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Research Article

Performance Improvement of Spaceborne SAR Using Antenna Pattern Synthesis Based on Quantum-Behaved Particle Swarm Optimization

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This study improves the performance of a spaceborne synthetic aperture radar (SAR) system using an antenna mask design method and antenna pattern synthesis algorithms for an active phased array SAR system. The SAR antenna is an important component that affects the SAR system performance because it is closely related to the antenna pattern. This study proposes a method for antenna mask design that is based on several previous studies as well as the antenna pattern synthesis algorithm, which is based on quantum-behaved particle swarm optimization (QPSO) for an active phased array SAR system. The performance of the designed antenna masks and synthesized patterns demonstrate that the proposed mask design method and antenna pattern synthesis algorithm based on QPSO can be used to improve the SAR system performance for spaceborne applications.

1. Introduction

Generally, active phased array antennas are used for spaceborne synthetic aperture radar (SAR) because their electronic beam steering capability without satellite maneuvering or mechanical beam pointing provides flexibility and agility. Active phased array antennas should be designed to satisfy the performance requirement of a SAR system according to the various operation modes [1]. The significant performance parameters of a SAR system include the swath width (SW), noise equivalent sigma zero (NESZ), range ambiguity-to-signal ratio (RASR), and azimuth ambiguity-to-signal ratio (AASR). These parameters have a close relationship with the SAR antenna pattern and can be improved by synthesizing an adequate SAR antenna pattern. The most important step in synthesizing an adequate antenna pattern is to design the antenna mask template. Design guidelines for the antenna mask have been described previously [2, 3]. Several studies [4–8] have proposed synthesis techniques for creating an antenna pattern that improves the SAR system performance. The conventional particle swarm optimization (PSO) technique was used to improve SAR system performance [4, 5]; the simulated annealing algorithm was used as a beamformer optimization technique [6]; and the genetic algorithm (GA) was used for performance optimization [7, 8].

This paper proposes a method to design an antenna mask template and uses quantum-behaved particle swarm optimization (QPSO) as the optimization algorithm for the antenna pattern synthesis. We made a performance comparison between the QPSO and two other algorithms, the GA and the conventional PSO. The results of the antenna pattern synthesis and the performance analysis were evaluated and validated using the design parameters of active phased array antennas for Korea Multipurpose Satellite-5 (KOMPSAT-5) [9], which was successfully launched in 2013 and is currently operating normally in orbit.

The remainder of this paper is organized as follows. Section 2 introduces the spaceborne SAR satellite, the SAR

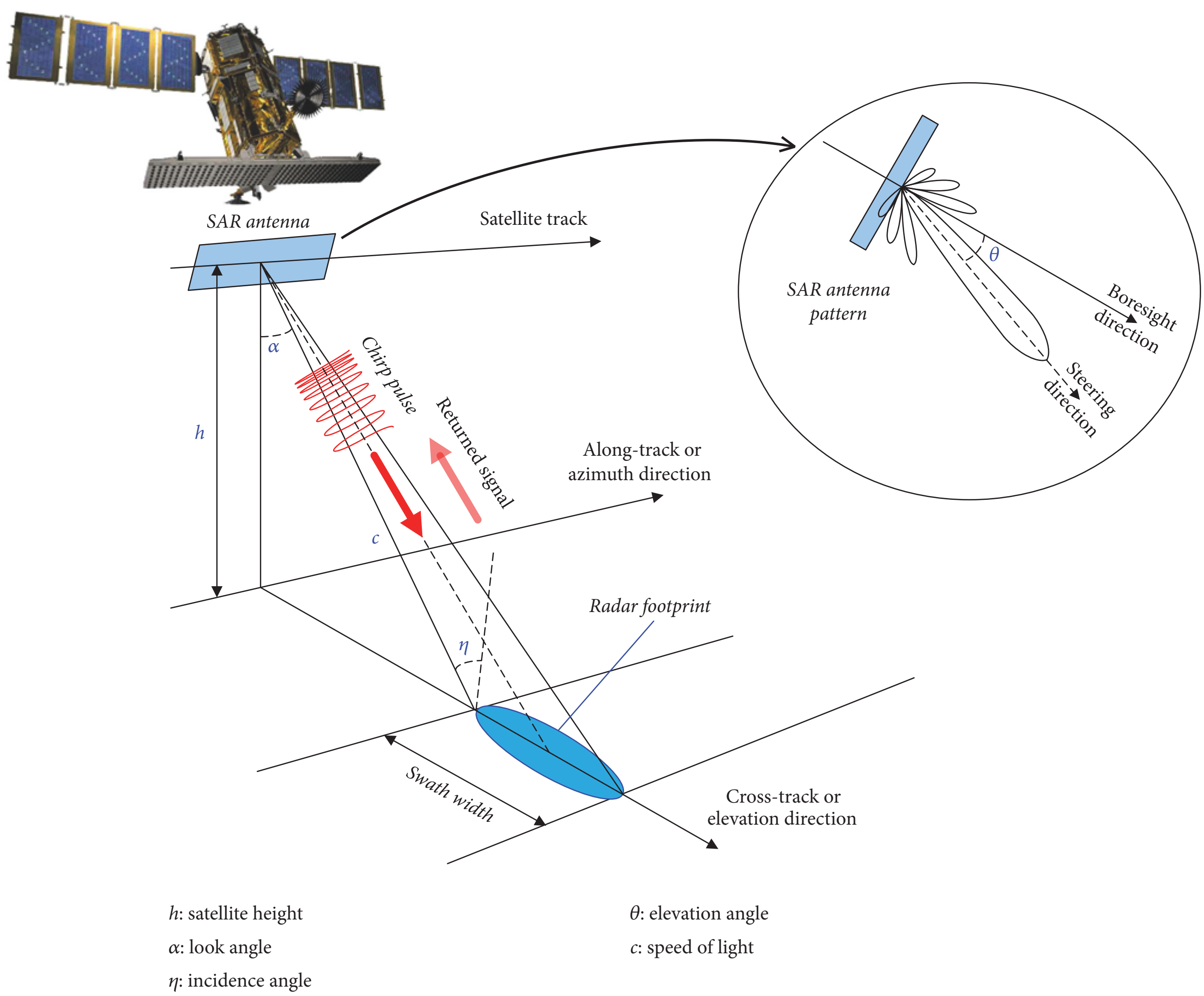

Figure 1: SAR satellite imaging geometry.

system performance, the antenna mask template design, and the antenna pattern synthesis algorithms for problem formulation. Section 3 explains the process for the antenna pattern synthesis. Section 4 summarizes and discusses the antenna pattern synthesis and the SAR system performance analysis results. Finally, Section 5 concludes the paper.

2. Theoretical Background

2.1. Spaceborne SAR Satellite. A spaceborne SAR is imaging radar installed on a moving platform. The SAR sensors transmit chirp pulses (frequency-modulated pulsed waveforms) and receive the echoes reflected from the radar footprint. Figure 1 shows the image acquisition geometry of a spaceborne SAR satellite.

