ISSN : 0974 - 7435 Volume 10 Issue 23

2014

BioTechnology
An Indian Journal

FULL PAPER
BTAIJ, 10(23), 2014 [14257-14264]

Parameters design of optical system in transmitive star simulator

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ABSTRACT

The star sensor has wide application prospect in high precision navigation system of the national defense and people's livelihood. To acquire ground testing and calibration criterion of the star sensor, the star simulator is more important for the development of star sensor. Therefore, development of star simulator attracts increasingly attention from the scientific research departments all over the world. For the optical structure design of the star simulator, the multi-tube multi-star scheme was finally adopted through fully comparison of various schemes. The implementation of kinds of star function simulation was presented in detail. In the design process, the parameters and indexes of each light-pipe were determined through the theoretical analysis with the Zemax software. Finally, optical parts were calibrated through experimental means and these can meet the user's demands.

KEYWORDS

Star simulator; Optical design; Multi-tube multi-star; Zemax.

INTRODUCTION

The star simulator can be used to simulate the star magnitude imaging of fixed stars and calibrate the star sensor. The star sensor is a kind of high-precision optical attitude sensor by which the fixed stars are used as attitude reference source. It is a photoelectric conversion measurement system where the starlight is seen as the measuring object. The development of star simulator is of great significance, since it can directly affect the accuracy of star sensor, and then the space attitude and positioning of spacecraft will be affected. With the extension of the use of star sensor, the development of star simulator will certainly be promoted. Besides, better accuracy and reliability of star sensor will be ensured by the multi-function and high-precision star simulator. The further research of star simulator will lead to a further development in the star sensor technology and the rapid development in aerospace, shipbuilding and other fields[1].

COMPOSITION AND OPERATION PRINCIPLE OF SINGLE STAR SIMULATOR

A separating light pipe structure is used in the system instead of a unitary one. Because the focal length of the single star simulator is long and a separating light pipe structure can be easily installed and calibrated. The structure of the light pipe is shown in Figure 1.

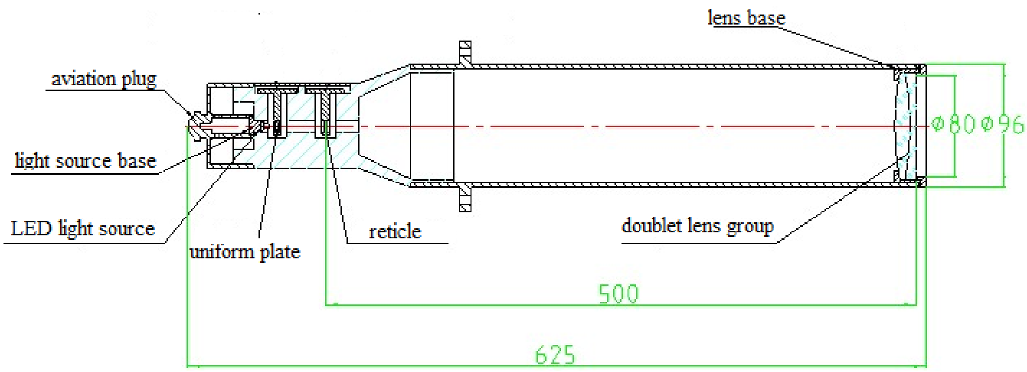

Figure 1 : The light pipe structure

The light path is shown in Figure 2. The light comes from a light source. After passing through the uniform plate and the reticle, the light exits from a group of collimating lenses and forms a beam of parallel light. It can be used to simulate an infinite target, for example the imaging of a fixed star.

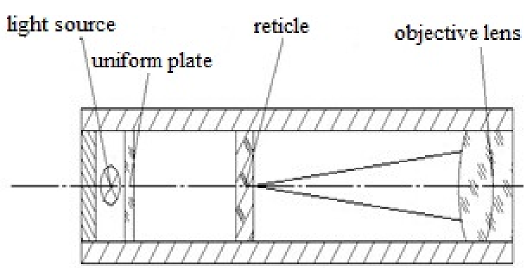

Figure 2 : Light path diagram

OPTICAL SYSTEM DESIGN

Design of the object lenses

The star map on the star point reticle which is in a focal plane of the collimating lens optical system is projected at the entrance pupil of star sensor by the optical system. Thus the star sensor is tested and calibrated. The image quality of the star simulator is directly depended on the object lenses. Therefore the object lenses play an important role in the system.

