RECENT ADVANCES IN POLARIMETRIC- INTERFEROMETRIC SAR THEORY & TECHNOLOGY AND ITS APPLICATION

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ABSTRACT

The development of *Radar Polarimetry* and *Radar Interferometry* is advancing rapidly. 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; with *radar interferometry* the spatial (in depth) structure can be explored. In '*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, including the extraction of *Digital Elevation Maps (DEM)* from either *Polarimetric (scattering matrix) or Interferometric (dual antenna) SAR systems*. Simultaneous *Polarimetric-plus-Interferometric SAR* offers the additional benefit of obtaining co-registered textural-plus-spatial three-dimensional *POL-IN-DEM information,* which when applied to Repeat-Pass Image-Overlay Interferometry provides differential background validation, stress assessment and environmental stress-change information with high accuracies. Then, by either designing '*Multiple Dual-Polarization Antenna POL-IN-SAR*' systems or by applying advanced POL-IN-SAR image compression techniques will result in '*POL-arimetric TOMO-graphic*' *(Multi-Interferometric) SAR*' or '*POL-TOMO-SAR Imaging*'. This is of direct relevance to wide-area, dynamic battle-space surveillance and local-to-global environmental background validation, stress assessment and stress-change monitoring of the terrestrial and planetary covers.

1. INTRODUCTION

Both Optical [026, 047, 088, 068, 134] and Radar [007-016] Imaging have matured considerably, and the benefits of using one imaging modality over the other are discussed frequently [047, 116, 102, 103, 073, 035]. For example, *'Hyper-spectral Optical (FIR-VIS-FUV) Radiometric Imaging'* [044, 047, 072, 080] is considered to become the exclusive remote sensing system of the 21st century, and thought to be superior to 'Ultra-wide-band Microwave (HF-UHF-SHF-EHF) SAR Imaging' [020, 021, 073]. Even, it was argued that *UWB-SAR Imaging* is superfluous and could be scrapped altogether because of the exorbitant costs in developing this abstract rather *'invisible'* Remote Sensing technology? [012]. 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 [070, 001, 165, 028, 074, 110, 112, 107, 144, 011, 101, 054]; 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 [041, 026, 057-067] in remote sensing. 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 [028-033, 052, 057-066, 145-149, 045, 133] and bio-mass assessment tasks - as will be discussed in the following; and maybe assessed by visiting the web-sites collected in chapter 15, specifically [w-01 to w-12].

2. EWB-HYPER-SPECTRAL (SPECTROMETRIC) OPTICAL IMAGING (URLs: u-01 to u-10)

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 [002, 025, 057-066, 080, 116, 153]; 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 [044, 047, 068, 067, 116, 130-132, 153] 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"* [047, 057-066, 067, 133]. 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 [154, 155, 016, 102, 103] in dependence of relative sensor versus scatterer versus source (sun) position. This seems to have been either forgotten or been disregarded altogether [012, 013, 016, 134]. This '*Arago Sphere'* dependence [154, 155] also applies throughout the optical (FUV-VIS-FIR) down to the millimeter wavelength region within which atmospheric particle scattering is effective [052, 073]. Complete polarimetric sensor and transceiver technology must be incorporated into future designs [026, 047]. 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 [016, 057-066] 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 Back-scattering* ' matrix [011, 150, 166, 140, 157].

And, *"all-weather, day and night"* sensing and imaging is a capability which only *'radar'* can provide [134, 101, 070, 054] and not *"Hyper-spectral FIR-VIS-FUV Radiometric Imagery"* [067, 068, 080]; hence, full attention is paid in the following to *'EWB (HF-VHF-UHF-SHF-EHF) POL-IN/TOMO-SAR'* sensing and imaging [016, 033, 108, 114, 151, 117-120].

3. HF - EHF RADAR AND SAR POLARIMETRY AND INTERFEROMETRY (URLs: v-01 to v-18)

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 [054, 070, 169, 001, 074, 028, 089, 090, 107, 146]; and it possesses increasing polarization dependent penetration capabilities into semi-transparent volumetric under-burden with associated decreasing image resolution [052, 057-066]. 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)*' [151, 169, 055] but of more sophisticated coherent and fully polarimetric (scattering matrix) POL-SAR [016] as well as fully coherent Interferometric (dual coherent sensor pair) IN-SAR (or IF-SAR) systems have become feasible [004, 093, 094]. 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*[107-109, 114, 115].**

3.1 Classical Amplitude-Only Radar and SAR, and "Scalar" IN-SAR Imaging

In classical radar, i.e. *"amplitude-only radar"* [134], 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 [113, 004], but not the polarization information of the electromagnetic vector wave - scatterer interrogation process [007, 008, 031, 016, 099]; 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 [114, 115]. Provided that coherent two-dimensional complex-valued phase-unwrapping can fully be achieved [004, 094], the IN-SAR information, derived from such interferometric complex image data sets [071, 107, 114], 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. [052]. 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 [004, 093, 094].

3.2 Optical Ellipsometry versus Radar Polarimetry and Polarimetric (Scattering Matrix) SAR Imaging

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) [012, 013, 016]. 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'* [070, 054, 016, 150, 101]. 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 [001, 169, 074-079, 036-039]. Whereas, this polarization transformation behavior, expressed in terms of the "polarization ellipse" is named "*Ellipsometry*" in Optical Sensing and Imaging [026, 028, 047, 091, 136], it is denoted as "*Polarimetry*" in Radar, Lidar/Ladar and SAR Sensing and Imaging [070, 054, 001, 101-103] - 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 [070, 136]. With the advent of optical and radar polarization phase control devices, *ellipsometry* advanced rapidly during the Forties (Mueller and Land [136]) 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. [070, 101, 016]), 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. [016]. Since then, *ellipsometry* and *polarimertry* have enjoyed steep advances; and, a mathematically coherent polarization matrix formalism is in the process of being introduced - - of which the lexicographic covariance matrix presentations [029, 030, 089-093, 105, 106] play an equally important role in *ellipsometry* as well as *polarimetry* [026, 047, 088]. Based on Kennaugh's original pioneering work [070], Huynen [054] developed a *"Phenomenological Approach to Radar Polarimetry"*, which had a subtle impact on the steady advancement of *polarimetry* [117-120] as well as *ellipsometry* by developing the "*orthogonal (group theoretic) target scattering matrix decomposition*" [054, 029, 070, 078, 112] and characteristic optimal polarization state concepts, which lead to the formulation of the '*Huynen Polarization Fork*' in '*Radar Polarimetry*' [054, 157, 001, 036-039, 161-163]. Here, we emphasize that for treating the general bistatic (asymmetric) scattering matrix cases, a more general formulation of fundamental *Ellipsometry* and *Polarimetry* in terms of a spinoral group-theoretic approach is strictly required [005, 096, 036-039].

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., [026, 032, 047, 123] 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 [011, 028-032, 144, 089, 111] 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 tri-hedral corner reflectors - - observed in a linearly superimposed aggregate measurement arrangement [074-079]; leading to various canonical target feature mapping [076-079, 029, 030, 082-086] and sorting as well as scatter-characteristic decomposition theories [110, 112, 089-092]. In addition, polarization-dependent speckle and noise reduction play an important role in both *ellipsometry* and *polarimetry* [076-079, 082-086, 138-143]. The implementation of all of these novel methods will fail 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 accepted [138-143, 016].

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 [144], Novak et al. [105, 106] Lüneburg [089, 083], Cloude [028], and of Cloude and Pottier [029, 030, 110-112]. Special attention must be placed on the Cloude-Pottier Polarimetric Entropy (H) [030, 111], Anisotropy (A), Feature-Angle (α) parametric decomposition because it allows for unsupervised target feature interpretation [111, 086]. Using the various fully polarimetric (scattering matrix) target feature synthesis [110-112, 143, 074-079, 055, 167, 161], polarization contrast optimization, [011, 101-103, 163] 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'* [124-127, 112, 016] 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. In most cases the *'multi-look SAR Image data take formatting'* suffices also for completely polarized SAR image algorithm implementation. However, in the sub-aperture polarimetric studies, in '*Polarimetric SAR Image Data Take Calibration*', and in '*POL-IN-SAR Imaging*', the '*SLC (Single Look Complex) SAR Image Data Take Formatting*' becomes an absolute *'MUST'* [016]. Of course, for SLC-formatted Image data, in particular, speckle filtering must be applied always. Implementation of the '*Lee Filter*' for speckle reduction in polarimetric SAR image reconstruction, and of the Wishart distribution for improving image feature characterization have further contributed toward enhancing the interpretation and display of high quality SAR Imagery [081-086, 087], again requiring fully

calibrated *SLC formatted POL-IN-SAR Image data takes*. **This distinguishes the limited use of a *'Multi-Amplitude-Polarization SAR'* from a *'Fully Polarimetric, Well-calibrated Scattering-Matrix-SAR'*. Using poorly or badly 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*** [138-143, 107-109].

