Application of a Ground-based Polarimetric SAR System for Environmental Studies(地表設置型偏波合成開口レーダの環境計測への応用)

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論文内容要旨

Potential of implementing recent advances made in the field of imaging radar polarimetry exploited in a ground-based polarimetric synthetic aperture radar (SAR) system for environmental application was studied. The sensitivity of microwave scattering to the change of vegetation and ground structures is an important feature for a wide range of environmental issues related to the natural conditions.

In this dissertation, the development of a broadband ground-based SAR system and its application to environmental studies are presented. We have used a newly developed ground-based polarimetric broadband SAR system to monitor seasonal variations in trees. This system provided valuable information about the scattering features of the trees in different conditions. Data interpretation identified the target scattering characteristics with frequency dependency, as well as changes in different situations. The experimental results demonstrated the good polarimetric performance of the developed SAR imaging system which should find many other applications.

Chapter 1 Introduction

Chapter 1 gives the introduction including recent advances of polarimetric SAR imaging, a summary on current studies of ground-based SAR, and research objectives of this dissertation.

Chapter 2 Ground-based Polarimetric SAR System and Its Evaluation

Design and features evaluation of a broadband ground-based polarimetric SAR system are described. Based on the conventional SAR formulation, the principle of a ground-based SAR was derived. By computer simulation, the estimated resolutions were obtained that were consistent with theoretical values. Including the description of the pertinent measurement equipments, specifications of a broadband ground-based polarimetric SAR system were presented. This system consisted of a vector network analyzer, one dual polarized antenna, and an antenna positioner. It can be operated in a frequency range from 50 MHz to 20 GHz, with a scanning aperture of 20 m in the horizontal and 1.5 m in the vertical direction, respectively.

Implementing polarimetric calibration and tests, the performances of the developed system were also demonstrated. Testing results showed satisfactory polarimetric performances of the developed system. Further a modified two-way orientation dihedral based polarimetric calibration was introduced and its use was verified. Theoretical RCS calculations for a metallic sphere and a dihedral corner reflector were also performed. Improvement of the specific polarimetric characteristics for the broadband ground-based SAR system was determined by polarimetric calibration results shown in Table 1.

Table 1 Auto-calibrated scattering matrices

	Measured scattering matrix	Calibrated scattering matrix
Vertical dihedral	$S_{m1}=\begin{bmatrix}0.9709e^{-j114.8^\circ} & 0.0173e^{-j115.6^\circ}\\ 0.0166e^{-j106.4^\circ} & 1\end{bmatrix}$	$S^c_{m1}=\begin{bmatrix}1.0004e^{-j180.0^\circ} & 0.0186e^{-j109.0^\circ}\\ 0.0182e^{-j116.6^\circ} & 1\end{bmatrix}$
45° dihedral	$S_{m2}=\begin{bmatrix}0.0850e^{-j91.1^\circ} & 1\\ 1.0095e^{j1.4^\circ} & 0.0175e^{-j166.7^\circ}\end{bmatrix}$	$S^c_{m2}=\begin{bmatrix}0.0001e^{j144.5^\circ} & 1\\ 1 & 0\end{bmatrix}$

Chapter 3 Test Experiments for Tree Monitoring

Due to the fact that trees are some of the most important vegetation scatterers in environmental studies, we implemented the developed SAR system for real measurements for the monitoring of different tree types during different seasons. Using the developed broadband ground-based polarimetric SAR system, contiguous data acquisitions were carried out for three different types of trees in three seasons, and for a cherry tree during different situations at two experimental sites. For each measurement, HH, VH and VV polarimetric scattering data were acquired simultaneously. By simple signal processing, signal verification with ground truth showed that good quality data have been acquired by the ground-based SAR system. It demonstrated that the acquired data not only included information about target polarimetric performances but also intimated frequency dependence of differently sized components of trees by signal comparison.

