

RETRIEVING EVAPORATION DUCT HEIGHTS FROM RADAR SEA CLUTTER USING PARTICLE SWARM OPTIMIZATION (PSO) ALGORITHM

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Abstract—Particle Swarm Optimization algorithm (PSO) is a popular stochastic searching optimization algorithm to solve complicated optimization problems. The approach of retrieving duct parameters from the sea-surface reflected radar clutter is also known as Refractivity From Clutter (RFC) technique. RFC technique provides the near-real-time duct parameters to evaluate the radio system performance, without adding any hardware. Basic principles of PSO and its applications and RFC technique are introduced. Evaporation duct is retrieved based on RFC technique using PSO. The performance of PSO is validated using experiment data launched at East China Sea and compared with those of genetic algorithm (GA) and ant colony algorithm (ACA). The results indicate that PSO has the advantages of faster convergence and higher retrieval precision than the other two methods.

1. INTRODUCTION

Atmospheric duct is an anomalous condition of atmosphere, which leads to the trap of electromagnetic waves within a certain atmosphere layer (Fig. 1). The performance of various radio systems is directly affected due to the anomalous propagation of electromagnetic waves. Ducts result in various anomalies such as a significant change in the maximum operational radar range, creation of radar holes where the

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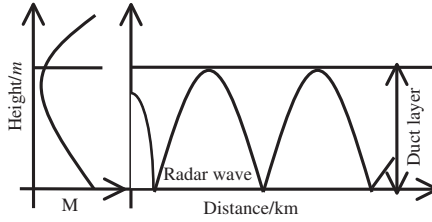


Figure 1. Effects of ducting on electromagnetic wave. m and M are presented meters and modified refractivity, respectively.

radar is effectively blind and an increase in the sea clutter. Hence, radio systems/radar systems operating in these environments would benefit from knowing the effects of the environment on their system performance. This requires the knowledge of atmospheric ducts, which refers to techniques that retrieve these parameters of ducts.

Conventionally atmospheric ducts can be measured using radiosondes and rocketsondes, microwave refractometers, lidar, GPS, and predicted by meteorological models. However, these techniques are high cost and can not provide real-time ducts parameters. Retrieving atmospheric ducts from radar clutter provides near-real-time parameters of ducts, which does not use additional hardware or extra meteorological/electromagnetic measurements. International researchers have done many theoretical and experimental researches, and developed some mature theories and techniques. And an experiment (called Wallops98) was carried out to estimate parameters of atmospheric ducts from radar clutter, whose results show the feasibility and efficiency [1–3] of the RFC technique. For the great important applications of atmospheric ducts, recently, many Chinese researchers have started researches on relevant theories, such as happening mechanism [4–7], occurrences probability [8, 9] and effects of ducts on radio systems [7, 10], and gotten some results of retrieval [11].

Because the relationship between duct parameters and radar sea clutter is clearly nonlinear and ill-posed, it is impossible to get analytical solutions according to current theories. Thus, optimization algorithms are good choice to get approximate solutions. Since 1960s, some novel intelligent optimization algorithms, such as Genetic Algorithm (GA), Evolutionary Programming (EP), Evolutionary Strategy (ES), Simulated Annealing algorithm (SA), Artificial Immune (AI) algorithm, Ant Colony Algorithm (ACA), Particle Swarm Optimization (PSO), and hybrid optimization algorithms, have provided novel ideas and techniques. Those algorithms are inspired by some natural phenomena or process [12].

PSO is a heuristic search technique, which was first developed by Kennedy and Eberhart in 1995. PSO is characterized by easy computing, fast convergence, and parallel operation, and it effectively solves many complicated non-linear and non-differential problems. PSO algorithm is developed quickly for it has only a few parameters and has been applied to many fields [12–15]. This paper extends the application fields of PSO and also provides a new method to RFC.