The satellite platform moves in the azimuth (or along-track) direction, whereas the radar signal is transmitted and received in the elevation (or cross-track) direction. Spaceborne SAR satellites often use active phased array antennas because of their operational flexibility to support various operation modes. Active phased array SAR systems consist of radiating elements, Transmit/Receive Modules (TRMs), feed networks, and a SAR transmitter/receiver [10].

2.2. SAR System Performance. The key performance parameters of spaceborne SAR systems are the SW, NESZ, RASR, and AASR.

The SW is defined as the on-ground extension of the imaged area. The NESZ is the backscattering equivalent value that produces signal intensity equal to the thermal noise. The NESZ is an index of the system sensitivity and the minimum sensitivity when the signal-to-noise ratio (SNR) is 1. The NESZ is calculated using (1) as follows [3, 11]:

$$\mathrm{NESZ} = \frac{4 \cdot (4\pi)^3 \cdot R^3 \cdot V_s \cdot \sin\eta \cdot k \cdot T_0 \cdot \mathrm{NF} \cdot B \cdot L_{\mathrm{tot}}}{\lambda^3 \cdot c \cdot G_t \cdot G_r \cdot \tau \cdot P_t \cdot \mathrm{PRF}}, \quad (1)$$

where R is the slant range; V_s is the velocity of the satellite; η is the incidence angle; k is Boltzmann's constant; T_0 is the equivalent noise temperature; NF is the system noise figure;

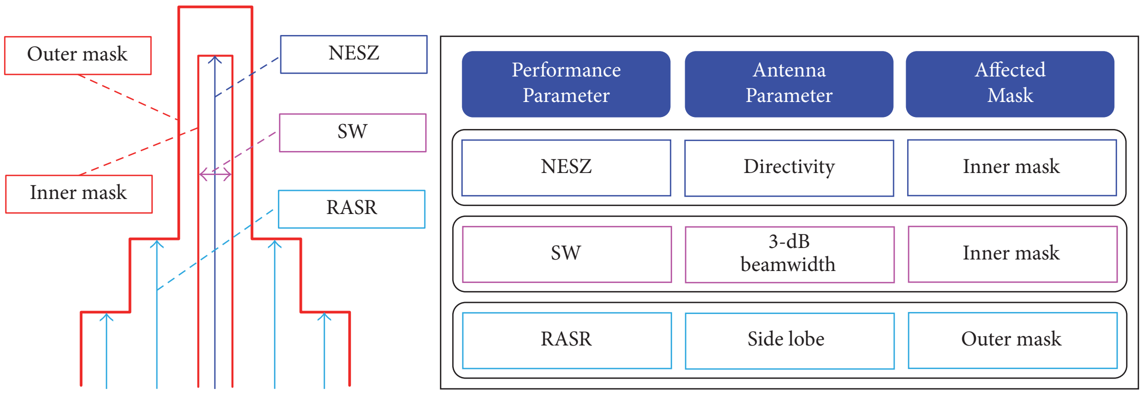

FIGURE 2: Relationship between SAR performance and antenna parameters.

B is the signal bandwidth; L_{tot} is the system total losses; λ is the wavelength; c is the speed of light; G_t is the antenna gain in transmitting; G_r is the antenna gain in receiving; τ is the transmitted pulse length; P_t is the transmitted power, and PRF is the pulse repetition frequency.

The RASR is the ratio of the range ambiguous signal power to the desired signal power described in [1]

$$\text{RASR} = \frac{\sum_{i=1}^{N} S_{a_i}}{\sum_{i=1}^{N} S_i}, \tag{2}$$

where S_{a_i} and S_i are the range ambiguous and desired signal powers, respectively, in the ith time interval of the data recording window, and N is the total number of time intervals.

S_i and S_{a_i} are expressed by (3) and (4), respectively, as follows:

$$S_i = \frac{\sigma_{ij}^0 G_{ij}^2}{R_{ij}^3 \sin\left(\eta_{ij}\right)} \quad \text{for } j = 0, \tag{3}$$

$$S_{a_i} = \sum_{\substack{j=-n \\ j\neq 0}}^{n} \frac{\sigma_{ij}^0 G_{ij}^2}{R_{ij}^3 \sin\left(\eta_{ij}\right)} \quad \text{for } j \neq 0, \tag{4}$$

where j is the pulse number; σ_{ij}^0 is the normalized backscatter coefficient at a given incidence angle (η_{ij}); G_{ij} is the elevation antenna gain pattern, and R_{ij} is the slant range.

The AASR is the ratio of the ambiguous signal to the desired signal within the SAR correlator azimuth processing bandwidth (B_p) in the Doppler domain described by (5) as follows [1]:

$$\text{AASR} \approx \sum_{\substack{m=-\infty \\ m\neq 0}}^{m=\infty} \frac{\int_{-B_p/2}^{B_p/2} G^2\left(f + m f_p\right) df}{\int_{-B_p/2}^{B_p/2} G^2\left(f\right) df}, \tag{5}$$

where B_p is the SAR correlator azimuth processing bandwidth, G is the azimuth antenna gain pattern in the Doppler domain, and f_p is the pulse repetition frequency. The performance parameters of a SAR system, for example, the SW, NESZ, RASR, and AASR, are closely related to the antenna pattern from (1) to (5).

2.3. Antenna Mask Template Design. The performance of a SAR system is closely associated with the antenna pattern of the active phased array antennas as shown in Figure 2. The SW, NESZ, RASR, and AASR are related to the main lobe beamwidth, directivity, side lobe level in the range direction, and side lobe level in the azimuth direction, respectively, and these parameters can be improved by a suitable antenna pattern synthesis. Therefore, the antenna mask template should be designed to meet the performance requirements of a SAR system taking into consideration this relationship [3, 5, 12, 13].

In previous studies, various design techniques for deriving the antenna mask template have been proposed, for example, a synthesis criterion to use the adaptive array theory [2], an iterative method to design an antenna side lobe mask in an ambiguous region [3], and an adaptive weighting factor method to minimize the cost function in each ambiguous region [4]. The ambiguous signal is a signal received from an ambiguous region, and it functions as noise against a useful desired signal. An ambiguous region is a region where the reflected echo signals behave as undesired signals or noise as shown in Figure 3 [1].

We developed a design method for the mask based on previous studies as described below.

(1) The side lobe level of the outer mask in the ambiguous region should be suppressed to minimize the ambiguous signal and improve the RASR requirement.

(2) An excessive level of discontinuity in the outer mask should be avoided because the directivity and beamwidth can be affected.

(3) The level of the inner mask should be established to satisfy the NESZ requirement.

(4) The width of the inner and outer masks should be set to meet the SW requirement.

In summary, the design guidelines for the mask minimize the ambiguous signal and maximize the desired signal.