Chapter 4 Three Dimensional Image Reconstruction

Chapter 4 is to review signal processing methods for broadband ground-based polarimetric SAR data. Algorithms of time gating, matched filtering and diffraction stacking are very effective techniques for ground-based SAR data processing, especially the time gating method and diffraction stacking migration. The advantages are discussed in Sections 4.1 and 4.2. They made up for the drawbacks of the ground-based imaging system, for instance, restraining antenna direct coupling of monostatic measurement and reflection of ground clutter, and extrapolating the imaging space by alternate diffraction stacking. Antenna directivity compensation was also realized easily. Reconstructed 3-D images of HH, VH and VV polarization components showed good consistency with ground-truths and polarimetry theory shown in Figure 1. Hence, radar polarimetry provided valuable scattering information about targets, particularly the scattering features of trees in different seasons so that the different components of trees in different conditions could be distinguished.

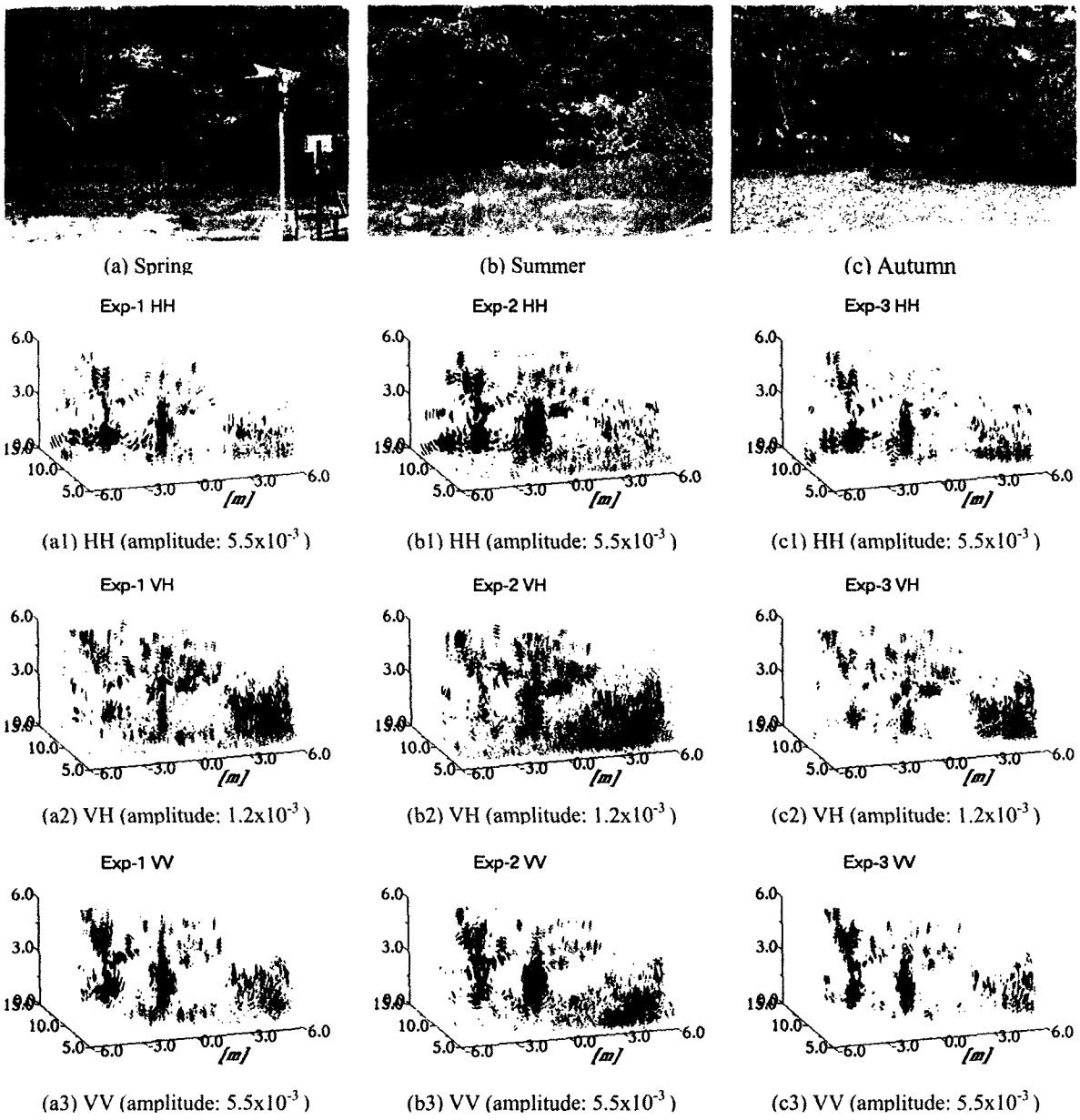

Figure 1 Polarimetric 3-D images of different trees in three seasons

