An Inverse Model for Sea Ice Thickness Retrieval Using Simulated Annealing

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Abstract— An inverse model named the Radiative Transfer Inverse Scattering Model (RTISM) for the retrieval of sea ice thickness using Radiative Transfer Theory (RTT) had previously been developed by the authors. The model incorporates the use of the Dense Medium Phase and Amplitude Correction Theory (DMPACT) for better accuracy in the radar backscatter calculations and the application of the Levenberg-Marquardt Algorithm (LMA) to predict the sea ice thickness from the radar backscatter data. While the model has been successful in its attempts to predict the sea ice thickness from radar backscatter data, it has limitations in extending its applications to other sea ice parameters. In this paper, the study of using Simulated Annealing (SA) as an alternative solution for the LMA in the RTISM is presented. SA is appealing as a viable option to replace the LMA due to several reasons. It is a global optimizer and reduces the likelihood of being trapped in a local extremum, thus improving convergence. In addition, SA eliminates the cumbersome recalculation of the Jacobian matrices of the problem function for different applications, as required by LMA. Thus, the use of SA generalizes the inverse model and allows for more room to extend its applications. A comparison between the performances of both optimizers implemented in the RTISM shall be explored in terms of the execution time and accuracy in predicting the sea ice thickness.

1. INTRODUCTION

The physical properties of sea ice are crucial towards studies on global climate change and polar research [1]. The attempts to use inverse theoretical models to retrieve the physical properties of sea ice from microwave remote sensing data has been an ongoing study for many years [2]. Prior to the development of inverse models, many forward scattering models has been proposed and studied to relate between the sea ice characteristics and the radar backscatter data [3]. Many of the inverse models that are developed and presented in [2] use a combination of forward models to perform radar backscatter predictions, an optimization technique to optimize the target parameter and supporting theorems related to the sea ice.

Previously, the authors developed an inverse model named the Radiative Transfer Inverse Scattering Model (RTISM) for the retrieval of sea ice thickness, which is loosely based on the Radiative Transfer-Thermodynamic Inverse Model for Sea Ice Thickness from Time-Series Scattering Data [4]. In the RTISM, the forward model used to estimate radar backscatter data from a set of sea ice parameters in the algorithm is the Radiative Transfer Theory (RTT). This model has been improved with the incorporation of the Dense Medium Phase and Amplitude Correction Theory (DMPACT), which gives a better prediction in the radar backscatter calculations. The Levenberg-Marquardt Algorithm (LMA) is then used to perform prediction of the sea ice thickness from the radar backscatter data. The model has shown potential in its attempts to predict the sea ice thickness from radar backscatter data, but it has limitations in extending its applications to other sea ice parameters or multiple parameters. As such, an alternative method of optimization has been considered as a replacement for the LMA.

2. RADIATIVE TRANSFER INVERSE SCATTERING MODEL (RTISM) WITH SIMULATED ANNEALING (SA)

2.1. Background

In this paper, a modification to the RTISM is introduced by replacing the optimization technique LMA with Simulated Annealing (SA). While the LMA is robust and offers good predictions, it requires the calculation of Jacobian matrices of the problem function to cater for different applications, which can be cumbersome when multiple parameters or changes in the application are involved. The application of SA offers the following benefits. It is a global optimizer and reduces the likelihood of being trapped in a local extremum, thus improving convergence rate. In addition, SA does not require calculating the Jacobian matrices of the problem function, which allows the inverse model to become more generalized and allows for more room to extend its applications

