AFRL-AFOSR-JP-TR-2016-0068

Multi-scale Computational Electromagnetics for Phenomenology and Saliency Characterization in Remote Sensing

Hean-Teik Chuah
UNIVERSITI TUNKU ABDUL RAHMAN

07/15/2016
Final Report

Air Force Research Laboratory
AF Office Of Scientific Research (AFOSR)/ IOA
Arlington, Virginia 22203
Air Force Materiel Command

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
15-07-2016

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
30 Sep 2013 to 29 Mar 2016

4. TITLE AND SUBTITLE
Multi-scale Computational Electromagnetics for Phenomenology and Saliency Characterization in Remote Sensing

5a. CONTRACT NUMBER

5b. GRANT NUMBER
FA2386-13-1-4140

5c. PROGRAM ELEMENT NUMBER
61102F

6. AUTHOR(S)
Hean-Teik Chuah

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
UNIVERSITI TUNKU ABDUL RAHMAN
NO.9 JALAN BERSATU 13/4
PETALING JAYA, 46200 MY

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AOARD
UNIT 45002
APO AP 96338-5002

10. SPONSOR/MONITOR'S ACRONYM(S)
AFRL/AFOSR IOA

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
AFRL-AFOSR-JP-TR-2016-0068

12. DISTRIBUTION/AVAILABILITY STATEMENT
A DISTRIBUTION UNLIMITED: PB Public Release

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This project focuses on new approaches in extending current basic computational electromagnetics to the application in microwave remote sensing as well as extension of modelling capability with computational flexibility to study scattering from scatterers of all types in the earth terrain.

15. SUBJECT TERMS
Electromagnetics

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
Unclassified	Unclassified	Unclassified	SAR	16	HONG, SENG
					19b. TELEPHONE NUMBER *(Include area code)* 315-229-3519

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

AOARD Final Report

Multi-scale Computational Electromagnetics for Phenomenology and Saliency Characterization in Remote Sensing

(Award No: FA2386-13-1-4140)

H.T.Chuah[1] (PI), H.T.Ewe[1], Lijun Jiang, W.C. Chew[2], and Y.J.Lee[1]

[1]Universiti Tunku Abdul Rahman, Malaysia
[2]University of Illinois at Urbana Champaign, U.S.A.

Abstract

With the advent of computational electromagnetics and increasing speed and power of computing, it is promising where modelling in microwave remote sensing can be pursued with more realistic physical configuration. This project focuses on new approaches in extending current basic computational electromagnetics to the application in microwave remote sensing as well as extension of modelling capability with computational flexibility to study scattering from scatterers of all types in the earth terrain. The outcomes are promising with the development of basic microwave remote sensing model for scattering study from a simper layer of earth medium with computational electromagnetics and new method in computational modeling of scattering from basic scatterers.

1. Introduction

This report provides the description of work done under this grant from Sep 2013-March 2016 with the research work in the area of computational electromagnetics in microwave remote sensing. The project continues and extends the work which was previously supported under FA2386-12-1-4082 for 1 year.

This project is a collaborative research efforts among three institutions (Universiti Tunku Abdul Rahman in Malaysia; University of Hong Kong in Hong Kong, and University of Illinois at Urbana Champaign in USA）where the objectives are to further study and develop basic methods needed to apply computational electromagnetics in microwave remote sensing and also to construct a basic theoretical framework that will extend and integrate existing Equivalence Principle Algorithm (EPA) in Computational Electromagnetics (CEM) with the domain of Microwave Remote Sensing (MRS) for better interpretation of satellite Synthetic

Aperture Radar (SAR) images, radar returns from the earth terrain and scattering mechanisms within the earth terrain.

Under the domain of CEM, progress and achievements have been made in this project in extending the current Equivalence Principle Algorithm (EPA) that computes efficiently the radiation and interference of man-made objects and semiconductor components to the realm of microwave interaction in embedded scatterers in the earth terrain, as well as incorporation of such technique in better representing the embedded scatterers to its natural form in the computation of radar backscattering returns and scattering mechanisms involved in the interaction of incoming microwave and natural media (such as vegetation, forest, sea ice, snow, etc). The theoretical framework and model developed allows the solution of microwave remote sensing problem through iterative solution of Radiative Transfer Theory. In addition, dense medium improvement theories such as Dense Medium Phase and Array Correction Theory is also incorporated to allow the application of such solution in the electrically dense medium such as sea ice, snow and dense vegetation. Through the project, advancement has also been made in improving the techniques of EPA for wider application in larger range of problem areas. A novel relaxed hierarchical algorithm based on the surface equivalence principle for the volume integral equations (VIEs) has also been proposed and developed.

