RADAR POLARIMETRY AND INTERFEROMETRY: Past, Present and Future Trends

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ABSTRACT

Recent developments of wave polarization effects in radar remote sensing are summarized in historical sequence resulting in Radar *Polarimetry, Radar Interferometry and Polarimetric SAR Interferometry,* which represent the current culmination in airborne and space borne '*Microwave Remote Sensing'* technology. Whereas with *radar polarimetry* the textural fine-structure, target orientation, symmetries and material constituents can be recovered with considerable improvement above that of standard *'amplitude-only' radar*; by implementing '*radar interferometry'* the spatial structure can be explored. With *Polarimetric Interferometric Synthetic Aperture Radar (POL-IN-SAR) imaging,* it is possible to recover such co-registered textural and spatial information from POL-IN-SAR digital image data sets simultaneously – as will be demonstrated.

INTRODUCTION

The development of *Radar Polarimetry* and *Radar Interferometry* is advancing rapidly [1], and these novel radar technologies are revamping "*Synthetic Aperture Radar Imaging*" decisively. In this exposition the successive advancements are sketched; beginning with the fundamental formulation of radar polarimetry, and high-lighting the salient points of these diverse remote sensing techniques [2]. Whereas with *radar polarimetry* the textural fine-structure, target-orientation and shape, symmetries and material constituents can be recovered with considerable improvements above that of standard '*amplitude-only Polarization Radar'*; with *radar interferometry* the spatial (in depth) structure can be explored [3]. In '*Polarimetric-Interferometric Synthetic Aperture Radar(POL-IN-SAR) Imaging'* it is possible to recover such co-registered textural plus spatial properties simultaneously [4]. This includes the extraction of *'Digital Elevation Maps (DEM*)' from either '*fully Polarimetric (scattering matrix) or Interferometric (dual antenna) SAR image data takes'* with the additional benefit of obtaining co-registered three-dimensional *'POL-IN-DEM'* information [5]. *Extra-Wide-Band POL-IN-SAR Imaging* when applied to *'Repeat-Pass Image Overlay Interferometry',* provides differential background validation and measurement, stress assessment, and environmental stress-change monitoring capabilities with hitherto unattained accuracy [6]. More recently, by applying multiple parallel repeat-pass EWB-POL-D(RP)-IN-SAR imaging along stacked (altitudinal) or displaced (horizontal) flight-lines will result in *'Tomographic (Multi-Interferometric) Polarimetric SAR Stereo-Imaging'*, including foliage and ground penetrating capabilities [7]. It is shown that the accelerated advancement of these modern '*EWB-POL-D(RP)-IN-SAR'* imaging techniques is of direct relevance and of paramount priority to wide-area dynamic battle-space surveillance and local-to-global environmental ground-truth measurement and validation, stress assessment, and stress-change monitoring of the terrestrial and planetary covers [2].