2.4. Algorithms for Antenna Pattern Synthesis. Antenna pattern synthesis is done with optimization algorithms after the antenna mask template is designed. For the antenna pattern synthesis, we considered a new optimization algorithm based on the QPSO.

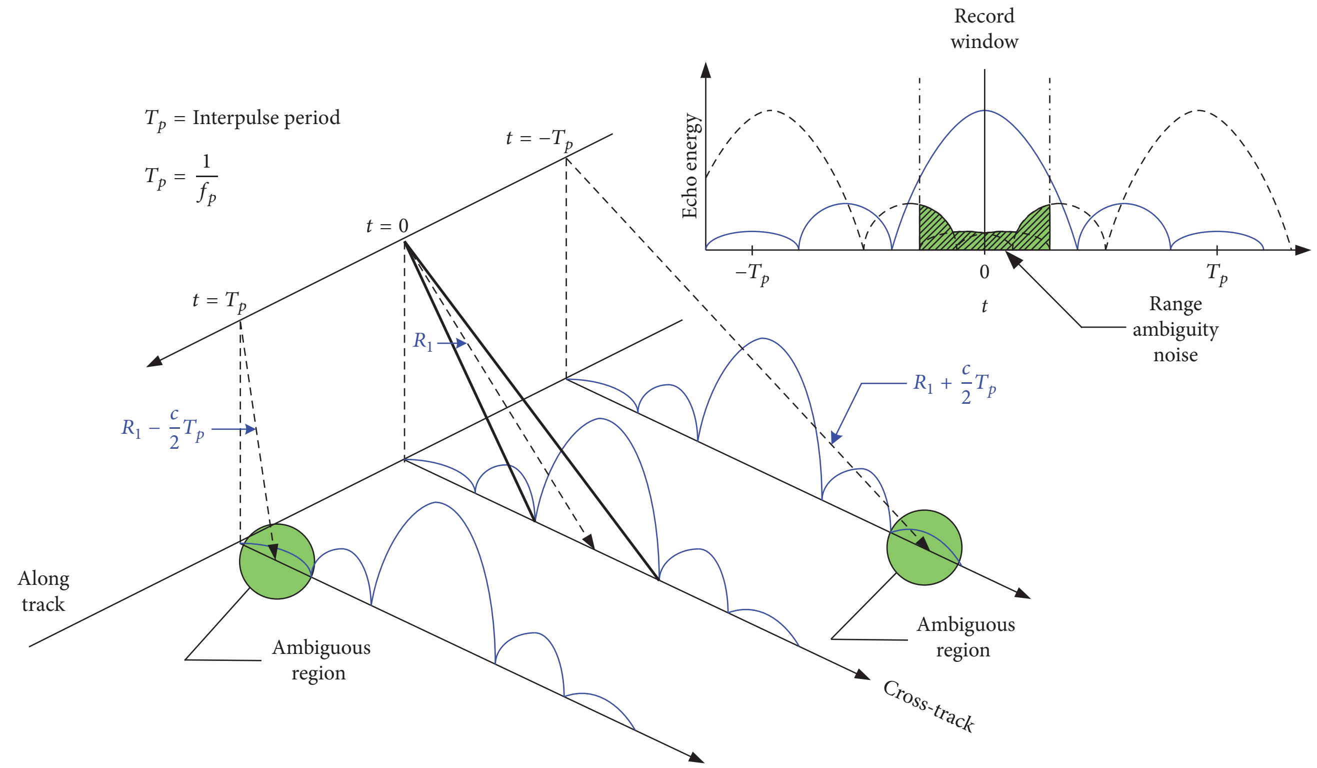

FIGURE 3: Concept diagram of range ambiguity.

The conventional PSO algorithm was first introduced by Kennedy and Eberhart in 1995: it is a swarm intelligence optimization algorithm based on evolutionary computation and social behavior, such as birds flocking or fish schooling. The conventional PSO algorithm uses three basic operators: particle generation (the position X and the velocity V), velocity update, and position update [14].

The QPSO algorithm was developed by Sun et al. by introducing quantum theory into the conventional PSO. The QPSO algorithm enables all particles to have a quantum mechanics behavior instead of the Newtonian mechanics behavior as in the conventional PSO algorithm. The QPSO algorithm searches for the global best position using operations that include particle generation (position X and personal best position P), the mean best position C calculation, and position update [15, 16].

The advantages of the QPSO are summarized below.

(1) In contrast to the conventional PSO algorithm, the characteristics of the QPSO improve the convergence speed and enhance the global searching capability by allowing particles to appear in any position in the entire search space with a certain probability.

(2) Velocity vectors are not required to implement the QPSO algorithm. Thus, the QPSO algorithm can be easily implemented because it uses a smaller number of parameters to optimize a given problem without the velocity vectors.

A comparison of the conventional PSO and QPSO is summarized in Table 1. Detailed explanations of the parameters can be found in the literature [14–16].

The QPSO algorithm described in Table 1 is called the QPSO-Type 2-I. Another variant type is denoted as QPSO-Type 2-II in which the mean best position C_n^j is replaced by the personal best position of a randomly selected particle in the swarm at each iteration. Because the QPSO- Type 2-I and Type 2-II have the best performance [17], we used them as a synthesis algorithm to synthesize the antenna pattern.

In the QPSO algorithm, α is a positive real number known as the contraction expansion (CE) coefficient and is a critical parameter that requires adjustment to balance the local and global searches of the algorithm during the search process [15]. The α value can be selected with the fixed-value method or the linear time-varying approach. Empirical studies were done by Sun et al. in which an α value was selected for several benchmark functions [17].

Figure 4 shows details on the cost function that optimizes the synthesis of a linear array.

The cost function f for the optimization of array weights for a linear array is described in

$$f = 10\log\left(\sum_{\substack{\text{Pattern points}\\ \text{outside outer mask}}} \left|\text{Outer}_{\text{excess}}\right| + \sum_{\substack{\text{Pattern points}\\ \text{outside inner mask}}} \left|\text{Inner}_{\text{excess}}\right|\right),$$
$$\text{Outer}_{\text{excess}} = E_{\text{Far}}(\theta,\phi) - \text{Mask}_{\text{outer}},$$
$$\text{Inner}_{\text{excess}} = \text{Mask}_{\text{inner}} - E_{\text{Far}}(\theta,\phi), \quad (6)$$

where E_{Far} is the antenna far-field pattern; $\text{Outer}_{\text{excess}}$ is the outer excess power; $\text{Inner}_{\text{excess}}$ is the inner excess power; $\text{Mask}_{\text{outer}}$ is the outer mask level, and $\text{Mask}_{\text{inner}}$ is the inner

Table 1: Comparison of the conventional PSO and QPSO.