2. Description of Project Activities and Achievement

a) Dense Medium Microwave Backscattering Model for Remote Sensing of Oil Palm

Very little work has been carried out to examine the potential of synthetic aperture radar (SAR) imaging data for growth monitoring, disease monitoring, and yield prediction of oil palm plantations. A scattering model has been developed for oil palm based on the radiative transfer equations, solved iteratively up to the second order, to better understand the backscattering behavior of oil palm canopies for SAR image interpretation. The oil palm canopy is modeled as a multilayer background host medium embedded with discrete scatterers of different shapes, with elliptic disks representing the leaves and cylinders representing the fronds and trunks. The effects of coherent scattering are considered through the dense medium phase and amplitude correction theory, as well as the near-field interactions between closely spaced scatterers through the Fresnel phase and amplitude corrections. Ground-truth data are used as input parameters for the model.

The model is used to calculate the backscattering coefficients of oil palm canopies at different stages of growth and for different polarizations, frequencies, and incident angles. Comparisons between model calculations and C-band scatterometer measurements of multipolarization backscattering coefficients of 4-year-old oil palm canopies in Bangi, Malaysia show good agreement. The model also predicts that SAR images at L-band are more sensitive to changes in the structure of the canopies, particularly that of the fronds, so will be the best frequency for oil palm growth monitoring and disease detection.

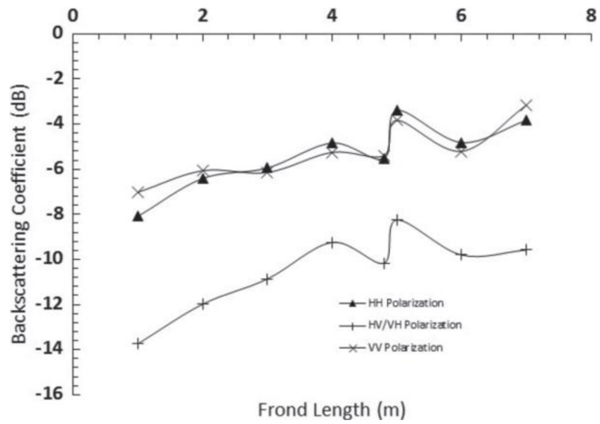

Figure 1. Change in total backscattering coefficient from the model for increasing frond lengths of 8-year old oil palm at 1 GHz at 32◦ incident angle.

b) Backscattering Analysis for Snow Remote Sensing Model with Higher Order of Surface-Volume Scattering

The study of earth terrain in Antarctica is important as this region has a direct impact on global environment and weather condition. There have been many research works in developing remote sensing technologies, as it can be used as an earth observation technique to monitor the polar region. This is an extended work from previous studies of the team, where an improved theoretical model to study polar region has been developed. Multiple-surface scattering, based on an existing integral equation model (IEM) that calculates surface scattering and additional second-order surface-volume scattering, were added in the model from prior research works for improvement in the backscattering calculation.

The application of this model on a snow layer above ground is modeled as a volume of ice particles that are closely packed and bounded by irregular boundaries above a homogenous half space. The effect of including multiple surface scattering and additional surface-volume scattering up to second order in the backscattering coefficient calculation of snow layer is studied for co-polarized and cross-polarized returns. Comparisons with satellite data are also done for validation. Results show improvement in the total backscattering coefficient for cross-polarized return in the studied range, suggesting that multiple-surface scattering and surface-volume scattering up to second order are important scattering mechanisms in the snow layer and should not be ignored in polar research.

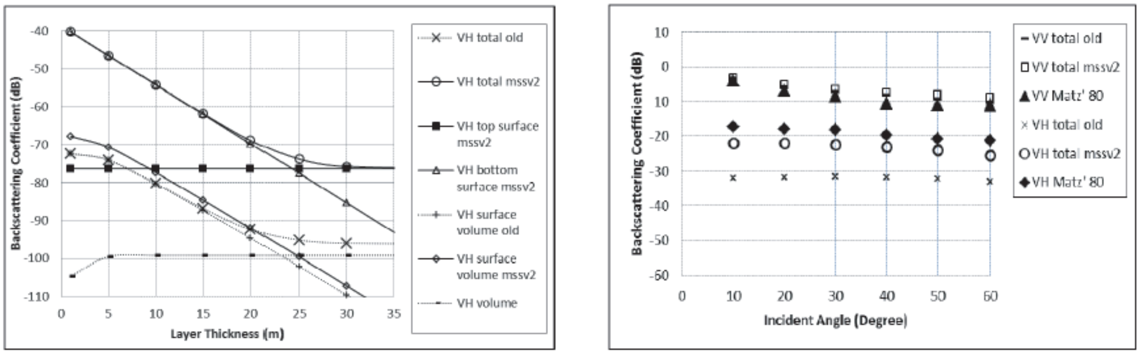

Figure 2. (left) Backscattering coefficient against layer thickness at 5 GHz frequency and 15◦ incident angle (VH polarized). (right) Backscattering coefficient of model prediction and measurements by Matzler et al..

