Optimal Design of Antenna for Spaceborne SAR Based on Differential Evolution Algorithm

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Abstract: An important feature of future spaceborne synthetic aperture radar (SAR) is the adoption of large mesh reflectors fed by arrays. The main advantage of this SAR sensor is the provision of large antenna apertures and reconfigurable feed excitation. A large deployable mesh-reflector antennas combined with feed arrays is designed for the application of spaceborne SAR on geosynchronous orbit. To decrease the transmit power of feed element and increase the flexibility, a large scale of two-dimensional feedarray is adopted. An approach based on defocused reflector is used to broaden the beams from feed element, so almost all the feed elements can participate in the pattern synthesis in the complete angular domain. This paper presents a new optimization method of the defocused reflector system. The method aims at getting high gain and low sidebores by optimizing the reflector parameters together with the feed array. The differential evolution algorithm(DE) is used to get globally optimal solution. The performance of the reflector after optimization is computed to demonstrate the effective of the method presented.

1. Introduction

The concept of SAR on geosynchronous orbit was put forward by Tomiyasu[1] in 1978. Compared with low orbit SAR system, SAR on geosynchronous orbit has the advantages of wide observation range, short revisit time and long continuous observation time. It is suitable to monitor dynamic processes on earth’s surface. Important applications are oceanography, measurements of polar ice and snow cover, the generation of terrain models, as well as disaster monitoring related to earthquakes, typhoon events, and volcano eruptions. Although many experts have done a lot of reserach work[2-4], but due to the limination of high transmitting power, high gain, volume and weight, it has not been applied in engineering. With the development of deployable large aperture reflector technology, reflector in combination with feed arrays[5-8] has been sucessfully applied to low-orbiting SAR system. The design of SAR antenna on geosynchronous orbit may benifit from this technoloty. The most widely used SAR antenna is the planar phased array antenna. The drawback of this kind antenna for high orbit satellite applications is that the array size can render a mission infeasible. Consequently, an antenna design is needed, which combines the flexibility of a planar array antenna with the high gain of a large unfoldable reflector antenna. This concept involves a defocusing of the individual element beams by moving the feed out of the focal point[9].

The paper is organized as follows: Section II introduces the system operation concept of defocusing reflector based SAR systems on geosynchronous orbit. Section III explains the analysis metod of reflector and the optimization algorithm. A numerical example of design and optimization of a reflector at L band is proposed in section IV. Therefore, conclusions are drawn.
2. Spaceborne SAR With Defocusing Reflector Antennas

The structure of reflector-based SAR systems with planar digital feed arrays is sketched in Fig. 1. The electromagnetic wave is transmitted with all feed elements simultaneously and deflection by the reflector to the ground. The electromagnetic wave returning from the ground is again scattered by the reflector and successively collected the feed array.

![Figure 1. Cross-sectional View of Reflector Fed by Array.](image)

High power and high gain are contradicting requirements for SAR systems on geosynchronous orbit. To decrease the power of feed element, the planar arrays will be very large. Because the secondary beam of large parabolic reflector is very narrow, only a few part of the feeds can participate in the synthesis of transmission pattern, resulting in low transmission gain.

The defocusing effect can be achieved by moving the feed out of the focal point. A paraboloidal reflector with an axially shifted feed will generate a broader rotational symmetric beam. If the axial defocus is large enough, the secondary pattern of each feed element can be broadened to all angular domain. High transmission gain and low sidelobe can be obtained by optimizing the phase of array. A simple method to defocus a parabolic reflector is to construct a reflector with two focal points[9]. Such a geometry can be described in Cartesian coordinates as

\[ z = \frac{x^2}{4F_x} + \frac{y^2}{4F_y} \]

where \( F_x \) and \( F_y \) denote the focal lengths in the x- and y-dimension, respectively. The linear feed array is placed in the upper focal plane parallel to the x-axis in a centered position. Here the feed elements are simply directed in z-direction of feed coordinate as shown in figure 1.

3. Analysis Method And The Optimization Algorithm

The antenna radiating field is spherical, so the problem will be solved by using the spherical coordinate system, and such an antenna fed by array is analyzed using the method of physical optics(PO). The induced currents on a perfectly conducting infinite plane surface illuminated by an arbitrary incoming field are given by the formula as follow:

\[ J_{po} = 2n \times H_i \]

Here \( J_{po} \) is the induced electric current, \( n \) is the unit surface normal (pointing outward on the illuminated side of the surface) and \( H_i \) is the incident magnetic field. The radiated far field from a set of induced or equivalent currents can be computed from:

\[ E = -j \frac{k \eta}{4\pi} \int_{S'} \left[ J_{po} - (J_{po} \cdot r)r \right] e^{jkr} ds' \]
$k$ is the wavenumber which is related to the wavelength and $\eta$ is the free-space impedance. The parameter $r$ is the observation point and $r'$ is the integration variable running over the surface $S$. The radiation pattern of the antenna is obtained as a superposition of fields reflected by the reflector.

As already being pointed out, the objective of the antenna design is to get high gain and low side lobes within a certain angle range. To meet this design demand, the radiated field reflected by the reflector must be added constructively in some desired directions and added destructively to cancel other in the remaining space. It is a typical multi-objective optimization problem that antenna parameters and the feed array excitation coefficient need to be optimized. Differential evolution (DE) [10-11] is suitable for solving this multi-objective optimization problem due to its global search ability, effectiveness and simple operation.