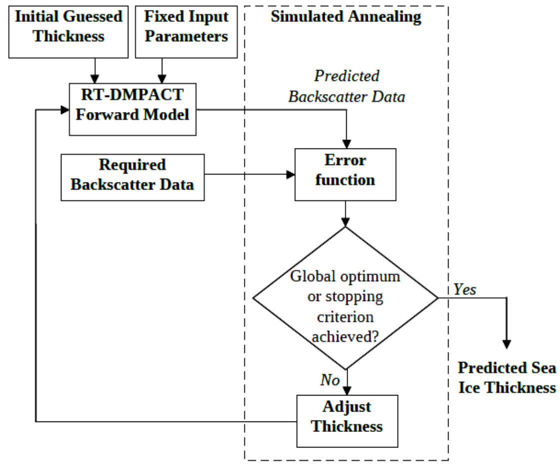

Figure 1: Flowchart of the modified RTISM.

to retrieve other sea ice parameters or to predict multiple sea ice parameters simultaneously. A flow chart of the modified RTISM is shown in Figure 1, where the SA is used as the optimization algorithm.

2.2. Simulated Annealing (SA)

SA is a global optimizer that explores a function's entire parameter space before trying to optimize a function while moving uphill or downhill [5]. This means the optimizer is largely independent of the starting values, often a critical input in other conventional algorithms, such as the LMA. In addition, SA is capable of escaping from local optima and go on to find the global optimum by the uphill and downhill moves. Another advantage of SA is that it makes less stringent assumptions regarding the function, thus making it easier to deal with functions that have ridges and plateaus. Finally, it can also optimize functions that are not defined for some parameter values.

SA is based on thermodynamics, which involves the study of a system's thermal energy, particularly in the way metals cool and anneal. In metallurgy, "annealing" is a technique involving the heating and controlled cooling of a metal to increase the size of its crystals and decrease the thermodynamic free energy of the metal. When a metal is annealed, it eventually arrives at a lower energy state. If the metal is cooled too quickly, or 'quenched', the metal may end up in a polycrystalline or amorphous state, having somewhat higher energy when fully cooled compared to an annealed metal [6]. Therefore, the essence of the process is slow cooling, giving sufficient time for the redistribution of the atoms as they lose mobility. This is the technical definition of annealing, and it is essential for ensuring that a low energy state will be achieved. The SA program used in the inverse model is based on Goffe et al., which itself is a modification of the program by Corana et al. for continuous variable problems [7].

2.3. Forward Model

In the RTISM, the RT-DMPACT forward model is used to relate between the sea ice characteristics and the radar backscatter data. Based on RTT and incorporated with the DMPACT, it is configured for a single layer medium only. In this study, the model is applied to sea ice and considers the sea ice as an electrically dense media [8]. The configuration for the forward model is shown in Figure 2 and caters for single layer only, where θ and θ_S are defined as the angle of propagation of the incident and scattered wave, respectively. In this configuration, the sea ice layer is sandwiched between the air layer (top medium) and the ocean layer (bottom medium) to simulate the actual sea ice conditions. Further details and formulations of the RT-DMPACT applied to sea ice can be found in Albert et al. [8]

3. METHODOLOGY

In order to verify the applicability and function of the modified RTISM with SA, a series of test runs were conducted using simulated results from the RT-DMPACT itself as the comparison data. The following function was to be optimized by the SA in order to predict the sea ice thickness from radar backscatter data:

$$\varepsilon_\sigma = \sigma'_{HH} - \sigma_{HH} \tag{1}$$

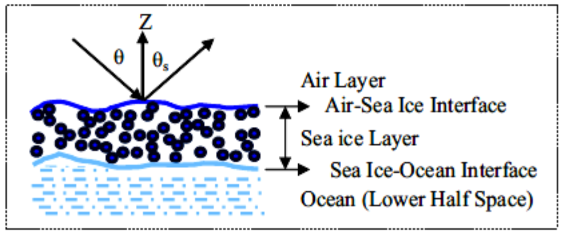

Figure 2: Model configuration for the RT-DMPACT single layer forward model.

where ε_σ is the error difference, σ'_{HH} is the estimated radar backsatter data from the forward model with guessed sea ice thickness and σ_{HH} is the required radar backscatter data (simulated using RT-DMPACT with correct sea ice thickness). The optimization will be performed by the SA by varying the sea ice thickness to find the sea ice thickness that gives the global minimum of ε_σ.