c) Scattering from a Layer of Random Discrete Medium with Relaxed Hierarchical Equivalent Source Algorithm (RHESA)

This is a new numerical method which can be used in computational electromagnetics in microwave remote sensing of random discrete medium embedded with irregular shape of scatterers. Current Radiative Transfer (RT) theoretical modeling is normally used to simulate wave propagation in the medium and wave scattering by basic shapes of scatterers, e.g., cylinder, disk, needle or sphere where the scattering of those scatterers was normally derived analytically with some assumption and approximation. To simulate the total backscattering coefficient from a layer of random medium, traditionally it was quite common that Mie phase matrix was used to compute the scattered fields of the scatterers which were approximated to be spherical shape. This has limited the extension of current theoretical model to be used to compute cases where irregular shape of scatterers are found embedded in the medium where many of the scatterers in real world are normally irregular or of complex shapes.

As computational electromagnetics (CEM) becomes important in current modern engineering field, this provides an approach to model the scattering of such scatterers using CEM. In this work, the Relaxed Hierarchical Equivalent Source Algorithm (RHESA) is used to compute scattered fields based on hierarchically structured equivalence sources residing within relaxed spherical equivalence surfaces. The 3D scatterer model used in RHESA can be created using a 3D modeling software. After the 3D scatterer model is divided into smaller groups and each group is enclosed with a spherical equivalence surface, the scattered fields can be computed by equivalence source residing on smooth spherical equivalence surface through integral formulations. By incorporating RHESA method into the current RT theoretical modeling, this can provide the improved theoretical model the capability to compute scattering of irregular or non-basic shape of scatterers embedded within the medium. The simulated scattering coefficient and extinction coefficient results from the newly implemented RHESA based theoretical model were compared with those of current RT theoretical model and it was found that both results agreed with each other. The new model is then ready to be further extended to next stage of research to simulate backscattering from a layer of earth medium for further theoretical analysis.

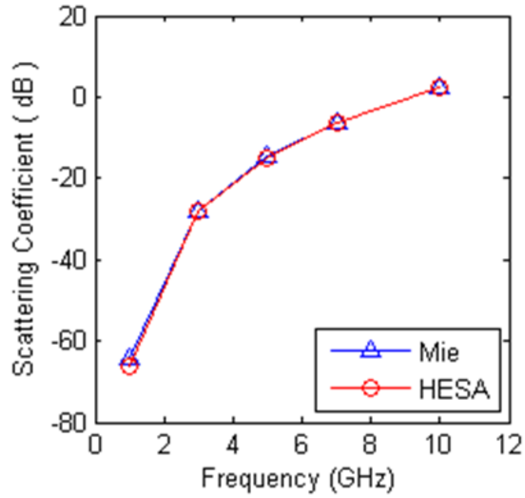

Figure 3. Scattering coefficient (v-polarization) comparison between RHESA and MIE for spherical scatterers with radius 2mm against frequencies.

d) A new efficient method for analysis of finite periodic structures

Periodic structures (PSs) have attracted much attention in the past decades due to numerous applications such as metamaterials, antenna arrays, frequency selective surface (FSS), photonic band gap (PBG) or electromagnetic band gap (EBG) structures, etc. Infinite PSs are impossible in a realistic fabrication. When truncating infinite PSs, discontinuities occur at the interface and surface waves (SWs) will be excited according to mode conversion. In finite PSs, only allowed Bloch waves (BWs) can propagate, and SWs become evanescent and localized around the discontinuities, which leads to the edge effects of finite PSs. The prediction of wave natures in the edge cells of finite PSs is an indispensable procedure during the design of finite process. The conventional element-by-element method is rigorous and suitable for small finite PSs. However, it requires heavy computational resources for very large ones. The well-established infinite periodic approximation approach neglecting the edge effect, although reduces the computational domain to a unit cell, is not sufficiently accurate for engineering applications.

