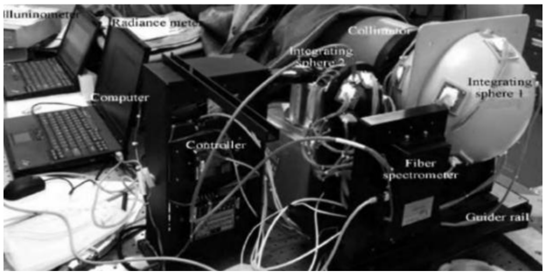

Figure.4 Automatic Calibration Tunable Star Simulator Light Source System[7]

According to the research of spectral simulation technology by scholars at home and abroad, at present, in the research of spectral simulation technology, the main light sources used are xenon integrating sphere light source, LED integrating sphere light source and spectral tunable light source.

1)Integrating sphere light sources such as xenon lamps and halogen lamps

The integrating sphere light source such as xenon lamp is based on xenon lamp, etc., and the spectrum is simulated through the filter, and the integrating sphere is used to mix and homogenize the light. The principle is to use a narrow-band filter to differentially divide the broad spectrum into multiple bands, and to simulate the target spectrum through the filter attenuation.

2)LED integrating sphere light source

The LED integrating sphere light source uses the monochromaticity of LED and the characteristics of controllable light intensity, selects a large number of LEDs, simulates the target spectrum through the spectral matching algorithm, and finally uses the integrating sphere to mix and homogenize the light. The LED integrating sphere light source has the advantages of good output spectral uniformity and high irradiation intensity, and the spectral simulation accuracy is generally better than 20%.

3)Spectral tunable light source

The spectral tunable light source is mainly composed of a beam splitter prism and a space light modulation device, the prism is the function of the spectrometer, and the space modulator is the modulation spectrum, and the two cooperate to simulate the target spectrum. This kind of spectral simulation method has the advantages of small size, controllable light source distribution and high spectral simulation accuracy.

In this paper, we propose to simulate the starlight transmission and complex background light environment in near space on the ground, aiming to provide close to the actual target characteristics and background characteristics for the optoelectronic system operating in the near space range. Conducting relevant research on the ground simulating the starlight environment of near space can eliminate the need to launch sounding rockets, sounding balloons, aircraft and other detection equipment, which greatly saves resources and research costs. Therefore, the research on simulating starlight radiation and background light environment in near space is of great significance, which can greatly promote the development of optoelectronic instruments in near space.

2. THEORETICAL PLAN

2.1 Spectral simulation principle

The main principle of this scheme is based on the least squares method, based on the halogen light source, using a variety of monochromatic narrowband LED light sources, through the integrating sphere to form a spectral energy distribution of different color temperatures and different magnitudes. The automatic calculation of parameters under different color temperatures and magnitudes is realized by software control, and the luminescence control of the final LED light source is realized by digital dimming. The combination of monochromatic light with different wavelengths and different intensities is used to superimpose the blackbody radiation curve with a synthetic spectrum close to the same color temperature to realize the transformation of star magnitude.

Taking the spectral energy distribution at a color temperature of 4800K as an example, it can be seen as the result of the superposition of an infinite number of sufficiently narrow spectral energies, so from the perspective of the mathematical model, the superposition of an infinite number of monochromatic light sources can be used to simulate the required spectral energy distribution. However, in reality, it is not possible to obtain enough monochromatic light sources with sufficient brightness to simulate the spectral distribution of high-precision multi-color temperature and multi-magnitude, considering that the point simulation error of spectral energy distribution is not more than 15%, so it is possible to use xenon light sources as the basis, and multiple monochromatic LED light sources with narrow spectral distribution can be used as the basis to compensate and then superimpose to obtain the required target spectrum.

The spectral distribution of LED light sources is different from that of typical light sources, and the typical monochromatic LED light output is a narrow-band spectrum with a full width at half maximum typically between 20nm and 40nm. According to the physical characteristics of the LED light source, the distribution of the radiant power in the unit solid angle of the monochromatic LED light source with the spectrum (i.e., the radiance intensity) in the direction of its optical axis can be approximated as the Gaussian distribution function [8] , and its specific relationship is shown in Eq. (2.1) and (2.2):

$$L(\lambda) = \alpha \cdot \exp\left[\frac{-(\lambda - \lambda_p)^2}{2\mathrm{w}^2}\right] \quad (1)$$

$$W_{FWHM} = 2\mathrm{w}\sqrt{\ln 4} \quad (2)$$

λ_p is the peak wavelength of the LED light source, α is the scale factor, and W_{FWHM} is the half-peak width of the spectral distribution of the LED radiant intensity, and the spectral distribution curve is shown in Figure.5 (the half-peak width is 25nm).