The fully polarimetric (scattering matrix) POL-SAR and its UWB-POL-SAR Imaging applications [003, 017-019, 043, 045, 053, 075-079, 082-086, 087, 095, 098, 100, 135, 128, 168, 170-172] are described in the proceedings of various recent ***'Polarimetric Radar Workshops'*** [009-012, 026, 102, 103, 117-120, w-01 to w-12]; and, especially in ***Chapter 5 on "Polarimetry in Radar Remote Sensing: Basic and Applied Concepts"*** [016] of Volume 2 , ***'Principles and Applications of Imaging Radar'*** [052] in the Third Edition of the ***Manual of Remote Sensing*** [116].

3.3 SAR Polarimetry Versus SAR Interferometry

Whereas with *'Radar Polarimetry'* textural fine-structure, *target orientation*, symmetries, and material constituents can be recovered with considerable improvement above that of standard *'Amplitude-Only Radar'* [134, 150, 151]; with standard (scalar) *'Radar Interferometry'* the spatial (range/in depth) structure may be resolved, from which *'Digital Elevation Maps'* can be reconstructed [004, 093, 094]. 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 [057-066, 145-149]. Although, IN-SAR enables the recovery of *'Digital Elevation Maps (DEMs)'*; without polarimetry [094], it will be difficult to discern - in all cases - the source orientation/location of the scattering mechanisms [031, 107, 109, 124-127]. Without the full implementation of POL-IN/TOMO-SAR imagery [114, 115], 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 [145-149]. Many more additional studies of the kind executed by Treuhaft, Cloude, et al., as reported in [145-149], 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 [016]. In order to satisfy the correct implementation of Maxwell's equations fully [007-010], it is necessary - in all cases - to incorporate fully coherent polarimetric (scattering matrix) POL-SAR [016, 070, 117, 120] and especially *'Polarimetric-Interferometric Synthetic Aperture Radar (POL-IN-SAR)'* imaging methods [031, 107-109, 114, 115, 099].

4. POLARIMETRIC SAR INTERFEROMETRY

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 [031,107-109]. 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 [004, 093, 094] - derived from IN-SAR, it is possible to generate two DEMs [124-127] 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 [018, 019] 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 [031, 056, 071, 109]. This provides the additional benefit of obtaining *'co-registered textural/orientational + spatial three-dimensional POL-IN-DEM information'*. 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 [031, 016, 109, 113, 114]. 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 [109, 114, 115]. There exists a wide range of hitherto unforeseen surveillance and environmental monitoring applications, which require extensive additional analytical investigations next to the acquisition of the well calibrated and ground-truth validated *EWB-POL-D-IN-SAR Image data takes* [107, 122, 018, 019].

For example, more in-depth analyses are required to assess whether *non-polarimetric IN-SAR* alone could in some, but may not in all cases, separate ground scattering mechanisms from those of volumetric scattering layers [145-149, 057-066] by utilizing simultaneously the *'canopy-gap scaling method'*, first

introduced in *Optical Hyper-spectral Mapping* [002, 025, 080, 104, 130-132]. Indeed, *'POL-SAR Interferometry'* opened a huge treasure chest of novel modeling methods for an unforeseen large number of hitherto un-approachable problems of environmental stress-change measurement and interpretation. [028-033, 110-112, 107, 108, 114, 115]

5. EWB (HYPER-BAND) POL-IN-SAR IMAGING

Depending on the dispersive material and structural properties of the scattering surface, the vegetative over-burden and/or geological under-burden, a careful choice of the appropriate frequency bands - matched to each specific environmental scenario - must be made [016, 057-066]. This is strictly required in order to recover - next to material bio-mass parameters - canopy versus sub-canopy versus ground-surface versus sub-surface DEM + STRUCTURE information. With increasing complexity of the environmental multi-layered scattering scenario, the implementation of increasing numbers of scenario-matched frequency bands - in the limit - contiguous *EWB (HYPER-BAND and ULTRA-WIDE-BAND) POL-IN-SAR* becomes all the more necessary and essential [021]. For example, in order to assess - as accurately as ever possible - the bio-mass of specific types of forested regions - - such as *boreal tundra shrubbery,* versus *boreal taiga,* versus *temperate-zone rain-forests,* versus *sparsely vegetated savannahs,* versus *dense sub-tropical to equatorial jungle-forests* - - requires in each case [057-066] a different choice of multiple-to-wide-band POL-IN-SAR imaging platforms, not necessarily operated at one and the same band and altitude, for optimal performance within the HF/VHF{(10)100 MHz} to EHF {100 GHz} regime [016]. For most semi-dense to dense forests of the temperate zones, the EWB VHF/UHF/SHF (600 - 5000 MHz) regime may be optimal [054-066]. Whereas, for a dense virgin equatorial rain forest with huge trees of highly conductive hard-wood, the UWB (100 - 1000 MHz) regime is required, etc. [066]. Thus, the current choice of frequency bands for bio-mass determination is indeed very poor and insufficient in that the L/S/C/X-Bands all lie well above the upper saturation curve; and, the nominal P-Band (420 MHz) well below the lower saturation curve of the bio-mass hysteresis - - for most types of forested regions within the temperate climatic zones [150, 151]. Similarly, in order to recover the three-dimensional sub-surface image information of dry to wet soils including its soil moisture properties, the optimal EWB HF/VHF-regime [152] lies below the nominal P-Band (420 MHz) to well below 10 MHz. Thus, adaptive EWB-POL-IN-SAR modes of operation become a stringent requirement for three-dimensional environmental background validation, stress assessment, and stress-change monitoring. In addition, next to the UHF/SHF (300 MHz - 30 GHz) regime, the EHF (30 - 300 GHz) spectral regime becomes important for the detection of man-made structures - - such as telephone and electric power-lines - - embedded in forests, shrubbery, thickets, grasslands; and - in addition - for vegetative canopy plus rugged terrain as well as for atmospheric scatter analyses [104, 105].

Therefore, every possible effort must be made to expand and to extend but not to give up the existing, highly insufficient availability of free scientific '*remote sensing spectral windows'*, which must absolutely be spread *with 'deca-logarithmic periodicity'* throughout the pertinent frequency bands of about 1 MHz to 300 GHz.

6. ALLOCATION OF ADDITIONAL SAR IMAGING FREQUENCY BANDS

In order to secure the required frequency windows within the ELF (**HF/VHF**) to (**UHF-SHF**) EHF regime for environmental remote sensing, we must place our requests - at once - to the '*World Radio Frequency Conference (WRC'03, Sept./Oct., Geneva, Switzerland)*' via the pertinent *National Research Councils (NRC), Committees on Radio Frequencies (CoRF)* in a unified, concerted effort [034]. The pertinent frequency bands between HF to EHF are already over-crowded; but with the rapidly accelerating conversion to digital communications and worldwide digital video transfer, etc.; we had better wake up. The "*Remote Sensing Community*" must relentlessly request that the rights to operate in periodically spaced "*deca-logarithmic (octave) windows*", extending from below the HF to beyond the EHF bands, be granted.

This indeed represents a very serious, major problem for all of military surveillance and environmental stress-change monitoring [008-013, 057-066, 128]. It is indeed one of the most pressing issues that could reach catastrophic proportions within the near future unless we act immediately. The commercial '*Mobile Radio Communications, Telephone and Video Transmission'* industry has already initiated a fierce battle for acquiring various frequency bands hitherto allocated exclusively for military radar, and for radar sensing and imaging [016]. It is 'densely over-packing' the *"commercially appropriated frequency windows"* plus '*encroaching into neighboring scientific bands'*.

We must follow the successful example of the '*International Radio Astronomic Research Community'* [034], who had to address a similar problem a few decades ago - - in the early Fifties - - in order to ensure that far-distant Radio-Stars could be detected without interference by radio communications clutter - - for then a still relatively *"sparsely occupied"* VHF, UHF, SHF frequency region. Now, with the imminent threat of the ever accelerating *"Digital Communications Frequency Band Cluttering , Mobile Communications Pollution, and 'www' Propagation Space Contamination"*, we - - '*the International Remote Sensing Research Community'* - - are called to duty;

and, we must take the helm - once held by the *'Radio Astronomic Research Community'* - in forcing a visionary solution on behalf of future generations to ensure that environmental background validation, stress assessment and stress-change monitoring of the terrestrial and planetary covers - - under the relentless onslaught of an un-abating population explosion and with it the quest for higher standards of living and quality of life - - can be carried out also in the future.

7. POLARIMETRIC SAR TOMOGRAPHY

Because the *'twin-antenna-interferometer POL-D-IN-SAR optimization method'* [041, 031, 107, 108, 145-149] at narrow band operation allows formally the delineation only of three spatially - in vertical extent - separated scattering surfaces, characterized by polarimetrically unique scattering mechanisms [107, 108, 145-149], 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 [097, 019, 114, 115] which might also be used for ocean current environmental monitoring and assessment. 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. This will allow the separation not only of layered but also of isolated closed ("point") scattering structures, occluded under heterogeneous clutter canopies; and embedded in inhomogeneous layered under-burden. This represents a good example on what we cannot achieve merely by implementing *'EO-Hyper-spectral Imagery'* [145-149].