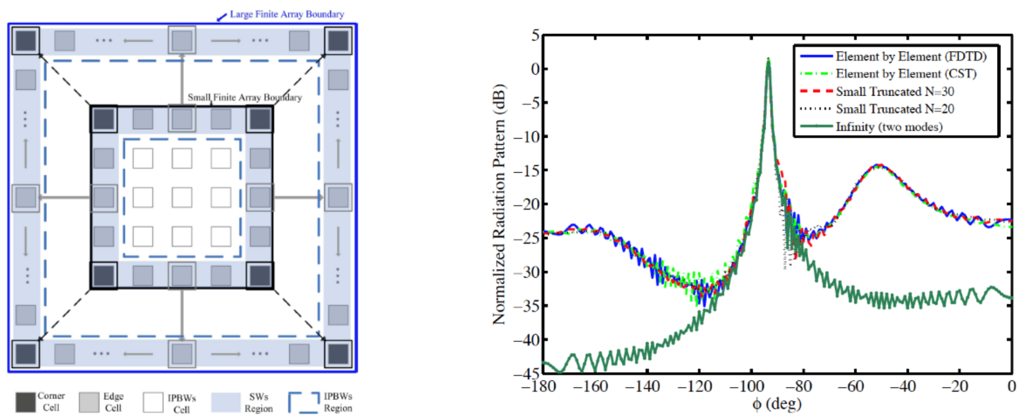

Figure 4. (Left) Mechanism for the field reconstruction in large 2D finite periodic structures from relative small ones. “SW” and “IPBW” are the short notations for surface wave and infinite-periodic Bloch wave, respectively. (Right) Comparison of the normalized far-field radiation patterns of the leaky wave antenna simulated by different methods. The solid and dash-dot lines are the element-by-element results of N = 60 structure calculated by the in-house developed FDTD method and the commercial software CST; the dashed line and dotted line are the results calculated based on the simulation of N = 30 and N = 20 structures, respectively; the marked solid line is the result of an infinite periodic array with N = 60 elements.

To overcome the difficulties in simulating large finite PSs, two different categories of methods have be proposed. The first category bypassed the difficulties by improving the computational capabilities of the existing methods. Among them, the fast multipole method and the domain decomposition method are very powerful for modeling large finite PSs. The other category of methods considers the edge effect with the help of the information in an infinite array, i.e. the convolution of the infinite array solution with an appropriate window function.

We aimed to develop an efficient method for predicting the electromagnetic (EM) response of large finite PSs accurately from that of relatively small ones. In this work, surface waves are numerically disentangled from the propagating Bloch waves contributions. Based on the universally exponential decay feature of the surface waves, a novel method is developed by connecting the solution to the large finite periodic structure with that to a relatively small one resulting in low complexity and memory consumption. The method numerically reconstructs propagating Bloch waves and surface waves according to the Bloch-Floquet theorem of periodic structures and translation invariant properties of semi-infinite periodic structures, respectively. Finite periodic antenna arrays are investigated by the newly developed method. The results are compared to those calculated by the element-by-element method. Excellent agreements are obtained and particularly the proposed method saves considerable computer resources. The presence of SWs is critical for the low side-lobe antenna design.

e) The error controllable mixed-form fast multipole algorithm based on high order multipole rotation

The fast multipole algorithm (FMA) was first proposed to handle the evaluation of coulomb or gravitational interaction in large scale ensemble of particles corresponding to Laplace's equation or Poisson's equation, and later extended into dynamic problems corresponding to Helmholtz equation. The low frequency FMA (LF-FMA) and multilevel FMA (MLFMA, conventionally it means in middle frequency) manifest two very different forms, i.e. multipole expansions and plane wave expansions, although both of them are marked with the term "FMA". LF-FMA and MLFMA can operate in their respective regimes efficiently, but are not applicable in the other regime. In 2005, a novel mixed-form fast multipole algorithm (MF-FMA) was proposed to provide a complete solution for wide-band applications. MF-FMA contains transformers between multipoles and plane waves. Hence, it combines both expansions into one oct-tree browsing process to cover both low frequency and midfrequency efficiently. There are some other works dedicated to build a wide-band FMA later.

In MF-FMA, the accuracy at the transition region between LF-FMA and MLFMA is not very satisfactory. LF-FMA requires many multipoles that cause unaffordable computational load, while MLFMA begins to lose accuracy when the frequency goes down due to the evanescent wave's existence. Increasing multipoles in LF-FMA to push the transition region up is a way to remedy the accuracy if we can make the workload acceptable. In this work, the error controllable mixed-form fast multipole algorithm (MF-FMA) has been implemented through high order multipole rotation. Two kinds of rotation techniques can be applied here. One is the coordinate system rotation method, and the other is the pseudo-spectral projection method based on Fast Fourier Transform (FFT). Translation matrices would become very sparse through rotation, enabling us to save both the storage and the CPU time. Thus, we can increase the number of multipoles in the low frequency regime to shift up the transition region of MF-FMA. The broadband accuracy of the MF-FMA is thereby improved significantly.

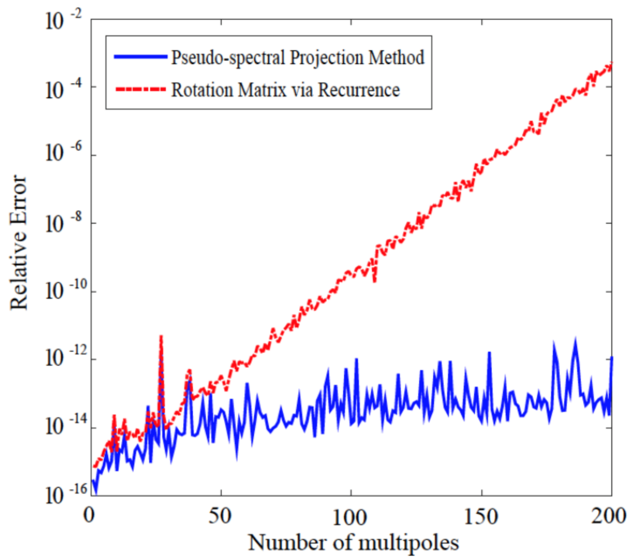

Figure 5. Relative error analysis of the coordinate rotation and pseudospectral projection rotation.

