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New optimization method for SPS-ALPHA Mark-Ⅱ based on improved ACO algorithm

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Abstract

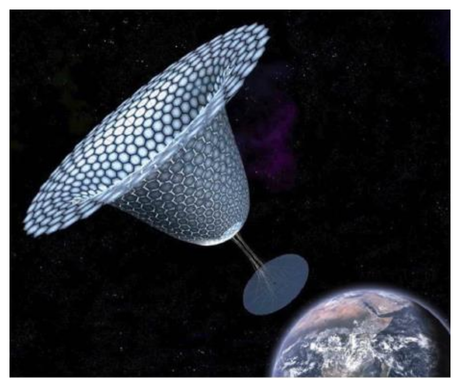
SPS-ALPHA, a novel concept of Space-based Solar Power Station (SSPS), is composed by a large number of small modules that enables the modularity and low cost of machining/space transport. The optical performance of SPS-ALPHA Mark-I type had been investigated in last year. It was found that the cosine effect and blocking shadow effect of ray path exist in the Mark-I type model and make the optical efficiency unstable on orbit. The totally new optical model for SPS-ALPHA Mark-Ⅱ, which adopts conical structural system, would be developed in current study, in order to find the possibility of a better solution for improving the optical efficiency. The source-target mapping would be established considering the effect of solar cone angle. A two-step feedback method are adopted, including initial Monte-Carlo ray tracing (MCRT) process, source-target re-mapping by Ant Colony Optimization(ACO) algorithm and second MCRT simulation. Finally the optimal design parameters and adjustment strategy of SPS-ALPHA Mark-Ⅱ would be discussed at different tracking angle and structrual parameters. This method can mostly ensure high optical efficiency at every moment on orbit.

Keywords: Solar Power Satellite, SPS-ALPHA, solar concentrator, MCRT, ACO

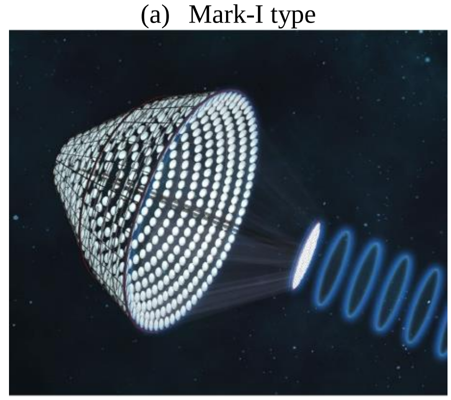
1. Introduction

The prospect of delivering solar power to the earth from platforms in space has been paid attention in recent years, which is still facing many problems, such as steady performance and control method on orbit, the weight and cost. Internationally, Concentrated Photovoltaic (CPV) system was widely used in Solar Power Satellite (SPS) [1]. SPS-ALPHA is composed by a large number of small modules which enables the modularity and low cost of machining/space transport. Until now, two options of SPS-ALPHA have been proposed [2], Mark-I (sigmoid curve-based shape， as Fig. 1 (a) shows) and Mark-Ⅱ (conical shape， as Fig. 1 (b) shows). It has been found that the cosine effect and blocking shadow effect of ray path exist in Mark-I model and make the optical efficiency unstable with different tracking angle.

The optical transmission performance plays important role when SPS-ALPHA satellite travels on orbit. The incident solar rays firstly hit several thousands of hexagonal solar reflecting modules, and then be reflected on the "sandwich" type solar panel. The solar reflectors keep tracking the sun like heliostats of solar tower, simultaneously the sandwich module faces to the ground for wireless power transmission. Compared with Mark-I, conical Mark-Ⅱ structure is designed to reduce the above two negative effects especially blocking shadow between facets at high incident degrees.



(a) Mark-I type



(b) Mark-Ⅱ type

Fig. 1. Computer Renderings of two SPS-ALPHA Options

Two aspects play most important role for electrical output performance: optical efficiency and heat flux uniformity. The former represents total received photons on solar panel, which is determained by the cosine angle of every facets that tracking the sun on real-time. A higher cosine angle will make the effective reflection area lower, as Fig.2 shows. This is a tradeoff with heat flux uniformity because we can not ensure the uniformity when adjusting the lower angles of reflectors at the same time.

