doi:10.3788/gzxb20164512.1222002

具有均匀天空背景的高精度静态星模拟器设计

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摘　要:为解决现有星模拟器只关注星图模拟精度而忽略天空背景模拟的问题,设计了具有均匀天空背景的高精度静态星模拟器.重点阐述星模拟器的组成和工作原理,详细论述光学系统优化设计方法.根据模拟器光学系统透镜大、精度高的特点,采用筒套筒的镜筒设计形式;为了保证星图模拟精度,采用激光直写技术制作星点板,刻划精度优于±1 μm.测试结果表明:设计的具有均匀天空背景的高精度静态星模拟器的星图模拟精度优于3″,天空背景均匀性优于95%,满足导航敏感器的高精度地面标定与功能测试需求.

关键词:光学设计;静态星模拟器;高精度;星图模拟;天空背景模拟

中图分类号:V524.2　　**文献标识码**:A　　**文章编号**:1004-4213(2016)12-1222002-5

Design of High-precision Static Star Simulator with Uniform Sky Background

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Abstract: To solve the problem that the existing star simulators are only concerned with the precision of star map simulation while neglects the sky background simulation, a high-precision static star simulator was designed under a uniform background of sky. In this paper, the components and operating principles of the star simulator were elaborated emphatically, and the optimal design method was also discussed in detail for the optical system. According to simulator's optical system which was featured with big lens and high precisions, the lens cone was designed to have a fixed, tube-in-tube structure. Moreover, in order to guarantee the precision of star map simulation, the laser direct writing technology was adopted to fabricate star testers with a precision exceeding ±1 μm. Test results indicated that the star map simulation precision of the designed high-precision static star simulator with a uniform sky background is greater than 3″and the sky background uniformity is larger than 95%. Therefore, it is able to satisfy requirements of high-precision ground calibration and functional test for navigation sensors.

Key words: Optical design; Static star simulator; High-precision; Star map simulation; Sky background simulation

OCIS Codes: 220.0220; 220.4840; 220.4830; 120.4570; 120.4640

0 Introduction

With the rapid development of Chinese space technology in recent years, higher requirements have been proposed for attitude measurement accuracy of satellite[1-2]. Considering that such an attitude

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Foundation item: The National Science and Technology Special Public Industry (Nos. GYHY200706003, GYHY201006043), the Project Development Plan of Science and Technology in Jilin Province (Nos. 20150520093JH, 20160204008GX)

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Received: Aug. 1, 2016; **Accepted**: Oct. 10, 2016

measurement is fulfilled by star sensors, measurement requirements for such sensors become increasingly high[3]. Hence, a ground calibration system which can be used to realize the high-precision calibration and the functional test is in urgent need[4-5].

As an important component of star sensor ground calibration system, star simulator is developed from low precision and large mass to high precision and light weight; moreover, it is growing toward a high-precision, high-dynamic and miniaturization trend. According to different display modes of star maps, they are divided into dynamic and static, star simulators[6]. While the latter has been widely applied into ground calibration experiments of star sensors dependent on its smaller volume and weight as well as higher star map simulation accuracy[7]. Concerning the existing static star simulators, field of view is able to reach 1°～28° and spectrum simulation range can cover ultraviolet, visible and infrared bands in line with various operating requirements[8-9]. In addition, star map simulation precision can simulate 5 to 10 grades of star magnitudes ranging from 1″ to 20″ in accordance with field angle requirements of a single star. However, sky background which serves as important star map simulation information has been missed. During actual in-orbit operation, the sky background information is one of the influencing factors on the precision of navigation star sensors[10].

In this paper, dependent on actual engineering requirements for ground calibration of navigation star sensors, a high-precision static star simulator is designed with a background of sky. Such a star simulator is able to simulate sky background images and star map images according to operating requirements and then output them after stacking and imaging. As a result, both detection and calibration precisions of star sensors are improved.

1 Compositions and operating principle of star simulators

A static star simulator with sky background is mainly constituted by light source of fixed star, star tester, light source of sky background, background plate, collimating optical system, beam splitter prism and electrical control system. Its compositions and operating principle have been demonstrated in Fig. 1.

