The Calculation of Thermal Temperature of Specified Radar Based on Domain Decomposition Method

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Abstract. Approach the method of Domain Decomposition Method calculating specified radar’s thermal temperature. Used Domain Decomposition Method to analyze the specified radar, changed the complex geometric object to simple one, which simplified the calculation procedure. Through the calculation of practical, we calculated the radar’s thermal temperature when solar horizon and vertical incidence. The thermal temperatures of radar in two conditions are all agreed to physical circumstances, which indicated this method is valid.

Keywords: Radar; Domain Decomposition Method; IR; Thermal temperature.

1. Introduction

At present, the research of target infrared thermal imaging modeling has become one of the research hot spots in China. The calculation of the target temperature field is the key to complete the simulation of the target thermal imaging. How to effectively calculate the temperature field of the target has become the top priority[1]. In this paper, radar is used as an example, and the geometric model of the radar is established by using the area decomposition algorithm. The radar surface temperature field distribution is calculated in two cases, which provides a reference for infrared search.

2. Domain Decomposition Algorithm

The area method was first proposed by Hottel H.C. and Cohen E.S. in 1958[2], and it is actually an extension of the net radiation method for calculating radiative heat transfer between surfaces[3]. In actual engineering, the calculation area usually has high-dimensional and large-scale problems, and the shape is likely to be irregular, with too many influencing factors, which will make the calculation amount very large. With new achievement of parallel computing algorithms[4-6], many solutions were proposed for partial differential numerical solution. These proposed methods have achieve huge success. In simple terms, the area decomposition algorithm decomposes the calculation area \( \mathcal{\Omega} \) into sub-regions \( \omega_i \): \( \mathcal{\Omega} = \bigcup_{i=1}^{N} \omega_i \) (where \( \mathcal{\Omega} \) is the closure of \( \Omega \)).

The shape of the sub-regions is as regular as possible, so the solution of the original problem is converted to the sub-region. Generally, the target is mainly composed of rectangle, cylinder, circular table, cone and other geometry, so the target (calculation domain) can be decomposed into sub-regions composed of regular geometry. Each surface of the target generally has different interface characteristics. Therefore, the calculation of radiative transmission should consider the universality of various radiant cross-sectional characteristics.

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3. Area Decomposition of Radar

The simplification of a certain type of radar. According to the above description, it is divided into two parts: a spherical cap and a cylindrical part.

The surface of the ball is divided. The geometric description of the spherical crown surface in the spherical coordinate system is

\[
\begin{align*}
0 \leq \theta &\leq \pi / 2 \\
0 \leq \phi &\leq 2\pi \\
R & = 0.35
\end{align*}
\]

(1)

In the formula, \( \phi \) is the circumferential angle of the crown, \( \theta \) is the zenith angle of the crown, and \( R \) is the radius of the crown. Taking \( N\theta = 10 \) and \( N\phi = 40 \), divide them into 400 grids.

The meshing of the cylindrical surface is as follows. The geometric description of the cylindrical surface cylindrical coordinate system is

\[
\begin{align*}
0.5 \leq z &\leq 1.7 \\
0 \leq \phi &\leq 2\pi
\end{align*}
\]

(2)

In the formula, \( \phi \) is the circumferential angle of the cylinder, and \( z \) is the height range of the cylinder. Take \( Nz = 12 \) and \( N\phi = 40 \), which are divided into 480 grids.

4. Calculation of Radar Surface Temperature Field

4.1. Determination of the Coordinate System

As the mutual position between the earth and the sun and between the radar and the earth is constantly changing, three coordinate systems are established here: the earth coordinate system \( i-j-k \); the earth surface coordinate system \( X-Y-Z \); the radar coordinate system \( p-q-r \).

1. Earth coordinate system \( i-j-k \)

The \( ioj \) plane (\( o \) is the origin of the coordinate system) is the equatorial plane of the earth, the \( k \)-axis is the axis of rotation of the earth, and the north-centre points to the north pole, and the sun's rays are in the \( iok \) plane. For a certain day, let the relative position of the earth and the sun remain unchanged, that is, a fixed \( i-j-k \) coordinate system. The change of local time at a point on the surface of the earth is reflected by the change of the circumferential angle \( \phi \). The coordinates \( (x, y, z) \) of a point on the surface of the earth in the \( i-j-k \) coordinate system at time \( t \) are

\[
(x, y, z) = R_e (\sin \theta \cos \phi, \sin \theta \sin \phi, \cos \phi)^T
\]

(3)

In the formula, \( R_e \) is the radius of the earth. At this time, \( (\pi / 2 - \theta) \) is the latitude of the point.