Because the optical path is close to optical axis, errors such as chromatic aberration, spherical aberration and distortion are caused in imaging system[2]. These errors should be eliminated. Chromatic aberration, spherical aberration and distortion all have positive or negative signs. The positive lens cause negative chromatic aberration, spherical aberration and distortion, on the contrary, the negative lens cause negative ones. Doublet lens group is used in order to eliminate these errors. However, in the real environment, in addition to plane mirror imaging, optical system with on aberration does not exist. In optical design, the aberration which influences the image quality is always kept within a limit according to the function of optical system and characteristic of the receiver. Under this condition, the image quality can be seen as satisfactory.

The star simulator is the important calibration equipment of star sensor on the ground. The technical index of the star simulation system must meet the requirement of the star sensor. The mainly technical index in this system is shown in TABLE 1.

TABLE 1 : The mainly technical index of star simulation system

	Magnitude	Range	2~7
The simulated star		Accuracy	≤0.2
		Wavelength	0.4μm~0.8 μm
	Starlight	Field angle	<5″
		Parallelism	-2″~2″
Relative aperture of star sensor			Φ80mm

1) Design of objective lens focal length

In order to simplify the structure of objective lens, improve stability of optical path and ensure high image quality, the relation between relative aperture *D* and its focal length *f* is required as follows:

$$\frac{D}{f} \leq \frac{1}{4} \quad (1)$$

It is required that $D = \emptyset 80\text{mm}$, so obviously the focal length $f \geq 320\text{mm}$.
According to optical principle, the relation between defocusing amount of reticle *x* and intercept of image *L*(m) is[3]:

$$L = \frac{f^2}{1000x} \quad (2)$$

The parallax of collimator ε (second) is given as

$$\varepsilon = \frac{3.44D}{L} \quad (3)$$

It is required that $\varepsilon/2 \leq 2''$, the defocusing amount of reticle namely the position error of star point at the optical axis is 0.1mm. It is obtained that $f \geq 203\text{mm}$.

The focal length of collimator is related to the luminous flux, modulation transfer function, balance of aberration and many other factors on the promise that the aperture and the field of view are certain. Considering the result calculated above and the difficulty in designing and processing of the object lenses, the focal length of collimator *f* is finally determined as 500mm.

2) Initial conditions design of objective lens

Generally, the traditional optical design is based on experience of predecessors. It is scaled according to pertinent data referring to system structures which have already existed. Then the computer aided optical design software ZEMAX is used to design and improve the required results. If there are no mature systems that can be refer to, the PWC method can be used to solve the initial conditions of objective lens based on characteristics of lens groups.

According to the PWC method, each lens group has four unknowns called intrinsic parameter[4]. They are:

$$P: P = \sum_{i=1}^{n} \left(\frac{\Delta u_i}{\Delta(1/n_i)}\right)^2 \Delta \frac{u_i}{n_i} \quad (4)$$

$$W: W = \sum_{i=1}^{n} \left(\frac{\Delta u_i}{\Delta(1/n_i)}\right) \Delta \frac{u_i}{n_i} \quad (5)$$

$$\mu: \mu = \frac{\sum \varphi_i/n_i}{\sum \varphi_i} \quad (6)$$

$$C: C = \sum \frac{\varphi_i}{n_i} \quad (7)$$

$$v = \frac{n-1}{n_F - n_C} \quad (8)$$

$$\Delta u_i = u_i{}' - u \quad (9)$$

$$\Delta \frac{1}{n} = \frac{1}{n_i{}'} - \frac{1}{n_i} \quad (10)$$

$$\Delta \frac{u_i}{n_i} = \frac{u_i{}'}{n_i{}'} - \frac{u_i}{n_i} \quad (11)$$

In the formula above, u_i is the objective aperture angle of the *i*th lens; $u_i{}'$ is the imaged aperture angle of the *i*th lens; n_i is the refractive index of the incidence surface of the *i*th lens; $n_i{}'$ is the refractive index of the exit surface of the *i*th lens; φ_i is the optical power of the ith lens; φ is the total optical power of the lens system; v_i is the abbe number of the ith lens; v is the total abbe number of the lens system. After normalization of imaged characteristic parameter, the initial condition of doublet lens is solved as follows.

