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AN OPTIMAL ANTENNA PATTERN SYNTHESIS FOR ACTIVE PHASED ARRAY SAR BASED ON PARTICLE SWARM OPTIMIZATION AND ADAPTIVE WEIGHTING FACTOR

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Abstract—This paper shows that an optimal antenna pattern for active phased array synthetic aperture radar (SAR) has been synthesized to meet the best performances based on particle swarm optimization (PSO) and adaptively selected weighting factors. Because the antenna radiation pattern has a very close relation with the performance of an active phased array SAR system, the authors derived the multi-objective cost functions on the basis of the system performance measures such as the range-to-ambiguity ratio, noise equivalent sigma zero, and radiometric accuracy. The antenna mask templates were derived from the SAR system design parameters in order to optimize the system requirements. To effectively minimize the cost functions and to search for the amplitude and phase excitations of an active phase array SAR antenna, the authors applied the PSO technique to SAR antenna pattern design and also carefully selected weighting factors to improve the fitness of the cost functions on the basis of the SAR performance.

1. INTRODUCTION

Modern synthetic aperture radar system requires a variety of operational modes based on the mission requirements. An active phased array synthetic aperture radar (SAR) system needs to generate various antenna patterns to meet the system performance measures of the range-to-ambiguity ratio (RAR), noise equivalent sigma zero (NESZ), and radiometric accuracy (RA) [1].

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The RAR results are derived from the preceding and succeeding pulse echoes of sidelobe beams that arrive at the antenna simultaneously with a desired return from the mainlobe [2]. The antenna directivity should be maximized to get the best sensitivity within the swath [3, 4].

Both the gain slope and flatness of the mainlobe beam are closely related to the radiometric accuracy. Because the system parameters degrade the quality of the end-product image, the mainlobe and sidelobe levels must be effectively controlled by the shape of the antenna pattern. There are many optimizing techniques that can fit the antenna beam pattern into a mask template. With its capability of adjusting the amplitude and phase settings in transmit/receive (T/R) modules, an active phased array SAR system has versatile functions for achieving multiple modes, such as the strip map, wide-swath, and spotlight modes. In the case of an active type SAR system using T/R modules, the digital attenuator and phase shifter will give rise to problems induced from the quantization effect, random error and element pattern. To optimize the antenna pattern on the basis of the system requirements, we applied an evolutionary algorithm called the particle swarm optimization (PSO) to synthesize the antenna mainlobe and sidelobe levels within a specified mask pattern [5, 6]. We used the PSO technique to improve the SAR performance, thereby minimizing the multi-objective cost functions. In [7], we demonstrated that PSO may be used to design optimal antenna patterns for SAR.

In this paper, the cost function was defined to optimize the antenna pattern for the respective mainlobe and sidelobe in terms of the RAR, NESZ, and RA. In order to effectively increase the convergence speed of the PSO, the weighting factor was adaptively determined on the basis of the receiving power level at the ambiguous areas, and it was utilized to calculate the sidelobe cost function. To increase the optimization efficiency, we chose 10 particles in the swarm, and each particle had a 96-dimensional space.

We now propose the use of PSO algorithm and adaptive weighting factors as a novel SAR antenna pattern synthesis technique to obtain optimal RAR and NESZ values for active phased array SAR with a shaped antenna pattern.

2. ACTIVE PHASED ARRAY SAR AND COST FUNCTION DEFINITION

Figure 1 shows an active phased array radar configuration in which the T/R modules are used to set up the amplitude and phase excitations to synthesize the array antenna pattern. Active phased array SAR has