The extension from *'narrow-band to wide-band POL-IN-SAR to POL-TOMO-SAR to POL-HOLO-SAR imaging systems'* is feasible, and will then enable the realization of true *'Wide-band Vector-Electromagnetic Inverse Scattering'* [009-011, 016, 033, 128, 135, 087], i.e., the full recovery of three-dimensional bodies embedded in heterogeneous, multi-layered scattering scenarios [087, 135, 128]. This implies that fully polarimetric multi-baseline interferometry and tomography may obviate the need for introducing constraining assumptions on the models used for estimating polarimetric scattering parameters [145-149]. Full polarimetric multi-baseline, multi-sensor interferometry *(POL-IN/TOMO-SAR)* - which can now be synthesized by air-borne multi-altitudinal polarimetric interferometry [114, 115] - will result in improved accuracy. It will allow the treatment of more complicated realistic inverse scattering models than the fundamental "*stripped-down*" analytic models, which must currently be implemented for non-polarimetric and also for most of POL-SAR twin-interferometric sensing and imaging [016]. The development of these modes of high resolution, fine-structure stress-change imaging and 3-D DEM mapping techniques are of direct and immediate relevance to wide-area, dynamic battle-space surveillance as well as to local-to-global environmental background measurement and validation, stress assessment, and stress-change monitoring of the terrestrial covers [012, 013]. The price to be paid is *high* in that the POL-IN-SAR systems must satisfy stringent performance standards (40 dB channel isolation, high side-lobe suppression of about 35 dB) with calibration sensitivity of 0.1 dB in amplitude and 1* in polarimetric phase. They must become extra-wide-band, covering the HF to EHF frequency regime, and they must be fully coherent *'Polarimetric (coherent scattering matrix) SAR Multi-Interferometers'*, which in the limit approach the tomo/holo-graphic imaging capabilities [004, 009, 010, 031, 107, 108, 114, 115]. Yet, in retrospect, the exorbitant costs are justifiable because of the immense gains made. Similar to the early negative predictions of the MRI technology, the cost per Imaging Platform will steadily decrease - opening up never anticipated additional fields of applications.

8. LARGE DENSITY DATA BASES AND ULTRA-HIGH SPEED DIGITAL PROCESSING

Since the advent of digital SAR technology in the late seventies, digital image processing, storage and high-density memory device technology has advanced phenomenally; and there exists every reason to be confident that this accelerated advancement will continue [129, 132]. Only two decades ago, the realization of fully polarimetric radar and especially POL-SAR imaging was set in doubt; mainly because of the exorbitantly large digital memory data space required, the insufficient high speed digital processing capacities available in the late seventies and early eighties. However, we have advanced dramatically with the introduction of optical memory devices and high-speed parallel processing technology, now reaching at - 10 Tera-Bytes - another temporary threshold level that cannot easily be overcome without the advent of entirely new device technologies. Such a timely turn of events has occurred in that *'Acousto-Optic Analog Processor (AOAP)' technology* has experienced a similar dramatic advancement like digital *'UWB-POL-IN-SAR Repeat-Pass'* technology. This makes possible an entirely novel approach to both *'Wide-band Range-Doppler Imaging (WRDI)' plus 'UWB-POL-IN-SAR Image Acquisition, High-Speed Processing'* with the potential for considerable image data compression. This new hybrid acousto-optic analog-digital conversion, electro-optic digital data

compression, and exceedingly light-weight, electronic-processor size-reduction technology should strongly contribute to overcoming the problem. Real-time air-borne as well as space-borne implementation of Repeat-Pass UWB-POL-D-IN-SAR environmental stress change monitoring can then be realized within the foreseeable future [046] by accommodating the entire set of extra-wide-band sensors with processors on one and the same air-borne or space-borne platform. . A processor currently under development, the ESSEX High Performance Optoelectronic (HPO) Processor (also known as ImSyn), demonstrates this potential. The ImSyn HPOP captures the best advantages of digital and optical processing technologies to provide data handling and processing performance which, when completed, promises to eclipse digital-only performance for imaging applications while also having significant size, weight, and power advantages [173].

The advantage of returning to acousto-optical device technology is that the first function to be performed in the *"vector signal acquisition and processing chain of events"* in radar as well as in SAR - - amplitude-only or polarimetric - - is to correlate the returned signal with the transmitted signal which in the case of fully polarimetric SAR are complex and vector in nature. In '*Modern Optics*' [022, 023, 048] this has become a straightforward functional task to be performed with the aid of a *'Fourier Lens'*; whereas in the '*Digital World*' [129, 132] - - as is currently still being applied without exception - - one needs to A/D-convert the return signal first. This approach is sufficient as long as one is dealing with a LFM waveform, but there are severe problems with the conversion of all data points that need to be processed especially in the case of fully polarimetric-interferometric UWB SAR systems. For digital processing this equates to memory, storage and speed of the devices. Optical processing takes advantage of analog processing in that the signal is converted from electrical to a laser medium (vertical cavity matrix laser) , and it is then processed 'almost instantaneously' through acousto-optic Bragg cell and Fourier Optical (FO) processors which at the current state of the art already can handle huge image data blocks as encountered in UWB-POL-IN-SAR image acquisition, processing and storage. We are thus dealing with *a* '*Hybrid FO-DIG Processor*' which performs the correlation functional process in the optical domain; the signal/image analysis, identification, classification - - that follows next - - in the digital domain; and the SAR or POL-IN-SAR processing again in another set of hybrid acousto-optical/digital processor chains. There would be two major '*Hybrid Fourier-Optical-Digital Processor Chains*' required - - one for the signal acquisition/detection/identification and a second set for the SAR processing. Although, not yet fully realized, this novel hybrid vector-signal/tensor-image processing concept would, in the end, reduce the exorbitant processing workload by taking advantage of the true merits of both acousto-optical and digital processing modalities, as for example discussed in [046, 173]. Thus, the symbiotic fusion of Modern Optics with advanced Digital Image Processing will pave the path to follow [047, 129], bringing a realistic solution for the full implementation of UWB-POL-D-IN/TOMO-SAR Repeat-Pass imaging in sight.

9. PRESERVATION OF DIGITAL SAR IMAGE INFORMATION (URLs: t-01 to t-03)

One of the major shortcomings of the *"Digital Communications Age"* is that it does not provide the means of long-term information storage and preservation, in spite of its enormous benefits for immediate and global direct information exchanges at all levels [024]. Of course, the instantaneous dissemination and interactive flow of huge data files presents indeed an enormous benefit to trade, commerce, transportation, global banking and also to accelerating the advancement of science and technology in all fields of human endeavor. However, we are accumulating meta (mega of mega) data banks at a mind-boggling pace, we find no time nor resources for screening the amassing information, but even worse than that, we do not seem to possess the high-density storage and information media guaranteeing long-lasting information preservation. For example, the transition from *the 'HARD-COPY BOOK LIBRARY'* to the *'FLOATING DIGITAL LIBRARY - - THE TERRA DIGITALIS*" [021] cannot yet and must not yet be realized in that we are indeed still missing two major essential components for realizing this dream. For one important basic requirement may not be able to be fulfilled for a long time to come, namely that of developing and manufacturing permanent high-density digital information storage devices. The magnetic tape drives and discs possess a rather limited life-span of only a few years, and need to be replaced at exorbitant costs periodically every five, and definitely by at least every ten years. Its current replacement by EO-CD ceramic/glass compact discs are also not fulfilling the once sought solution of replacing the magnetic disk drives, in that those not only seem to be, but truly are vulnerable to cosmic ray and neutrino bombardment; against which there does not exist a foreseeable cure. This places additional constraints on the SAR Image data refreshment tasks, which have not yet been fully recognized. Furthermore, the extremely rapid pace of digital computer operating systems advancements make the newest operating systems obsolete as soon as those appear on the market, requiring perpetual time-consuming updating, too often every year, at exorbitant costs, with older versions becoming unsupported in some cases. At the same time, the computer programming languages are being upgraded even at a higher pace so that within only a short period of time of a few years major blocks of valuable information may

be lost for ever unless con-current information screening and transfer to the latest computer software package has been maintained. But, who possesses the time and resources to do so? Transfer of most invaluable information onto acid-free paper storage has become exceedingly difficult and expensive in case laser-writing techniques are to be implemented. In retrospect, we must ask ourselves whether we might be creating an insurmountable *'Digital Tower of Babel'*; and at the end very little is gained in extracting useful knowledge, and a lot of most valuable information may be lost for posterity in perpetuity [024].