The first intrinsic parameter P_0 is given by

$$\overline{P_\infty} = P_0 + 0.85(\overline{W_\infty} + 0.1)^2 \quad \textbf{(12)}$$

When the object is at infinity,$\overline{P_\infty} = 0$, $\overline{W_\infty} = 0$, so $P_0 = -0.0085$. The laminated glass of "K7+ZF3" is chosen. According to relevant information, the chromatic aberration$C_I = 0$;$Q_0 = -4.11$;$v_1 = 60.63$; $v_2 = 29.51$

The second intrinsic parameter Q is given by

$$Q = Q_0 - \frac{\overline{W_\infty} - 0.15}{2.35} \quad \textbf{(13)}$$

The optical power distribution is given as

$$\varphi_1 = \frac{\overline{C} - \frac{1}{v_2}}{\frac{1}{v_1} - \frac{1}{v_2}} \quad \textbf{(14)}$$

$$\varphi_2 = 1 - \varphi_1 \quad \textbf{(15)}$$

At last the initial conditions design of objective lens is given by

$$\frac{1}{r_2} = \rho_2 = \varphi_1 + Q \quad \textbf{(16)}$$

$$\frac{1}{r_1} = \rho_1 = \frac{\varphi_1}{n_1 - 1} + \rho_2 \quad \textbf{(17)}$$

$$\frac{1}{r_3} = \rho_3 = \rho_2 - \frac{1 - \varphi_1}{n_2 - 1} \quad \textbf{(18)}$$

Where r_1 r_2 r_3 are the curvature radius of each surface in the doublet lens group.

3) Parameter optimization by Zemax software

According to the calculated results, the initial conditions were input into Zemax software. Then the parameters were optimized in order to improve the image quality.

The light path before and after optimization were shown in Figure 3 and Figure 4. It can be seen clearly that the light path were more focused and the system were improved. The image quality was evaluated by the methods below.

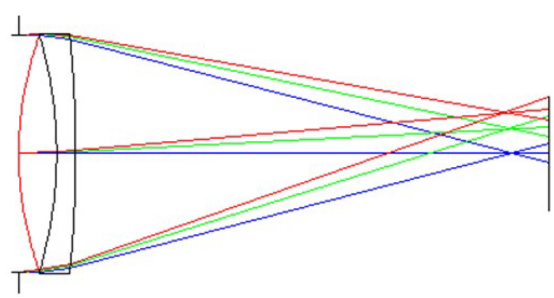

Figure 3 : Light path before optimization

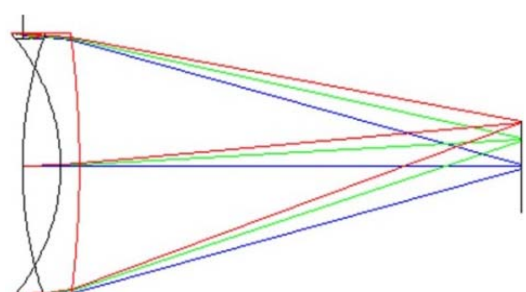

Figure 4 : Light path after the optimization

Figure 5 and Figure 6 are the modulation transfer function (MTF) curve of the optical system before and after the optimization. The MTF curve shows the attenuation degree of contrast ratio while a sum of sinusoidal intensity distribution functions at different frequencies were imaged through the optical system. It can synthetically reflect the image quality of the lens group. Figure 5 shows that the contrast ratio is small and the resolution is low, that means the image quality is bad. From the optimized curve shown in Figure 6 all MTF curve in the field are improved. The contrast ratio is larger which means the images are more arranged and the quality is better. Besides, the resolution of the system is improved and the image quality in the field is uniform. The curves of each band have more common area; more information will be transferred by the optical system.