RADAR AND OPTICAL POLARIMETRY

Polarimetry deals with the full vector nature of polarized (vector) electromagnetic waves throughout the frequency spectrum from Ultra-Low-Frequencies (ULF) to above the Far-Ultra-Violet (FUV) [2]. Where there are abrupt or gradual changes in the index of refraction (or permittivity, magnetic permeability, and conductivity), the polarization state of a narrow-band (single-frequency) wave is transformed, and the electromagnetic *"vector wave"* is re-polarized. When the wave passes through a medium of changing index of refraction, or when it strikes an object such as a radar target and/or a scattering surface and it is reflected; then, characteristic information about the reflectivity, shape and orientation of the reflecting body can be obtained by implementing '*polarization control' [1]* . The complex direction of the electric field vector, in general describing an ellipse, in a plane transverse to propagation, plays an essential role in the interaction of electromagnetic '*vector waves'* with material bodies, and the propagation medium. Whereas, this polarization transformation behavior, expressed in terms of the *"polarization ellipse*" is named "*Ellipsometry"* in Optical Sensing and Imaging, it is denoted as *"Polarimetry*" in Radar, Lidar/Ladar and SAR Sensing and Imaging - using the ancient Greek meaning of "*measuring orientation and object shape*". Thus, *ellipsometry* and *polarimetry* are concerned with the control of the coherent polarization properties of the optical and radio waves, respectively [1, 2]. With the advent of optical and radar polarization phase control devices, *ellipsometry* advanced rapidly during the Forties (Mueller and Land) with the associated development of mathematical *ellipsometry*, i.e., the introduction of '*the 2 x 2 coherent Jones forward scattering (propagation) and the associated 4 x 4 average power density Mueller (Stokes) propagation matrices'*; and *polarimetry* developed independently in the late Forties with the introduction of dual polarized antenna technology (Sinclair, Kennaugh, et al.), and the sub-sequent formulation of *'the 2 x 2 coherent Sinclair radar back-scattering matrix and the associated 4 x 4 Kennaugh radar back-scattering power density matrix'*, as summarized in detail in Boerner et. al. Since then, *ellipsometry* and *polarimetry* have enjoyed steep advances; and, a mathematically coherent polarization matrix formalism is in the process of being introduced - - of which the lexicographic and Pauli phase-preserving covariance matrix presentations play an equally important role in *ellipsometry* as well as *polarimetry*. In *ellipsometry*, the Jones and Mueller matrix decompositions rely on a product decomposition of relevant optical measurement/transformation quantities such as di-attenuation, retardance, depolarization, bi-refringence, etc., measured in a '*chain matrix arrangement, i.e., multiplicatively placing one optical decomposition device after the other*' [2]. In *polarimetry*, the Sinclair, the Kennaugh, as well as the covariance matrix decompositions are – today - based on a group-theoretic series expansion in terms of the principal orthogonal radar calibration targets such as the sphere or flat plate, the linear dipole and/or circular helical scatterers, the dihedral and tri-hedral corner reflectors - - observed in a linearly superimposed aggregate measurement arrangement [8]; leading to various canonical target feature mapping and sorting as well as scatter-characteristic decomposition theories. In addition, polarization-dependent speckle and noise reduction play an important role in both *ellipsometry* and *polarimetry*, and the polarimetric Lee-Wishart distribution functions were introduced for this purpose. **The implementation of all of these novel methods will however fail badly unless one is given fully calibrated scattering matrix information which applies to each element of the Jones and Sinclair matrices; and the realistic requirements on the calibration of the *'polarimetric radar data takes'* at the order of about 0.1 dB in amplitude and 1° in phase must be progressively accepted. In addition, it is most desirable to develop POL-IN-SAR Imaging systems with sufficient resolution ($1m^2$ achievable) in order to discern the finer scattering structure of complex scattering scenarios.**

Very remarkable improvements above classical "*non-polarimetric*" radar target detection, recognition and discrimination, and identification were made especially with the introduction of the covariance matrix optimization procedures of Tragl, Novak et al. Lüneburg, Cloude, and of Cloude and Pottier [1, 2, 3]. Special attention must be placed on the *'Cloude-Pottier Polarimetric Entropy (H), Anisotropy (A), Feature-Angle ($\overline{\alpha}$) parametric decomposition'* because it allows for unsupervised target feature interpretation [3]. Using the various fully polarimetric (scattering matrix) target feature syntheses, polarization contrast optimization, and polarimetric entropy/anisotropy classifiers, very considerable progress was made in interpreting and analyzing POL-SAR image features. This includes the reconstruction of *'Digital Elevation Maps (DEMs)'* directly from *'POL-SAR Covariance-Matrix Image Data Takes'* next to the familiar method of DEM reconstruction from IN-SAR Image data takes [5]. Implementation of the '*Lee Filter'* for speckle reduction in polarimetric SAR image reconstruction, and of the *' Polarimetric Lee-Wishart distribution'* for improving image feature characterization [9] have further contributed toward enhancing the interpretation and display of high quality SAR Imagery, again requiring fully calibrated *SLC formatted POL-IN-SAR Image data takes*. This distinguishes the limited use of a '*Multi-Amplitude-Polarization SAR'* - like the ENVISAT or of the currently planned TERRA-SAR - - from a '*Fully Polarimetric, Well-calibrated Scattering-Matrix-SAR'*, - - like RADARSAT-2 or of JERS-2 (ALOS). Using poorly calibrated POL/IN-SAR Image data takes is also not sufficient and strongly detracts from recognizing the truly superior performance of '*fully polarimetric POL-IN-SAR Imaging*' [1 - 4]