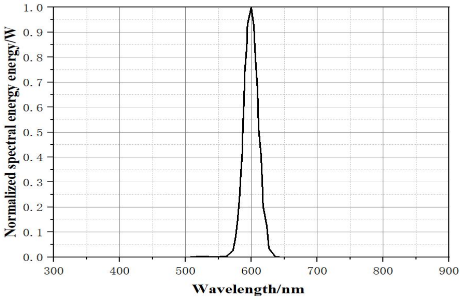

Figure.5 Spectral energy distribution diagram of Gaussian ideal LED light source

Spectral energy distribution diagram of Gaussian ideal LED light source. For example, to obtain a spectrum with a wide spectral range of 500nm~1000nm, the joint action of each different peak wavelength LED in the range of 450nm~1050nm is required.

The synthesis of the target spectrum is based on the principle of spectral superposition [9], according to which the basic mathematical model of spectral synthesis of multiple bands can be established, as shown in Eq. (2.3):

$$L\overset{\Lambda}{(\lambda)} = \sum k_i L_i(\lambda) \tag{3}$$

$L\overset{\Lambda}{(\lambda)}$ is the fitting target spectrum, k_i is the weight coefficient of each band spectrum, and $L_i(\lambda)$ is the radiation distribution function of a single band spectrum.

The target spectrum is continuously changing, but the fitting target spectrum is composed of multiple discrete spectra and is not continuous, so the fitting target spectral data is discretized, and multiple discrete spectra are used instead of the fitting target spectrum [10]. Assuming that the target spectral data set is $\{\lambda_i, y_i\}(i=1,2,3,...m)\,y_i$ the spectral energy distribution corresponding to wavelength λ_i, the discrete data function fitting the target spectrum can be expressed as:

$$f(\lambda) = k_1L_1(\lambda) + k_2L_2(\lambda) + k_3L_3(\lambda) + ... + k_nL_n(\lambda) \tag{4}$$

Where the weight coefficient k determines the spectral simulation accuracy.

Equation (2.3) is expressed as a matrix such that $A=[L_1, L_2, L_3 \cdots L_n]$, L_n is denoted as:

$$\vec{L}_1 = \begin{bmatrix} L_1(\lambda_1) \\ L_1(\lambda_2) \\ \vdots \\ L_1(\lambda_n) \end{bmatrix} \tag{5}$$

Let vectors b and X respectively:

$$b = \begin{bmatrix} y_1 & y_2 & y_3 & \cdots & y_m \end{bmatrix}^T \tag{6}$$

$$X = \begin{bmatrix} k_1 \\ k_2 \\ \vdots \\ k_n \end{bmatrix} \tag{7}$$

When m>n, we can get a system of supered finite equations about A、b、X, as shown in equation (2.8):

$$AX=b \tag{8}$$

For a system of supered finite equations, there is no exact solution, only an approximate solution [11] can be found, as shown in equation (2.9):

$$r = b - AX \tag{9}$$

Equation (2.9) is solved, and when the bi norm reaches the minimum [12] , the overall error of the overdetermined equation system in Equation (2.10) is minimal:

$$\left\| b - AX^* \right\|_2 = \min_{X \in R^m} \left\| b - AX \right\|_2 \tag{10}$$

In an application, the scale factor k_i can only be taken as a non-negative value, so by solving only the non-negative least squares solution of the supered finite linear equation X^* [13] , the fit target spectrum L can be obtained as:

$$L = \hat{A} X^* \tag{11}$$

According to Eq. (2.11), the simulation of the target spectrum can be realized by adjusting the weight coefficient of each band spectrum by using the principle of spectral superposition.

2.2 The basic working principle of the starlight simulation system

The core of near-space starlight simulation technology is the simulation of spectrum, through the understanding of the previous research on spectral simulation technology, this scheme proposes to use halogen lamp as the base light source, combined with multiple single-wavelength LED light sources in the integrating sphere for light mixing, and then realize the simulation of spectrum. The basic working principle of this solution is described as follows.

The schematic diagram of the overall scheme of the starlight simulation system is shown in Figure.6, which is composed of: stellar light source system, multispectral light source system, optical system, beam combiner system, and tested system. The basic working principle is as follows: the light emitted by the starlight source system generates parallel light from infinity through the off-axis optical system, and the background light emitted by the multispectral light source system is combined together under the action of the semi transparent and semi reflective mirror to enter the star sensor and other measured systems for subsequent measurement and research.