2. Earth surface coordinate system \( X-Y-Z \)

Take a point \( (x, y, z) \) on the surface of the earth as the origin of the coordinates and establish a \( X-Y-Z \) coordinate system. Let the normal of the earth tangent plane passing this point be the \( Z \) axis, and its direction cosine in the \( i-j-k \) coordinate system is

Where \( \Omega \) is the integral region and \( k(x, y, z) \) is the integrand function. Consider a probability density function \( f(x, y, z) \) on \( \Omega \), which satisfies the following conditions

\[
[tZ (1) \ , \ tZ (2) \ , \ tZ (3)] = \left( \frac{x_j}{R_e}, \frac{y_j}{R_e}, \frac{z_k}{R_e} \right)
\]

(4)

The west axis is the \( X \) axis, and its cosine in the \( i-j-k \) coordinate system is
\[ [tX(1), tX(2), tX(3)] = \begin{bmatrix} y_j \sqrt{x_j^2 + y_j^2} & -x_j \sqrt{x_j^2 + y_j^2} & 0 \end{bmatrix} \] (5)

The south direction is the Y axis, and its cosine in the i-j-k coordinate system is

\[ [tY(1), tY(2), tY(3)] = \begin{bmatrix} x_j z_k \sqrt{x_j^2 + y_j^2} & y_j z_k \sqrt{x_j^2 + y_j^2} & - \sqrt{x_j^2 + y_j^2} \end{bmatrix} \] (6)

3. Radar coordinate system p-q-r

Take the intersection of the radar's center axis and the sea surface as the origin of the coordinates, the submarine's heading is the p axis, the center axis is the r axis, and then the q axis is determined by the right-hand rule. According to the position of the submarine on the surface of the earth, the angle between the p-axis and the X-axis is assumed to be \( \beta \). From this, the direction cosines of the coordinate system p, q, and r axes in the X-Y-Z coordinate system can be calculated as:

\[ [tp(1), tp(2), tp(3)] = [\cos \beta \sin \beta, 0] \] (7)

\[ [tq(1), tq(2), tq(3)] = [\sin \beta, -\cos \beta, 0] \] (8)

\[ [tr(1), tr(2), tr(3)] = [0, 0, 1] \] (9)

4.2. Determination of the Direction of Solar Incidence

The earth makes a uniform circular motion around the sun with a period of one year. The angle \( \gamma \) between the connection between the center of the earth and the sun and the equatorial plane is related to the position of the earth and the sun, and the change law is a sinusoidal relationship, that is,

\[ \gamma = 23.5^\circ \frac{\pi}{180} \sin \alpha \] (10)

In the formula, \( \alpha \) is the sweeping angle between the center of the earth and the sun on the nth day of the year (on March 21, the 80th day of the year is a zero degree angle, and the sun is directly on the equator, \( \alpha = 0, \gamma = 0 \)).

\[ \alpha = \frac{2\pi}{365} (n - 80) \] (11)

In the i-j-k coordinate system, since the sun's rays are always in the iok plane throughout the day, the angle between the sun and the i-axis is the angle \( \gamma \) between the sunlight and the equatorial plane. The number of directions of the sun's rays in the i-j-k coordinate system is \( (\cos \gamma, 0, \sin \gamma) \). After two coordinate transformations, the number of directions of the sun's rays in the i-j-k coordinate system is converted into the number of directions \( (x_p, y_q, z_r) \) in the radar coordinate system p-q-r, that is,

\[
\begin{bmatrix}
    x_p \\
    y_q \\
    z_r
\end{bmatrix} =
\begin{bmatrix}
    tp(1) & tp(2) & tp(3) \\
    tq(1) & tq(2) & tq(3) \\
    tr(1) & tr(2) & tr(3)
\end{bmatrix}
\begin{bmatrix}
    tX(1) & tX(2) & tX(3) \\
    tY(1) & tY(2) & tY(3) \\
    tZ(1) & tZ(2) & tZ(3)
\end{bmatrix}
\begin{bmatrix}
    \cos \gamma \\
    0 \\
    \sin \gamma
\end{bmatrix}
\]
Thus, the circumferential angle $\psi_{sun}$ and zenith angle $\theta_{sun}$ of the sun's rays in the $p$-$q$-$r$ coordinate system can be obtained, that is,

$$\begin{align*}
\theta_{sun} &= \cos^{-1}\left(\frac{z_r}{\sqrt{x^2_q + y^2_q + z^2_r}}\right), \\
\psi_{sun} &= \cos^{-1}\left(\frac{x_r}{\sqrt{x^2_q + y^2_q}}\right).
\end{align*}
$$