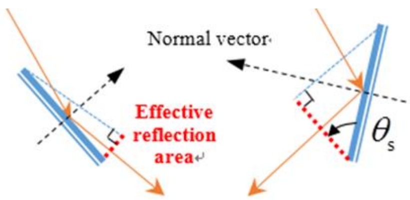


Fig. 2. Cosine effect of small facets on SPS-ALPHA

To reach a balance, the current study adopt source-target mapping to build the 'one by one' relationship between reflecting modules and receiving surface/solar panel that will be divided by discrete meshes at the same quantity with reflectors. Thus one target mesh on solar panel mirror can not receive energy from second mirror at the mapping design process. Here a two-step feedback method are adopted, including initial Monte-Carlo ray tracing (MCRT) process, source-target re-mapping by Ant Colony Optimization(ACO) algorithm and second-time MCRT simulation. Finally the optimal design parameters and adjustment strategy of SPS-ALPHA Mark-Ⅱ would be discussed at different tracking angle and structrual parameters. This method can mostly ensure high optical efficiency at every moment on orbit.

2. Structural model of SPS-ALPHA Mark-Ⅱ

The entire structure of SPS-ALPHA is based on conical shape. Fig.3 shows the structural model at 3-D Cartesian coordinates, including the top main structure composed by reflecting modules and the bottom solar panel.

According to the modular strategy of SPS-ALPHA, the solar concentrator are composed by the so called " Reflectors and Deployment Module" (RDM)[3], which are large, thin-film hexagon reflectors. The hexagon flat reflectors are equally distributed along the sigmoid structure when keeping the surface arrangement as above: generatrix A-B putting along the z axis. Suppose the length of hexagon is d_i, the corresponding distances between horizontal and vertical direction are $3d_i/2$ and $\sqrt{3}d_i$, respectively.

The geometrical model has been built in Fortran program. In order to figuratively presents the structure, the discrete base points of RDM are shown in Fig.4 at the height H_c of 3km, when the radius of RDM Rc and rc are 5km and 2km, the height H_{pv} and the radius of solar panel are 12km and 1km. The dividing quantity of modules along the generatrix A-B is set as 20.

Based on the discrete points above, the hexagon reflecting modules would be generated using local corresponding equation and six constraints.