All of these digital information storage and preservation problems are compounded in the case of *'EWB-POL-D-IN-SAR and EO-Hyper-spectral Remote Sensing'*, because of the rapidly accumulating Exa-Byte, DLTs, and other current mass storage media, once thought to be the answer for years to come. Well, the years ***have*** come and we need to develop most rapidly highly improved super-high-density information preservation and not only storage media as well as supra-high-speed digital image processing operating-systems which are independent of the past, current and future computer operating and software systems. The ongoing development from *UNIX* to *JAVA* must be accelerated with *JAVA* still required to becoming much more universal and much, much faster. Furthermore, the electronic-chip manufacturing industry must adopt a much more universal far-reaching and visionary approach of accelerating the development of long-lasting digital information storage media so that we may be able to preserve vital '*EWB-POL-D-IN-SAR and EO-Hyper-spectral Information'* on the *'Local and Global Terra Digitalis Meta (mega of mega) Information Bases*' in perpetuity for posterity. Thus, before we really have become aware of the severity of the serious calamity so created, we have created a historical void - '*the Digital Tower of Babel'* - of most valuable knowledge preservation, which commenced - during the Eighties - with the advent of the digital age, and valuable information may be lost irretrievably for ever.

10. JOINT RF & OPTICAL REPEAT-PASS SAR OPERATIONS

Furthermore, whereas most '*Hyper-spectral Optical Radiometers'* and "*Microwave Multi-band Radioaltimeters*" operate in a down-look Nadir mode, and the '*UWB-POL-IN/TOMO-SAR Imaging Sensors'* in left/right-side-looking operation, inducing shadowing and 'front-porching (fore-shortening or overlay)', the simultaneous implementation and operation of three imaging platforms - - flying side-by-side, and being fully equipped with Microwave Multi-band (polarimetric) *Radioaltimeters* and Hyper-spectral Optical plus UWB-POL-IN/TOMO-SAR systems - - is strictly required. For example, for the environmental stress-change monitoring within the *Baikal Lake Basin, Siberia* [069, 017-019, 042, 156] or of the multitude of pertinent Pacific Rim (PACRIM) regions, monitored by the SIR-C/X-SAR Mission-2 as well as the PACRIM-AIRSAR-1/2 measurement campaigns [017, 018], such simultaneous triple platform imaging modes of operation may be ideal. By implementing Differential GPS, the three platforms must be flown side-by-side with perfectly overlapping foot prints, and by executing contiguously spaced, parallel repeat-pass flight operations so that the complete wide-band microwave *radioaltimeters* plus hyper-spectral optical down-look image information can properly be overlaid on top of the strip images produced by the two left/right side-looking UWB-POL-IN/TOMO-SAR platforms. In addition, it is most desirable and necessary for testing newly to be developed *'EWB-POL-D (RP) -IN-SAR mage Processing Algorithms'* to execute with highest possible precision, *'Square-Loop - parallel (0), orthogonal (90), anti-parallel (180), and cross-orthogonal (270) Flight-Line Repeat-Pass Operations'* over carefully selected, most diverse geo-environmental calibration test and ground-truth validation sites. The execution of such demanding flight operations has - in principle - been realized, is no longer a distant dream, and can be implemented now and immediately thanks to the accelerated advancement of Differential High Precision GPS electronic real-time navigation [099, 097, 122, 114, 115]. In addition, due to the rapidly developing "Terra Digitalis" - - which is to preserve detailed environmental mapping information even of the most distant, hidden, corners of our terrestrial and also planetary covers for posterity - - we should be able to collect a long-lasting complete geo-environmental data base which can be updated continuously.

11. DESIGN OF MISSION-ORIENTED MULTI-SENSOR IMAGING PLATFORMS

However, in order to realize the implementation of such highly demanding multi-sensor technologies , it will at the same time be necessary to develop a strategy for the design and manufacture of air-borne sensor platforms which are mission-oriented specifically for the joint *'Extended Radio-Frequency EWB-POL-D-IN/TOMO-SAR'* plus '*Extended Optical Hyper-Spectral FIR-VIS-FUV' Repeat-Pass modes of operation.* Also, considering that there exist currently efforts to perfect Forward-Looking POL-IN-SAR technology, it is necessary to design platforms with minimal structural interference obstructions, so that the entire frequency regime from at least VHF, if not even HF, up to EHF plus the extended Optical (FIR-VIS-FUV) Regime can be accommodated. Considering that there was no truly mission-oriented new '*Multi-purpose IMAGING AIRCRAFT PLATFORM'* designed since that of the P-3 Orion sub-marine hunting platforms of the late Fifties, it is a timely and highly justifiable request to our forward looking, visionary Planning Offices of DOD, NASA (HQT.-JPL), DOC (USGS+NOAA), NATO,

ESA, NASDA, etc., to place top priority on this long overdue demand of having access to the '*ideal imaging platforms*' required to execute both the military wide area surveillance as well as the environmental background validation, stress assessment and stress-change monitoring missions - world-wide [016-019]. Just to make use of existing air-borne platforms of opportunity; e.g., the B-707 for the non-polarimetric AWACS, the carrier-based E-2C Hawkeye for the non-polarimetric APS-145, the P-3 Orion for the NAWC UWB-POL-IN-SAR [152], the DC-8 for the AIR/TOP-SAR, etc., is no longer sufficient [099, 128, 134, 135]; because EWB/UWB fully polarimetric POL-SAR Multi-SAR-Interferometers cannot tolerate any multi-path scattering obstructions unavoidably encountered with all of these "polarimetrically clumsy", venerated platform designs. Platforms that could utilize such improvements are among others, also future JSTARS class platforms, plus Predator (UAV), and Global Hawk (UAV) types of aircraft, etc.. Thus, instead of expending any more dead-end efforts on the elimination of platform interference effects of existing imaging platforms for the purpose of developing hyper-fine image processing algorithms in the high-resolution imaging and target detection programs; why not directly and without any further ado aggressively attack the planning and design of the "*Ultimate POL-IN/TOMO-SAR Platforms*", varying in size according to application and mission performance, required already now, and immediately! Specifically, we require to develop the ideal set of low/medium/high-altitude versus small/medium/large-sized imaging platforms.

12. NEED FOR SUB-AQUATIC MULTI-SENSOR (SAS) STRESS-CHANGE MONITORING

In concluding this overview, here we need to pay attention also to another related, most serious environmental stress change monitoring problem dealing with the detection of the rapid destruction of our sub-aquatic flora and fauna in our rivers, ponds, lakes, coastal surf-zones and the shallow to deep ocean environments - - which has assumed absolutely catastrophic almost irreversible conditions. A solution may be in sight, and can be achieved by incorporating multi-sensor high resolution magneto-metric, various forward/side/bottom-scanning sonars, EO sub-aquatic polarimetric high-resolution imaging, '*chemical trace element sniffing*' [040, 081] as well as *Synthetic Aperture Sonar (SAS)* multi-sensor technology [051] into the *'Sub-aquatic Environmental Stress Change Monitoring'* operations - - over land including lakes, rivers and ponds; aquifers below land; and in the deep ocean water environment [040, 049-051]. Because of the close relations among image digital and analytical processing techniques for *UWB SAR* [049, 050] and *Wide-band SAS, Polarimetric Magneto-Metric Wide-Area Imaging and POL-SAR Imaging*, more attention needs to be paid by the "*UWB-POL-D-IN/TOMO-SAR*" [050] research community toward the accelerated co-development of UWB-IN-SAS technology. In addition, it will become necessary to combine directly various - if not all - all of these multi-sensor technologies for the increasingly more complex problems of environmental stress-change monitoring in the littoral coastal surf zones, of the continental wetlands [016, 069], and of the receding glacial ice fields.

13. 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, NAWC-AD and DLR* imaging platforms; and those of high resolution SAS multi-sensor monitoring platforms using the *NCSC-MUDSS* systems. With the choice of associated examples provided in the pertinent URLs, we will - at the same time - be able to assess the current '*State-of-the-Art in UWB-POL-IN-SAR and UWB-SAS Technology*'; and to identify the current associated inadequate sensor platform availability, the introduction of hybrid acousto-optical/digital processing technology as well as the threat imposed by densely packed worldwide digital communications and video image data transfer. Finally, we will conclude that in order to utilize fully the sensing and imaging capabilities in optical as well as radar vector-electromagnetic surveillance and monitoring, in addition to all the timely and urgent requests made in Sections 6, 8 and 10, 11, 12 ; more emphasis must be placed on the accelerated development of *'International Collaboratories'*, such as the *'ONR-EUR-NICOP-WIPSS Collaboratory'*, for the advancement of pertinent Vector-Electromagnetic Modeling (Inverse Scattering), Image Processing and Interpretation tools for UWB-POL-IN-SAR Image Data Sets, the associated algorithm hardening, and implementation in practice. In summary, we require to develop the "*Collaboratorium Terra Digitalis*" as proposed in [021], and for Baikal Lake, Siberia, the "*Collaboratorium Terra Digitalis Baikalum [021], respectively [t-01 to t-03].*

The *ESA-CEOS-MRS'99 SAR-CAL/VAL Workshop* [w-11] provided another valuable modicum of close international cooperation for the steady accelerated advancement of EWB-POL-D-IN-SAR principals and technology - - - and, at the current pace of development there just cannot be enough of these highly productive Workshops as well as Collaboratories - - like the

"CEOS Collaboratory" - - as summarized in the *'Report on Polarimetric & Interferometric Polarimetry of Friday, 1999 October 25.*

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15. REFERENCES

[001] Agrawal, A. P., "A Polarimetric Rain Back-scattering Model Developed for Coherent Polarization Diversity Radar Applications", Ph.D. thesis, UIC-GC, University of Illinois, Chicago, IL, December 1986.