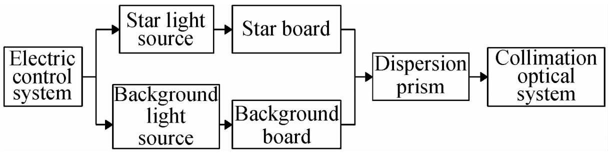

Fig. 1 System principle of star simulator

Collimating optical system and beam splitter prism are designed to realize the stack imaging of fixed star images and background images. In detail, fixed star images are placed in reflected light path of beam splitter prism and the star tester is located at focal plane of the collimating optical system. Subsequently, light source of the fixed star is utilized to lighten star tester. Hence, 0Mv-＋5Mv star magnitude simulation can be realized by electrical control system. In addition, the simulation accuracy of star map is also guaranteed to be larger than 3″. Furthermore, the background image is placed in the incident light path of beam splitter prism and the background plate on conjugate focal plane of the collimating optical system. Then, sky background light source is employed to illuminate the background plate. Thus, sky background simulation of $3\times10^5\,\mathrm{cd/m^2}$ is fulfilled thourgh an electrical control system. The corresponding uniformity is also guaranteed to be greater than 95%. On this basis, star map images with sky background from infinity are realized on emitting end of star simulator.

2 Collimating optical system design

According to ground calibration experiment requirements for navigation star sensors, primary parameters of the designed collimating optical system are shown in Table 1.

Table 1 Main design parameter of the collimation optical system

Design indicators	Index parameters
Focal length	1 000 mm
Field of view	$2\omega=\Phi 3°$
Exit pupil distance	500 mm
Work spectral range	600～800 nm

While the optical path diagram of designed collimating optical system has been shown in Fig. 2, distortion graph of this system is given in Fig. 3 and its distortion is greater than 0.002%. Fig. 4 displays the system′s spot diagram. Clearly, spot diagrams of each field of view are all next to the Airy disk. Besides, Fig. 5 shows the transfer function curve of collimating optical system where the full field at 50lp/mm is greater than 0.45.

Based on the aberration design result of the collimating optical system, it is able to not only meet index requirements for high-precision static star simulator with sky background, but guarantee its uniformity of sky background and the accuracy of star map simulation.