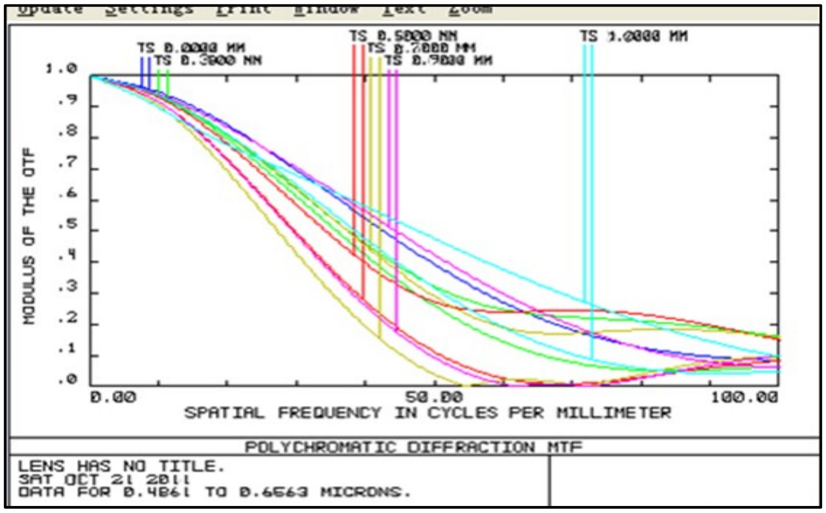

Figure 5 : The MTF curve before optimization

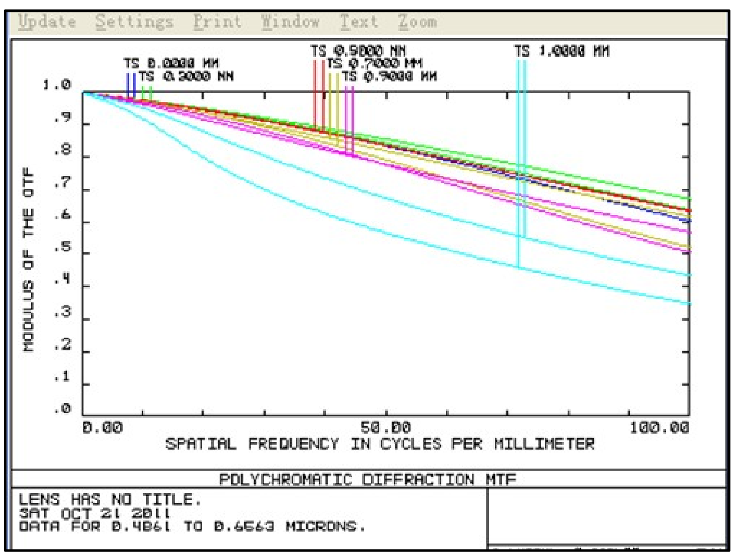

Figure 6 : The MTF curve after optimization

The field curvation and distortion of the prism series were shown in Figure 7. The curve on the left shows the narrow beam field curvation, the right one shows the distortion percent after normalization. The vertical axis stands for the normalized field. The field curvation shows the position change of the image point of thin beam in different field point from the image surface. The distance between T and S of same color stands for the value of astigmatism. The distortion is less than 0.001%, which means the objective and the image are almost the same. The edge field curvation is less than 0.1%. So the field curvation and distortion meet the design requirements.

Figure 8 shows the spot diagram of the prism series optical system. Although there is distortion at the edge of the field and different degrees of chromatic and spherical aberration in each field, they were all in the airy disk. So the image quality meets the requirements.