[002] Andrieu, B., Sohbi, Y. and Ivanov, N., "A direct method to measure bi-directional gap fraction in vegetation canopies",Remote Sens. Environment, Vol.50: 61-66, 1994

[003] Armand, N.A., A.M.Volkov, A.I.Zakharov, et al, "Prospective spaceborne SAR systems in Russia", Radiotekhnika i Elektronika, 1999, v44, n4, pp. 442-447., in Russian.

[004] Bamler, R. and P. Hartl, "Synthetic Aperture Radar Interferometry", State of the Art Review, Inverse Problems, Vol. 14, pp. R1-R54, IOC Publications, Bristol, UK, 1998.

[005] Bebbington, DH O, "The Expression of Reciprocity in Polarimetric Algebras", Progress in Electromagnetics Research Symposium (PIERS98) published in Proceedings of the 4th International Workshop on Radar Polarimetry (JIPR98) pp 9-18, IRESTE, Nantes, July 1998.

[006] Bedard, A.J. Jr., "Infrasonic and Near Infrasonic Atmospheric Sounding and Imaging", http://www4.etl.noaa.gov/infra/infrasonic.html, September 1999

[007] Boerner, W-M.,et al., (Guest Eds.), IEEE Transactions on the Antennas & Propagation Society, Vol. 29(2), Special Issue, Inverse Methods in Electromagnetics, (417 pages) 1980-81(1981a).

[008] Boerner, W-M., "Use of Polarization in Electromagnetic Inverse Scattering", Radio Science, Vol. 16(6) (Special Issue: 1980 Munich Symposium on EM Waves), pp. 1037-1045, Nov./Dec. (1981b).

[009] Boerner, W-M. et al. (eds), "Inverse Methods in Electromagnetic Imaging", Proceedings of the NATO-Advanced Research Workshop, (18-24 Sept. 1983, Bad Windsheim, FR Germany), Parts 1&2, NATO-ASI C-143, (1500 pages), D. Reidel Publ. Co., Jan. 1985.

[010] Boerner, W-M. et al. (eds.), "Direct and Inverse Methods in Radar Polarimetry", NATO- ARW, Sept. 18-24, 1988, Proc., Chief Editor, 1987-1991, (1,938 pages), NATO-ASI Series C: Math & Phys. Sciences, Vol. C-350, Parts 1&2, D. Reidel Publ. Co., Kluwer Academic Publ., Dordrecht, NL, 1992 Feb. 15.

[011] Boerner, W.-M., C. L. Liu, and Zhang, "Comparison of Optimization Processing for 2x2 Sinclair, 2x2 Graves, 3x3 Covariance, and 4x4 Mueller (Symmetric) Matricies in Coherent Radar Polarimetry and its Application to Target Versus Background Discrimination in Microwave Remote Sensing", EARSeL Advances in Remote Sensing, Vol. 2(1), pp. 55-82, 1993.

[012] Boerner, W-M., Keynote Address on "Polarimetry in Ultrawideband Interferometric Sensing and Imaging", in H. Anderson and R.A. Chipman, Proceedings on the Fourth US Army MI-LAB Polarimetry Workshop. Sparkman Auditorium, Redstone Arsenal, AL, pp. 289-378, 1995a (dedicated to L.W. Root and W-M Boerner).

[013] Boerner, W.-M., "Polarimetry in Remote Sensing and Imaging of Terrestrial and Planetary Environments", Proceedings of Third International Workshop on Radar Polarimetry (JIPR-3,95), IRESTE, Univ-Nantes, France, pp. 1-38, 1995b.

[014] Boerner, W-M., Invited Review on "Introduction to Radar Polarimetry - with Assessment of the Historical Development and of the Current State-of-the-Art", pp. 139-214, in A. Guran, R. Mittra and P.J. Moser, eds., Electromagnetic Wave Interaction - Selected Reviews: the Herbert Überall Sixty-Fifth Birthday-Emeritation Lecture Series at the Catholic University of America, 1995 June 03, World Scientific Publish. Co., Singapore, 1996: 407 p.

[015] Boerner, W-M., W-L. Yan, A-Q. Xi and Y. Yamaguchi, "On the Principles of Radar Polarimetry (Invited Review): The Target Characteristic Polarization State theory of Kennaugh, Huynen's Polarization Fork Concept,

and Its Extension to the Partially Polarized Case", IEEE Proc., Special Issue on Electromagnetic Theory, Vol. 79(10), pp. 1538-1550, Oct. 1991.

[016] Boerner, W.M., H. Mott, E. Lüneburg, C. Livingston, B. Brisco, R. J. Brown and J. S. Paterson with contibutions by S.R. Cloude, E. Krogager, J. S. Lee, D. L. Schuler, J. J. van Zyl, D. Randall P. Budkewitsch and E. Pottier, "Polarimetry in Radar Remote Sensing: Basic and Applied Concepts", Chapter 5 in F.M. Henderson, and A.J. Lewis, (eds.), Principles and Applications of Imaging Radar, vol. 2 of Manual of Remote Sensing, (ed. R.A. Reyerson), Third Edition, John Willey & Sons, New York, 1998.

[017] Boerner, W-M. et al., "Polarimetry and Polarimetric Interferometry for the Remote Sensing of the Selenga Delta Region of SE Baikal in Buriatia, SE Siberia, Russia", Proc. NASA-JPL AIR-SAR Workshop 1999-02-11/12, Pasadena, CA., in print (15 p.)(1999a)

[018] Boerner, W., Dhiantravan, Y., Mott, H. Miller, V., Cloude, S., Papathanassiou, K., Treuhaft, R., Kim, Y., Imel, D., O'Leary, E., VanZyl, J., Schmullius, C., Gabriel, J., Moreira, A., Reigber, K., Darizhapov, D., Suchkov, V., Tatkov, G., Bulgakov, S., Tsybjitov, T., 'Air/Space-Borne Repeat-Pass Pol-D-In-SAR image overlay interferometry & its application to geo-ecologic stress-change monitoring within the Selenga Delta, Kudara Polygon, SE Baikal, Buriatia using SIR-C/X-SAR Mission 2', NASA-JPL 8 AIRSAR W'shp. 98-01-15/16, PASADENA, CA, 1-11, 1998

[019] Boerner, M-W., V. A. Miller, W. K. Volkert, H. Mott, O. Kessler, J.S. Verdi, D. D. Darizhapov, B. Ch. Dorjiev, T. Kh. Tsybjitov, V. M. Korsumow, G. I. Tachkov, Y. Bh. Bashkuyev, C. K. Schmullius, K. P. Papathanassiou, S. R. Cloude, E. Pottier, E. Krogager, J-S. Lee, T. L. Ainsworth, D. L. Schuler, G. de Grandi, P. A. Rosen, R. N. Treuhaft, J. J. van Zyl, "Air/Space-borne, Repeat-Pass Polarimetric Synthetic Aperture Radar Imaging and its Application to Environmental Stress Change-Monitoring of the Baikal Basin World Heritage Site, BINS-RAS-SD, Ulan-Ude, Buryatia, S.E. Siberia, Russia", International Conference on "Baikal as a World Natural Heritage Protection Site", Round-Table I Monitoring of the Lake Baikal ecosystem and International Environmental Standards, Remote Sensing of the Earth's Surface by Aerospace Methods, Ulan-Ude, Buryatia, S.E. Siberia, 1998 Sept 9-(11)-12.

[020] Boerner, W-M. and H. Überall, SOC-MOT (NATO), "Advanced Research Short Course, Vector Inverse Methods in Radar Target/Clutter Imaging", Co-Ed., Proceedings ARSC, Ecole Superieur d'Electricité, Gif-sur-Yvette, France, 1986 Sept. 1-4, Springer-Verlag, Heidelberg, 1995, 428p. (ISBN3-540-57791-2).