RADAR INTERFEROMETRY

Some of the very latest developments have addressed polarimetric interferometry and multi-baseline radar tomography [10]. By operating at longer wavelengths such as L and P bands, these techniques [11, 12] provide penetration into vegetation and the ground and hence provide vertical structure information not available from optical or laser sensors. This technology promises to provide the basis for important new radar remote sensing instruments for global biomass and vegetation mapping [12]. Radar Interferometry was developed initially as a technique for measuring surface topography. Here the interferometric phase is the key radar observable and this phase can be simply related, through the geometry of the sensor, to the local elevation of a scattering point above a reference plane. To a first approximation it can be assumed that the speckle phase for the two signals at either end of the baseline is strongly correlated. Hence the phase difference cancels this speckle and we obtain a deterministic phase signal. In these early studies any residual phase variance was perceived primarily as a nuisance, acting to reduce the accuracy of the terrain elevation model [10]. However, it was quickly realized that the local phase variance or a closely related parameter, the interferometric coherence, contains information about the scattering mechanisms on the surface. This realization arose following a decomposition of the complex coherence into a product of terms, most of which are related to system bandwidth and geometry effects but one of which, the volume decorrelation, contains important information on penetration depth in vegetation, ice and ground applications. This had two important consequences for the development of interferometric methods in remote sensing: (1) the change of coherence over vegetated areas provides a means for scene classification based on vegetation cover. It was also noted that as the vegetation height increases so the coherence generally decreases. Hence this provided a means of classifying vegetation on the basis of its height; (2) unlike other sources of decorrelation, the volume coherence is complex i.e. it has an associated phase. This phase adds to that of the underlying ground topography to provide what is called vegetation bias [11, 12, 7]. This bias is a nuisance if ground mapping is the desired aim of the processing. However, this phase offset itself contains important information about the density and height of the vegetation. This, when combined with the coherence provides two parameters which are directly related to the vertical structure of the vegetation cover on the surface [4, 11, 12].

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This observation is frustrated by the multi-parameter dependence of the observables. For example a large vegetation bias can be caused by very tall vegetation with low density and low extinction or by shorter denser vegetation with high wave extinction. A further complication is the multiplicative nature of the coherence decomposition. In particular, the vegetation bias is measured in combination with the (unknown) ground phase. Hence there seems no way to separate the phase terms in the data. One solution to this problem is to have a digital elevation model of the scene in advance and then the ground phase can be calculated and subtracted from the observed interferometric phase to obtain the vegetation bias. However this is less than satisfactory and it would be much better if we could estimate the two phase terms separately from the data itself. This is the point where interest began in using polarization effects in interferometry, made possible by the availability of data from the space shuttle radar mission SIR-C in 1994 [4]. At the end of the October mission the system was operated in 1-day repeat pass fully polarimetric interferometric mode at two frequencies, C and L band. This enabled a detailed analysis of the effects of polarization on the phase and coherence of radar interferograms and led to the realization that polarization is an important parameter in determining interferometric coherence. Eventually, by employing the coherence in different polarization channels, it was shown that the desired separation of phase terms can be achieved without the need for a reference DEM. This enables estimates of height, underlying ground topography and mean wave extinction to be made from single wavelength sensors without the need for auxiliary information on the ground conditions. Here, we emphasize that with increasing resolution, polarization dependence becomes all the more pertinent; and that there exists a threshold level about which polarimetric IN-SAR becomes absolutely necessary and prevalent [4, 6]. Although, IN-SAR enables the recovery of *'Digital Elevation Maps (DEMs)*'; without polarimetry, it will be difficult to discern - *in most cases* - the source orientation/location of the scattering mechanisms. Without the full implementation of POL-IN/TOMO-SAR imagery, it will be difficult or close to impossible to discern the tree-top canopy from that of the understore, thicket under-burden or of the layered soil and sub-surface under-burden. Many more additional studies of the kind executed by Treuhaft [12], Cloude, et al [4, 11]., as reported in [13], are required to establish fully the capabilities of one method as compared to the other, and to their integral POL-IN-SAR implementations. So, speaking strictly in terms of Maxwell's equations, '*amplitude-only SAR'* and '*Scalar IN-SAR'* can only apply to the either the TM (magnetic field parallel to surface) or TE (electric field parallel to surface) incidence on a perfectly conducting two-dimensional surface, by also neglecting the inherent TE-TM hybrid shadowing and front-porching (fore-shortening or overlaying) effects [1, 2].

