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Design for segmented optical antenna with hexagon-shaped spherical sub-mirrors based on three-dimensional vector rotation and reflection theories

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A B S T R A C T

Segmented antenna is an effective method to cut costs of the large-aperture optical antenna. A 10 m-aperture segmented antenna model is established by using three-dimensional (3-D) vector rotation theory. Ray tracing and transmission characteristic analysis are performed based on 3-D vector reflection theory. The receiving efficiency of the segmented antenna composed of 36 spherical sub-mirrors is 80.19%. Results of the optical aberrations caused by tilt ray incidence and defocusing of the secondary reflector indicate that the performance of the proposed segmented antenna with spherical sub-mirrors is very approximate to that of the segmented antenna with paraboloidal sub-mirrors, and hence of great significance for realization of large-aperture optical antenna.

1. Introduction

With the rapid development of optical communications, optical antennas have been widely researched in recent years [1,2], and a series of improved structures have been proposed, such as hollow beams [3,4], Bessel beams [5,6], vortex beams [7,8], novel structures of reflectors [9,10] and so on. Large-aperture antenna has important significance for reducing the influence of atmospheric turbulence and realizing long distance optical communication [11,12]. Segmented antenna is an effective method to cut costs of the large-aperture optical antenna and has been studied and applied in several fields such as high resolution imaging [13,14], astronomical observation [15,16], and solar energy collection [17–19]. However, few systematic analyses were made on the theoretical modeling and the sub-mirror shapes effect on the aberrations and receiving efficiency of the segmented antenna.

In this article, segmented receiving antenna with hexagon-shaped sub-mirrors is designed by using theories of 3-D vector rotation and reflection. The effects of tilt ray incidence and on-axial defocusing of secondary reflector on aberrations and receiving efficiencies of the segmented antenna are discussed. An optimized structure of the segmented antenna with optical characteristics similar to that of the paraboloidal reflector is proposed to cut costs of large-aperture optical antenna. This proposed method based on 3-D vector rotation and reflection theories is applicable to design other complex optical systems and is more convenient and accurate for computer programming.

2. Design for the segmented primary reflector

Top view of the segmented primary reflector with hexagon-shaped sub-mirrors is shown in Fig. 1.

As is shown in Fig. 1, the paraboloid primary reflector of the receiving antenna is composed of hexagon-shaped sub-mirrors. Φ is the aperture of primary reflector and Λ is the side length of the hexagon-shaped sub-mirror. The total number of k-circle sub-mirrors is $n = 3k(k+1)$. Point $H(x_h, y_h, z_h)_{ij}$ denotes the center of the ith hexagon-shaped sub-mirror at the jth cycle.

2.1. 3-D vector rotation and reflection theories

The model of segmented antenna is established by using 3-D vector rotation theory. As is shown in Fig. 2, the main coordinate system is described by cartesian coordinate system (x, y, z). Assuming that the optical axis of the optical system is along z axis, a hexagon-shaped sub-mirror is located in the x–o–y plane and centered at the origin point O (0, 0, 0). Once the sub-mirror rotates around its center and shifts to point $H(x_h, y_h, z_h)_{ij}$ which is on the paraboloidal surface of the primary reflector, a new coordinate frame (x', y', z') is formed.

As is shown in Fig. 2, each hexagon-shaped sub-mirror is tangent to the paraboloidal primary reflector at point $H(x_h, y_h, z_h)_{ij}$. According to the 3-D rotation theory in vector form, the coordinate of an arbitrary point $M(x', y', z')$ on the sub-mirror is [20]

$$\left[x', y', z', 1\right] = [x, y, z, 1] \cdot T \tag{1}$$

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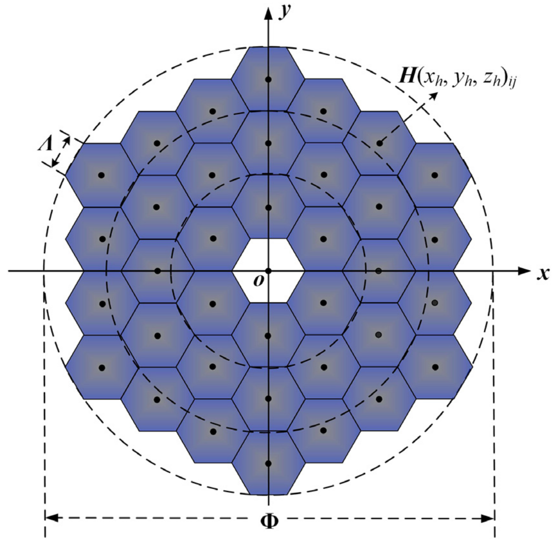

Fig. 1. Top view of the segmented primary reflector with hexagon-shaped sub-mirrors.