Chapter 5 Data Interpretation with SAR Polarimetric Analysis

In this Chapter, different analysis tools for viewing and interpreting broadband polarimetric SAR data are reviewed. Various color-coded polarimetric images are presented and their interpretations are discussed. Broadband polarimetric images were first displayed in this dissertation. Those could indicate scattering mechanisms for vegetation. Scattering mechanisms of different components of vegetation, e.g. trees, were demonstrated by polarimetric analysis techniques. We also discussed, using different data acquired for different cases to interpret the amount of diffuse scattering, for instance, for buds, flowers and leaves. The eigenvector based alpha/entropy target decomposition provided a convenient way to obtain more information on vegetation scattering as functions of species and seasonal plus diurnal variations shown in Figure 2. It showed that they all provide similar information but different features could be identified by polarimetric analysis.

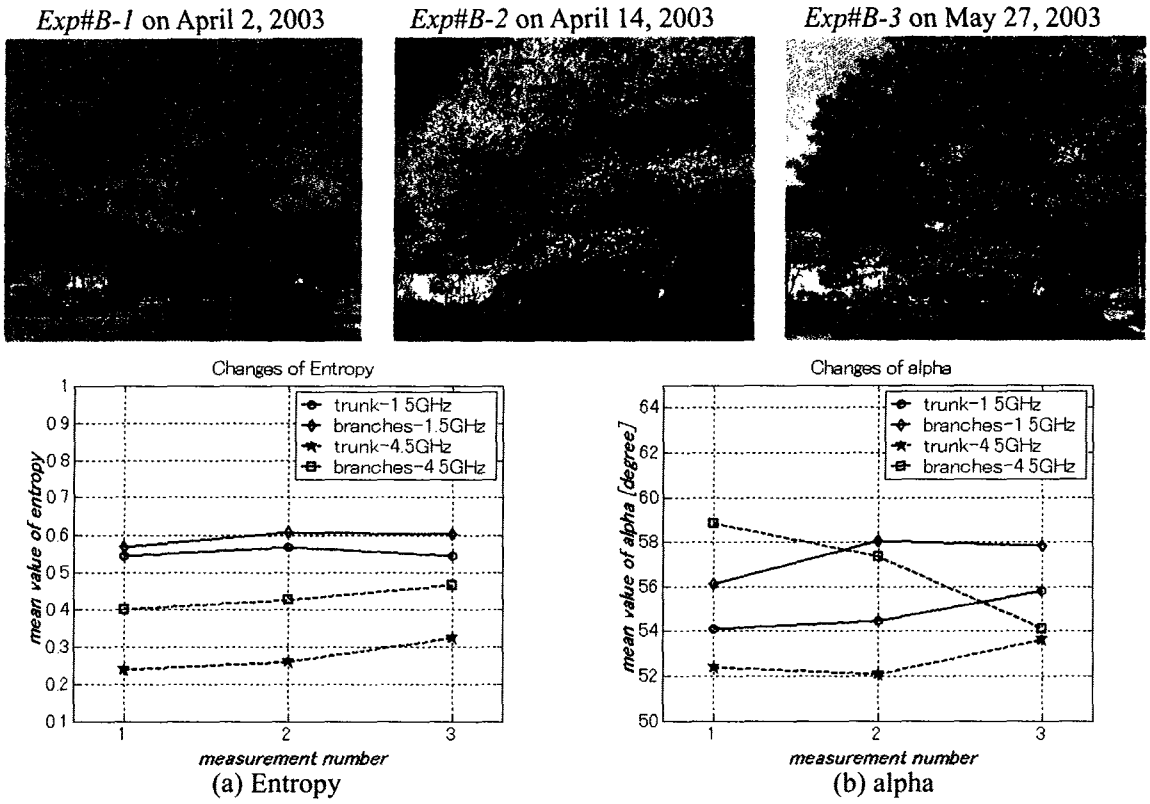

Figure 2 Changes of mean value: (a) Entropy and (b) alpha in the two analysis areas.