POLARIMETRIC SAR INTERFEROMETRY AND TOMOGRAPHY

In POL-IN-SAR imaging, it is then possible to associate textural/orientational finestructure directly and simultaneously with spatial information; and to extract the interrelation via the application of novel '*Polarimetric-Interferometric Phase Optimization'* procedures. This novel optimization procedure requires the acquisition of *highly accurate, well calibrated,* fully polarimetric (scattering matrix), *SLC-formatted POL-IN-SAR image data sets*. In addition, several different complementing DEM extraction methods can be developed which make possible the precise determination of the source-location of the pertinent scattering centers. Thus, in addition to the standard interferometric "scalar" DEM - derived from IN-SAR - it is possible to generate two DEMs directly from the 3x3 covariance matrices of the two separate fully polarimetric sensor data sets as well as various additional ones from the 6x6 POL-IN-SAR correlation matrix optimization procedure for the reciprocal 3x3 symmetric scattering matrix cases. This provides the additional benefit of obtaining '*co-registered textural/orientational + spatial three-dimensional POL-IN-DEM information'* [14]. Another approach was recently developed by Yamada and Yamaguchi [15], which is based on the ESPRIT algorithm, which made possible the comparison of various partially versus fully polarimetric approaches in various different polarization bases. Stebler [6] recently investigated multi-band and multiple repeat-pass fully polarimetric SAR image data sets, and further advanced above cited methods. Applying this POL-IN-SAR mode of operation to '*REPEAT-PASS*

Image Overlay Interferometry' makes possible the '*Differential Environmental Background Validation, Stress Assessment and Stress-Change Monitoring'* with hitherto unknown accuracy and repeatability. The full verification and testing of these highly promising imaging technologies requires - *first of all* - that *well-calibrated, fully polarimetric EWB-POL-IN/TOMO-SAR Imaging data takes* become available; and its development has only just begun.

CONCLUSIONS

Because the *'twin-antenna-interferometer POL-D-IN-SAR optimization method*' at narrow band operation allows formally the delineation only of three spatially - in vertical extent - separated scattering surfaces, characterized by polarimetrically unique scattering mechanisms, it is of high priority to accelerate the development of not only twin-antenna-interferometers but of multi-antenna-interferometers - all being completely coherent *POL-IN-SAR IMAGING* systems. Furthermore, by stacking the *"polarimeters*" on top of one another (cross-range) and in series next to each other (along-track and cross-track) results in a *'Polarimetric Tomographic SAR Imaging system'* with *'Moving Target Imaging (MTIm) capability'*, so that a *'POL-TOMO-SAR'* imaging system can be synthesized which might also be used for ocean current environmental monitoring and assessment [4, 7, 6, 11, 14]. In addition, using extra-wide-band multiple Repeat-Pass Over-flight operations, at precisely stacked differential altitudes and/or vertically displaced flight-lines, will result - - in the limit - - into a Polarimetric Holographic SAR imaging system, a '*POL-HOLO-SAR'* imaging system [6, 13, 14]. This will allow the separation not only of layered but also of isolated ("point") scattering structures, occluded under heterogeneous clutter canopies; and embedded in inhomogeneous layered under-burden. This represents a good counter-example on what we **cannot** achieve by implementing '*EO-Hyper-spectral Imagery'* [1, 2].

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