Algorithms	Items	Descriptions
Conventional PSO	Formulas	$V_{i,n+1}^{j} = wV_{i,n}^{j} + c_1 r_{i,n}^{j}\left(P_{i,n}^{j} - X_{i,n}^{j}\right) + c_2 R_{i,n}^{j}\left(G_{n}^{j} - X_{i,n}^{j}\right)$ $X_{i,n+1}^{j} = X_{i,n}^{j} + V_{i,n+1}^{j}$
	Operators	Particle generation (X and V), velocity V update, and position X update
	Critical parameters	Acceleration coefficients c_1 and c_2 Inertia weights w
	Remarks	Velocity vector V is required
QPSO	Formulas	$X_{i,n+1}^{j} = p_{i,n}^{j} \pm \alpha \left\lvert X_{i,n}^{j} - C_{n}^{j}\right\rvert \ln\left(\frac{1}{u_{i,n+1}^{j}}\right)$ [Type 2-I] $C_{n}^{j} = \left(\frac{1}{M}\right)\sum_{i=1}^{M} P_{i,n}^{j}$ $p_{i,n}^{j} = \varphi_{i,n}^{j} P_{i,n}^{j} + \left(1 - \varphi_{i,n}^{j}\right) G_{n}^{j}$
	Operators	Particle generation (X and P), mean best position C calculation, and position X update
	Critical parameters	The contraction expansion coefficient α
	Remarks	Velocity vector V is not required

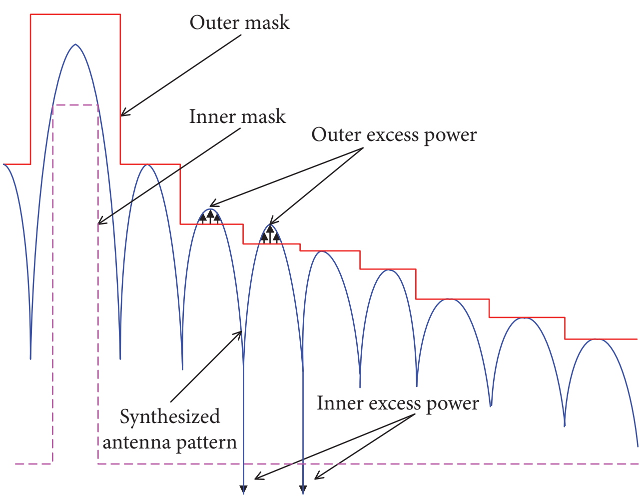

Figure 4: Cost function description for the synthesis of a linear array.

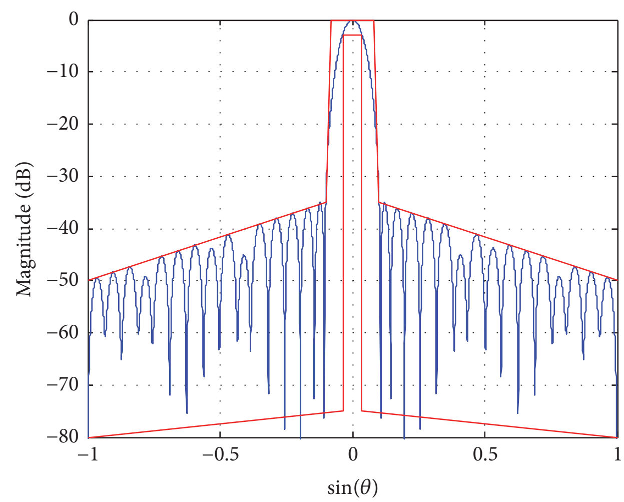

Figure 5: Antenna pattern synthesis simulation for parameter selection.

mask level. The cost function is defined as the sum of the excess side lobe power outside the specified outer and inner masks. As the cost decreases, the solution improves. For a given far-field pattern, each pattern point that lies outside the specified mask limits contributes a value to the cost function equal to the power difference between the mask and the far-field pattern [18]. For the inner excess power calculation, to reduce the computing time of the sum for the pattern points outside the inner mask, the sum range of the cost function can be modified to limit the critical points (inner mask's main lobe bound) because the inner mask's lower bound does not significantly affect the cost function.

To select a parameter value for the synthesis of the antenna pattern, a parameter selection simulation was performed for a simple antenna pattern mask to suppress the side lobe levels shown in Figure 5. Figure 6 shows the results of the cost function for QPSO-Type 2-I and Type 2-II with various CE coefficients, α. The best cost function values obtained by the QPSO are summarized in Table 2. The results show that the performance results are very similar to those of empirical studies and that the performance can be optimized by selecting the appropriate parameter.

Thus, we selected the fixed-values of α for the QPSO-Type 2-I and Type 2-II as 0.75 and 0.54, respectively. The linear time-varying values were limited from 1.0 to 0.5 and from 0.6 to 0.5 for the QPSO-Type 2-I and Type 2-II, respectively, based on empirical studies. These values were appropriately selected according to the complexity of the antenna mask. Figure 7 shows a search flowchart for the global best solution by the QPSO technique.

To formulate the problems, the relationship between the SAR system performance and the antenna pattern was examined. The design method for the antenna mask template was summarized, and the QPSO technique was proposed as

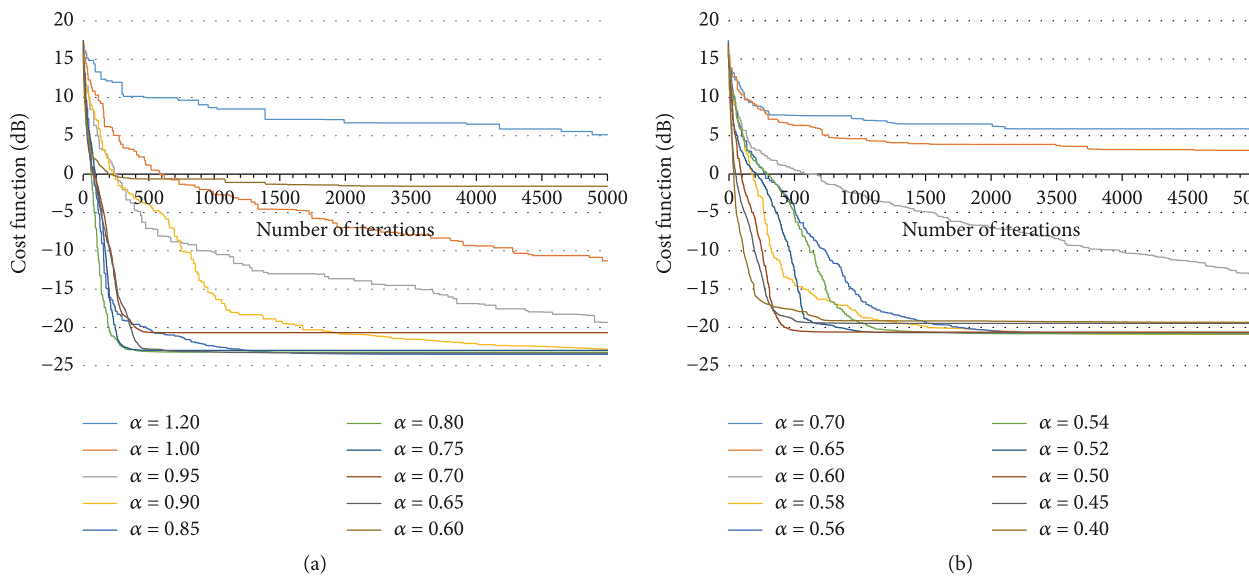

FIGURE 6: Performance results for various CE coefficients. (a) QPSO-Type 2-I. (b) QPSO-Type 2-II.