Chapter 6 Conclusions

The last chapter summarizes the conclusions of the dissertation, including considerations for ongoing future studies.

The most important achievements of this dissertation are the resolution estimation by simulation of a ground-based SAR that is consistent with theory, system performance improvement by dihedral based polarimetric calibration, and data comparative processing analysis with polarimetric interpretation for broadband ground-based SAR data.

It was demonstrated that the broadband ground-based polarimetric SAR system presented advantages for vegetation monitoring as well as environmental studies for a great variety of vegetation structures. More measurements for the vegetation structures would be desirable in order to more clearly distinguish the associated scattering mechanisms, for instance, study on microwave vegetation scattering analyses, especially the diurnal (day-cycle) variations, the dependence on the relative observer versus sun plus scattering-patch locations, plus the interlaced dependence on the diurnal vegetation-phases will be very interesting. At the same time, a ground-based SAR system also can be used as ground truth demonstration tool for airborne SAR and space-borne SAR in a great variety of applications.

論文審査の要旨

本学位論文は，地上設置型ポーラリメトリック合成開口レーダ（SAR）システムを利用したイメージングレーダポーラリメトリの近年の研究成果を取り入れた環境科学への応用についての研究をまとめたものである。植生や地表構造の変化に対するマイクロ波散乱の特性は自然条件に関連する幅広い環境問題において重要な役割を占める。地表設置型 SAR データの正確な解釈は災害防止だけでなく，植生保護についても意義深い貢献につながる。

本研究では，まず環境研究のための広帯域地表設置型ポーラリメトリック SAR システムを開発した。このシステムはベクトルネットワークアナライザと 2 偏波アンテナ，アンテナポジショナで構成される。周波数範囲 50MHz から 20GHz で運用され，水平方向 20m，垂直方向 1.5m の範囲でアンテナ走査を行なう。このシステムの偏波校正と性能評価を行ない，標準反射板による試験で満足のいく偏波特性を得ている。

次に開発された SAR システムを用いて，春，夏，秋それぞれの季節に 3 種の樹木の計測を行なった。更に，桜の木の計測を開花前，満開，葉桜の状態でそれぞれ行なった。得られたデータから 3 次元画像を再構成した。それぞれの計測における偏波画像を解析することにより，異なる偏波画像の差異を見い出した。異なる季節における樹木の散乱特性に関する有益な情報がこのシステムにより得られる。特にシステムの広帯域特性がデータ解析に有効であることを示した。実験結果は，開発された SAR イメージングシステムの優れた偏波計測性能を示すものであり，このシステムのさまざまな応用が期待される。

更に，偏波間の差異についての解析手法を用いて得られた偏波データの解釈を行なった。RGB カラー画像は着目するターゲットの広帯域偏波特性を表現している。これから単一周波数の共分散電力密度カラー画像を作り，固有ベクトル基底による分解アルゴリズムによってターゲットの散乱特性の周波数依存性を条件依存性とともに明らかにした。また異なる散乱行列，共分散行列などの偏波情報表現からは樹木について同様の情報を得られ，季節だけではなく樹木の部分にも依存する様々な散乱特性を明らかにした。

最後に偏波 SAR の最近の技術進歩の成果を取り入れてどのようにこのシステムを発展させていくか，将来構想を議論した。

本研究は環境計測に対する新しい手法の導入を提案し，具体的な事例として植生に関する応用から重要な知見を得ることができた。こうした成果は今後の環境測定技術に資するところが極めて大きいと判断した。

よって，本論文は博士(工学)の学位論文として合格と認める。