DE is a stochastic search method that starts to explore the search space by randomly chosen initial point. The M+4-dimensional parameter vector in generation $G$ (population size, $M$= feed element number) utilized can be formulated as follows:

$$X_{i,G} = \left( F_x, F_y, H, D_z, c_1, c_2, \ldots, c_M \right)^T$$

where $F_x$ and $F_y$ are respectively focal lengths in the x- and y-dimension and $H$ is offset height of reflector. $D_z$ is the defocusing distance of feed array in z-axis direction and $c_m$ is the excitation coefficient of the m-th feed, $1 \leq m \leq M$.

DE generates new parameter vectors by adding the weighted difference of two population vectors to a third randomly selected vector. The mutant vector is generated according to the following equation [10-11]:

$$V_{i,G} = X_{n,G} + P \times (X_{m,G} - X_{l,G})$$

where $i$, $m$, $n$, and $l$ are randomly selected from \{1, 2, …, NP\} and $i \neq m \neq n \neq l$. $P \in [0,2]$ is a real and constant factor.

The crossover operation is utilized to increase the diversity of the population, The crossover scheme can be written as:

$$U_{y,G} = \begin{cases} V_{y,G} & \text{if } \text{rand}_{0,1} \leq C \\ X_{y,G} & \text{otherwise} \end{cases}$$

Where $j=1,2, \ldots, M+4$, $C \in [0,1]$ is the crossover constant and rand$(0,1)$ is the jth evaluation of a uniform random number generator.

After the crossover operation, the fitness value of each vector is calculated. There are many parameters that can be used to evaluate the fitness function when designing an antenna. In our case, the gain(G) and side lobel level(SLL) are of importance. It is possible to define total fitness function expression:

$$f(X_{i,G}) = a \times (G(X_{i,G}) - G_0)^2 + b \times (SLL(X_{i,G}) - SLL_0)^2$$

where $G_0$ and $SLL_0$ are respectively the gain and side lobel design requirement, $a$ and $b$ are corresponding weight coefficient.

The fitness value of the new vector generated by the above mutation and crossover operation is compared with that of its parent vector. The individuals with fitness better fitness value survives and becomes a member of the next generation.

4. Design Examples
In order to confirm the effectiveness of the described method, a numerical example is presented here. According to formula (6), the objective function is constrained. The DE method is used to search the globally optimal solution. The specifications of the reflector before and after optimization are given in table 1.
Table 1. Antenna parameters

| Parameter                | Initial Value | Optimized Value |
|--------------------------|---------------|-----------------|
| Frequency                | 1.25(GHz)     | 1.25(GHz)       |
| Reflector diameter       | 30m           | 30m             |
| Focal lengths            | F_x=20m, F_y=22m | F_x=21.6m, F_y=23.98m |
| Offset height            | H=8m          | H=9.36m         |
| Defocusing distance      | D_z=3m        | D_z=3.88m       |
| Number of feed elements  | 18×18         | 18×18           |
| Feed element spacing     | 0.66λ         | 0.66λ           |

When the antenna scanning angle(θ) is 0 and 2.5°, the optimized amplitude and phase distributions of feed elements are respectively shown in Figures 2 and 3.

Figure 2. Amplitude and Phase Excitations of the Array Elements(θ=0°)

Figure 3. Amplitude and Phase Excitations of the Array Elements(θ=2.5°)
Figures 2 and 3 show the amplitude and phase excitations of the array elements for different scanning angle. In order to reduce the radiation power of the feed element, all the units work at the same power when they are in the transmitting mode, so only the phase is optimized. In the receiving mode without power limitation, the amplitude and phase are optimized at the same time. The maximum difference of receiving unit amplitude is only 7.3dB in the normal case, but it increases to 24.4dB when the scanning angle is 2.5°.

The radiation pattern of the antenna after optimization is depicted in Figure 4 ~ 5 and the antenna performance is summarized in table 2.

![](image1.png)

**Figure 4. Radiation Pattern of Antenna(θ=0°).**

![](image2.png)

**Figure 5. Radiation Pattern of Antenna(θ=2.5°).**

| model | Directivity(dBi) | side lobe(dB) |
|-------|-----------------|---------------|
|       | E-plane         | H-plane       |
| θ=0°  | Tx 48.7         | -16           | -19.4          |
|       | Rx 48.9         | -18.2         | -21.7          |
| θ=2.5°| Tx 46.9         | -14.6         | -17            |
|       | Rx 48.1         | -17.1         | -20.1          |

It can be seen with the increase of scanning angle, the directivity of antenna decreases, especially in the Tx model. All side lobes are below the -14.6 dB level in Tx model, but below -17.1dB in Rx.
The amplitude is involved in the Rx model optimization, so the performance is better than that in Tx model.

5. Conclusions
In this study, an optimized algorithm for the design of large deployable reflectors fed by arrays is presented. The approach is based on the DE method applied on antenna parameters, taking into account both the phase and the amplitude of the feed element. A numerical example showed the validity of the method for antenna optimization, thus overcoming the problems highlighted in antenna parameter selection. Such defocused reflector concepts have the potential to significantly reduce the costs for spaceborne SAR systems on geosynchronous orbit.

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