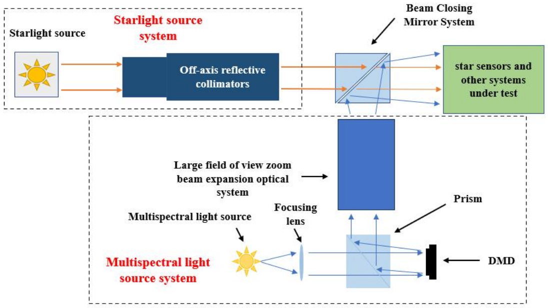

Figure.6 Schematic diagram of the starlight simulation system

2.2.1 Principles of stellar light source simulation system

The schematic diagram of the stellar light source system scheme is shown in Figure.7, which includes an integrating spherical shell, a variable diaphragm, a halogen lamp (1 x 150W, including a cooling fan), an LED (e.g., 420nm, 530nm, 660nm, 740nm, 1200nm, 1550nm, including a cooling fan), an aperture control module (including a controller and a driver card), a single-wavelength light source control box, a single-wavelength light source, an optical fiber, a halogen lamp power supply, and an industrial computer (including a display with built-in control software). The basic working principle is as follows: the industrial computer controls the brightness and darkness of the LED lamp and halogen lamp, and the opening percentage of the diaphragm reaches the energy of each light entering the integrating sphere, and then the integrating sphere conducts light uniformization, and the light generated by the required energy is transmitted to the optical system through the optical fiber.

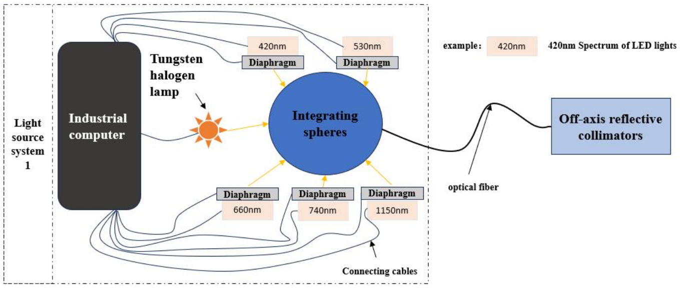

Figure.7 Schematic diagram of a stellar light source system

2.2.2 Principle of off-axis reflective optical system

An off-axis reflective collimator is shown in Figure.8 and consists of three mirrors, a primary, secondary, and triple mirror. It reflects the light entering the fiber multiple times and then emits a parallel beam into the beam mirror system. A beam mirror system is a half transmitted and half reflected mirror that combines stellar light and background light into the system under test.

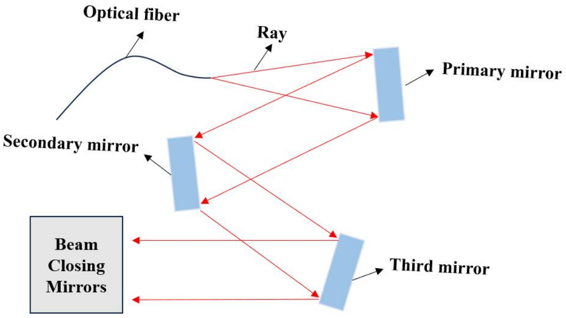

Figure.8 Schematic diagram of the optical system

2.2.3 Principle of background light source simulation system

The multispectral light source system is composed of a multispectral light source and a DMD light modulator, and the light emitted by the multispectral light source from the background spectrum enters the beam expansion system to increase the field of view after DMD modulation, and then enters the beam combiner system.

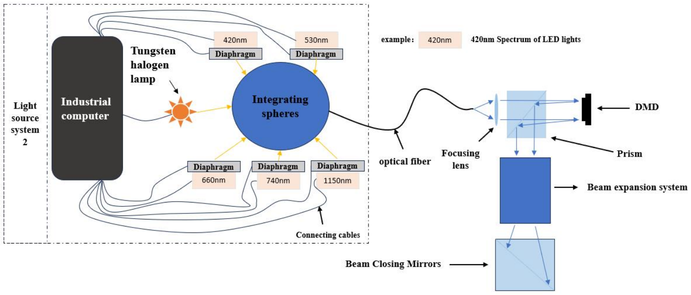

Figure.9 Schematic diagram of the background light system

3. CONCLUSION

Adjacent space is a popular area for space research. The study of the scientific laws of this region has become the focus of attention of all countries, especially the environment, changes and their impact on near-space vehicles, which has ushered in an unprecedented upsurge in the observation and research of near-space. The technology of simulating and studying the observation characteristics of starlight targets (such as stars, atmospheric radiation starlight, etc.) is of great significance for astronomical observation, satellite navigation, space weather forecasting, spacecraft navigation and control, and other fields. Therefore, this paper proposes the research on the simulation technology of starlight targets in near space, and proposes a feasible starlight simulation scheme and an off-axis three-mirror optical system suitable for the starlight simulation system.

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