[021] Boerner, W-M., O. Kessler, and J. S. Verdi. "Consolidation of Multi-Sensor, Extra-Wide-Band Synthetic Aperture Signal/Image Fusion for Integrating Environmental Stress-Change Monitoring with Dynamic Battle-space Surveillance: paving the way towards creating the 'global digital imaging and mapping collaboratories: Terra Digitalis'", Proc. PIERS-WARM (A. Franchois ed) Baveno, It, 1998 July 20 - 22,EC-JRC (also see: 'The Development of the "Collaboratorium Terra Digitalis Baikalum", Int'l. UNESCO/INTAS Conf. on 'Baikal as a World Natural Heritage Protectorate', Ulan-Ude, Buriatia, SE Siberia, Ru., 1999 Sept. 05-12).

[022] Bracewell, R. N., The Fourier Transform and its Applications, Sec. Rev. Ed., McGraw Hill, New York, 1986 (Third Revised Edition: 1999).

[023] Bracewell, R. N., Two-Dimensional Imaging, Prentice Hall, Englewood Cliffs, NJ,1995

[024] Brand, S., *The CLOCK of the LONG NOW - - eternal time and responsibility,* Basic Books, New York, 1999

[025] Chen, J-M., Rich, P. M., Gower, S. T., Norman, J. M. and Plummer, S., "Leaf area index of boreal forests: theory, techniques, and measurements", J. Geophysical Research, vol. 102, D24, pp. 29429-29443, 1997

[026] Chipman, R. A., and J. W. Morris, eds. , "Polarimetry: Radar, Infrared, Visible, Ultraviolet, X-Ray", Proc. SPIE-1317, 1990 (also see SPIE Proc. 891, 1166, 1746, 1988, 1989, and 3121).

[027] Clarke, J. E. H., K. A. W. Crook, D. E. Montgomery, K-Y. Lu, G. P. Whitmore, and D. P. Johnson, Combining AIRSAR Data of Huon Peninsula and Hawaii MR1 Data of Huon Golf, Papua New Guinea, for Tectonic and Sedimentary Processes, Marine Geodesy, 212: 111 - 128, 1998 (1998 Taylor & Francis 0149-0419/98)

[028] Cloude, S. R., Polarimetry: The Characterization of Polarimetric Effects in EM Scattering, Ph.D. thesis, University of Birmingham, Fac. of Eng., UK, Oct. 1986.

[029] Cloude, S. R. and E. Pottier, "A review of target decomposition theorems in radar polarimetry", IEEE Trans. GRS, vol. 34(2), pp. 498-518, Mar. 1996.

[030] Cloude S.R. and E. Pottier, "An Entropy-Based Classification Scheme for Land Applications of Polarimetric SAR", IEEE Trans GRS-35(1), 68-78, 1997

[031] Cloude, S. and K. Papathanassiou, "Polarimetric SAR Interferometry", IEEE Trans. Geosci. Remote Sensing, vol. 36, pp. 1551-1565, Sep. 1998.

[032] S R Cloude, "Polarimetry in Wave Scattering Applications", Chapter 1.6.2 in SCATTERING, Eds R Pike, P Sabatier, Academic Press, to be published December 1999

[033] S R Cloude, J Fortuny, J M Lopez, A J Sieber, "Wide Band Polarimetric Radar Inversion Studies for Vegetation Layers", IEEE Transactions on Geoscience and Remote Sensing, Vol 37/2 No 5, pp 2430-2442, September 1999

[034] CRAF Handbook for Radio Astronomy, 2nd Ed., Published by the Committee on Radio Astronomy Frequencies (CRAF), Secretariat, the Netherlands Foundation for Radio Astronomy, PO-2, NL-7990 Dwingelo, Netherlands, 1997 (ISBN: 2-903148-94-5) .

[035] Curlander, J.C. and R.N. McDonough, Synthetic Aperture Radar: Systems and Signal Theory, John Willey & Sons, New York, 1991.

[036] Czyz, Z.H., "Advances in the Theory of Radar Polarimetry," Prace PIT, No.117, Vol.XLVI, 1996, Warsaw, Poland, pp.21-28. (In English).

[037] Czyz, Z.H., "Fundamental Properties of the Polarimetric Two-Ports," Prace PIT, No.119, 1997, Warsaw, Poland, pp.25-37. (In Polish).

[038] Czyz, Z.H., "Basic Theory of Radar Polarimetry - An Engineering Approach", Prace PIT, No.119, 1997, Warsaw, Poland , pp.15-24. (In English).

[039] Czyz, Z.H., "Analysis of the Cascade Connection of the Polarimetric Two-Ports", Prace PIT, No.122, 1998, Warsaw, Poland, pp.6-22. (In Polish).

[040] Darrach, M. and A. Chutjian, Trace Explosives Signatures from Unexploded Under-Sea Ordnance -- using the READ (Reversal Electron Attachment Detector) System, NASA-JPL Report (Prepared for NSWC-DD-CSS, Panama City, FL), June 1997

[041] Das, Y. and Boerner, W-M., "On Radar Target Estimation Using Algorithms for Reconstruction from Projections", IEEE Trans. APS-26(2), pp. 274-279, 1978

[042] Diamond, J., '*Guns, Germs, and Steel: the development of human societies*', Norton, New York, 1997

[043] Dubois, P.C. and J.J. van Zyl, "An Empirical Soil Moisture Estimation Algorithm Using Imaging Radar", IEEE Trans. GRS-33(4), pp. 915-926, 1995.

[044] Fitzgerald, M., "the NASA-ARC Air-borne MASTER (MODIS + ASTER: 460 - 1263 nm) Simulator", Proceedings of the US-AU PACRIM Significant Results Workshop, MHPCC, Kihei, Maui, HI, 1999 August 24 - 26 (10 pages)

[045] Freeman, A. and S.T. Durden, "A Three-Component Scattering Model for Polarimetric SAR Data", IEEE Trans. GRS, Vol. 36(3), pp. 963-973, 1998.

[046] Frampton, K. R, D. A. Coon and M. J. Dorsett, "Acousto-Optic Range Doppler Processor for Target Discrimination", in Proc. SPIE Vol.3462, Radar/Ladar Processing and Applications, pp. 320 - 331, 1998

[047] Goldstein, D.H. and R.A. Chipman, "Optical Polarization: Measurement, Analysis, and Remote Sensing", Proc. SPIE-3121, 1997 (see Proc. SPIE 891, 1166, 1317, 1746, 1988, 1989, dealing with OPT-POL).

[048] Goodman, J. W., Introduction To Fourier Optics, 2nd Revised Edition, McGraw Hill, New York, 1996

[049] Gough, P. T & D. W Hawkins, "Unified Framework for Modern Synthetic Aperture Imaging Algorithms", Journal of Imaging Systems and Technology (John Wiley & Sons, Inc.), Vol. 8, pp. 343 - 358, 1997

[050] Gough, P. T. and D. W. Hawkins, "Imaging algorithms for a strip-map synthetic aperture sonar: minimizing the effects of aperture errors and aperture under-sampling" , IEEE Journal of Ocean Engineering, Vol. 22(1), pp. 27-39, Jan 1997

[051] Hawkins, D. W. Synthetic Aperture Imaging Algorithms: with applications to wide bandwidth sonar, Ph. D. thesis, School of Graduate Studies (ECE), The University of Canterbury, Christchurch, N Z, 1995.

[052] Henderson, F. M. and A. J. Lewis, guest editors, Principles and Applications of Imaging Radar, Manual of Remote Sensing, Third Edition, Volume 2, John Wiley & Sons, Inc., New York, July 1998 (940p.), see: Ch. 5: "Polarimetry in Radar Remote Sensing: Basic and Applied Concepts" (Wolfgang-M. Boerner, Harold Mott, Ernst Lüneburg, Charles Livingstone, Brian Brisco, Ronald J. Brown and J. Scott Patterson -- with contributions by S. R Schuler, J. J. van Zyl, D. Randell, P. Budkewitsch and E. Pottier), 98 p.

[053] Hensley, S., "Interferometric Studies in Queensland Australia", Proceedings of the US-AU PACRIM Significant Results Workshop, MHPCC, Kihei, Maui, HI, 1999 August 24 - 26 (10 pages)

[054] Huynen, J. R., Phenomenological Theory of Radar Targets, PhD. thesis, University of Technology, Delft, The Netherlands, December 1970.

[055] Imbo, P., J.C. Souyris, A. Lopes, Ph. Marthon, Synoptic presentation of the polarimetric information. Proceedings of the ESA-CEOS-MRS'99 SAR-CAL/VAL Workshop, CNES, Toulouse, France, 1999 October 25-29 (6 pages)

[056] Imel,D. A., "AIRSAR Along-track Interferometry Data", Proceedings of the US-AU PACRIM Significant Results Workshop, MHPCC, Kihei, Maui, HI, 1999 August 24 - 26 (10 pages).

