POLARIMETRY, INTERFEROMETRY AND POLARIMETRIC INTERFEROMETRY IN SYNTHETIC APERTURE REMOTE SENSING

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1. Introduction

Both Optical and Radar Imaging have matured considerably, and the benefits of using one imaging modality over the other are discussed frequently. For example, *'Hyper-spectral Optical (FIR-VIS-FUV) Radiometric Imaging'* is considered to become the exclusive remote sensing system of the twenty-first century, and thought to be superior to *'Ultra-wide-band Microwave (HF-UHF-SHF-EHF) SAR Imaging'* Remote Sensing technology [2]. In either case, the inherent electromagnetic vector wave interaction processes are subjected to Maxwell's equations; and constrained by the carrier frequency and bandwidth, the amplitude, phase and polarization; the dispersive and polarization-dependent material constituents of the propagation medium as well as of the illuminated scattering surface, its geometry and structure, and its voluminous vegetative over-burden as well as its composite geological under-burden. However, in order to identify parameters describing voluminous scattering scenarios beyond the skin depth of the vegetation canopy, the entire amenable air/space-borne frequency regime from MF (100 KHz) to FUV (10 PHz) needs to be implemented in remote sensing [3]. This implies that we require both radar and optical imaging together with full scattering matrix acquisition capabilities - in order to recover fully the intricate scattering mechanisms and bio-mass assessment tasks - as will be discussed in the following.

2. EWB-Hyper-Spectral (Spectrometric) Optical Imaging

Thus, whereas '*hyper-spectral optical radiometry'* will provide high resolution characterization of scattering surface parameters - subject to the skin depth - with appreciable penetration only for a rather limited number of transparent media it lacks manageable coherent phase information and strongly depends on the heterogeneous and dispersive propagation medium such as non-transparent meteorological scatter, smoke and other atmospheric pollution. So, it provides very useful direct '*hyper-spectral'* indicators of the vegetative cover and of surface chemical pollutants. However, *'hyper-spectrally extended optical (FIR-VIS-FUV) sensing'* does not increase the received radiance, but it just divides the overall observation band in order to collect specific wavelength-dependent spectroscopic information in each of the "*hyperfine sub-bands"* [2]. Whereas, hitherto in most of the hyper-spectral optical remote sensing techniques polarization effects were in general totally neglected, it needs to be strongly emphasized that *'Hyper-spectral Optical Radiometry'*, and especially '*LIDAR/LADAR'*, is subjected to the '*Arago Sphere'* axioms of light scattering in dependence of relative sensor versus scatterer versus source (sun) position. Complete polarimetric sensor and transceiver technology must be incorporated into future designs. Therefore, any non-polarimetric '*Scalar (amplitude only) Hyper-spectral Radiometric Imagery'* must be interpreted with great caution; and, some of the highly overrated attributes for the exclusive use of EO hyper-spectral information are at their best rather misplaced unless full polarimetric sensor design is being rapidly developed also for the extended optical spectral regime. This implies the instantaneous acquisition - not the consecutive time-consuming *ellipsometric measurements* - of the Stokes parameters for the instantaneous reconstruction of the '*Stokes Reflection'* or the '*Kennaugh Backscattering* ' matrix. **And, *"all-weather, day and night"* sensing and imaging is a capability which only *'radar'* can provide and not *"Hyper-spectral FIR-VIS-FUV Radiometric Imagery"*; hence, full attention is paid in the following to *'EWB (HF-VHF-UHF-SHF-EHF) POL-IN/TOMO-SAR'* sensing and imaging [1 - 6].**

3. HF - EHF Radar and SAR Polarimetry and Interferometry

With increasing wavelength from the EHF (sub-millimeter) via UHF (cm/m) to HF (deca-meter) regimes, the radar imaging process becomes less dependent on the meteorological propagation parameters but more so on parametric target orientation/fine structure/resonance effects; and it possesses increasing polarization dependent penetration capabilities into semi-transparent volumetric under-burden with associated decreasing image resolution. With the recent advances made in modern radar electronics device and systems technology, not only the design of '*Scalar (amplitude only) Multi-Polarization Synthetic Aperture Radar (SAR*)' but of more sophisticated coherent and fully polarimetric (scattering matrix) POL-SAR as well as fully coherent Interferometric (dual coherent sensor pair) IN-SAR (or IF-SAR) systems have become feasible. In fact, it is safe to state that ***'Non-polarimetric and Non-interferometric SAR Imaging'* is on its way out, and that the IN-SAR Systems are also becoming fully polarimetric *POL-IN-SAR Imaging Systems* [2,3].**

In classical radar, i.e. *"amplitude-only radar"*, mainly the energy of the returned pulse is utilized; and in basic imaging radar, it is the Doppler phase information in addition. Interferometric SAR (IN-SAR) exploits fully the phase and Doppler information, but not the polarization information of the electromagnetic vector wave - scatterer interrogation process; and especially the coherent phase difference of at least two complex-valued SAR images acquired from two different flight-pass/orbit positions and/or at different times are utilized. Provided that coherent two-dimensional complex-valued phase-unwrapping can fully be achieved, the IN-SAR information, derived from such interferometric complex image data sets, can be used to measure several geophysical quantities such as topography, tectonic surface deformation, bulging and subsidence (earthquakes, volcanoes, geo-thermal fields and artesian irrigation, ice fields), glacial flows, snow avalanches and mud flows, ocean currents, vegetative growth patterns and environmental stress assessment, etc.. Thus, the amplitude and coherent phase information that electromagnetic wave interrogation can recover, is fully utilized in IN-SAR imaging, but not its intrinsic polarization information.