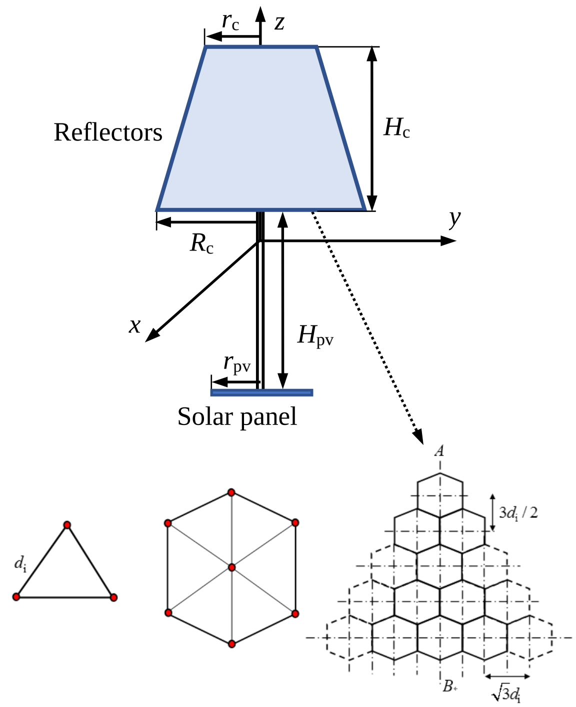


Fig.3. Structural model of SPS-ALPHA Mark-Ⅱ

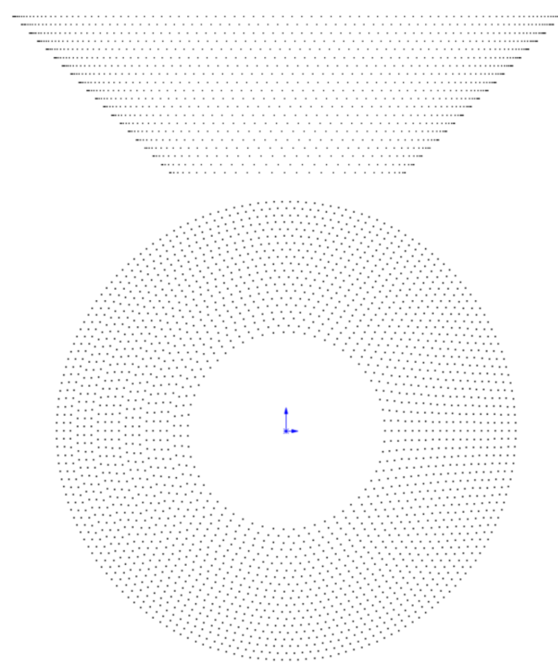


Fig.4. Calculated base points of hexagon solar reflectors

3. Optical modelling and optimization method

The current study develops a flexible optical transmission and adjustment model for SPS-ALPHA Mark-Ⅱ based on skew ray tracing in homogeneous coordinates. It includes several steps for generating the optimized structural parameters for RDM, such as source-target mapping, Monte-Carlo ray tracing and feedback modification. Firstly the basic mathematic method adopted in this article would be introduced as follows:

3.1 Skew ray tracing modelling

There are three types of rays during the optical transmission: paraxial ray, meridional ray and skew ray. The skew ray represents the most general rays that are not even parallel or coplanar with the optical axis. The current study develops the optical model for SPS-ALPHA with the aid of skew ray tracing. The process of optical transmission and transformation of RDM were represented in 4x4 homogeneous coordinates which made the modelling process more convenient and efficiency.

Assume that the incident vector is $\mathbf{L}_\mathrm{s}$, it then become as follows at tracking status:

$$\mathbf{L}_\mathrm{s} = [\cos\alpha\sin\mathrm{A}_\mathrm{z} \quad \cos\alpha\cos\mathrm{A}_\mathrm{z} \quad \sin\alpha \quad 0]^\mathrm{T} \quad (1)$$

The above definition is based on local coordinates and regards the concentrator as relative static. Note that A_z and α represent the solar azimuth angle and altitude angle, respectively.

The normal vector of a RDM is:

$$\mathbf{n}_1 = \mathbf{Rot}(\mathrm{k},\theta_1)(-\mathbf{L}_\mathrm{s}) \quad (2)$$

When θ_1 represents the equally divided angle between incident and reflected rays which can be derived by:

$$\theta_1 = \frac{1}{2}\cos^{-1}(-\mathbf{L}_\mathrm{s}\mathbf{L}_\mathrm{z}) \quad (3)$$

k is the rotation axis of symmetry which is the cross products of incident vector $\mathbf{L}_\mathrm{s}$ and reflected vector $\mathbf{L}_\mathrm{z}$ ($\mathbf{k} = \mathbf{L}_\mathrm{s} \times \mathbf{L}_\mathrm{z}$). $\mathbf{Rot}(\mathrm{k},\theta_1)$ represents the rotation matrix based on local coordinate (Anticlockwise for + and clockwise for -), as follows:

$$\mathbf{Rot}(\mathrm{k},\theta_1) = \begin{bmatrix} k_x k_x(1-\cos\theta_1)+\cos\theta_1 & k_y k_x(1-\cos\theta_1)-k_z\cos\theta_1 & k_z k_x(1-\cos\theta_1)+k_y\sin\theta_1 & 0 \\ k_x k_y(1-\cos\theta_1)+k_z\sin\theta_1 & k_y k_y(1-\cos\theta_1)+\cos\theta_1 & k_z k_y(1-\cos\theta_1)-k_x\sin\theta_1 & 0 \\ k_x k_z(1-\cos\theta_1)-k_y\sin\theta_1 & k_y k_z(1-\cos\theta_1)+k_x\sin\theta_1 & k_z k_z(1-\cos\theta_1)+\cos\theta_1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