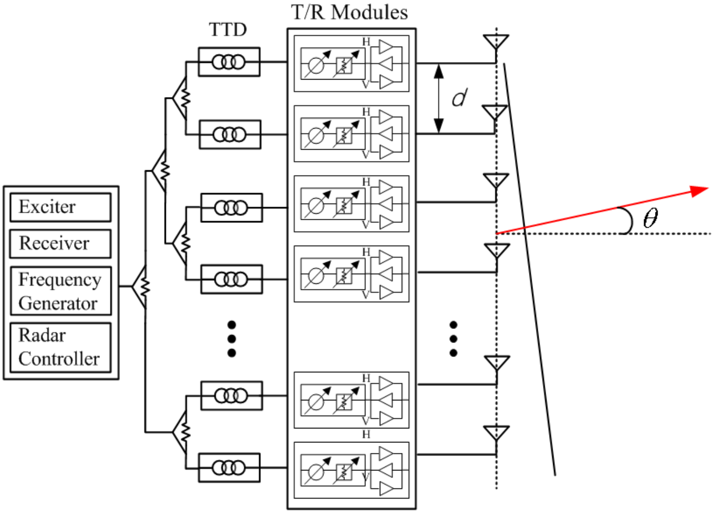


Figure 1. Active phased array SAR configuration. The radiating elements are composed of the slot coupled microstrip patch antenna. Each T/R module provides (H/V) horizontal and vertical polarizations. The true time delay (TTD) can stabilize the antenna pattern in relation to the frequency bandwidth.

an N-element array, and each element consists of a T/R module and a microstrip patch radiator. Each T/R module can feed dual polarized antenna with horizontal (H) and vertical (V) radiators. The true time delay (TTD) can stabilize the antenna pattern by using different delay lines with respect to the instantaneous frequency bandwidth. The far-field radiation pattern, $E_{\text{rad}}(\theta)$, for an N-element array is defined as follows:

$$E_{\text{rad}}(\theta) = E_{\text{ele}}(\theta) \sum_{n=0}^{N-1} A_n \exp\left(-jkdn \sin\theta_n + j\phi_n\right) \tag{1}$$

where $E_{\text{ele}}(\theta)$ represents the element radiation pattern; A_n, ϕ_n, k and d are each element's amplitude, phase, wave number and inter-element distance; n is the total number of the elements; θ_n is the beam steering angle. When each T/R module's amplitude and phase value are adjusted, an active phased array SAR can electrically steer and also synthesize an antenna beam pattern. In particular, an effectively well synthesized antenna pattern can minimize the sidelobe echoes reflected from the ambiguous regions and maximize the mainlobe's directivity, thereby leading to an improvement of the RAR, NESZ, and radiometric accuracy. To search for the amplitude and phase excitations of the Tx and Rx aperture on the basis of mask templates, which are given by the system requirements, we defined the mainlobe cost functions as the following three items: $G_1(\theta)$, the desired directivity cost function; $G_2(\theta)$, the gain flatness cost function; and $G_3(\theta)$, the gain slope cost function. These items are expressed as follows, respectively:

$$G_1(\theta) = W_{\text{dir}} \sum_{\theta} (G_{\text{dir}} - P_\theta) \qquad G_{\text{dir}} > P_\theta \tag{2}$$

$$G_2(\theta) = W_{\text{flat}} \sum_{\theta} |(P_{\max} - P_\theta)| \qquad G_{\text{flat}} > |P_{\max} - P_\theta| \tag{3}$$

$$G_3(\theta) = W_{\text{slope}} \sum_{\theta} \left| \left(\frac{P_{\Delta\theta}}{\Delta\theta} - G_{\text{slope}} \right) \right| \qquad P_{\Delta\theta} = P_\theta - P_{\theta-1} \tag{4}$$

where W_{dir}, W_{flat} and W_{slope} represent the weighting factors for the directivity, flatness, and slope of the mainlobe, respectively; G_{dir}, G_{flat} and G_{slope} are the system requirements for the directivity, flatness, and slope of the antenna; P_θ is the directivity at a single observation angle, θ; $P_{\max}$ is the maximum directivity; $P_{\Delta\theta}$ is the directivity difference between the adjacent angles. The overall cost function, $F(\theta)$, which is composed of the sum of the respective cost functions of the mainlobe and sidelobes, is expressed as follows:

$$F(\theta) = \min \left(G_1(\theta) + G_2(\theta) + G_3(\theta) + W_{s\theta} \sum_{\theta} \left(S_\theta - \tilde{S}_\theta \right) \right) \tag{5}$$

where $\min(\cdot)$ represents the minimum value of the argument; $W_{s\theta}$ is the weighting factor for the sidelobes; S_θ is the desired directivity for the sidelobes; $\tilde{S}_\theta$ is the synthesized sidelobe pattern at a specific observation angle, θ. We heuristically determined these parameters with respect to the optimization priority. The cost function for the sidelobes consists of the sum of a series of difference between the desired pattern and synthesized pattern in Equation (5). In addition, each sidelobe is multiplied by the weighting factor, $W_{s\theta}$, which is adaptively determined from the echo return range, backscattering coefficient, and geometrical configuration. The ambiguous region changes in accordance with the pulse repetition frequency (PRF) and operational modes. Equation (5) should be minimized to meet the system requirements and to synthesize an optimal pattern.

3. USE OF THE PSO TECHNIQUE TO IMPROVE THE SAR PERFORMANCE

The PSO algorithm is a sort of evolutionary algorithm utilizing swarm intelligence to optimize a specific goal function, and it operates on a model of the social interaction of independent particles [6]. The position, X, and velocity, V of the particles are updated in each iteration according to the following velocity and position update Equations [5, 7]:

$$\mathbf{X} = X_p + V \tag{6}$$

$$\mathbf{V} = V_p + W_1\ \xi_1(L - X) + W_2\ \xi_2(G - X) \tag{7}$$

where X and V are the position and velocity vectors; L and G represent the best local position and the best global position in the swarm; ξ_1 and ξ_2 are random variables between 0 and 1; W_1 and W_2 are optimization parameters that depend on the particle's movement; the subscript p denotes the previous state of the particle. In addition, X and V of a particle are a function of the distance from the particle's current position to the previous local position and the best global position.

$$\mathbf{X} = \begin{bmatrix} Tx & \text{amplitude} \\ Tx & \text{phase} \\ Rx & \text{amplitude} \\ Rx & \text{phase} \end{bmatrix} = \begin{bmatrix} T_{xa1} & T_{xa2} & \cdots & T_{xai} \\ T_{xp1} & T_{xp2} & \cdots & T_{xpi} \\ R_{xa1} & R_{xa2} & \cdots & R_{xai} \\ R_{xp1} & R_{xp2} & \cdots & R_{xpi} \end{bmatrix} \tag{8}$$

$$\mathbf{V} = \begin{bmatrix} V_{11} & V_{12} & \cdots & V_{1(i-1)} & V_{1i} \\ V_{21} & V_{22} & \cdots & V_{2(i-1)} & V_{2i} \\ V_{31} & V_{32} & \cdots & V_{3(i-1)} & V_{3i} \\ V_{41} & V_{42} & \cdots & V_{4(i-1)} & V_{4i} \end{bmatrix} \tag{9}$$

where T_{xai}, T_{xpi}, R_{xai} and R_{xpi} represent the amplitude and phase distribution for the respective Tx and Rx, and i is the number of T/R module. A particle's initial is defined by the amplitude and phase distribution represented by all T/R modules in the elevation plane as given in Equation (8), and a particle's initial is randomly initialized between -1 and 1 in Equation (9). As depicted in Figure 2, the PSO technique was applied to SAR system design to optimize the multi-objective cost functions such as the antenna gain, gain slope, gain flatness and sidelobe level. Heuristically, we determined the particle's number and optimization parameters after considering the tradeoff between optimal efficiency and computational speed. The particle's position and velocity were randomly produced, and the antenna pattern was then calculated by using the excitation of the initial particle. If the cost function is not satisfied with the fitness