[057] Imhoff, M. L., "Radar backscatter/biomass saturation: Observations and implications for global bio-mass assessment", International Geoscience and Remote Sensing Symposium (IGARSS'93), Tokoyo, Japan Aug. 18-21, 1993

[058] Imhoff, M. L., "Mapping human impacts on the global biosphere", Bioscience Vol. 44 No. 9 p598. (1995)

[059] Imhoff, M. L., "A theoretical analysis of the affect forest structure on synthetic aperture radar backscatter and the remote sensing of biomass", IEEE Transactions on Geoscience and Remote Sensing, Vol. 33, No.2 March 1995, pp 341-352.

[060] Imhoff, M. L., "Radar backscatter and biomass saturation: ramifications for global biomass inventory", IEEE Transactions on Geoscience and Remote Sensing, Vol. 33, No. 2 March 1995, pp. 510-518.

[061] Imhoff, M. L., "Mapping Vegetation Structure in Kakadu National Park: An AIRSAR and GIS Application in Conservation", Proceedings of the US-AU PACRIM Significant Results Workshop, MHPCC, Kihei, Maui, HI, 1999 August 24 - 26 (10 pages)

[062] Imhoff, M. L., T.D. Sisk, A. Milne, G. Morgan, and T. Orr, "Remotely sensed indicators of habitat herogeneity: Use of synthetic arpeture radar in mapping vegetation structure and bird habitat", Remote Sensing of Environment Journal, Vol. 60, pp. 217-227, 1997

[063] Imhoff, M. L., W.T. Lawrence, C. Elridge, T. Paul, E. Levine, M. Prevalsky, and V. Brown, Using nighttime DMSP/OLS images of city lights to estimate the impact of urban land use on soil resources in the U.S.", Remote Sensing of Environment Journal, Vol. 59, pp. 105-117, 1997

[064] Imhoff, M. L., W. T. Lawrence, D.C. Stutzer, and C.D. Elvidge, "A technique for using composite DMSP/OLS 'citylights' satellite data to accurately map urban areas", Remote Sensing of Environment Journal, Vol. 61, pp. 361-370, 1997

[065] Imhoff, M. L., S. Carson, and P. Johnson, "Alow frequency radar sensor for vegetation biomass measurement", IEEE Transactions on Geoscience and Remote Sensing, Vol. 36, No. 6, 1998

[066] Imhoff, M. L., P. Johnson, W. Holford, J. Hyer, L. May, W. Lawrence, and P. Harcombe, "An Inexpensive Airborne VHF Multi-band SAR System for Vegetation Biomass Measurement", IEEE Transactions on Geoscience and Remote Sensing, Vol. 337 No. 6, November 1999

[067] International Symposia on Spectral Sensing Research (ISSSR), Nov 92, July 94, Nov 95, July 97, Nov 99 (http://www.tec.army.mil)

[068] Jacobs, P.A., "Thermal Infrared Characterization of Ground Targets and Backgrounds", SPIE, Tutorial Texts in Optical Engineering, SPIE Vol. TT-26, 1996

[069] Valentin A. Koptyug, editor, The Present and Future State of the Baikal Lake Region - - Part 1, INFOLIO, Novosibirsk, Siberia/RF (ISBN 5-85826-017-9), 1996

[070] Kennaugh, E. M., Polarization Properties of Radar Reflections, MSc Thesis, Ohio State University, Columbus, March 1952.

[071] Kim Y-J, "Polarimetric Interferometry", Proceedings of the US-AU PACRIM Significant Results Workshop, MHPCC, Kihei, Maui, HI, 1999 August 24 - 26 (10 pages)

[072] Klein, L.A., MM-Wave - IR Multi-sensor Design & Signal Processing, Artech House, Inc., Boston, 1977

[073] Kramer, H. J. , Observation of the Earth and its Environment - Survey of Missions and Sensors, Springer Verlag, Heidelberg-New York, 1996

[074] Krogager, E., Aspects of Polarimetric Radar Imaging, Ph.D. thesis, Techn. Uni. of Denmark, Electromagnetics Institute, Lyngby, DK, March 1993.

[075] Krogager, E., W.-M. Boerner, S. N. Madsen; "Feature-Motivated Sinclair Matrix (sphere/diplane/helix) Decomposition and Its Application to Target Sorting For Land Feature Classification," SPIE-3120, 144-154, 1997.

[076] Krogager, E., and Z.H. Czyz, "Properties of the Sphere, Diplane and Helix Decomposition" Proc. of 3rd International Workshop on Radar Polarimetry, IRESTE, University of Nantes, France, pp. 106-114, April 1995.

[077] Krogager, E, and W.M. Boerner, "On the Importance of Utilizing Polarimetric Information in Radar Imaging Classification", AGARD Proc. 582-17, 1-13, April 1996

[078] Krogager, E., Comparison of Various POL-RAD and POL-SAR Image Feature Sorting and Classification Algorithms, Journées Internationales de la Polarimétrie Radar, Proc. JIPR'98, pp. 77-86, Nantes, France, 13-17 July, 1998.

[079] Krogager, E., S.R. Cloude, J.-S. Lee, T.L. Ainsworth, and W.-M. Boerner, Interpretation of high resolution polarimetric SAR data, Journées Internationales de la Polarimétrie Radar, Proc. JIPR'98, pp. 165-170, Nantes, France, 13-17 July, 1998.

[080] Kucharik, C. J., Norman, J. M., Murdock, L. M. and. Gower, S. T, "Characterizing canopy non-randomness with a multi-band vegetation imager (MVI)", J. Geophysical Research, vol. 102, no. D24, pp. 29455-29473, 1997

[081] Lathrop, J. D, J. F. McCormick, P. J. Bernstein, J. T. Bruno, D. J. Overway, G. S. Sammelmann, T. -H. Chao, K. C. Scott, "Mobile Underwater Debris (SAS) Survey System (MUDSS) -- A Feasibility Demo.", Proc. UXO Forum 1996

March 26-28, Williamsburg, VA, pp. 427-435, US Army Environmental Center, Env.Tech.Div. Attn: USAEC/ETD, SFM-AEC-ETP, Aberdeen Proving Grounds, MD/USA, 1996

[082] Lee, J.S., "Speckle suppression and analysis for synthetic aperture radar images", SPIE Optical Engineering, Vol. 25 No. 5, pp. 636-643, May 1986.

[083] Lee, J.S., M.R. Grunes and W.M. Boerner, "Polarimetric Property Preserving in SAR Speckle Filtering," Proceedings of SPIE, Vol. 3120, 236-242, San Diego, 1997.

[084] Lee, J.S. and M. R. Grunes, Polarimetric SAR Speckle Filtering and Terrain Classification-An Overview 26p., Book Ch. in XX, World Sci.Publ., Singapore, 1999

[085] Lee, J.S., K.P. Papathanassiou, T.L. Ainsworth, M.R. Grunes and A. Reigber, "A New Technique for Noise Filtering of Sar Interferometric Phase Images", IEEE Trans. GRS Vol. 36 , No.5 pp. 1456-1465.

[086] Lee, J. S, M R Grunes, T L Ainsworth, L J Du, D L Schuler, S R Cloude, "Unsupervised Classification using Polarimetric Decomposition and the Complex Wishart Distribution", IEEE Transactions Geoscience and Remote Sensing, Vol 37/1, No. 5, p 2249-2259, September 1999

[087] Lee, R. L., J. Teti, F. Gambucci, S. Krasznay, J. Verdi, A. Rouan, Polarimetric Techniques for Enhancing P-3 SAR Imagery, NAWCAD Code 4.5.5.5, Patuxent River, MD, Fin-Rep./ONR-313,1996-03-20.

[088] Lu, S-Y L and R. A. Chipman, "Interpretation of Mueller Matrices - in the optical domain - based on polarimetric decomposition", JOSA-A, Vol. 13(5), pp. 1106 - 1113, May 19

[089] Lüneburg, E., V. Ziegler, A. Schroth, and K. Tragl, "Polarimetric Covariance Matrix Analysis of Random Radar Targets", pp.27.1 - 27.12, in Proc. NATO-AGARD-EPP Symposium on Target and Clutter Scattering and Their Effects on Military Radar Performance, Ottawa.Canada,1991 May 6 - 10.

[090] Lüneburg, E., "Principles of Radar Polarimetry", Proceedings of the IEICE Trans. on the Electronic Theory, Vol. E78-C, no. 10, pp. 1339-1345, 1995.

[091] Lüneburg, E., Radar polarimetry: A revision of basic concepts, in "Direct and Inverse Electromagnetic Scattering", H. Serbest and S. Cloude, eds., Pitman Research Notes in Mathematics Series 361, Addison Wesley Longman, Harlow, U.K., 1996, pp. 257 – 275.

[092] Lüneburg, E., Comments on "The Specular Null Polarization Theory" IEEE Trans. Geoscience and Remote Sensing, Vol. 35, 1997, pp. 1070 – 1071.

[093] Madsen, S. N., and H. A. Zebker, "Imaging Radar Interferometry", Chapter 6 in F.M. Henderson, and A.J. Lewis, (ed.), Principles and Applications of Imaging Radar, vol. 2 of Manual of Remote Sensing, (ed. R.A. Reyerson), Third Edition, John Willey & Sons, New York, 1998.