In system coordinate, assume the starting point is $\mathbf{P}_{i\text{-}1} = \begin{bmatrix}\mathrm{P}_{i\text{-}1,x} & \mathrm{P}_{i\text{-}1,y} & \mathrm{P}_{i\text{-}1,z} & 1\end{bmatrix}^\mathrm{T}$ which emits a skew ray along the vector of $\mathbf{L} = \begin{bmatrix}\mathrm{L}_{i\text{-}1,x} & \mathrm{L}_{i\text{-}1,y} & \mathrm{L}_{i\text{-}1,z} & 0\end{bmatrix}^\mathrm{T}$ and intersects a certain surface at $\mathbf{P}_i = \begin{bmatrix}\mathrm{P}_{i,x} & \mathrm{P}_{i,y} & \mathrm{P}_{i,z} & 1\end{bmatrix}^\mathrm{T}$, therefore the point of intersection can be obtained by:

$$\mathbf{P}_i = \begin{bmatrix}\mathrm{P}_{i\text{-}1,x} + \lambda_i \mathrm{L}_{i\text{-}1,x} & \mathrm{P}_{i\text{-}1,y} + \lambda_i \mathrm{L}_{i\text{-}1,y} & \mathrm{P}_{i\text{-}1,z} + \lambda_i \mathrm{L}_{i\text{-}1,z} & 1\end{bmatrix}^\mathrm{T} \quad (5)$$

Where λ_i represents the length of corresponding vector $\overrightarrow{\mathbf{P}_{i\text{-}1}\mathbf{P}_i}$. Next point $\mathbf{P}_i$ can be therefore obtained when the variable λ_i is solved. When the next intersection point is on RDM, λ_i can be derived as:

$$\lambda_i = \frac{-\left(I_{i,y}P_{i-1,x} + J_{i,y}P_{i-1,y} + K_{i,y}P_{i-1,z} + t_{i,y}\right)}{I_{i,y}L_{i-1,x} + J_{i,y}L_{i-1,y} + K_{i,y}L_{i-1,z}} \quad (6)$$

When the transformation matrix from system to local coordinates ${}^{i}A_0$ is:

$${}^{i}A_0 = \begin{bmatrix} I_{i,x} & J_{i,x} & K_{i,x} & t_{i,x} \\ I_{i,y} & J_{i,y} & K_{i,y} & t_{i,y} \\ I_{i,z} & J_{i,z} & K_{i,z} & t_{i,z} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (7)$$

Note that *I*, *J*, *K* represent the direction vectors of local coordinates in system coordinates. *t* is the positions.

3.2 Solution procedure

The existence of solar cone angle and error factors makes it impossible to achieve direct solution. Therefore several steps as follows need to be adopted before obtaining the optimal design parameters. Firstly, according to the transmission pattern of RDM, the source-target mapping in specific directions based on the point to point assumption should be established. With the aid of skew ray tracing method, the entire structure and discrete central points of RDM can be obtained. After that the normal vectors of RDM and constraint boundary of hexagon surfaces are achieved for RDM surfaces modelling. Then the MC ray tracing method has been developed for SPS-ALPHA. The simulation matrix data can be finally optimized through ACO algorithm. The following sections will present the detail solutions.

3.3 Source-target mapping

The energy conservation between the source and target mapping is expressed as the following equation assuming that the optical transmission is lossless:

$$\iint_{D_I} I(\theta_I, r_I)d\theta dr = \iint_{D_E} E(\theta_E, r_E)d\theta dr \quad (8)$$

Where (θ, r) are the polar coordinates used to stand for the positions of discrete points. *I* is the solar irradiance which we take equal to 1353W/m^2. *E* is the heat flux intensity on the target surface.

