A High-orbit Collimating Infrared Earth Simulator

Guoyu Zhang, Huilin Jiang, Yang Fang, Huadong Yu, Xiping Xu, Lingyun Wang, Xuli Liu, Lan Huang, Shixin Yue, Hui Peng

1 Changchun University of Science and Technology, Changchun, China
2 Beijing Institute of Controlling Engineering, Beijing, China

E-mail: zh_guoyu@yahoo.com.cn

Abstract. The earth simulator is the most important testing equipment ground-based for the infrared earth sensor, and it is also a key component in the satellite controlling system. For three orbit heights 18000Km, 35786Km and 42000Km, in this paper we adopt a project of collimation and replaceable earth diaphragm and develop a high orbit collimation earth simulator. This simulator can afford three angles 15.19°, 17.46° and 30.42°, resulting simulating the earth on the ground which can be seen in out space by the satellite. In this paper we introduce the components, integer structure, and the earth’s field angles testing method of the earth simulator in detail. Germanium collimation lens is the most important component in the earth simulator. According to the optical configuration parameter of Germanium collimation lens, we find the location and size of the earth diaphragm and the hot earth by theoretical analyses and optics calculation, which offer foundation of design in the study of the earth simulator. The earth angle is the index to scale the precision of earth simulator. We test the three angles by experiment and the results indicate that three angles errors are all less than ±0.05°.

1. Introduction
The collimation earth simulator is the testing equipment used for simulation of the infrared earth sensor on the ground, mainly calibrates the rolling and pitching warp of infrared earth sensor through the size of earth simulator angle [1-4]. How precise the infrared earth sensor demarcation test is directly affect work precision of satellite on the orbit.

Analogous simulator instrument previously developed can simulate Earths when synchronous satellites work normally, in other words, when satellites locate earth synchronous orbit, at a distance about 36000Km to ground with the earth’s field angle of 17.46°, we can’t have demarcation test exceeding synchronous orbit[5-7]. It is demanded that the Earth simulator offer various Earth field angles when the infrared Earth sensor is demarcated on the ground. In this paper we study an Earth simulator which can alter diaphragm, simulate three different orbit heights, and afford three field angles 15.19°, 17.46° and 30.42°.

2. Components and Overall Structures of the Earth Simulator
Figure 2.1 shows the integer structure of the high-orbit, large field angle collimation earth simulator. In order to simulate status of the earth which can be seen in the firmament on the ground and make incident light of the infrared earth sensor to be parallel light, the earth simulator adopts collimation design project, in other words, a Germanium collimation lens is laid before the earth which is laid on the lens focal...
plane of finite dimension. The earth that can be seen before lens is laid at infinity. In order to simulate
different heights, we alter dimension of Earth on the focal plane to realize simulating variety of height.
Then altering Earth diaphragm is adopted to realize altering the Earth field angle by the Earth diaphragm of
different diameter. The Earth simulator instrument can simulate not only Earth field angle but also
radiant luminance difference between Earth and firmament. Earth radiating intensity is variable with
different latitude or in different seasons is variable. The radiant luminance difference between Earth and
firmament can be simulated by temperature control system which can adjust the temperature of hot
Earth. The work wave-range of the Earth simulator instrument is $14\mu m \sim 16.25\mu m$, using optical axis
reference lens to realize the switch between visible light reference and infrared reference.

![Image of the Earth simulator](image)

**Figure 2.1** Integer structure of the high-orbit, large field angle collimation earth simulator

3. **Theoretical Calculations and Analysis of the Earth Simulator**

3.1. Calculation of the Earth angle at Different Orbit

The field angle of germanium collimation lens can be determined by the orbit of plane, and its calculation
can be expressed as:

$$2\omega = 2\times \sin^{-1}(R + S)$$  \hspace{1cm} (1)

Where $2\omega$ is the angle of the earth, $r_0=6378.24Km$, and it is the equatorial radius, $r =6371Km$, and
it is the average value of the earth, $L = 22 Km$, which is the thick of atmospheric of CO$_2$, ant the final
calculation results three orbital altitude are 18000Km, 35786Km 42000Km and the corresponding
Earth angle is 30.42, 17.46 and 15.19 respectively.

3.2. Designation of the germanium collimation lens

The design of germanium collimation lens starts with an angle of view field and its shape is meniscus lens.
In the design the Earth diaphragm is placed on the least image plane of disc of confusion in order to make
the simulator effectually simulate the state when the sensor is on the inter space orbit.

Germanium collimation lens with two forms can be used in the system, and we select meniscus lens[9-
14]. The optical structure parameters used in the designation of germanium collimating lens is the
biggest aperture $\Phi D=\Phi 250mm$, valid aperture $\Phi D_0=\Phi 220mm$, refractive index $n=4.0014$, focal
length $\ell =650.1271mm$.