f) The accuracy enhancement technology of EPA algorithm based on the meshless spherical surface

Conventional equivalence principle algorithm (EPA) employs cubical boxes to support equivalence sources. However, it introduces strong discontinuities. In this work, a spherical surface is employed as the equivalence surface in EPA to avoid singularities from non-smooth surfaces. Further to achieve high order accuracy, meshless samples are used for the integrals on the spherical surface to avoid the equivalence surface mesh discretization. Theoretically the accuracy of EPA can be significantly improved, which was further benchmarked though numerical examples. Various meshless schemes are also discussed to achieve the optimal solution based on the spherical equivalence surface.

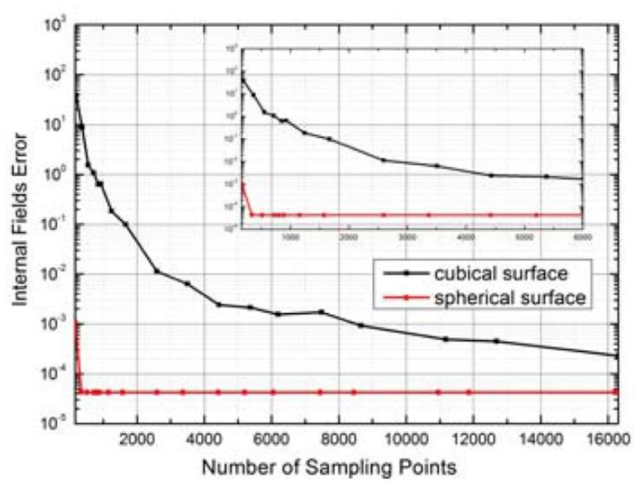

Figure 6. The internal field error for NASA Almond using the new method (spherical) and the conventional method (cubical). It is seen that the new method is of great accuracy advantage under the same computational cost.

g) The blackbox macro-modeling of the nonlinearity based on Volerra series of X-parameters

Volterra series representation is a powerful mathematical model for nonlinear devices. However, the difficulties in determining higher-order Volterra kernels limited its broader applications. This work proposed a systematic approach that enables a convenient extraction of Volterra kernels from X parameters for the first time. Then the Vandermonde method is employed to separate different orders of Volterra kernels at the same frequency, which leads to a highly efficient extraction process. The proposed Volterra series representation based on X parameters is further benchmarked for verification. The proposed new algorithm is very useful for the blackbox macro-modeling of nonlinear devices and systems.

h) A Novel Relaxed Hierarchical Equivalent Source Algorithm (RHESA) for Electromagnetic Scattering Analysis of Dielectric Objects

A novel relaxed hierarchical algorithm based on the surface equivalence principle for the volume integral equations (VIEs) is proposed and developed. The equivalent sources residing on relaxed spherical equivalence surfaces are established by exact integral formulations. The equivalence surfaces are exploited hierarchically to accelerate matrix-vector product in iterative solutions for the VIEs.

Basically, the single level algorithm includes three steps: inside-out radiation, translation and outside-in radiation and computes the far-field interactions via equivalent sources residing on smooth spherical equivalence surface. The equivalent sources are established by Stratton-Chu integral formulation rigorously rather than numerical approximations.

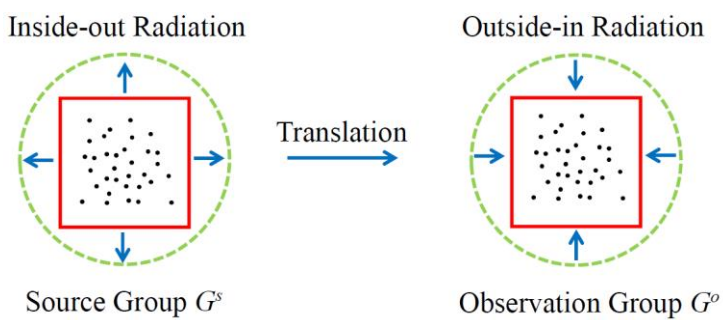

Figure 7. Illustration of the procedure of ESA to compute the far-field contributions from source G^s group to observation group G^o

Starting from the single level algorithm, we can also extend it to a hierarchical one. The hierarchical algorithm is based on oct-tree structure on which the object will be mapped to. The parent equivalent sources residing on higher levels will be introduced. The communications between parent and child level including inside-out radiation from child to parent and outside-in from parent to child are also conducted by integral formulation.