Irradiance uniformity is a crucial factor for solar panel and largely influences the output efficiency. Considering the effect of solar cone angle (32 ´), the overlapped focal spots would inevitably form a Gaussian distribution especially for the multi-surface optical system such as traditional solar tower or the current studied model.

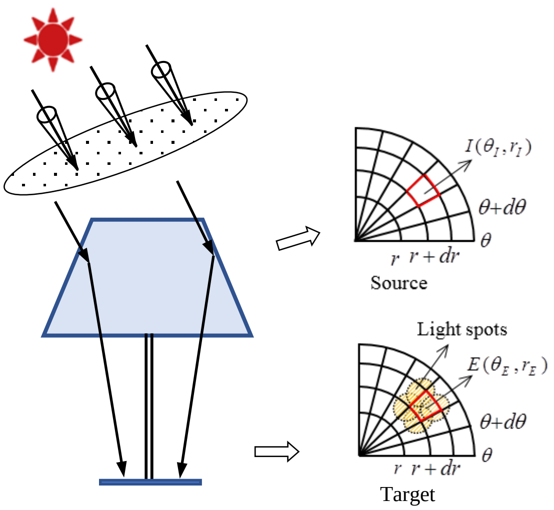


Fig.5. Ray mapping between source and target surface in SPS-ALPHA system

The left of Fig.5 shows the optical transmission process of SPS-ALPHA. Similar with the traditional solar tower, the RDM works as solar tracking heliostats that can ensure to reflect the incident solar rays onto the solar panel. Imagine that the incident solar forms a circular source which can be divided in several grids based on polar coordinates. The light spots on target solar panel are overlapped with each other when considering solar cone angle and supposing that the surfaces are generated based on point-point mapping. Note that the heat flux at every grid (θ_E, r_E) of target surface is formed by several pairs of light spots. However, the prediction of obtaining a target value of $E(\theta_E, r_E)$ is possible through modifying only one parameter of (θ_E, r_E) and keeping the other one fixed. In other words, the ray mapping becomes as the following equation (9):

$$(\theta_E, r_E) = (\theta_I, g(\theta_I, r_I)) \qquad (9)$$

Where g is the continuous function representing the relationship between the source location (θ_I, r_I) and target radius r_E. Based on the above assumption, the variables can be much easier to be solved in 3-D dimension.

Note that under the sun tracking condition, the mapping mode changes with time. The concentrated heat flux distribution deviated from the center of receiver and this level depends on:

3.4 RDM generation and Monte-Carlo ray tracing

The RDM surfaces are generated based on specific equations and corresponding boundary constraints in Fortran program. Typically, each modular needs six constraints that limit the area of hexagons. The normal vector of RDM can be derived by equation (3). Combined with the central points as Fig.3 obtains, all the reflectors can be modelled.

MCRT treats the incident sunlight as a large amount of independent and random sampled rays in order to trace the path[4]. The current study treats the RDM surfaces as independent solar reflectors and tracing the rays. Before proceeding the ray tracing, the cluster data of possible intersecting surfaces which correspond every sequential facets will be stored. That can help to speed up the simulation efficiency by MCRT. More details about MCRT please refer to [5, 6].

3.5 ACO optimizations

The cosine effect and heat flux uniformity would be both considered in current study. Thus the source-target mapping is 'one mesh by one mesh' instead of 'multi meshes by one mesh'. Therefore hundreds or even thousands of variables exist in optimization process, traditional methods can hardly satisfy the target. New emerging technologies such as intelligent optimization algorithms[7] provide possibilities for treating more variables. The ant colony optimization algorithm (ACO) is a probabilistic technique for solving computational problems[8]. Through depositing pheromone which is an evaporable material, the ants tend to select the path with higher pheromone value and can finally find the shortest way between the nest and food sources. The biggest challenge for the application of ACO in current case is to convert the target variables into crawling distance of ants. As Fig. 6 shows, each nest represents one mapping relationship. The optical heat flux field and associate information would be divided into discrete area and meshing points, through adjusting which the optimized effective reflection area/optical efficiency (highest pheromone & shortest path) can be achieved.