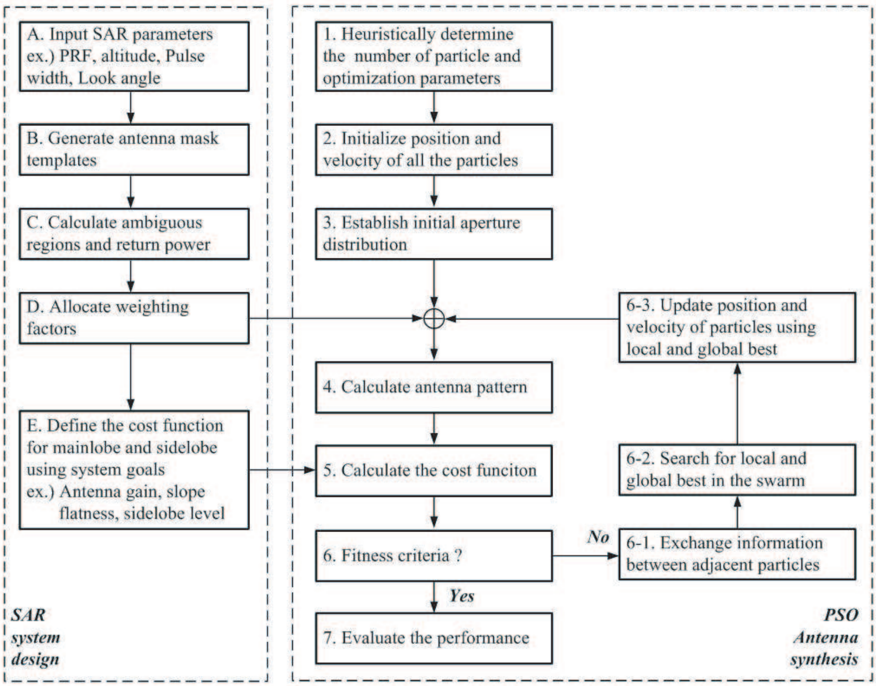


Figure 2. Design flow diagram for the SAR performance evaluation based on PSO. The PSO technique is applied to the SAR system design. For optimization of the cost function, the mask pattern and weighting factors are calculated with respect to the SAR parameters.

criteria, each particle exchanges information to search for the local best L in a small group composed of a few adjacent particles and the global best G in the entire swarm. As a result, the particle's next position and velocity are updated by means of Equations (6) and (7) [8–10]. By continually updating X and V, we can effectively synthesize the SAR antenna patterns with the mask template.

4. SELECTION OF THE ADAPTIVE WEIGHTING FACTORS

The selection of the weighting factor is a very important task because the fitness of the cost function for the mask pattern is primarily determined by the PSO technique on the basis of the adaptively selected weighting factors. To fit the antenna pattern into the mask template, we need to assign the mainlobe weighting factors W_{dir}, W_{flat}, and W_{slope} in Equations (2), (3), and (4) in order of priority with respect to the system requirements. In addition, the sidelobe weighting factor $W_{s\theta} = [W_{s1}\ W_{s2}\ W_{s3}\ W_{s4}\ W_{s5}\ \ldots\ W_{sm}]$ in Equation (5) should be assigned to an appropriate level for increasing the antenna pattern optimization speed, where subscript m represents the angle defined at the ambiguous regions. In Figure 3, $m = 1, 3, 5, \ldots$ are the weighting factors on the left-hand side of the mainlobe, and $m = 2, 4, 6, \ldots$ are the weighting factors on the right-hand side of the mainlobe. The sidelobe weighting factor $W_{s\theta}$ can be determined from the following sequences:

Step1: Determine the ambiguous region using the observation geometry.

Step2: Generate the two-way antenna pattern assuming a uniform antenna distribution.

Step3: Calculate the return power by using the reference antenna pattern, the mean backscattering coefficient, and the radar parameters established at each ambiguous region [7, 11].

Step4: Choose the weighting factor at each ambiguous region based on the calculated return power.