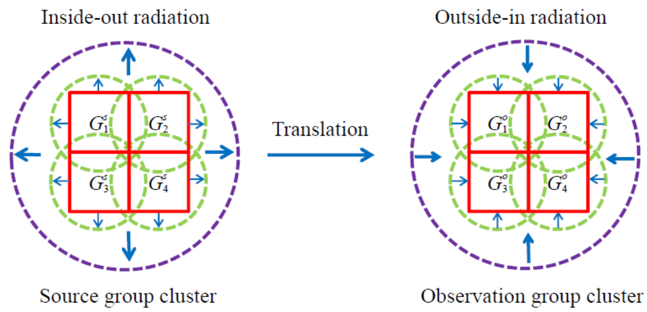

Figure 8. Illustration of the procedure of RHESA with two levels to compute the far-field contributions from source group cluster to observation group cluster

A dielectric sphere illuminated by a plane wave is used to test accuracy of the proposed RHESA. The reference solution comes from method of moment (MoM) with high order Gaussian quadrature. There are two levels for computation in RHESA. The error of far scattered fields versus the number of sampled sources at the lowest level is plotted in the following figure. It is noted that the accuracy will be improved as the number of sampled sources increases.

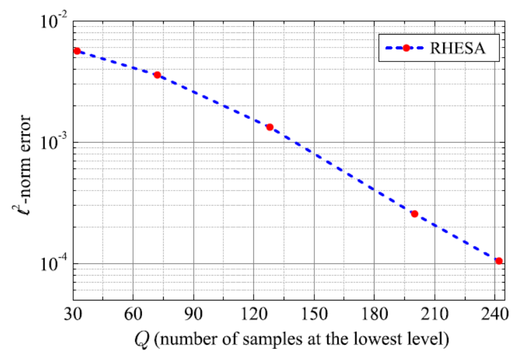

Figure 9. Accuracy test for far scattered fields of a dielectric sphere illuminated by a plane wave.

Next, the scattering of a layered sphere is investigated. The sphere is discretized with 15255 tetrahedrons and 31377 unknowns in total. Bistatic RCS solutions are plotted in the following figure. The reference solution comes from MLFMA. We can see that the solution from RHESA has an excellent agreement with MLFMA.

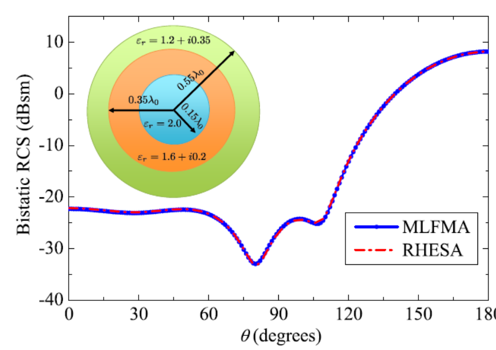

Figure 10. Bistatic RCS solutions for a layered dielectric sphere

Finally, the computation complexity of RHESA is tested. It involves different electrical sizes of a dielectric slab. The complexity scaling is plotted in the following figure. We can see that the computation time complexity and the memory cost complexity scale as ($N^{4/3}$) and (N), respectively.