2. SIMULATION OF THE RADAR SEA CLUTTER POWER

A forward simulation of received radar sea clutter power has to be performed, and its accuracy determines the veracity of evaluating the performances of radar systems and affects the precision of retrieved duct parameters. Using the classical radar equation, received radar clutter power can be calculated as follows (in dB) [2]:

$$P_{rc}(r, \mathbf{m}) = -2L(r, \mathbf{m}) + 10 \log_{10} r + \sigma^0(r) + C \quad (1)$$

where L is one-way propagation loss in ducts and obtained using the split-step fast Fourier transform (FFT) parabolic equation (PE) [16]. r is distance. $\sigma^0(r)$ is the normalized sea surface radar cross section (scattering coefficient) at r . C is a constant that includes wavelength, transmitter power, antenna gain, etc.

Obviously, $\sigma^0(r)$ and L must be calculated accurately, if we want to get an accurate radar sea clutter power P_{rc} .

2.1. Scattering Coefficient at Grazing Angle

In reality, radar scattering coefficient (radar cross section) is a function of grazing angle, the effective clutter height, range and duct parameters. The grazing angle is usually less than 0.8° , and almost constant for long ranges. There are many techniques to compute scattering coefficient [17–20], such as classical Kirchhoff approximation (KA), phase perturbation technique (PPT), and small slope approximation (SSA). Unfortunately, all of them can not calculate the scattering coefficient properly at a low grazing angle. Thus, one uses the assumptions of $\sigma^0 \propto \theta^0$ and $\sigma^0 \propto \theta^4$, where θ is the grazing angle.

Moreover, considering that the scattering coefficient is a function of sea surface wind speed, grazing angle, frequency, and polarization, some appropriate empirical or semi-empirical models are established, such as Adjusted Barton Model [21, 22], Adjust Morchin Model [23]

and GIT Model [24]. Adjusted Barton Model is introduced as follows:

$$\sigma^0 = \begin{cases} 6K_B - 10 \lg \lambda + 10 \lg \sin \theta - 10 \lg(\theta_c/\theta) - 64 & \theta < \theta_c \\ 6K_B - 10 \lg \lambda + 10 \lg \sin \theta - 64 & \theta \geq \theta_c \end{cases} \quad (2)$$

where K_B is the Beaufort wind force scale; λ is the wavelength of radar; θ is the grazing angle; θ_c is the critical grazing angle, which is a function of sea condition as follows:

$$\theta_c = \arcsin(\lambda/4\pi h_e) \quad (3)$$

where h_e is the sea surface roughness and is given by:

$$h_e \approx 0.025 + 0.046K_B^{1.72} \quad (4)$$

Equation (2) is called Adjusted Barton Model. It is easy and fast to compute, but the effect of polarization on scattering coefficient is not included. Thus, Equation (2) should be modified according to different sea conditions and polarization.

2.2. Evaporation Duct Model

Normally, the atmospheric refractivity has a negative slope of the altitude. In this condition, electromagnetic waves would slowly move away from the surface. If the negative slope is stronger than the curvature of the earth, the wave will be partially trapped and forced to bend downward, and an atmospheric duct is formed.

In troposphere, refractivity (N) is usually expressed as [25]:

$$N = \frac{77.6}{T} \left(p + \frac{4810e}{T} \right) \quad (5)$$

where T , p , and e represent absolute temperature (K), atmosphere pressure (hpa) and water vapor pressure (hpa) of atmosphere, respectively. When the refractivity sharply decreases with height, and the refractivity gradient satisfies Equation (6), atmospheric ducts happen:

$$\frac{dN}{dh} \leq -157 \text{ (N-units/km)} \quad (6)$$

The modified refractivity (M) is usually introduced in the form of flat earth. N and M can be computed as [25]

$$M = N + \frac{h}{a} \times 10^6 \text{ (M unit)} \quad (7)$$

where h is height; a is earth radius. From (5), (6) and (7), ducts occur when M satisfies (8):