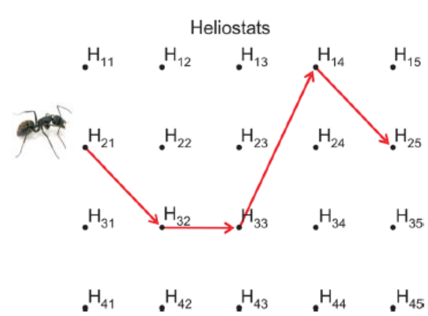


Fig.6. Ant colony optimization algorithm for current model

After getting the optimized path as well as the mapping relationship from ACO, MCRT ray tracing will be adopted for the second time, as Section 3.4. Then the output performance can be greatly improved through current model.

4. Results and discussion

4.1 Solar tracking characteristics

Based on local coordinates of RDM, the solar incident angle changes when tracking around the satellite. Due to the cosine effect, the effective reflection areas are different between each module and it also changes at incident angle. Since the structure of SPS-ALPHA is axis-symmetrical, it can be known that the energy transmission of RDM is also symmetrical when the incidence is 0 degree. The solar tracking characteristics can be revealed through changing the incident angle at the axial plane of symmetry. When the solar incident angle is nonzero, the effective reflection area at the back RDM is apparently smaller than the front RDM. In addition, the light path through some modules can be blocked by others. These two effects above result into the changing of the receiving energy at different incidences.

At different incident altitude angle, the energy proportions have been investigated. Define that the energy proportion is as follows:

$$E_{\text{corrected}} = \frac{E_\alpha}{E_{\max}} \qquad (14)$$

When E_α is the total receiving energy at the altitude angle α, $E_{\max}$ represents the maximum value of receiving energy.

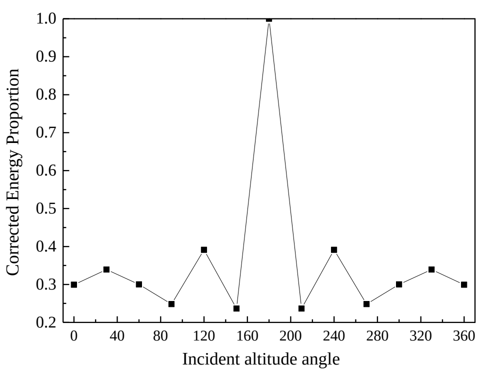
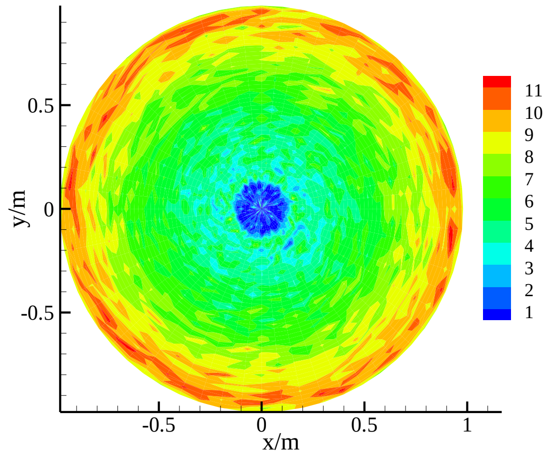


Fig.7. Corrected energy proportion at different incident altitude angles

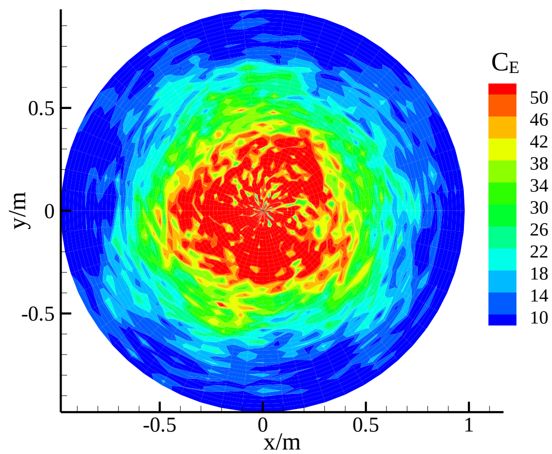
According to Fig.7, we can find that the maximum receiving energy happens at α =180°, when the solar is just under the bottom of SPS-ALPHA and the cosine effect is weakest. There are two trough and corresponding minimum energy at α =90° and 150°, when the ray paths have been blocked most seriously and the receiving energy is few.