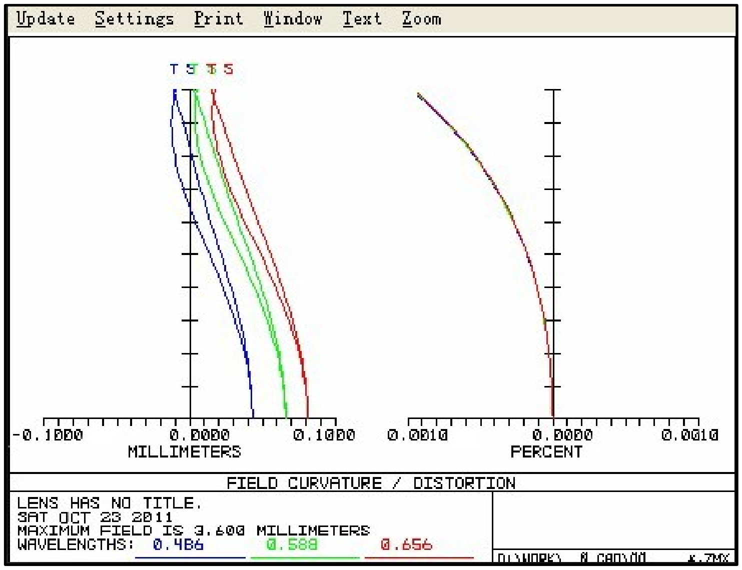

Figure 7 : Field curvation and distortion

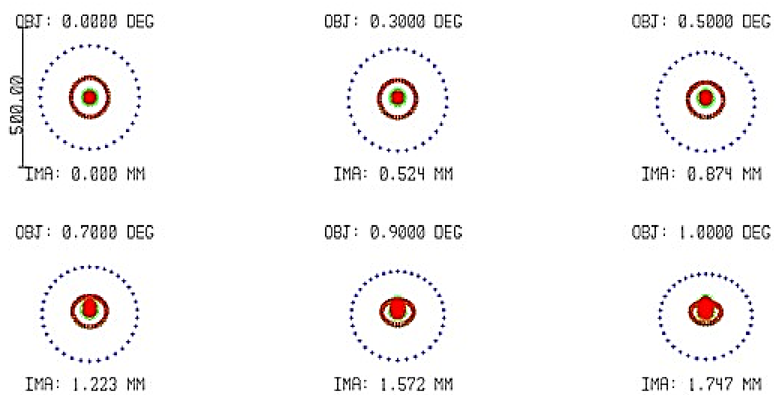

Figure 8 : Spot diagram

Design of star point reticle

It is required that the field angle $\theta < 5''$, the star point diameter should be as small as possible. That is:

$$d < f \times \tan\theta \quad (19)$$

But the diameter is also limited by the diffraction limit. It is required that:

$$d > \frac{0.16\lambda f}{D} \quad (20)$$

Considering present process technology and the results above, the value of d is 5μm.

The reticle must be installed strictly in the same plane with the focal plane in case of the defocus error which will influence the parallelism of emergent light. Generally the caliber of star sensor is less than 80mm. The alignment error between primary optical axis of star sensor and of simulated star is less than half of the caliber. The parallelism error is given by

$$\varepsilon = \arctan\left(\frac{d_i\Delta}{f^2}\right) \quad (21)$$

It is required that $\varepsilon < 2''$, than $\Delta <$ 0.8mm.

While installing, the simulated star is aimed by a telescope of which the magnification $\Gamma = 40^{\times}$. The error of focusing is given by

$$\Delta = \sqrt{2}\sqrt{\left(\frac{a_e}{\Gamma D}\right)^2 + \left(\frac{8\lambda}{KD^2}\right)^2} \quad (22)$$

Generally, $a_e = 2'$ K=6 than $\Delta = 0.6$mm which meets requirements of installing.

Design of the light source

The LED is used as the light source in the system. Comparing with the traditional halogen tungsten lamp, the LED has the advantage of long life, low power dissipation, high illumination uniformity and so on. Due to the influence of light source output directional and electrode materials, the frosted glass is used as a uniform plate in order to make light more evenly[5].

While choosing the LED, the Hertzsprung-Russel diagram, shown as in Figure 9, can be used as a reference. The main target of the design is to simulate the magnitude of 2 to 7. It can be seen from the Hertzsprung-Russel diagram that if the temperature of the star is lower than K5, than the brightness of it will be lower than a 7th magnitude star. So these stars needn't to be considered when simulating the star.

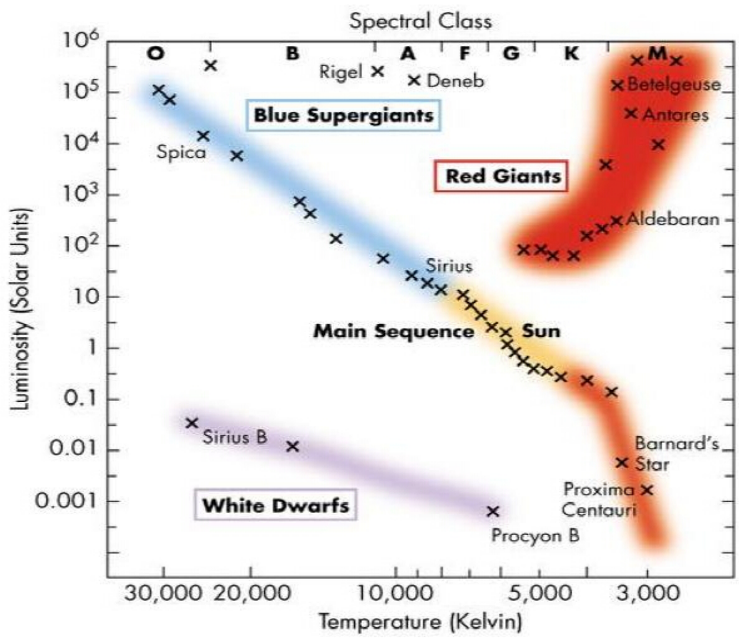

Figure 9 : Hertzsprung-russel diagram

The wavelength of the simulated star light in the system is between 0.4μm and 0.8μm. Let A_1 be the area of light pipe aperture; A_2 is the area of star point aperture; h_1 is the transfer efficiency of light pipe; h_2 is the transmittance of uniform plate. When the output star magnitude of the light pipe is m, the illumination will be $E^{(m)}$, and then the output luminous flux is given by