TABLE 2: Best cost function values obtained by QPSO.

α (QPSO-Type 2-I)	Cost function value [dB]	α (QPSO-Type 2-II)	Cost function value [dB]
1.20	5.1432	0.70	5.8545
1.00	−11.3132	0.65	3.0452
0.95	−19.3383	0.60	−13.1914
0.90	−22.8559	0.58	−21.0779
0.85	−23.5031	0.56	−21.0311
0.80	−23.2447	0.54	−21.0166
0.75	−22.9958	0.52	−20.8506
0.70	−20.6783	0.50	−20.7767
0.65	−23.3534	0.45	−19.6402
0.60	−1.5798	0.40	−19.4932

a new synthesis algorithm for the antenna pattern because it had a fast convergence speed and better global searching capability to synthesize an antenna pattern that can be adapted to the antenna mask template.

3. The Synthesis Process for the Antenna Pattern

The array antenna consists of two-dimensional array elements. The antenna far-field pattern (E_{Far}) is expressed as the product of the element pattern (E_{Ele}) and the array factor (AF) as shown in [19]

$$E_{\text{Far}}(\theta,\phi) = E_{\text{Ele}}(\theta,\phi)\cdot \text{AF}(\theta,\phi). \tag{7}$$

Here, the array factor is defined in

$$\text{AF}(\theta,\phi) = \sum_{n=1}^{N}\sum_{m=1}^{M}\left(A_{mn}e^{j[(2\pi/\lambda)(x_m\sin\theta\cos\phi+y_n\sin\theta\sin\phi)]}\right.$$
$$\left.\cdot\, e^{j[-(2\pi/\lambda)(x_m\sin\theta_0\cos\phi_0+y_n\sin\theta_0\sin\phi_0)]}\right), \tag{8}$$

where A_{mn} and (x_m, y_n) are the amplitude coefficient and position of the mnth element, respectively. λ is the wavelength, M is the number of radiating elements in the azimuth direction, and N is the number of radiating elements in the elevation direction. The array factor can be electronically steered to the desired angle (θ_0, ϕ_0), and the antenna pattern can be generated by adjusting the amplitude and phase of each element in (8).

This study considered an antenna pattern synthesis for a planar antenna from an active phased array SAR shown in the configuration example in Figure 8 [20]. Detailed explanations are given in Section 4.

During the synthesis process for the antenna pattern, the global positions of the amplitude and phase weights for N elements in the elevation direction were searched for the QSPO (or conventional PSO or GA) solver. After this step, the far-field pattern was produced with (7) and (8), and the

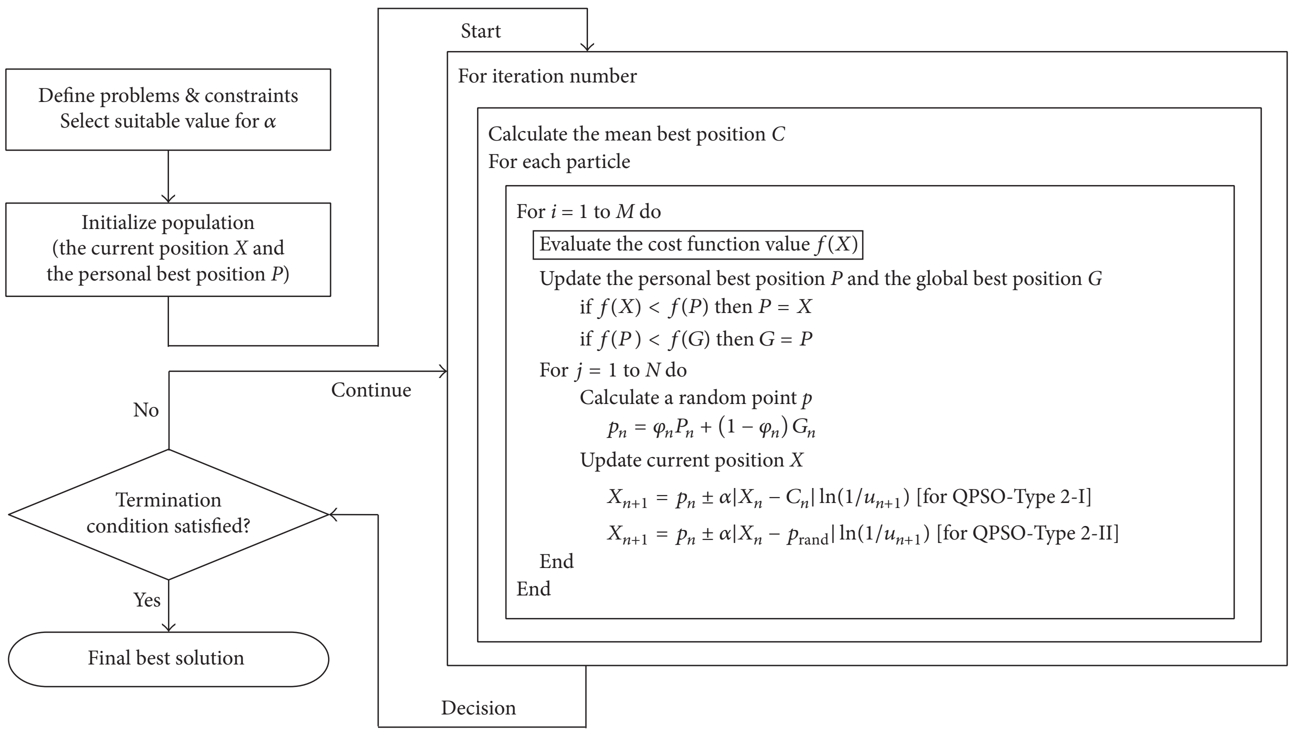

Figure 7: Flowchart of the QPSO algorithm.

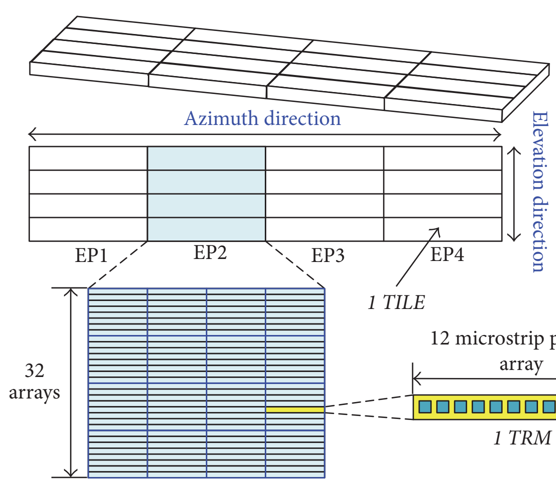

Figure 8: Example of the SAR antenna configuration.

cost function was calculated with the far-field pattern and the mask template designed previously.