$$\frac{dM}{dh} \leq 0 \text{ (M-units/km)} \quad (8)$$

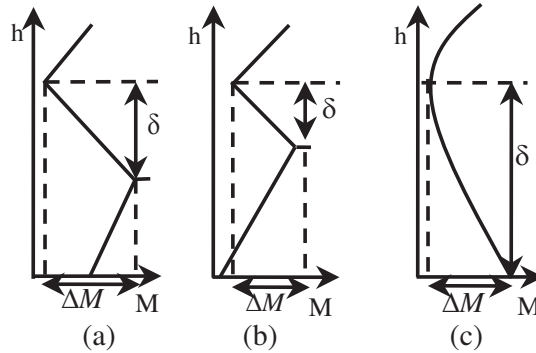


Figure 2. Most common three duct types. (a) Surface-based duct. (b) Elevated duct. (c) Evaporation duct.

Duct models play an important role in retrieving duct parameters, and they affect the final retrieved results. For sea environments, there are three major sea ducts frequently encountered (Fig. 2): Surface-based ducts, elevated ducts, and evaporation ducts.

Because evaporation ducts are the main consideration, a single parameter exponent model for Fig. 2(c) is given by Equation (9) [26]:

$$M(z) = M_0 + 0.125 \cdot z - 0.125 \cdot d \cdot \ln[(z + z_0)/z_0] \quad (9)$$

where z is height; d is the evaporation duct height; ΔM is the evaporation duct strength; $z_0 = 1.5 \times 10^{-4}$. M_0 is the modified refractivity at sea surface; its typical value is $370M$. This model has been extensively applied and especially precise to evaporation duct.

2.3. Retrieval Algorithm: Standard PSO

Actually, the technique used to retrieve atmospheric ducts from radar sea clutter is a minimum problem which estimates the fit of simulated and measured radar sea clutter power. PSO method can solve the problem effectively. Thus, a standard PSO algorithm is introduced.

Particle swarm optimization (PSO) is a population-based stochastic optimization technique. In PSO, each single potential solution is a “bird” in the search space which is called “particle”. All particles have fitness values which are evaluated by the fitness function to be optimized, and have velocities which determine the flying direction and space of the particles. PSO is initialized with a group of random particles (solutions) and then searches for optima by iteration. In each iteration process, each particle is updated by following two “best” values. The first one is the best solution (fitness)

it has achieved so far. This value is called *pbest*. The other “best” value that is tracked by the particle swarm optimizer is the best value, obtained so far by any particle in the population. This best value is a global best and called *gbest* [12].

Supposing that the state space is n dimensions. The size of the population is m . Each particle flies in the search space in its own flying velocity. The flying velocity is updated according to its own and its companions' flying experience. The i th particle is represented as an n -dimension vector $X_i = (x_{i1}, x_{i2}, \dots, x_{in})$. Its corresponding flying velocity is represented as another n -dimension vector $V_i = (v_{i1}, v_{i2}, \dots, v_{in})$. The best previous position of the i th particle is recorded and represented as $P_i = (p_{i1}, p_{i2}, \dots, p_{in})$. The best positions of the population are recorded and represented as $P_g = (P_1, P_2, \dots, P_m)$. By adding a new inertia weight into PSO, a standard version of PSO is introduced. The main equations can be written as:

$$v_{ij}(t+1) = \omega v_{ij}(t) + c_1 r_{1j}(t)[p_{ij}(t) - x_{ij}(t)] + c_2 r_{2j}(t)[p_{gj}(t) - x_{ij}(t)] \quad (10)$$

$$x_{ij}(t+1) = x_{ij}(t) + v_{ij}(t+1) \quad (11)$$

where $i = 1, 2, \dots, m$, $j = 1, 2, \dots, n$, ω is inertia weight; c_1 and c_2 are learning factors, usually between $[0, 2]$; r_1 and r_2 are two random functions in the range $[0, 1]$ independently. The flow chart of the procedure is shown in Fig. 3.