According to the selection of weighting factor, the total amount of cost function based on Equation (5) has a different value. In Table 1, the ambiguous regions with high weighting factor are considerably emphasized during the optimization process to reduce the

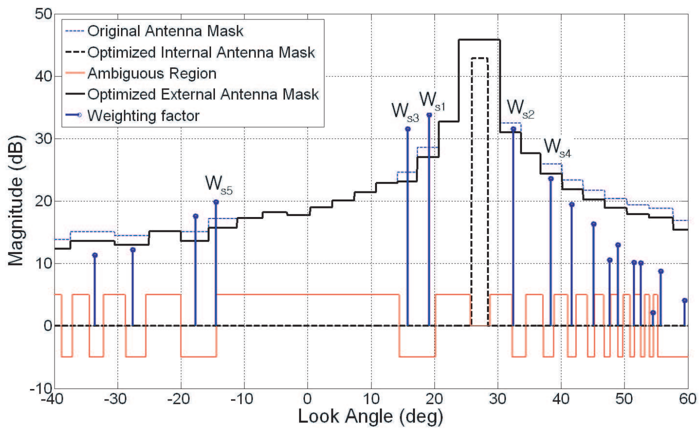


Figure 3. Antenna mask and adaptive weighting factors selected at the ambiguous regions in proportion to the return power based on Table 1. The shaded areas indicate the ambiguous region defined from the radar parameters.

Table 1. Adaptive weighting factor selection on the basis of the received power as a function of ambiguous region, backscattering coefficient, antenna gain and slant range.

Ambiguous Region (Look angle)	σ_o **(dB)**	**Antenna Gain (dB)**	**Slant Range (Km)**	**Normalized Return Power(dB)**	**Weighting factor**	
−33.6	−8.7	15.1	736	−22.1	W_{s11}	1
−27.6	−7.6	14.4	686	−20.0	W_{s9}	1
−17.7	−3.4	15.1	633	−12.3	W_{s7}	3
−13.3	1.6	17.2	618	−3.7	W_{s5}	5
15.8	−1.2	24.6	626	0.0	W_{s3}	10
19.2	−4.6	28.6	639	−0.4	W_{s1}	10
31.8	−8.4	32.4	719	−4.0	W_{s2}	5
38.4	−9.4	25.8	790	−13.6	W_{s4}	3
41.7	−9.9	23.3	836	−17.6	W_{s6}	3
45.1	−10.4	21.7	895	−20.9	W_{s8}	1
48.6	−11.0	20.5	970	−23.9	W_{s10}	1
52.1	−11.5	19.4	1068	−23.9	W_{s12}	1
55.7	−12.3	19.0	1203	−30.0	W_{s14}	1
59.5	−13.2	16.9	1413	−35.3	W_{s16}	1
63.3	−14.6	16.6	1788	−40.1	W_{s18}	1

cost function. Because the ambiguous regions near the mainlobe are the most critical contributors to the SAR performance, the weighting factors have to be adaptively selected in terms of the normalized return power. Even though the ambiguous regions with low weighting factor violate the mask template after the optimization process, their effect on the total cost function is negligible. As a result, when the weighting factors are prioritized, the PSO's convergence speed is increased, and the performance of the system is optimized.

5. SIMULATION RESULTS

In this simulation, ten particles as a potential solution are assumed, and each particle has a uniform distribution as an initial setting mixed with a random position in a 96-dimensional space, constrained between 0 and 1 in each dimension. To successfully suppress the antenna sidelobes as defined in Equation (5), we set the weighting factors at ambiguous region as shown in Table 1 after considering the geometrical configuration between the pointing direction of the antenna beam and distributed ground targets [12]. We assumed that the active phased array antenna has 24 T/R modules in the elevation plane, with each module having a 6 bit phase shifter and a 6 bit digitally controlled attenuator. Each particle had 96 dimensions: That is, 24 Tx amplitudes, 24 Tx phases, 24 Rx amplitudes, and 24 Rx phases. Table 2 lists all the parameters used in the SAR configuration and PSO

Table 2. SAR system parameters and particle swarm optimization parameters based on active phased array SAR configuration, operation parameter and geometry information.