4. Simulation Results and Discussion

This study considered the active phased array SAR antennas of KOMPSAT-5, as shown in Figure 8, to validate the proposed design method for the mask template and the proposed pattern synthesis algorithm based on the QPSO.

The SAR antenna of KOMPSAT-5 consists of four electrical panels (EPs). Each EP has four tiles, and each tile consists of 32 TRMs. Thus, the SAR antenna has 512 TRMs, and 1 TRM consists of 12 microstrip patches as the radiating element in the azimuth direction. The KOMPSAT-5 SAR antenna pattern can be synthesized by controlling the attenuators and phase shifters of 32 and 16 TRMs in the elevation and azimuth directions, respectively [20].

The synthesis of the antenna pattern and an analysis of the SAR system performance were done based on the simulation parameters and the system performance requirements of KOMPSAT-5 as summarized in Table 3.

Twelve antenna beam patterns are necessary to cover the nominal access region at an incidence angle range of 20 to 45 degrees. The synthesis of the antenna pattern was done to optimize the designed antenna mask template according to the mask design method. A transmitting (Tx) antenna pattern was generated through a uniform distribution to maximize the transmitting power, and the receiving (Rx) pattern was synthesized with the QPSO algorithm. The SAR system performance was analyzed by applying a Tx and Rx two-way pattern. The proposed antenna pattern synthesis algorithm was used to generate a beam pattern optimized for the antenna mask template only along the elevation direction.

The mask templates were designed according to the suggested mask design method, and an example was produced as shown in Figure 9. The initial mask was generated by a uniform distribution in advance, and the mask template was designed according to the mask design method previously described.

The outer mask determines the side lobe levels and the beamwidth. To determine the main lobe width of the outer mask, the outer mask should be designed to satisfy

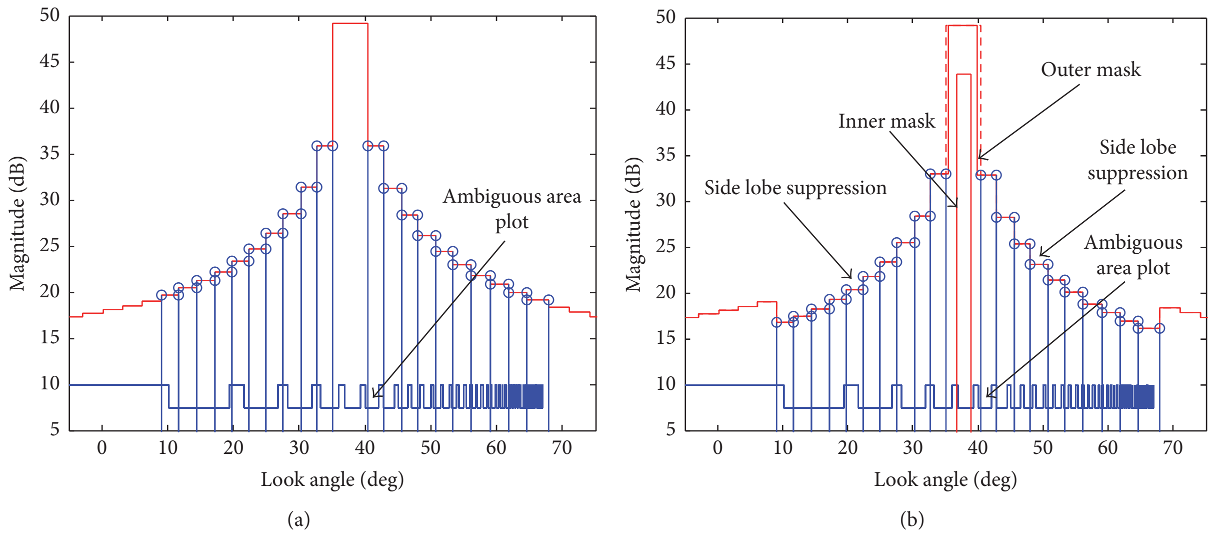

FIGURE 9: Example of a mask design for beam number 10 of KOMPSAT-5. (a) Initial elevation mask. (b) Designed elevation mask.

TABLE 3: Simulation parameters and system performance requirements of KOMPSAT-5.

Parameters	Values
Operating frequency	9.66 GHz
Altitude	550 km
Radiating element in elevation direction	32
Radiating element in azimuth direction	192
Elevation spacing	0.67 wavelength
Azimuth spacing	0.71 wavelength
Gain control bits	6 bits (0.5 dB step)
Phase control bits	6 bits (5.625-degree step)
SW requirement	≥30 km at 45-degree incidence angle
NESZ requirement	≤ −17 dB at nominal access region
RASR requirement	≤ −17 dB at nominal access region

the SW requirement. For the side lobe levels of the outer mask, the outer mask should be designed to meet the RASR requirement. We calculated and plotted the ambiguous area which depends on the PRF and SAR geometry [3] as shown in Figure 9. The ambiguous area plot shows whether the specified areas are ambiguous areas, and the low level identifies the ambiguous area. Thus, if the mask section falls under the ambiguous area, the side lobe levels of the outer mask should be lowered to suppress the ambiguous signals to a certain extent. The antenna directivity and the beamwidth are determined by the inner mask. The main lobe levels and the width of the inner mask should be designed to meet the NESZ and SW requirements.

The antenna pattern synthesis results by the QPSO are shown in Figure 10. The convergence results of the cost function following the iteration process depending on the optimization algorithm are shown in Figure 11.

Because a particle can be located at any position in the search space and the QPSO has better global searching capabilities than other algorithms, the convergence results show that the QPSO algorithm has a faster convergence speed than the GA and conventional PSO for several complex mask templates as shown in Figure 11. Performing on-board beam pattern synthesis or real-time antenna pattern resynthesis may be necessary in some instances due to the failure of array elements in the next generation SAR satellite. Thus, the fast convergence characteristics of the QPSO algorithm will be an advantage for the on-board beam pattern synthesis function, which is necessary for the next generation SAR satellite.

Figure 12 shows the 2-way antenna patterns synthesized with the QPSO algorithm for each designed antenna mask.

To evaluate the usefulness of the results for the antenna mask template and the antenna pattern synthesis, an analysis of the SAR system performance was done for twelve synthesized antenna beam patterns. Figure 13 shows the analysis results for the RASR and NESZ, respectively. The red solid line represents the initial uniform antenna pattern results, and the blue dotted line represents the results of the optimized pattern using the QPSO, and the red dotted line shows the requirements that are less than −17 dB for all swath widths. Figure 13 shows that the RASR performance is improved by the suggested design method for the mask template and the proposed technique for the antenna pattern synthesis based on the QPSO as is evident by the suitable suppression of the side lobes at the mask design step and the efficient pattern synthesis ability of the QPSO during the pattern synthesis step. Of note, the requirement margin became sufficient for a swath width number from 6 to 9, and the average values for the RASR were substantially improved as summarized in Table 4. The NESZ performance of the optimized patterns meets the requirements with margins.