4.2 Heat flux distribution

The 2-D heat flux distributions have been obtained when the incidence is 0°, as fig. 8 shows. Before the optimizations and based on the original source-target mapping relationship, the concentrated heat flux presents an annular distribution with the concentration radio between 4~11suns. It can be seen that the solar spot mainly distributes at the edge region. This will apparently waste the area of solar panel and reduce the PV efficiency.



(a) before optimization



(b) after ACO optimizations

Fig. 8 Concentrated heat flux distribution at receiving surface, α =0°

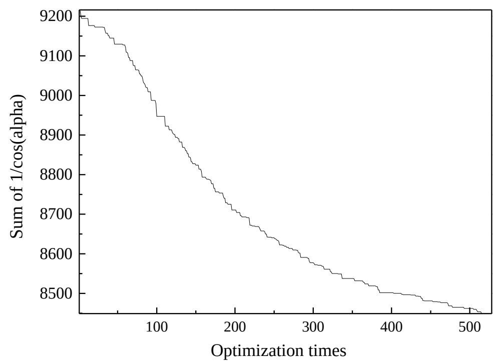


Fig. 9 Presents for ACO optimization efficiency

When the ACO method is adopted, the total harvest solar energy increase to 3.26 times compared with original mapping, as Fig.8(b) shows. The energy concentration ratio on solar panel is around 30~50 suns. In addition, the heat flux distribution become better. Figure 9 shows the ACO optimization efficiency for 2368 source by 2368 target grids mapping. The ACO optimization works well and the sum of 1/cos(alpha) decrease dramatically with optimization times. The Sum of 1/cos(alpha) for all the facets represents the decrease of cosine effect, or a parameter for the effective reflection area.

5. Conclusions

The current study focuses in the optical design method for SPS-ALPHA Mark-Ⅱ. The solving procedure is complex and involves source-target mapping, surface modelling, MC ray tracing and ACO feedback modifications. Based on the approach, the solar tracking characteristics of SPS-ALPHA Mark-Ⅱ have been investigated. It was found that the receiving energy apparently changes with incident angle, which is mainly caused by the cosine effect and the block of ray path. In addition, the 2-D simulation results show that the heat flux distribution largely changes with incident angle. The current model have strong ability to improve the optical efficiency to 3.26 times as well as the heat flux uniformity.

References

[1] J.C. Mankins. A fresh look at space solar power: New architectures, concepts and technologies. Acta Astronautica. 41 (1997) 347-59.
[2] J.C. Mankins. New Developments in Space Solar Power. NSS Space Settlement Journal. 2017.
[3] J.C. Mankins. SPS-ALPHA: The first practical solar power satellite via arbitrarily large phased array (a 2011-2012 NASA NIAC phase 1 project). Santa Maria, CA: Artemis Innovation Management Solutions LLC. (2012) 17.
[4] M.F. Modest. Radiative heat transfer. Academic press 2013.
[5] X.L. Xia, G.L. Dai, Y. Shuai. Experimental and numerical investigation on solar concentrating characteristics of a sixteen-dish concentrator. international journal of hydrogen energy. 37 (2012) 18694-703.
[6] X.L. Meng, X.L. Xia, C. Sun, G.L. Dai. Optimal design of symmetrical two-stage flat reflected concentrator. Solar Energy. 93 (2013) 334-44.
[7] Rana S, Jasola S, Kumar R. A review on particle swarm optimization algorithms and their applications to data clustering. Artificial Intelligence Review, 2011, 35(3): 211-222.
[8] Al Salami N M A. Ant colony optimization algorithm. UbiCC Journal, 2009, 4(3): 823-826.