Fig. 2 Layout of collimation optical system

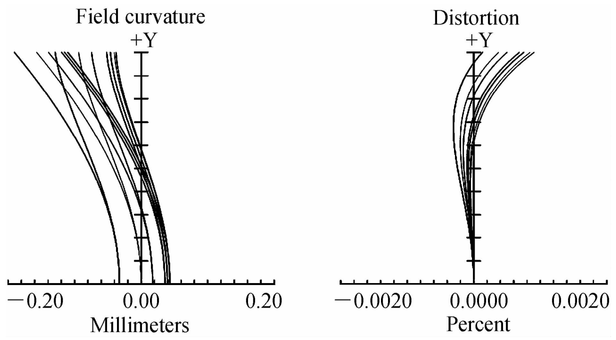

Fig. 3 Distortion of collimation optical system

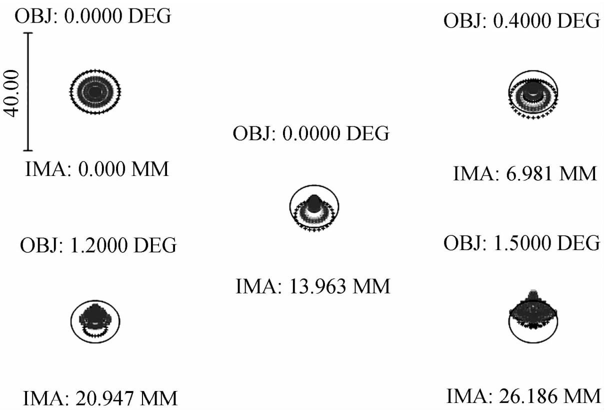

Fig. 4 Spot diagram of collimation optical system

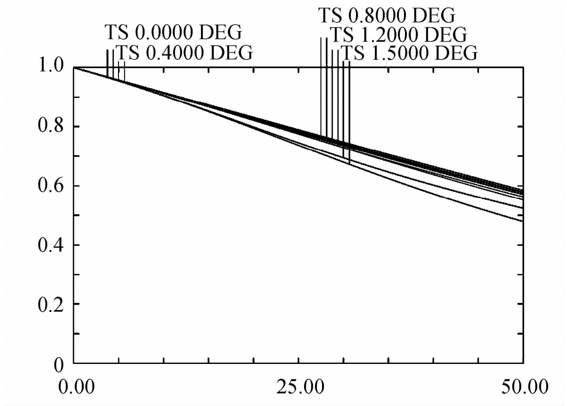

Fig. 5 MTF curves of collimation optical system

3 Optical-mechanical structure design and analysis

The entire mechanical structure of star simulator is given in Fig. 6. In this figure，1 stands for the collimating optical system，2 for beam splitter prism，3 for star tester and 4 for background plate.

Considering that the collimating optical system with lens of large aperture has a high requirement for entire accuracy，a tube-in-tube structure is adopted by the lens cone for the convenience of adjustment. In other words，five lens are mounted in lens barrel according to optical system requirements . In line with the design gap，lens and lens cone are separated from each other by spacers. Additionally，clearance fit is adopted for each lens barrel and outer lens cone. At the time of assembly，alignment is carried out by the optical centering instrument so that all lens can be guaranteed to be coaxial through eccentricity adjustment performed by regulating each adjusting screw.

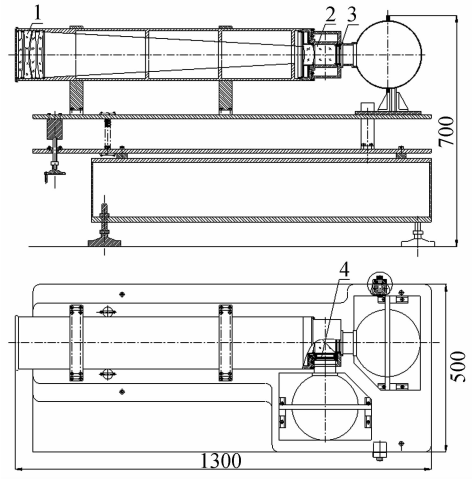

Fig. 6 Integral structure of star simulator

As essential components of star simulator，both star tester and background plate are employed to provide star map simulation images and background simulation images. According to optical system design results（field of view $2\omega=\Phi 3^{\circ}$；focal length $f=1000\mathrm{mm}$），Eq.（1）is utilized to determine the magnitude of them.

$$D=2f\tan(\omega) \tag{1}$$

Substrates of the star tester and the background plate are fused-silica glass with an effective working area of $\Phi 53\mathrm{mm}$. However，the other side is chromium plating. Star points and background images on this plating are fabricated by laser direct writing technology. To be specific，design positions of all star points on the star tester are calculated precisely in line with the actual aberration data of optical system. Afterwards，they are graved with an accuracy greater than $\pm 1\ \mu\mathrm{m}$.

4 Experimental verification

Star simulator is used to accomplish high-precision star map simulation and sky background uniformity simulation primarily. Aiming at verifying design results of the star simulator，star map simulation accuracy and sky background uniformity testing are performed after machining and adjustment of it. On this basis，a test system shown in Fig. 7 can be constructed.

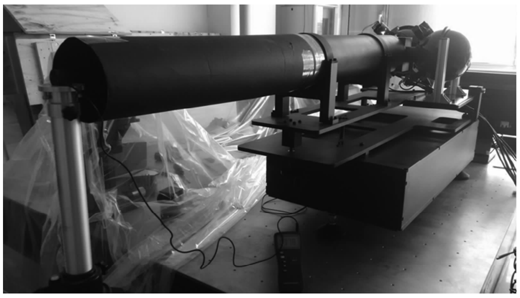

Fig. 7 Test system for star simulator

4.1 Star map simulation accuracy test

The simulation accuracy of star map is represented by the angular distance between stars. While angular positions of every star point in the star simulator are tested by the Leica TM6100 theodolite, the angular distance between any tested star points is computed according to Eq. (2).

$$\theta_{ij}=\arccos\left[\cos\delta_i\cos\delta_j\cos(\alpha_i-\alpha_j)+\sin\delta_i\sin\delta_j\right]\quad(2)$$

where, a_i refers to the azimuth angle value of any star point ranking i tested by the theodolite; a_j is the azimuth angle value of any star point ranking j tested by the theodolite; δ_i is the elevation angle value of any star point ranking i tested by the theodolite; δ_j is the elevation angle value of any star point ranking j tested by the theodolite.