$$\Phi_1^{(m)} = \frac{E^{(m)}A_1}{\eta_1} \qquad \textbf{(23)}$$

The lighted space of LED is a cone shaped area of which the taper angle is θ. When the distance between LED and the star point is R, the ratio that the star point take in the lighted space is given by

$$\mathrm{K} = A_2/\, A_3 \qquad \textbf{(24)}$$

Where

$$A_3 = \frac{2\pi R^2}{1-\cos(\theta/2)} \qquad \textbf{(25)}$$

The number of lumens the LED produces is

$$\Phi_2^{(m)} = \frac{\Phi_1^{(m)}}{\mathrm{K}} = \frac{E^{(m)}A_1A_3}{\eta_1\eta_2A_2} \qquad \textbf{(26)}$$

According to (24), when the caliber of light pipe is 80mm; the star point diameter is 5μm; the transmittance of light pipe is 0.98; the transmittance of uniform plate; the star magnitude is 2, and then the output luminous flux of LED should be at least 1.3lm.

If the light intensity of LED is *I* and the lighted space taper angle is , then the luminous flux of LED is

– **(27)**

It is required that

(28)

If the light intensity of LED is 18cd and the taper angle is 12°, then the output luminous flux is 2.47lm. It can provide the needed luminous flux for simulating a 2nd-magnitude star. So a LED which light intensity is 18cd is chosen as the light source of the system.

The chosen light source in the system is the natural white LED XLamp® XP-E of CREE Company. It has the advantages of high drive current (a maximum current of 1A) and large luminous flux (up to 100lm). The contour of the LED is shown in Figure 10.

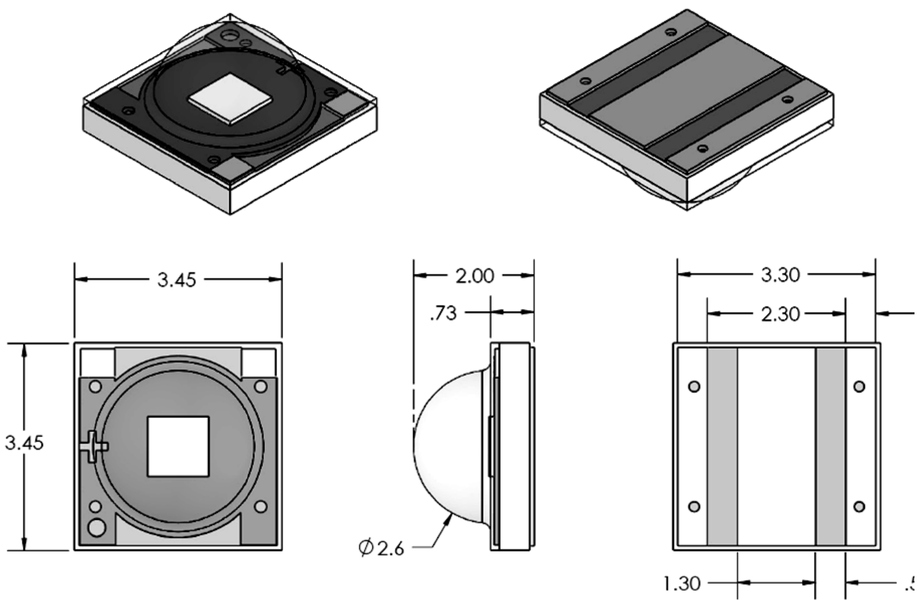

Figure 10 : XLamp® XP-E LED contour

CONCLUSION

The design process of the optical system is discussed in detail. Including:

1) The model of the objective lenses was determined in the design of objective lens group and the parameters were simulated according to the PWC method by using the Zemax software.

2) The size of the star point reticle was calculated theoretically and the installation process was discussed.

3) By analyzing the spectrum type of the simulated star, the light intensity of LED was determined.

In a word, through all aspects of the design above, the single star simulator optical system was designed and the performance meets the required technical index.

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