The results show that the new antenna pattern synthesis technique based on the QPSO and the design method for the antenna mask template together are an appropriate method to improve the SAR system performance. Thus, the suggested

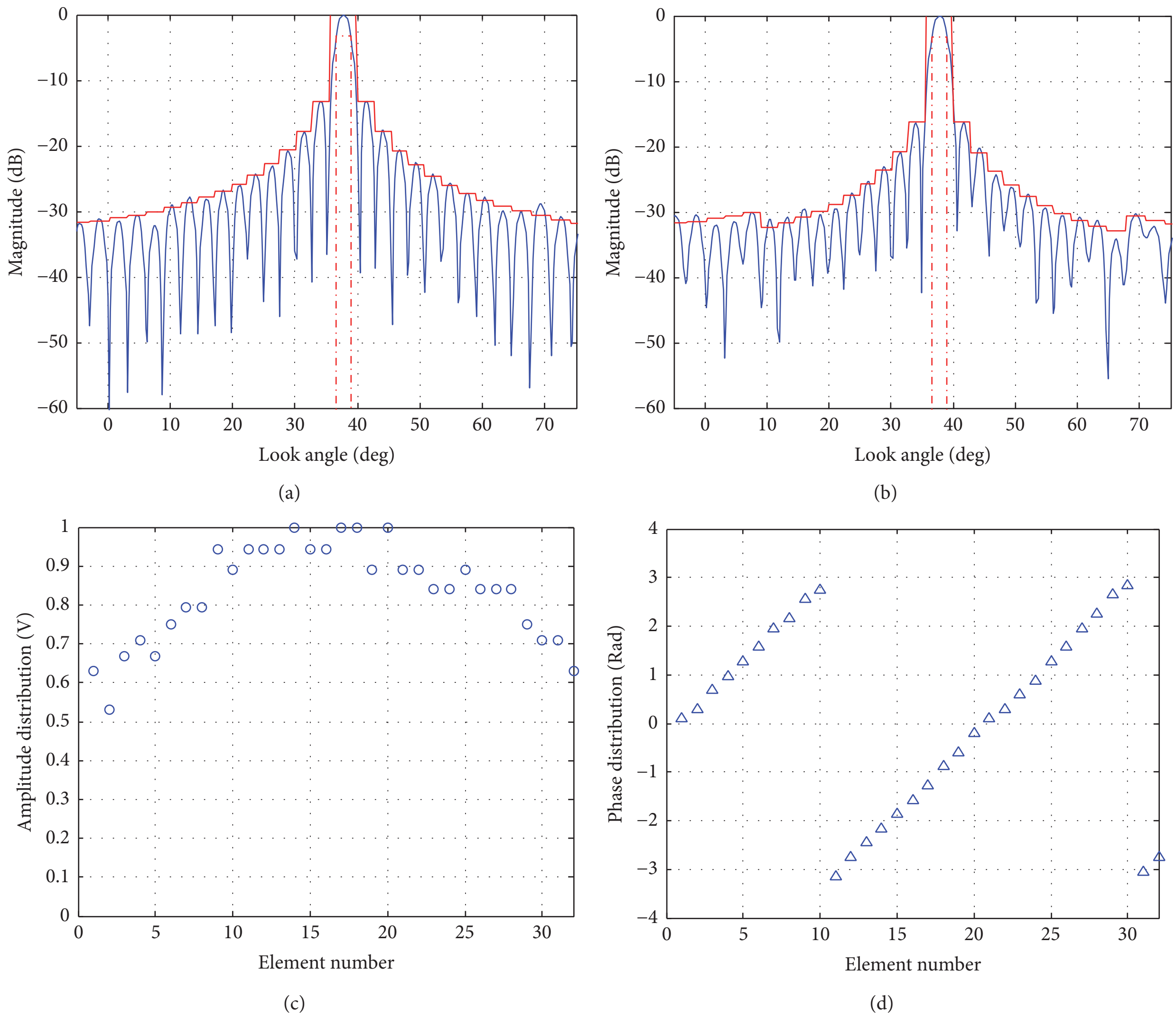

FIGURE 10: Antenna pattern synthesis results for beam number 10 of KOMPSAT-5. (a) Tx pattern (uniform). (b) Rx pattern (optimized). (c) Optimized amplitude. (d) Optimized phase.

TABLE 4: RASR performance summary.

Beam (SW) number	1	2	3	4	5	6	7	8	9	10	11	12
Initial pattern (Avg.) [dB]	−46.39	−37.36	−37.92	−37.43	−37.57	−32.01	−32.19	−25.87	−25.79	−25.76	−26.17	−26.15
Optimized pattern (Avg.) [dB]	−54.31	−42.54	−44.83	−45.40	−42.27	−37.00	−35.66	−30.65	−31.66	−29.07	−29.08	−29.43
RASR improvement [dB]	7.92	5.18	6.91	7.97	4.70	4.99	3.47	4.78	5.87	3.31	2.91	3.28

mask design method and the proposed antenna pattern synthesis technique can be an alternative method for next generation SAR satellites.

5. Conclusions

In this paper, we proposed an antenna mask design method to improve the SAR system performance and a QPSO optimization algorithm as a new antenna pattern synthesis algorithm. We validated the mask design method and the proposed QPSO algorithm by analyzing the SAR system performance of the KOMPSAT-5. The performance results show that the RASR performance improved, and the NESZ performance satisfied the system requirements for all antenna beams. Furthermore, we demonstrated that the proposed technique based on the QPSO algorithm resulted in better performance, compared to the other algorithms, for antenna pattern synthesis for a complex antenna mask.

In conclusion, the SAR system performance can be improved with the proposed antenna mask design method,