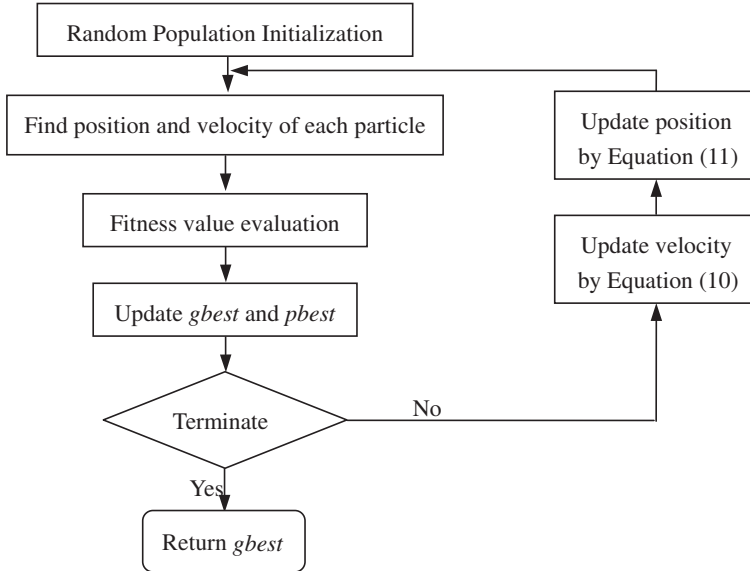


Figure 3. Standard PSO flow chart.

The learning factors c_1 and c_2 in Equation (10) are the weights determined by how importantly each particle experience and population experience play a role in flying and represent the abilities to learn from itself and population. Inertia weight ω is a coefficient employed to control global and local search abilities, a non-negative constant or function descending with time. A number of experiments show that convergence is improved significantly, if ω descends linearly with iterations [12].

2.4. Retrieval Steps Using PSO

In reality, the retrieval process is to estimate the fit of simulated and measured radar sea clutter power. A set of clutter power is obtained by changing the duct parameters randomly, and the error of each set is gained by comparing each set with observation power data. Then, the parameters corresponding to the minimal error are the final retrieved results. From the point of view of function optimization, retrieval is a global minimum problem between simulated and measured clutter power.

For evaporation duct retrieval, there is only one parameter, duct height, which means $n = 1$ in PSO. From published references, the general steps based on experimental data using PSO algorithm are presented as follows [2]:

1. A vector of sea clutter power $\mathbf{P}_c^{\text{obs}}$ at discrete range (r_1, r_2, \dots, r_N) is observed. The power sequence is the input data.
2. An environment mapping model maps environment vector \mathbf{m} into modified refractivity M profiles over the discrete ranges and heights of interest.
3. The replica field $\mathbf{P}_c(\mathbf{m})$ is calculated from M profiles using PE and radar range equation.
4. An objective function f is used to evaluate the fit of $\mathbf{P}_c(\mathbf{m})$ to $\mathbf{P}_c^{\text{obs}}$. The objective function used here is given by

$$f = \mathbf{P}_{\text{obs}} - \mathbf{P}_{\text{cal}} - \hat{T} \quad (12)$$

where $\hat{T} = \bar{P}_{\text{obs}} - \bar{P}_{\text{cal}}$, \bar{P}_{obs} and \bar{P}_{cal} are the mean values of \mathbf{P}_{obs} and \mathbf{P}_{cal} , respectively.

5. A global optimization procedure is used to search over all \mathbf{m} to find the optimal value $\hat{\mathbf{m}}$ of f .
6. An assessment is made of the quality of the solution by examining forward model solutions or parameter error estimates/distributions.

3. EXPERIMENTS

3.1. Experimental Data

The experiment used to examine the technique of retrieving atmospheric ducts from radar clutter is complicated and costly, and it needs a clear spot. Fortunately, a successful example, Wallops98, was provided in [1].