SAR parameters	**Value**
Frequency	9.65 GHz
PRF	3 kHz
Altitude	600 km
Swath width	30 km
Look Angle (Near, Far)	25.6 to 28.7 deg
Array element elevation distance	0.74 λ
Radiating element number	24 each (in the range direction)
Array azimuth element distance	0.68 λ
Phase control step	5.625 deg (0 to 360 deg)
Minimum required gain	45 dB
Element pattern	Slot coupled microstrip patch Sinc form or 0.54 edge tapering
Range-to-ambiguity ratio	−20 dB
Noise equivalent sigma zero	−17 dB
PSO parameters	**Value**
Initial aperture distribution	Uniform + random (0, 1)
Initial particle velocity setting	Random (−1, 1)
Number of Particle	10
Particle's total dimensional space	96
Tx & Rx amplitude/phase number	(24, 24, 24, 24)
Optimization parameter (W_1, W_2)	Random (0, 1)
ξ_1, ξ_2	Random (0, 1)
Weighting factor $[W_{s_7}, W_{s_5}, W_{s_3}, W_{s_1}, W_{s_2}, W_{s_4}, W_{s_6}]$ $[W_{s_8}, W_{s_9}, W_{s_{10}}, W_{s_{11}}, W_{s_{12}}, W_{s_{14}}, W_{s_{16}}]$ $[W_{\text{dir}}, W_{\text{flat}}, W_{\text{slope}}]$	 [3, 5, 10, 10, 5, 3, 3] [1, 1, 1, 1, 1, 1, 1, 1] [10, 10, 10]

simulation. The simulation was iterated up to 150 in a search for the optimal amplitude and phase values of the 10 particles. Figure 3 shows the antenna mask template, ambiguous regions and adaptive weighting factor in proportion to the return power. The ambiguous regions are defined by the PRF and SAR geometry, and the specific regions among the ambiguous regions have a different weighting value on the basis of the return power. Figures 4(a) and (b) show the T/R module's