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) [2-6]. 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*'. 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. With the advent of optical and radar polarization phase control devices, *ellipsometry* advanced rapidly during the Forties (Mueller and Land [50]) 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. [2]. 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 (covariance) and Pauli coherency 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 diattenuation, retardance, depolarization, birefringence, etc., measured in a '*chain matrix arrangement, i.e., multiplicatively placing one optical decomposition device after the other*'. In *polarimetry*, the Sinclair, the Kennaugh, as well as the covariance matrix decompositions are 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 trihedral corner reflectors - - observed in a linearly superimposed aggregate measurement arrangement; leading to various canonical target feature mapping and sorting as well as scatter-characteristic decomposition theories.

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 Cloude and Pottier [5]. Special attention must be placed on the Cloude-Pottier Polarimetric Entropy (H) ,Anisotropy (A), Feature-Angle (α) parametric decomposition because it allows for unsupervised target feature interpretation [5]. Using the various fully polarimetric (scattering matrix) target feature synthesis, 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. In all of these techniques well calibrated scattering matrix data takes are becoming an essential pre-requisite without which little can be achieved [3].

These fully polarimetric (scattering matrix) POL-SAR and its UWB-POL-SAR Imaging applications are described in the proceedings of various recent '***Polarimetric Radar Workshops' [3]***; and, especially in ***Chapter 5 on "Polarimetry in Radar Remote Sensing: Basic and Applied Concepts"*** of Volume 2, ***'Principles and Applications of Imaging Radar'*** in the Third Edition of the ***Manual of Remote Sensing*** [2].

4. SAR Polarimetry Versus SAR Interferometry

Whereas with ***'Radar Polarimetry' [2,6]*** textural fine-structure, *target orientation*, symmetries, and material constituents can be recovered with considerable improvement above that of standard '*Amplitude-Only Radar'*; with standard (scalar) ***'Radar Interferometry'*** [1] the spatial (range/in depth) structure may be resolved, from which '*Digital Elevation Maps'* can be reconstructed. However, neither method is complete in that POL-SAR by itself does not provide spatial information; and IN-SAR or military (non-polarimetric) air-borne imaging radar cannot provide textural fine-structure information. Although, IN-SAR enables the recovery of '*Digital Elevation Maps (DEMs)*'; without polarimetry, it will be difficult to discern - in all cases - the source orientation/location of the scattering mechanisms [3]. 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 thicket under-burden or of the layered soil and sub-surface under-burden.

5. Polarimetric SAR Interferometry

In POL-IN-SAR imaging, it is then possible to associate textural/orientational fine structure directly and simultaneously with spatial information; and to extract the interrelation via the application of novel '*Polarimetric-Interferometric Phase Optimization'* procedures [4]. This novel optimization procedure requires the acquisition of *highly accurate, well calibrated*, fully polarimetric (scattering matrix), *SLC-formatted POL-IN-SAR image data* .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. Even better so, from multi-band POL-IN-SAR imaging systems, one can extract directly and simultaneously

'*Polarimetric + Interferometric SAR Information'* by implementing the Cloude-Papathanassiou *'POL-IN-SAR Optimization'* procedure developed for a fully polarimetric twin-SAR-interferometer [4]. This provides the additional benefit of obtaining '*co-registered textural/orientational + spatial three-dimensional POL-IN- DEM information' [2]*. 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 [3].

6. Polarimetric SAR Tomography

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), so that a *'POL-TOMO-SAR'* imaging system can be synthesized which might also be used for ocean current environmental monitoring and assessment [3].

7. Conclusions

A succinct summary on the current state of development of Polarimetric and Interferometric Synthetic Aperture Radar theory, technology and applications is provided with a view towards the expected rapid developments of fully integrated "*Polarimetric SAR Interferometry*" and its extension to '*POL-IN/TOMO-SAR Repeat-Pass'* environmental stress-change monitoring. The underlying basic systems analysis of these *POL-IN-SAR to POL-TOM-SAR algorithms* need to be complemented with recent *POL-IN-SAR to POL-TOM-SAR images* obtained with air/space-borne *NASA-JPL, NASDA-CRL, NAWC-AD and DLR-OP-HR* imaging platforms.

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9. References

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