4.3. Calculation of Temperature Field
The solar radiation that reaches the radar surface through the atmosphere is divided into two parts, direct and scattering, and the direct part accounts for about 70% to 85%. The direct sunlight is parallel light, and the scattering of solar radiation is diffuse reflection. Let: $H_{sun}$ be the radiance (transmitted radiance) of the sun in the direction of incidence, the unit is $W/m^2$; $A_i$ is the geometric area of the surface element $i$; $P_{ir}$, $P_{is}$ are Direct and Scattering Shares in Solar Radiation; $a_{\lambda,i}$ is the surface spectral absorptivity of the elemental $i$ below the solar projection source. Using the spectral band model, the $a_{\lambda,i}$ is divided into $M_{b,sun}$ spectral bands with the change of the solar spectrum. Then, the solar radiation heat flux rate of the surface element $i$ on the radar surface is:

$$Q_{sun}^i = H_{sun} \sum_{mp=1}^{M_{b,sun}} a_{\lambda,mp} B_{\lambda,sun}^{mp} \left(A_{\lambda,pro}^{sun} P_{ir} + A_{\lambda,sc}^{sun} P_{isc} \right).$$

In the formula $Q_{sun}^i$ ——The radiant heat flux of the sun to the surface element $i$, W;

$B_{\lambda,sun}^{mp}$ ——Share of blackbody radiant energy in the $mp$ band ($\Delta \lambda_{mp}$) at solar surface temperature $T_{sun}$

$$B_{\lambda,sun}^{mp} = \int_{\lambda_{min}}^{\lambda_{max}} I_{\lambda}(T_{sun}) d\lambda \left[\int_{\lambda_{min}}^{\lambda_{max}} I_{\lambda}(T_{sun}) d\lambda \right].$$

$A_{\lambda,pro}^{sun}$ ——The projection area of the surface element $i$ illuminated by the sun (taking into account the effect of occlusion) on the incident direction of the sun, referred to as the "sun incident projection area", the unit is $m^2$. After the area is decomposed, how to determine the direction of the sun's
incidence and calculate the projection area of the sun's incidence.

5. Example Calculation
A ship is located at a 30° northeast latitude, the infrared absorption rate of the radar is 1, the ambient air temperature is 303K, and the calculation time is 6:00 and 12:00 on March 21, regardless of the internal heat source. Suppose the projection share AA of direct sunlight and the projection share BB of solar scattering. First, calculate the incident incident area of the sun, including the calculation of the area of direct sunlight projection and the calculation of the area of solar scattering projection. The formula (14) is used to calculate the heat flow rate of the solar radiation on the radar surface, so as to calculate the temperature distribution of the radar surface. The temperature distributions of the radar and the radar at 0° and 90° in the horizontal direction are shown in Fig. 1 and Fig.2, respectively.

In Fig.1, It can be concluded that when the sun irradiates the radar at an angle of 0° from the horizontal direction, the temperature of the illuminated part of the front of the radar gradually decreases from the middle to both sides. The highest temperature is mainly concentrated in the radar column and the spherical cap. At the junction of parts, the maximum temperature is 34°C; It can be seen from Figure 3 that when the sun is irradiated to the radar at an angle of 90° from the horizontal direction, there is no obvious temperature change in the columnar part of the radar. The temperature change is mainly concentrated in the radar crown, and the temperature gradually decreases from the centre to the surrounding. The highest temperature is at the top of the radar, with a maximum temperature of 39°C. In both cases, the radar temperature field distribution is consistent with the actual situation.

![Figure 1. 0° Radar Surface Temperature Distribution of the Sun](image1)

![Figure 2. Surface Temperature Distribution of Radar at 90 ° Radiation](image2)

The area decomposition algorithm can simplify complex problems and facilitate calculation. The
calculation of the radar temperature field provides a basis for the calculation of the infrared radiation characteristics of the radar surface.

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