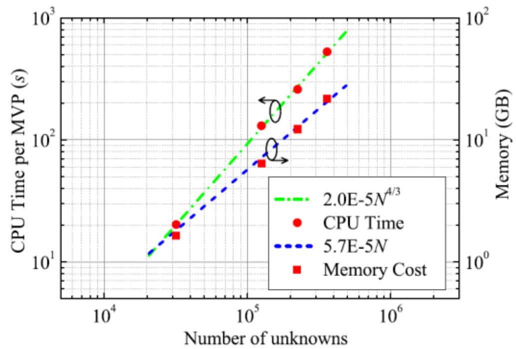

Figure 11. The computation complexity of RHESA

3. Journal Publications

1. X. Fu, L.J. Jiang, Z.H. Ma, and S.Q. He, "Performance enhancement of equivalence principle algorithm," IEEE AWPL, accepted.
2. Syabeela Syahali and H.T.Ewe, "Backscattering Analysis for Snow Remote Sensing Model with Higher Order of Surface-Volume Scattering," Progress in Electromagnetics Research M, Vol. 48, May 2016, pp 25-36.
3. Y. Cao, L.J. Jiang, and A. Ruehli, "Distributive radiation and transfer characterization based on the PEEC method," IEEE Trans. on EMC, vol. 57, no. 4, pp. 734-742, Aug. 2015.
4. K.C. Teng, J.Y. Koay, S.H. Tey, K.S. Lim, H.T. Ewe and H.T. Chuah, "A Dense Medium Microwave Backscattering Model for the Remote Sensing of Oil Palm," IEEE Trans. on Geoscience and Remote Sensing, Vol 53, No. 6, June 2015, pp. 3250-3259.
5. X.Y. Xiong, L.L. Meng, L.J. Jiang, W. Sha, and F. Yang, "Efficient Calculation of Large Finite Periodic Structures Based on Surface Wave Analysis," IEEE Trans. on AP, vol. 63, no. 1, pp. 69-80, Dec. 2014.
6. X.Y. Xiong, L.J. Jiang, and W. Sha, "Helmholtz Decomposition Based on Integral Equation Method for Electromagnetic Analysis," Microw. and Opt. Techn. Lett.,vol. 56, iss. 8, pp 1838 - 1843, Aug. 2014.
7. P. Li, Y.F. Shi, L.J. Jiang, H. Bagci, "A Hybrid Time-Domain Discontinuous Galerkin-Boundary Integral Method for Electromagnetic Scattering Analysis," IEEE Trans. on Ant. & Propag., vol. 62, no. 5, May 2014.
8. Y.P. Chen, S. Sun, L.J. Jiang, and W.C. Chew, "A Calderon Preconditioner for the Electric Field Integral Equation with Layered Medium Green's Function," IEEE Trans. on Ant. & Propag., Vol. 62, iss. 4, pp. 2022-2030, Apr. 2014.
9. P. Li and L.J. Jiang, "A Rigorous approach for the radiated emission characterization based on the spherical magnetic field scanning," IEEE Trans. on EMC, vol. PP, no. 99, pp.1-8, Jan. 2014.

10. Syabeela Syahali and H.T.Ewe, “Remote Sensing Backscattering Model for Sea Ice: Theoretical Modelling and Analysis,” Advances in Polar Science, Vol 24, No. 4, Dec 2013, pp. 248-257.
11. P. Li, Y. Li, L.J. Jiang, and J. Hu, “A Wide Band Equivalent Source Reconstruction Method Exploiting the Stoer-Bulirsch Algorithm with the Adaptive Frequency Sampling,” IEEE. Trans. on Ant. & Propag., vol. 61, no. 10, pp. 5338-5343, Oct. 2013.

4. Conference Papers

1. X. Fu, L.J. Jiang, and H.T. Ewe, “Hierarchical Equivalent Source Algorithm Based on Relaxed Spherical Equivalence Surface,” IEEE International Symposium on APS/USNC-URSI, Vancouver, Canada, Jul. 2015. (**Honorable Mention of the Student Paper Competition**)
2. Y.J. Lee, K.C. Yeong and H.T.Ewe, “An Inverse Model for Sea Ice Thickness Retrieval Using Simulated Annealing,” Progress in Electromagnetics Research Symposium (PIERS 2015), Prague, Czech Republic, 6-9, July, 2015.
3. C.F. Lum, Xin Fu, H.T. Ewe and L.J. Jiang, “A Study of Scattering of Scatterers Using Equivalence Principle Algorithm, “Progress in Electromagnetics Research Symposium (PIERS 2015), Prague, Czech Republic, 6-9, July, 2015.
4. C.F. Lum, Rathish Previn, Fu Xin, H.T. Ewe and L.J. Jiang, “A Study of Scattering from A Layer of Spherical Scatterers with EPA Model”, IEEE Workshop on Geoscience and Remote Sensing, Kajang, Malaysia, Nov 20, 2014.
5. Rathish Previn, C.F. Lum, Fu Xin, H.T. Ewe and L.J. Jiang, “An Equivalence Principle Approach to Electromagnetic Scattering in Vegetation,” IEEE Workshop on Geoscience and Remote Sensing, Kajang Malaysia, Nov 20, 2014.
6. X.Y. Xiong, L.J. Jiang, J. Shutt-Aine, and W.C. Chew, “Blackbox Macro-modeling of the Nonlinearity Based on Volterra Series Representation of X-Parameters,” IEEE EPEP, Portland, Oregon, Oct. 2014. (**The Best Oral Paper Award**)
7. P. Li and L.J. Jiang, “Uncertainty Quantification of EM-Circuit Systems Using Stochastic Polynomial Chaos Method,” IEEE Symposium on EMC, Raleigh, NC, USA, Aug. 2014. **(Finalist of Best Student Paper in EMC)**
8. Y. S. Cao, L.J. Jiang, and A. E. Ruehli, "Distributive Radiation Characterization Based on the PEEC Method," *IEEE Symposium on EMC*, Raleigh, NC, USA, Aug. 2014.
9. P. Li, Y.F. Shi, L.J. Jiang, and H. Bagci, "A Discontinuous Galerkin Time Domain-Boundary Integral Method for Analyzing Transient Electromagnetic Scattering," *IEEE International Symposium on APS/USNC-URSI*, Memphis, TN, USA, Jul. 2014.
10. Y.P. Chen, L.J. Jiang, S. Sun, and W.C. Chew, "Calderon Preconditioned PMCHWT Equation for Layered Medium Problems," *IEEE International Symposium on APS/USNC-URSI*, Memphis, TN, USA, Jul. 2014.
11. X.Y. Xiong, L.J. Jiang, Y. H. Lo, and W.C. Chew, "Second-harmonic

Generation in Metal Nanoparticles Modeling by Surface Integral Equation," *IEEE International Symposium on APS/USNC-URSI*, Memphis, TN, USA, Jul. 2014.