In this paper, the experimental data used to test the retrieval algorithm referring to [11]. An experiment was launched in East China Sea. The parameters for radar system are shown in Table 1. A set of measurement data are shown in Fig. 4.

A median filtering operation is made to remove sea spikes, when retrieval uses sea clutter power.

Table 1. Parameters for radar system.

Parameter	Value(Units)
Frequency	10 GHz
Beam width	0.7°
Antenna height	10 m
Polarization	HH

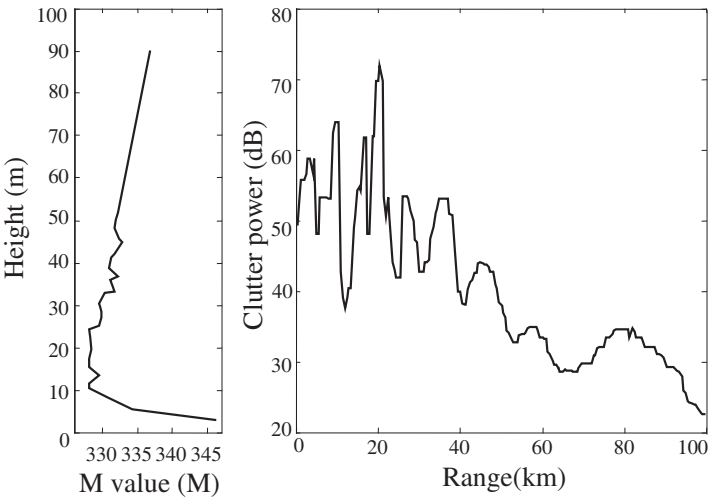


Figure 4. Measured vertical M profile and corresponding received clutter power as a function of range.

The M profiles are measured by low altitude captive balloon. During measurement, the balloon could not ascend in a straight line, because of sea breeze and man-made reasons. Thus, the picture shows abnormality and affects the precision of the measured section.

In order to determine the evaporation duct height of measured M profiles, a method is introduced as follows: Firstly, a set of height values at a certain range are chosen. Secondly, a set of M profiles corresponding height values are obtained by using Equation (9). Finally, the RMS error between each measured and computed profiles is calculated using error Equation (13), where N is the number of points compared in vertical; M_i^m is the i th measured M value; M_i^s is the i th calculated M value. The height that has the minimum RMS is considered as the measured height, and the true height is 13 m in Fig. 3, respectively.

$$E_{\text{std}} = \sqrt{\frac{1}{N} \sum_{i=1}^N (M_i^m - M_i^s)^2} \quad (13)$$

The interval of clutter power is 0.5 km in propagation path, and the maximum range is 100 km (Fig. 4). Clutter data are influenced by various factors and, thus, present different large and small peaks. The power simulated using PE is smooth, but both changing trends are coincident. The accuracy of calculated clutter power only affects the final results partially. The height which makes the simulated power agree with measured data is the retrieved parameter.

3.2. Retrieved Results Analyses

The parameters of PSO are initialized as follows: the size of population, $m = 40$, maximum iteration, $N_{\text{max}} = 25$, learning factors, $c_1 = c_2 = 2$. A dynamic inertia weight is introduced, $\omega = 0.9 - i * 0.4 / N_{\text{max}}$, where i is the iterative number. The retrieved evaporation duct height is 12.9 m. Fig. 5(a) is an instance, which shows that retrieved and measured heights are in a good agreement. Fig. 5(b) shows the convergence speed of PSO, which indicates that a good accuracy is achieved when iterating to about 5th generation.

In order to fully show the preponderance of PSO, a comparison among PSO, ACA, and GA is made. The parameters of the three methods are the same as follows: The size of population, 40, maximum iteration, 25, Monte Carlo simulations, 200. The MATLAB GA toolbox is used for GA results. It uses another 3 isolated parameters of rate of individuals of 0.9, a single-point crossover fraction of 0.7, a mutation rate of 0.04. ACA also uses another 2 isolated parameters of a move probability of 0.2, trail update coefficient of 0.2. All

the retrieved results are summarized in Table 2, and Fig. 6 is the probability distribution map of the retrieved results. From Table 1, PSO is obviously the best approach.