3.3. Calculation for earth stop and its position and diameter

The Earth diaphragm and infinite object plane is a pair of conjugate plane. When image formation is
perfect, the Earth diaphragm should be placed on the image space focus $F'$ of Germanium collimation
lens. Figure 3.1 shows the light path through lens with the lines of different incidence heights and different incidence angles on the meridian plane of the Germanium collimation lens. Because the Germanium collimation exists unperfected, except this parallel beam of light \( \omega = 0^\circ \) which is paralleled with optics axis converging on the optical axis near \( F' \), other incidence lights with different incidence obliquity not converging on the plane which is plumbed with optics of \( F' \), but converging on a height \( Y \) which has a distance \( Xr' \) apart from this plane. If the \( \omega \) is bigger, the \( Y \) is bigger. Thus it can be seen through the lens parallel light without different angles converging on the focal plane but converging on a curved image surface. Because of the existing of image formation, convergent point is not a point about one obliquity but a minimal “confusion disc” which can be called minimal image formation location of this parallel light. In order to enhance collimation precision, boundary of the Earth diaphragm is required on the optimum image plane (image formation disc is minimal), viz. the Earth diaphragm should be placed on the optimum image plane \( L' \) (the plane through the intersection point broad beam meridian ray via above and nether ray \( a, b \) on image plane \( B_T' \) also plumbing the plane of optics axis). Disc of confusion range is \( B'T'B'_Z \) when meridian image plane is on the optimum image plane. The size of diaphragm is decided by the center of gravity height of the disc of confusion \( Yp' \). Because of the difference of angle field angle, location of corresponding \( B_T' \) is different and optimum location of the Earth diaphragm and actual diaphragm diameter is different. The intersection point height \( Y \) of the same view field 11 meridian ray \( \pm (1.0, 0.85, 0.707, 0.5, 0.3, 0) h_m \) via optimum image plane is calculated, and its average is regarded as the radius of actual diaphragm.

![Figure 3.1 Beam path sketch map of Germanium collimation lens](image)

In Figure 3.1, \( Y'_a, Y'_b, Y'_c \) and \( Y'_a'', Y'_b'', Y'_c'' \) are respective intersection point heights of three rays \( a, b, c \) which start in extra-axial point one angle of view field \( \omega \) via Germanium collimation lens on the Gauss plane and location of the hot earth, and their results can be gained by ray path calculation. According to ray of extra-axial ray path calculation method, calculative formula of Earth diaphragm location \( L' \), Earth diaphragm diameter \( \phi D' \) and the hot earth diameter \( \phi D'' \) can be gained by analysis of ray path.

### 3.3.1. Calculation of the Hot Earth Location and Diameter \( \phi D' \)
- The location of the Earth diaphragm \( L' \) can be calculated by the formula below:

\[
L' = l_{f} - (-X'_r) = l_{f} + X'_r = l_{f} + \alpha_{2} + X'_r
\]  

(2)

where \( l_{f} \) is the distance from Gauss image plane to the last plane of optical system which is calculated by the first paraxial ray to the last plane in optics system; \( X'_r \) is the curvature of meridian image viz. the distance from \( B_{T}'' \) to the ideal image plane; \( \delta L_{T}'' \) is the spherical aberration of external axis; \( X_T' \) is the field curvature of beam let external axis; \( K_T' \) is the meridian coma viz. the distance \( B'T'B''Z \) from \( B'T \) to main ray; and

\[
l_{f} = f \left( 1 - \frac{d}{f_{i}} \right)
\]  

(3)

\[
X'_r = \frac{Y'_a - Y'_b}{\tan U'_a - \tan U_b}
\]  

(4)
\[ X'_T = \Delta L'_T + X'_r \quad (5) \]
\[ K'_r = Y'_z - \frac{1}{2}(Y'_r + Y'_s) \quad (6) \]

Where \( f' \) is the focus of the Germanium collimation lens, and \( f = \frac{mr_1}{(n-1)(n(r_2 - r_1) + (n-1)d)} \).

\( f'_i = \frac{n}{n-1} r'_i \); where \( r_1, r_2 \) is the curvature radius of the Germanium collimation lens; \( d \) is central thickness; \( n \) is refractive index; \( U_a, U_z, U_b \) and \( U'_a, U'_z, U'_b \) are respective inter angles three rays a, z, b which start in extra-axial point one angle of view field \( \omega \) via Germanium collimation lens and optics axis, and \( U_a = U_z = U_b = -\omega \).