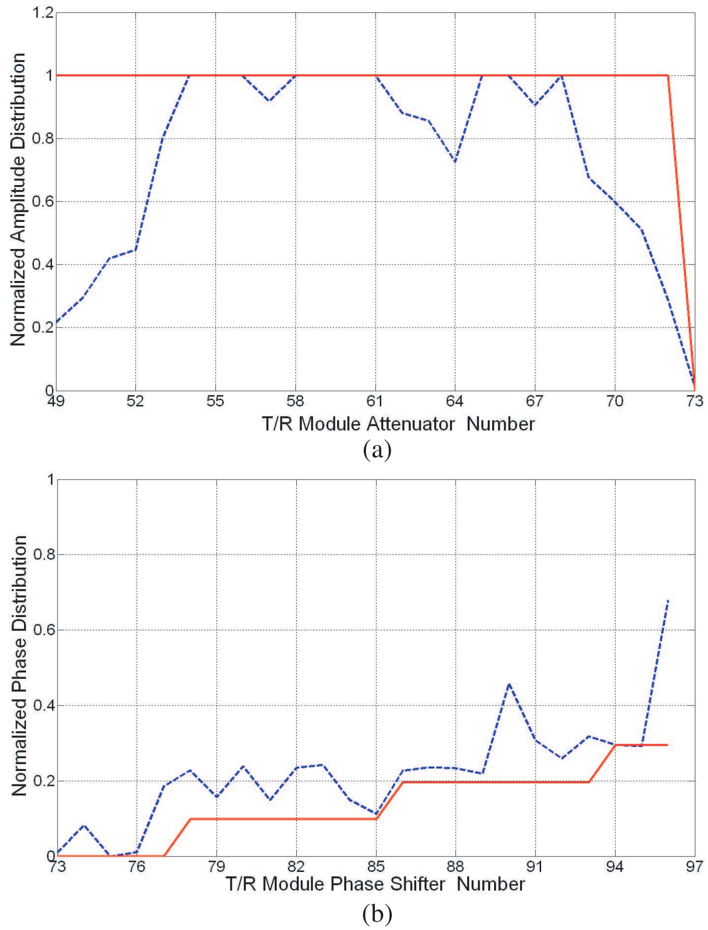
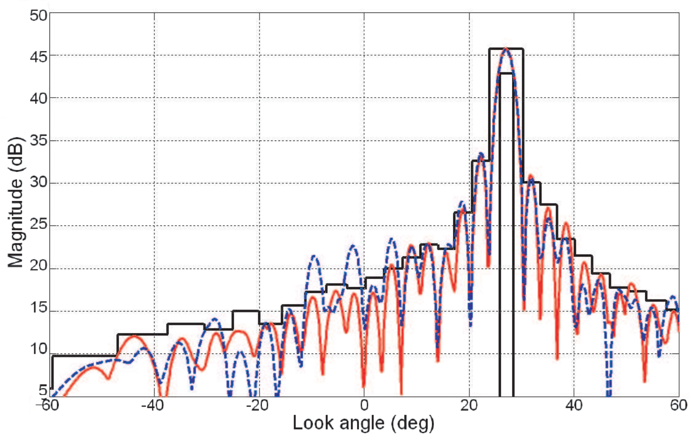
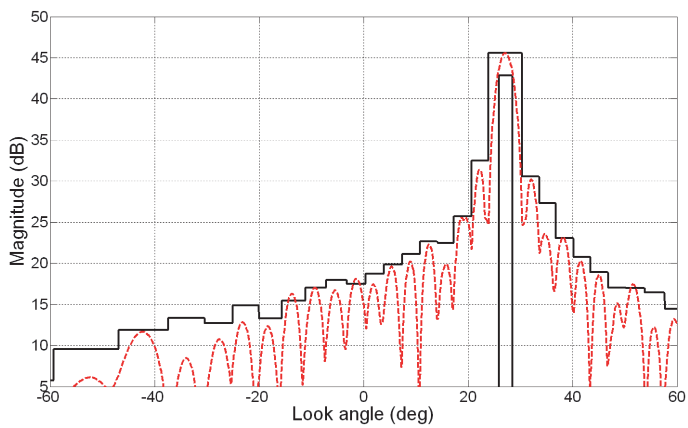


Figure 4. T/R module's excitation coefficients optimized by PSO after 150 iterations. (a) Normalized amplitude distribution and (b) normalized phase distribution (solid line: Initial amplitude and phase distribution; dashed line: Optimized amplitude and phase distribution).

optimized amplitude and phase excitation coefficient distribution of the best particle in the swarm for both uniform distribution and optimized aperture distribution.



(a)



(b)

Figure 5. Antenna pattern synthesis examples in terms of PSO and the weighting factor. Antenna patterns reveal the different convergence characteristic depending on the weighting factor value. (a) The dashed line is in the case of $[W_{s_7}, W_{s_5}, W_{s_3}, W_{s_1}, W_{s_2}, W_{s_4}, W_{s_6}]$=[3, 3, 3, 3, 3, 3, 3] and the solid line is in the case of $[W_{s_7}, W_{s_5}, W_{s_3}, W_{s_1}, W_{s_2}, W_{s_4}, W_{s_6}]$=[3, 5, 5, 5, 5, 3, 3] and (b) the adaptive weighting factors are selected on the basis of the return power as $[W_{s_7}, W_{s_5}, W_{s_3}, W_{s_1}, W_{s_2}, W_{s_4}, W_{s_6}]$=[3, 5, 10, 10, 5, 3, 3].