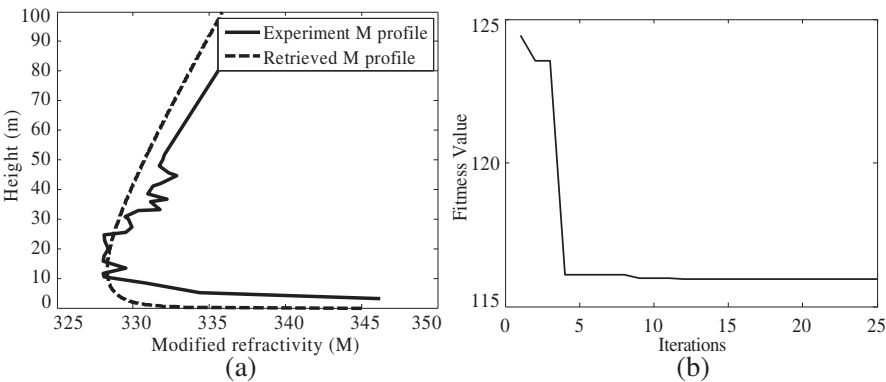


Figure 5. (a) Retrieved results (b) performance of PSO.

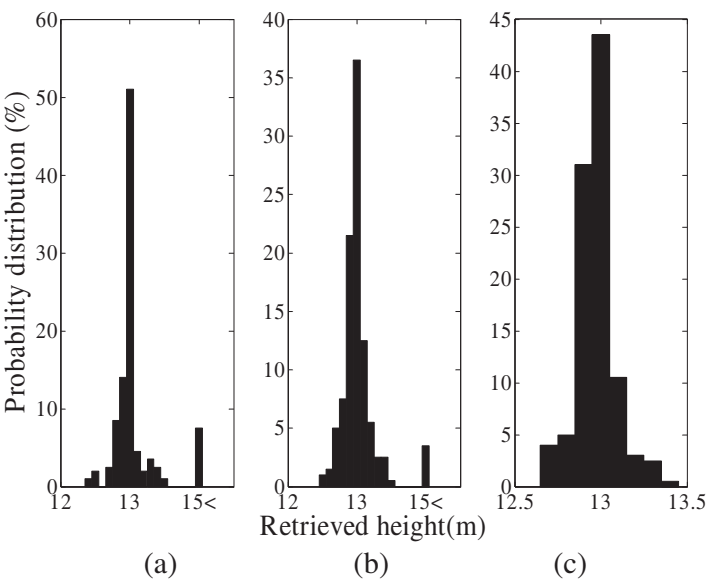


Figure 6. Probability distribution maps of retrieved results. (a) GA (b) ACA (c) PSO Table 2. Statistics of retrieved results (m).

Table 2. Statistics of retrieved results (m).

Methods	Min	Max	Mean	Std
GA	12.4	29.6	14.192	4.278
ACA	12.5	29.2	13.546	2.982
PSO	12.7	13.4	12.973	0.115

4. CONCLUSION

Retrieving atmospheric ducts from radar clutter power is a novel technique, which plays an important role in the full usage of radar systems. The principle of the technique is analyzed. The retrieving steps based on experiment data are introduced. The principle of PSO is also introduced and applied to retrieval. Examination of PSO is made using experimental data. The results compared with GA and ACA indicate that it is possible to retrieve ducts from radar clutter power and that PSO has the highest accuracy of atmospheric duct retrieval than GA and ACA. These results provide important data support for improving the performance of radio systems such as radar and other radio communication systems. The running time and stability of the three algorithms are not analyzed, and these will be the topics of future research.

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