- The diameter of the Earth diaphragm \( \Phi D \) can be calculated by the formula below:
  \[ Y = (L'_x - L') \tan U'_s \]
  \[ \Phi D = 2Y = \sum Y/11 \quad (7) \]
  \[ \Phi D = 2Y = \sum Y/11 \quad (8) \]

3.3.2 Calculated Results of the Location and the Diameter of the Hot Earth

If the distance from the hot Earth to the Earth diaphragm is \( L \), then

\[ Y'_a = (L'_x - L') \tan U'_a \]
\[ Y'_z = (L'_x - L') \tan U'_z \]
\[ Y'_b = (L'_x - L') \tan U'_b \]

Then the diameter of the hot Earth is:

\[ \Phi D' \geq 2 \max \{Y'_a, Y'_z, Y'_b\} \quad (9) \]

3.3.3 Calculated Results of the Location and the Diameter of the Diaphragm and the Hot Earth

Field angles (Earth field angles) \( 2\omega \) are respective 15.19°, 17.46° and 30.42°; \( L=40\text{mm} \), then the calculated results of the Earth simulator show as Table 3.2.

| Satellite Height (Km) | Earth Field Angle \( 2\omega \) (°) | Location of the Earth Diaphragm \( L' \) (mm) | Diameter of the Earth Diaphragm \( \Phi D \) (mm) | Diameter of the Hot Earth \( \Phi D' \) (mm) |
|-----------------------|---------------------------------|---------------------------------|-----------------|-----------------|
| 42000                 | 15.19°                          | 614.99                          | \( \Phi 168.32 \) | \( \geq \Phi 354.12 \) |
| 35786                 | 17.46°                          | 609.20                          | \( \Phi 192.07 \) | \( \Phi 314.70 \) |
| 18000                 | 30.42°                          | 562.38                          | \( \Phi 314.70 \) | \( \Phi 314.70 \) |

PS: In the table, the diameter of the hot earth is the maximum in different \( \omega \).

Figure 3.2 Spot diagram of the field angle

4. Testing Results and Analysis of the Earth Field Angle

The equipment which tests the earth field angle of the earth simulator is mostly made of small field view infrared probe, optics modulator, electric box, the earth signal electric testing box, and electric theodolite.
etc. Radiant output of Earth is tested by small field view infrared probe. Trapezoidal wave of Earth output is gained by altering direction of infrared probe. Chord width of Earth is gained by the midpoint of trapezoidal wave hypotenuse, so the Earth field angle can be gained. The testing results of the Earth field angle which is corresponding to three Earth diaphragms using above equipment is shown in Table 4.1, and its field angle curves of rolling direction and pitching direction is shown in Figure 4.1, Figure 4.2 and Figure 4.3. Testing values of three Earth field angles compare with corresponding theoretic values of the Earth field angle, so the testing precision of field angle can be confirmed. The results indicate that three angles error are all less than ±0.05°.

| Diameter of the earth diaphragm (mm) | Location of the earth diaphragm (mm) | Theoretical values of the earth field angle (°) | Actual testing value (°) | Error (°) |
|-------------------------------------|--------------------------------------|-----------------------------------------------|-------------------------|-----------|
| φ168.32                             | 614.99                               | 15.19                                         | Rolling 15.23           | 0.04      |
|                                     |                                      |                                               | Pitching 15.18          | -0.01     |
| φ192.07                             | 609.20                               | 17.46                                         | Rolling 17.48           | 0.03      |
|                                     |                                      |                                               | Pitching 17.43          | -0.03     |
| φ314.70                             | 562.38                               | 30.42                                         | Rolling 30.37           | 0.05      |
|                                     |                                      |                                               | Pitching 30.40          | -0.02     |

Figure 4.1 Field angle testing curves of rolling direction and pitching direction on 42000Km height

Figure 4.2 Field angle testing curves of rolling direction and pitching direction on 35786Km height

Figure 4.3 Field angle testing curves of rolling direction and pitching direction on 18000Km height
5. Conclusions
This paper used optical collimation technology, adopted the structure which can alter the Earth diaphragm, realized simulation of 18000Km, 35786Km and 42000Km orbit height from satellite to ground, and offered three Earth field angles. Adopting optical system design and calculation technology of big aperture and big view field, using optical structure parameter of the Germanium collimation lens to analyze and calculate the location and the size of the Earth diaphragm and the hot Earth, the high-orbit, large field angle collimation Earth simulator was designed. The Earth diaphragm adopted flat style water-cooling design. Its size and location can be disgusted to simulate three different orbit heights. The radiant luminance difference between Earth and firmament can be simulated by temperature control system which can adjust the temperature of hot Earth and used optical axis reference lens to realize the switch between visible light reference and infrared reference.

The high-orbit, large field angle collimation earth simulator is mostly use in simulator testing and precision demarcation of the infrared Earth sensor. In this paper we adopt testing technology of the earth field angle to test the field angles of rolling direction and pitching direction. The results indicate that three angles error are all less than ±0.05°, This simulator can accurately simulate the Earth on the ground which can be seen in firmament by the satellite, and satisfy the integer capability demand of the earth simulator.

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