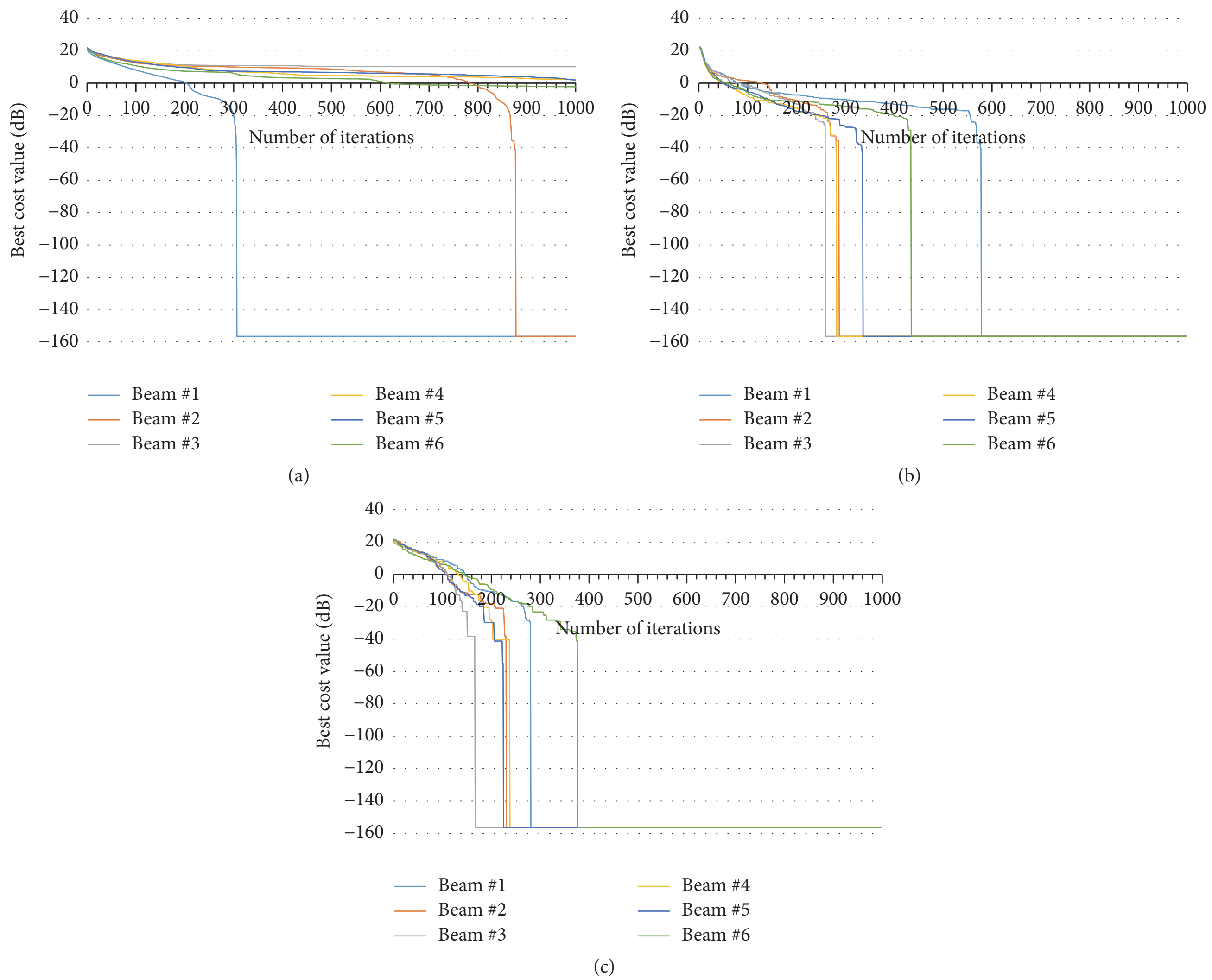

FIGURE 11: Comparison results of the convergence process. (a) GA. (b) Conventional PSO. (c) QPSO.

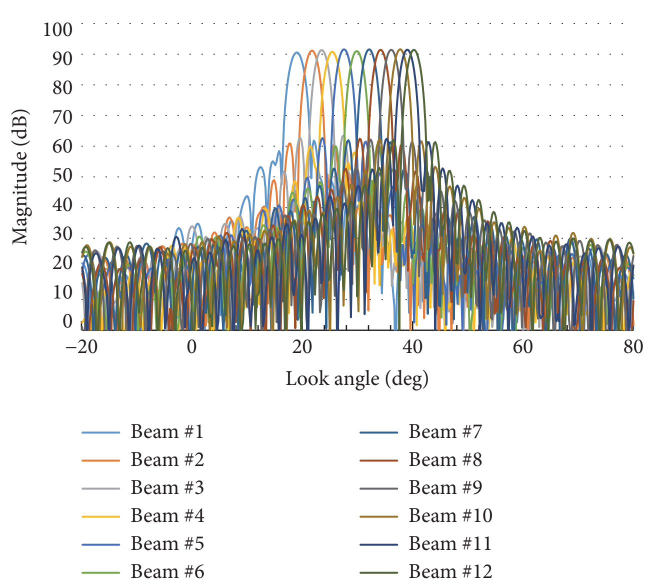

FIGURE 12: Total synthesized antenna patterns.

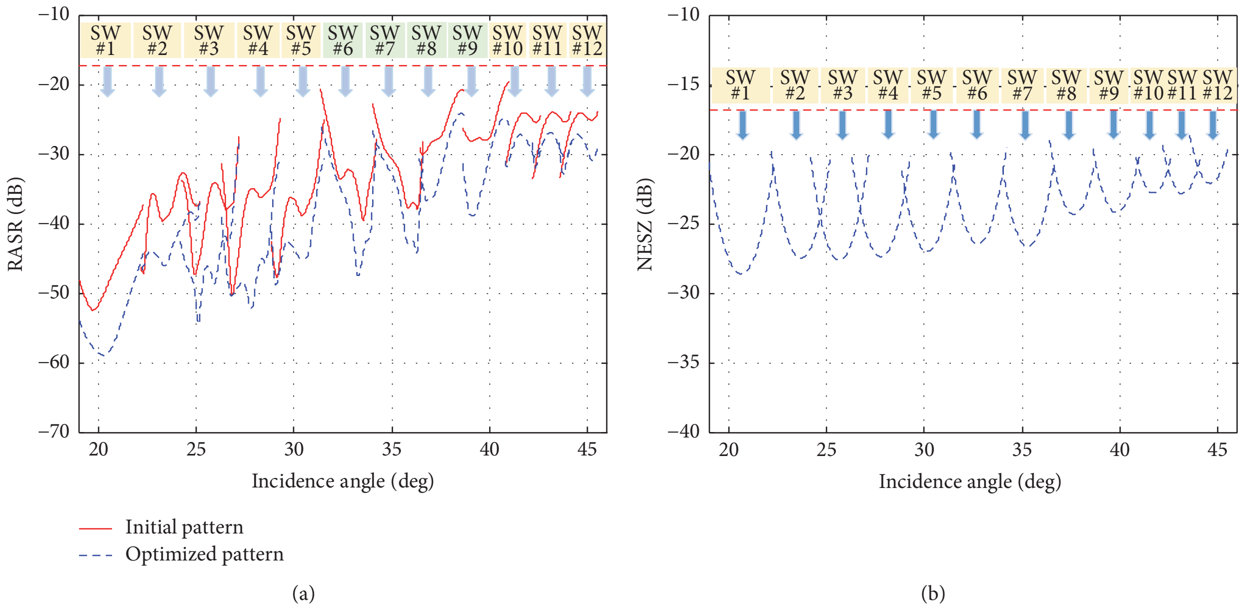

Figure 13: Analysis results for SAR system performance (a) RASR. (b) NESZ.

and the antenna pattern can be efficiently synthesized with the proposed algorithm based on the QPSO for spaceborne SAR applications.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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