Before beginning the simulation, the RT-DMPACT is first used to simulate two sets of radar backscatter data from two test frequencies (1 GHz and 5.3 GHz), σ'_{HH}, for a range of sea ice thicknesses from 0.1–3.0 m. For this step, only the sea ice thickness is a variable while all other sea ice parameters and the incident angle are fixed. Next, the radar backscatter data, σ'_{HH} is input into the SA to begin the tests. In order to ensure consistency, the following values in Table 1 are set for all the tests:

Table 1: Input parameters for SA.

Parameter	**Value**
Temperature reduction factor, r_T	0.85*
Error tolerance for termination, ε	1.0E–6
Number of cycles, N_S	20*
Number of iterations before temperature reduction, N_T	20
Maximum number of function evaluations	10000
Initial temperature, T_0	5.0
Step length vector, V	1.0*
Vector that controls step length adjustment, C	2.0*
Lower bound for solution variable, L_B	0.1 m
Upper bound for solution variable, U_B	4.0 m
Starting value for variables to be optimized, X	1.2 m

*As recommended in [5]

4. RESULTS AND DISCUSSION

Figure 3 shows the comparison between predicted sea ice thickness from the RTISM with SA and also from the RTISM with LMA for 12 test cases with the wanted sea ice thickness. Preliminary tests show that the SA is able to estimate the correct sea ice thickness by finding the minimum error between σ'_{HH} and σ_{HH}. The tests prove that the modified RTISM with SA is fully functional and ready to be applied to actual case studies to find out its effectiveness under read conditions. The predictions between both models are quite close with each other, however in terms of performance, the RTISM with SA used about 15 – 20 minutes to complete each test case while the RTISM with LMA only used about 5–10 minutes.

In all the test cases, it is assumed that there are no errors coming from the forward model and that the simulated results are as accurate as possible to the actual values. In real conditions however, this is not true as the predictions from the forward model is actually a reasonable estimate of the actual value within the allowed tolerances. It will be interesting to see whether the model will still be able to give a reasonable estimate of the sea ice thickness under these circumstances.

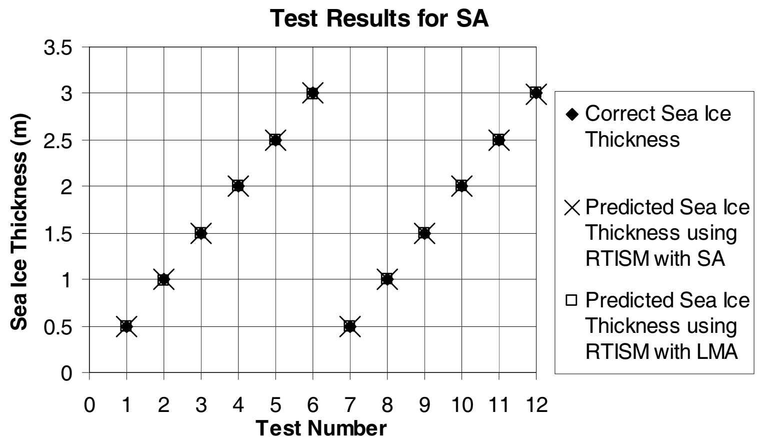

Figure 3: Comparison between sea ice thickness retrieval using RTISM with SA and LMA for data using test frequencies 1 GHz (tests 1–6) and 5.3 GHz (tests 7–12).

5. CONCLUSION AND FUTURE WORK

As a conclusion, a modification of the RTISM for the retrieval of sea ice thickness using SA has been proposed. Initial tests show promising results, with good agreements achieved between the model estimations and required sea ice thickness. In future works, more study needs to be done to find out the best configuration for the SA and also to test the model under actual conditions and measured parameters.

ACKNOWLEDGMENT

The research was supported with the research fund from MOSTI Malaysia [Grant Number: FP1213E 037_S2].

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