A star tester of the star simulator is designed to be an isometric matrix simulation star map of 17 points. In Fig. 8, measured data of a group of angular distance between stars are given. Testing results indicate that accuracy (θ_{ij}) of the angular distance from each point of stars to their center is no more than 3″. Resultantly, the technical index related is satisfied.

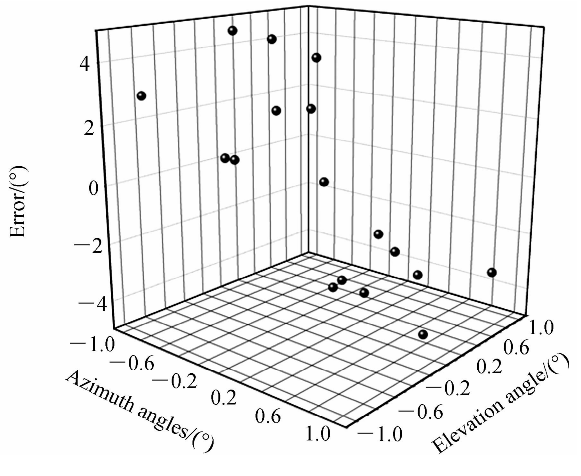

Fig. 8 Tested angular accuracy between stars

4.2 Sky background uniformity test

The key of sky background simulation is radiation uniformity simulation. In case that a luminosity detector is utilized to measure radiance within the operating area, in line with industrial standard, 8 feature points are taken from every circumference with a radius of 5mm by regarding background plate center as the center of a circle. Moreover, radiant uniformity of the entire luminous surface is calculated dependent on Eq. (3).

$$E_{\mathrm{uniformity}}=1-\left|\pm\frac{E_{\max}-E_{\min}}{E_{\max}+E_{\min}}\cdot 100\%\right|\qquad(3)$$

where $E_{\max}$ and $E_{\min}$ represent maximum and minimum values of light intensity in the radiant surface separately.

According to actual application needs of engineering, sky simulation area is Φ53 mm, and its uniformity is larger than 95%. In Fig. 9, a group of radiant uniformity testing data is given. Testing results reveal that the radiant uniformity within effective operating area of the star simulator is greater than 95%, and it is able to meet the corresponding technical specifications.

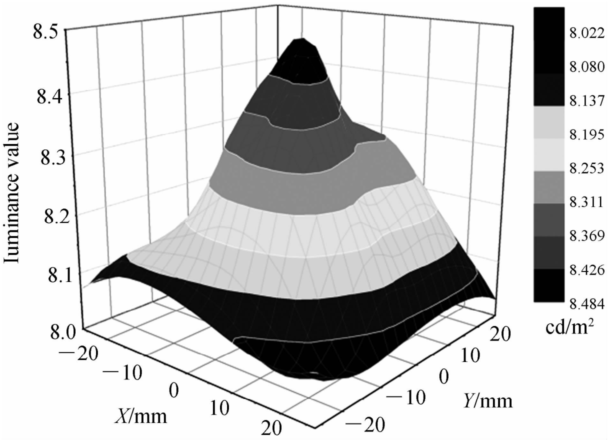

Fig. 9 Uniformity test data for background

5 Conclusions

Based on high-precision ground calibration and functional test requirements of navigation sensor, a high-precision static star simulator with sky background is designed. This simulator is mainly constituted by the light source of fixed stars, star tester, sky background light source, collimating optical system, beam splitter prism and electrical control system. Considering that the collimating optical system is featured with long exit pupil distance, large aperture and highly accurate imaging, both detailed optical-mechanical structure design and accuracy design are carried out for each component of the system. According to test results, the star map simulation accuracy of high-precision star simulator with sky background is designed to be greater than 3″. In addition, its background uniformity is larger than 95%. Therefore, the simulator satisfies high-precision ground calibration and functional test demands of navigation sensors.

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