12. Khar-Chun Teng, Jun-Yi Koay, Seng-Heng Tey, Hong-Tat Ewe and Hean-Teik Chuah, "Monitoring of Oil Palm Plantations and Growth Variations with a Dense Vegetation Model," IEEE Symposium on Geoscience and Remote Sensing (IGARSS), Quebec City, Canada, 13-18 July 2014/
13. X.Y. Z. Xiong, L.L. Meng, L.J. Jiang, and W. Sha, "A new efficient method for analysis of finite periodic structures," *International Review of Progress in Applied Computational Electromagnetics (ACES)*, Jacksonville, FL, Mar. 2014. (**The First Place of Best Student Paper Award**)
14. P. Li and L.J. Jiang, "An Adaptive Hierarchical Sparse Grid Collocation Method for Stochastic Characterization of Electromagnetics/Circuit Systems," *the 12th International Workshop on Finite Elements for Microwave Engineering*, Chengdu, China, May. 2014. (**Student Paper Award**)

5. Awards

1. X. Fu, L.J. Jiang, and H.T. Ewe, "Hierarchical Equivalent Source Algorithm Based on Relaxed Spherical Equivalence Surface," IEEE International Symposium on APS/USNC-URSI, Vancouver, Canada, Jul. 2015. (**Honorable Mention of the Student Paper Competition**)
2. X.Y. Xiong, L.J. Jiang, J. Shutt-Aine, and W.C. Chew, "Blackbox Macro-modeling of the Nonlinearity Based on Volterra Series Representation of X-Parameters," IEEE EPEP, Portland, Oregon, Oct. 2014. (**The Best Oral Paper Award**)
3. X.Y. Z. Xiong, L.L. Meng, L.J. Jiang, and W. Sha, "A new efficient method for analysis of finite periodic structures," *International Review of Progress in Applied Computational Electromagnetics (ACES)*, Jacksonville, FL, Mar. 2014. (**The First Place of Best Student Paper Award**)
4. P. Li and L.J. Jiang, "An Adaptive Hierarchical Sparse Grid Collocation Method for Stochastic Characterization of Electromagnetics/Circuit Systems," *the 12th International Workshop on Finite Elements for Microwave Engineering*, Chengdu, China, May. 2014. (**Student Paper Award**)
5. J. Z. Huang, L.J. Jiang, W.C. Chew, J. Peng, C.Y. Yam, and G.H. Chen, "Model order reduction for quantum transport simulation of nanoelectronic devices," *the 14th IEEE HK AP/MTT Postgraduate Conference*, Hong Kong, Oct. 2013 (**Second Place of Best Student Paper in MTT Session**).
6. X.Y. Z. Xiong, L.J. Jiang, V. A. Markel, and I. Tsukerman, "Surface effects on position-dependent parameters of periodic electromagnetic composites," *the 14th IEEE HK AP/MTT Postgraduate Conference*, Hong Kong, Oct. 2013 (**First Place of Best Student Paper in AP Session**).

6. Award of fund received related to this research efforts

1. University of Hong Kong: PI. ITP/045/14LP. (2014.10 ~ 2016.3). HKD 1,356,949.00 (~USD174k)
2. Flagship Research Grant, Ministry of Science, Technology and Innovation (MOSTI), Malaysia for Project "Development of microwave remote sensing model for monitoring of sea ice changes in global climate system" (2014-2016). RM 467,603.00 (~USD105k)

7. Summary

In summary, the impact and achievement of the project are as follows:

(i) Advancement of novel EPA methods in analysis of finite periodic structures, error controllable mixed-form fast multipole algorithm and new hierarchical algorithm based on surface equivalence principle with one to two order accuracy enhancement to the conventional EPA method.

(ii) Development of new approach and improved method in realistic modelling of earth terrain with actual shapes of embedded scatterers for better understanding of scattering mechanisms and radar returns from electrically dense natural media where conventional model deals with basic geometry shapes of scatterers.

(iii) Unique integration of fast and efficient EPA/RHESA of Computational Electromagnetics and Radiative Transfer formulation in Microwave Remote Sensing for the application of scientific community in earth observation and remote sensing.

The current work needs to be further extended in future for application to wider range of physical configuration of earth terrain, and more complex integration and development of new methods need to be pursued. For such extension, the computation speed and algorithm need to be further improved for more complex media in earth terrain.

Acknowledgement

The project team would like to acknowledge and thank AFOSR/AOARD for the grant awarded and strong support given to the project. Acknowledgement also goes to other related external funding agencies, the universities and organizations involved for their support and assistance in this project.