The antenna patterns are synthesized and optimized using PSO in terms of the different weighting factor value as shown in Figures 5(a) and (b). The synthesized antenna patterns with different weighting factors reveal the different convergence characteristics. Figure 5(b) shows the best synthesis results for the adaptively selected weighting

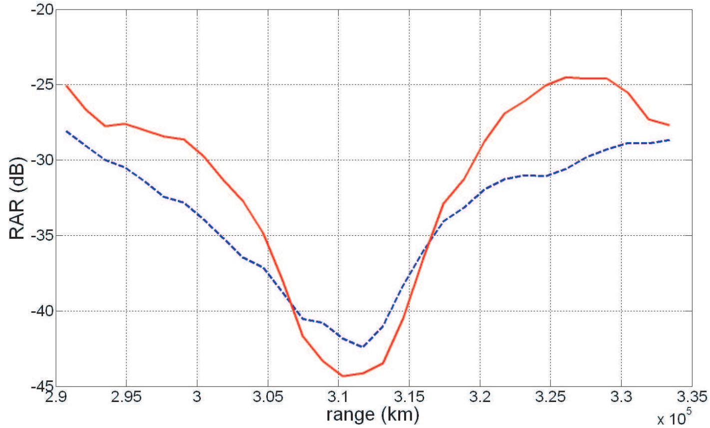


Figure 6. Range ambiguity ratio results calculated from the optimized antenna pattern (dashed line) and the uniform antenna pattern (solid line).

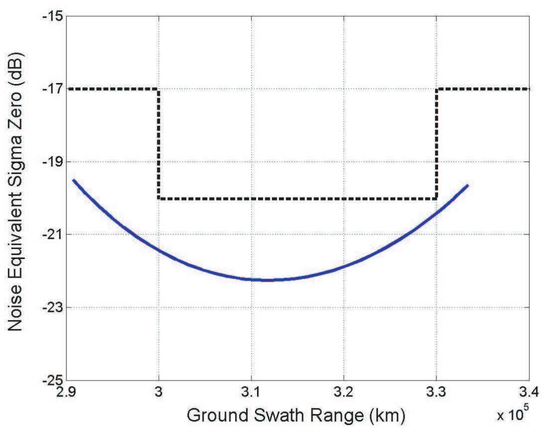


Figure 7. NESZ is calculated from the optimized antenna pattern and satisfies the system requirement defined in the swath width (dashed line: NESZ system requirement; solid line: Optimized NESZ).

factor. Figure 6 compares the RAR results of the optimized pattern with that of the uniform distribution. The range ambiguity ratio is improved at the near and far sides of the swath width; on the other hand it shows the slightly degraded result in the middle of the swath. However, the reduced level is negligible and meets the system requirement successfully. As shown in Figure 7, the optimized SAR antenna pattern satisfies the NESZ mask requirement in the swath region as a result of the effectively synthesized antenna pattern. As a result, the performance improvement is due to the effective optimization results over the adaptive weighting factor and PSO algorithm.

6. CONCLUSION

In this paper, we proposed that an optimal antenna pattern synthesis technique for active phased array synthetic aperture radar has been utilized to meet the best performances based on particle swarm optimization and adaptively selected weighting factors. The overall multi-objective cost function is derived to optimize the system performance measures such as the range-to-ambiguity ratio, noise equivalent sigma zero, and radiometric accuracy.

To increase the PSO synthesis efficiency and convergence speed of the cost function, the adaptive selection method of the weighting factor was proposed as follows. First, in order to effectively select the weighting factor, the ambiguous regions were defined in terms of SAR geometrical configuration and system parameters, and then the return power was calculated at the ambiguous regions. Finally, the weighting factors have been optimally selected in proportion to the return power.

To verify the effectiveness of PSO synthesis technique and weighting factor, we applied the PSO technique and adaptive weighting factors to SAR antenna pattern design and conducted a simulation to get the optimal RAR and NESZ with an optimized antenna pattern. By using the proposed technique, we can easily optimize the performance of an active phased array SAR in terms of the weighting factor value.

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