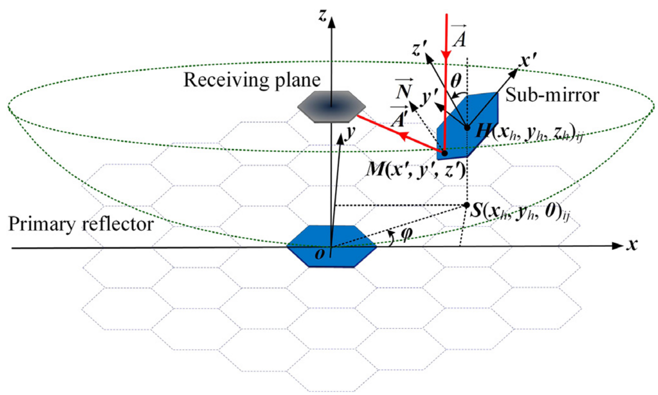

Fig. 2. Diagrammatic sketch of position and orientation of a single hexagon-shaped sub-mirror.

where the translation and rotation matrix T can be written as

$$T = \begin{bmatrix} \cos\varphi & \sin\varphi & 0 & 0 \\ -\sin\varphi & \cos\varphi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos\theta & \sin\theta & 0 \\ 0 & -\sin\theta & \cos\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \cos\varphi & \sin\varphi & 0 & 0 \\ -\sin\varphi & \cos\varphi & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}^{-1} \cdot \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ x_h & y_h & z_h & 1 \end{bmatrix} \tag{2}$$

where $\varphi (0 \le \varphi < \pi)$ is the spin angle between $\overline{ox}$ axis and the vector $\overline{os}$, θ $(0 \le \theta < \pi)$ is the nutation angle between the normal vector $\overline{o'z'}$ of the sub-mirror at point $H(x_h, y_h, z_h)_{ij}$ and the z axis. Angles φ and θ are determined by the following equations respectively

$$\varphi = \arcsin \frac{y_h}{\sqrt{x_h^2 + y_h^2}} \tag{3}$$

$$\theta = \arccos \frac{F_z'}{\sqrt{F_x'^2 + F_y'^2 + F_z'^2}} \tag{4}$$

where F'_x, F'_y, F'_z are the partial derivatives of the paraboloidal surface equation of the primary reflector.

3-D vector reflection theory is applied to performing ray-tracing and the performance evaluation of this segmented receiving antenna [21]. The relationship between the unit vectors of the incident ray $\vec{A}$ and its reflected ray $\vec{A'}$ can be described as

$$\vec{A'} = \vec{A} - 2\left(\vec{A} \cdot \vec{N}\right)\vec{N} \tag{5}$$

where $\overline{N}$ is the unit normal vector of the sub-mirror at the projecting point $M(x', y', z')$. Hexagon-shaped flat-facets, which are tangent planes of the paraboloidal primary reflector, are firstly selected as sub-mirrors. In this case, $\overline{N}$ is parallel to the normal vector of the paraboloidal primary reflector at point $H(x_h, y_h, z_h)_{ij}$. The direction cosine of the unit normal vector $\overline{N}$ of the flat-facet can be written as

$$\left[\cos\alpha_N, \cos\beta_N, \cos\gamma_N\right] = \left[\frac{-F_x'}{\sqrt{F_x'^2 + F_y'^2 + F_z'^2}}, \frac{-F_y'}{\sqrt{F_x'^2 + F_y'^2 + F_z'^2}}, \frac{-F_z'}{\sqrt{F_x'^2 + F_y'^2 + F_z'^2}}\right] \tag{6}$$

2.2. Design for the segmented primary reflector with flat-facets

The 3-D equation of the paraboloidal primary reflector is

$$F_1(x, y, z) = 2p(z - z_{01}) - (x - x_{01})^2 - (y - y_{01})^2 = 0 \tag{7}$$

where (x_{01}, y_{01}, z_{01}) is the apex coordinate of the paraboloidal primary reflector. After a series of parameters are set, namely the aperture of primary reflector $\Phi = 10$ m, the focal length $f = p/2 = 25$ m, the cycle number of the flat-facets $k = 3$, the total number $n = 36$ and the side length $\Lambda = 0.8220$ m, the simulation results of the segmented primary reflector with flat-facets are obtained and shown in Fig. 3.

It is shown that the incident rays, which are parallel to the optical axis z, are reflected by the segmented primary reflector with flat-facets and, finally, form a uniform spot distribution on the receiving plane which is located in the focal plane of the primary reflector. The spot diagram by Matlab programming (as shown in Fig. 3(b)) are compared with the simulation result by using Tracepro (as shown in Fig. 3(c)) to confirm the correctness of the 3-D vector rotation and reflection theories mentioned in Section 2.1. In the spot diagram simulation, each of the 36 sub-mirrors is illuminated by 1440 rays which means, in total, 51 840 rays are traced. As is shown in Fig. 3(b) and (c), the spot radius is about 0.8 m. Since a primary reflector with such a big spot can hardly be applied to large-aperture optical antenna, it is necessary to reselect sub-mirrors with different surface shapes for better performance.

2.3. Design for the segmented primary reflector with spherical sub-mirrors

In this section, some improvements are made by changing the flat-facets into the off-axis spherical sub-mirrors. The model of spherical sub-mirror segmented antenna is established by the method shown in Section 2.1. The radius of original sphere is $r = 2f = 50$ m, whose central coordinate is (x_0, y_0, z_0), where $x_0 = y_0 = 0, z_0 = 2f = 50$ m, so that the focuses of each spherical sub-mirror and the paraboloidal primary reflector are located at the same position. The central coordinate (x_0', y_0', z_0') of the spherical sub-mirror after translation and rotation can be written as

$$\left[x_0', y_0', z_0', 1\right] = \left[x_0, y_0, z_0, 1\right] \cdot T \tag{8}$$

where T is the translation and rotation matrix as shown in Eq. (2). The 3-D equation of the spherical sub-mirror is

$$F_2(x, y, z) = \left(x - x_0'\right)^2 + \left(y - y_0'\right)^2 + \left(z - z_0'\right)^2 - r^2 = 0 \tag{9}$$

The simulation results of the segmented primary reflector with spherical sub-mirrors are shown in Fig. 4.

From Fig. 4, it can be inferred that the segmented primary reflector with spherical sub-mirrors has better concentrating performance