[094] Massonet D. and K.L. Feigl, "Radar Interferometry and its Application to Displaying Stress-Changes in the Earth's Crust", Review of Geophysics, Vol. 36(4), 1998 Nov, pp. 441-500.

[095] Milne, T., "Estimating Bio-Mass and Vegetation Structure in Semi-Arid Woodlands of the NWT, Australia using AIRSAR and JERS-1 Data - - - a synergetic approach", Proceedings of the US-AU PACRIM Significant Results Workshop, MHPCC, Kihei, Maui, HI, 1999 August 24 - 26 (10 pages)

[096] Misner, C.W., K.S. Thorne and A Wheeler, "Gravitation", W.H. Freeman & Co., New York, 1970 (twentieth printing: 1997)

[097] Mittermayer, Josef, Alberto Moreira and Otmar Lofeld. "The Frequency Scaling Algorithm for Spotlight SAR Data Processing". IEEE Trans. on Geoscience and Remote Sensing, Vol. 37, No. 5, September 1999, pp 2198-2214.

[098] Moore, E., "Angkor AIRSAR Water control and conservation at Angkor", Proceedings of the US-AU PACRIM Significant Results Workshop, MHPCC, Kihei, Maui, HI, 1999 August 24 - 26 (10 pages)

[099] Moreira, A., "Synthetic Aperture Radar", Chapter in Book Radar mit realer und synthetischer Apertur. Oldenburg Verlag, Munich 1999, p.88.
(also see: Moreira, A., "E-SAR System: Specification of a high resolution Multi-Look Real-Time Azimuth Processor. DLR International Report R-551-11-11/88", Radar Group, 04 November 1988.)

[100] Moriyama, Toshifumi, Masafumi Nakamura, Yoshio Yamaguchi, Hiroyoshi Yamada, Wolfgang -M. Boerner, Classification of target buried in the underground by radar polarimetry, J-IEICE Trans. Commun., vol.E82-B, no.6, pp.951-957, June 1999

[101] Mott, H., Antennas for Radar and Communications, A Polarimetric Approach, John Wiley & Sons, New York, 1992, 521 p.

[102] Mott, H. and W-M. Boerner, editors, "Radar Polarimetry, SPIE's Annual Mtg., Polarimetry Conference Series", 1992 July 23 - 24, San Diego Convention Center, SPIE Conf. Proc. Vol. 1748, 1992

[103] Mott, H. and W-M. Boerner, editors, "Wideband Interferometric Sensing and Imaging Polarimetry", SPIE's Annual Mtg., Polarimetry and Spectrometry in Remote Sensing Conference Series, 1997 July 27- Aug 01, San Diego Convention Center, SPIE Conf. Proc. Vol. 3120, 1997.

[104] Nilson, T., "A theoretical analysis of the frequency of gaps in plant stands", Agric. Meteorol. 8, 25-38, 1971.

[105] Novak, L.M., and M.C. Burl, "Optimal Speckle Reduction in Polarimetric SAR Imagery" IEEE Trans. AES, Vol. 26, no.2, pp. 293-305, 1990

[106] Novak L.M., S. D. Halversen, G. J. Owirka, M. Hiett, "Effects of Polarization and Resolution on SAR ATR," IEEE Trans. AES, Vol. 33(1), pp. 102-116, Jan. 1997.

[107] Papathanassiou, K. P., Polarimetric SAR Interferometry, Ph. D. Thesis, Tech. Univ. Graz, 1999.

[108] Papathanassiou, K. P. and S. Cloude, "Phase Decomposition in Polarimetric SAR Interferometry", Proc. IEEE IGARSS'98, pp. 2184-2186, Seattle, 3-8 Aug. 1998.

[109] Papathanassiou, K. P., A. Reigber, R. Scheiber, R., Horn, A. Moreira, S. Cloude, "Airborne Polarimetric SAR Inter-ferometry," Proc. IEEE IGARSS'98, pp. 1901-1904, 1998

[110] Pottier, E., Contribution de la Polarimétrie dans la Discrimination de Cibles Radar, Application à l'Imagérie Electromagnétique haute Resolution, Ph.D. thesis, IRESTE, Nantes, France, December 1990.

[111] Pottier, E., Unsupervised Classification Scheme and Topology Derivation of POLSAR Digital Image Data Based on the (H/A/α) Polarimetric Decomposition Theorems, Proc. JIPR-4, U. Nantes/IRESTE, Nantes, Bretagne, 98 July 13-17, pp. 535-548.

[112] Pottier, E., Contribution à la Polarimétrie Radar: de l'approche fondamentale aux applications, Habilitation a Diriger des Recherches; Dr. Ing. habil., Ecole Doctorale Sciences pour l'Ingenieur de Nantes, Université de Nantes, l'IRESTE, La Chantrerie, Rue Pauc, BP 60601, F-44306 NANTES CED-3, 98-11-12

[113] Raney, R. K., "Processing Synthetic Aperture Radar Data", Int'l JRS, Vol. 3(3), pp. 243-257, 1982.

[114] Reigber, A., A. Moreira and K. Papathanassiou, "First Demonstration of Airborne SAR Tomography Using Multi-Baseline Data". Proc. IGARSS-99 (06-28_07-02), A03_10:50, Hamburg, Germany.

[115] Reigber, A., A. Moreira: First Demonstration of SAR Tomography using Polarimetric Airborne SAR Data. Submitted to IEEE Transactions on Geoscience and Remote Sensing, 1999

[116] Ryerson, R. A., Editor-in-Chief, MANUAL OF REMOTE SENSING - Third Revised Edition: Vol. 1, Earth Observing Platforms & Sensors (edited by S. A. Morain and A. M. Budge); Vol. 2,Principles and Applications of Imaging Radar (edited by F. M. Henderson and A. J. Lewis); Vol.3, Remote Sensing for the Earth Sciences (edited by A. Rencz), Published in cooperation with ASPRS - the American Society for Photogrammetry and Remote Sensing, John Wiley & Sons, Inc., New York, 1998.

[117] Saillard, J., F.A. Molinet and W-M. Boerner, eds., "Proc. : Int'l Workshop on Radar Polarimetry", JIPR-I, 1990 March 20- 23, University of Nantes, IRESTE-S2HF, LeChantrerie, Nantes, France, March 1990.

[118] Saillard, J., E. Pottier and W-M. Boerner, eds., "Proceedings: International Workshop on Radar Polarimetry", JIPR-2, 1992 Sept. 8-10: University of Nantes, IRESTIE-S2HF, Nantes, 1992

[119] Saillard, J., E. Pottier and S. R. Cloude, eds., "Proceedings: International Workshop on Radar Polarimetry", JIPR-3, 95-03-20_23 (dedicated: WMB)

[120] Saillard, J., E. Pottier & W-M Boerner, eds, "Proc. Int'l Radar Polarimetry W'shop", JIPR-4, 98-07-13_16

[121] Sato, Motoyuki, Editor, Proc. of 6th Intern. Conf.on Ground Penetrating Radar (GPR), Tohoku University, Aoba Campus, 1996 Sept. 30 - Oct. 03, Sendai, Japan

[122] Scheiber, R., A. Reigber, A. Ulbricht, K. Papathanassiou, R. Horn, St. Buckreuss and A. Moreira: "Overview of Interferometric Data Acquisition and Processing Modes of the Experimental Airborne E-SAR System of DLR". Proc. IGARSS-99 (06-28_07-02), A03_08:30, Hamburg, Germany.

[123] Schott, J.R., "Remote Sensing -- The Image Chain Approach", Oxford Univ. Pres., New York, 1997.

[124] Schuler, D.L., J-S. Lee and G. De Grandi, "Measurement of Topography using Polarimetric SAR-Images", IEEE Trans. GRS-34(5), 1210-1221, Sept. 96.

[125] Schuler, D.L, J.S. Lee, and T.L. Ainsworth, "Topographic Mapping using Polarimetric SAR Data", International Journal of Remote Sensing, vol. 19, no.1, pp 141-160, 1998.

[126] Schuler, D.L., J.S. Lee, and T.L. Ainsworth, "Terrain Topography Measurement using Multi-Pass Polarimetric SAR Data", submitted for review, Radio Science, September, 1999.

[127] Schuler, D.L., J.S. Lee, and T.L. Ainsworth, "Compensation of Terrain Azimuthal Slope Effects in Geophysical Parameter Studies using Polarimetric SAR Data", Remote Sensing of Environment , vol. 69/2, pp 139-155, July, 1999.

[128] Sheen, D. R, C. M. Strawitch, T. B. Lewis, "UHF Wideband SAR Design and Preliminary Results (NAWC ERIM P-3 QuadSAR)", Proc. IGARSS'94, Vol. 1, pp. 289-291, Pasedena, CA, August 1994.

[129] Smarr, L., Guest Editor, Special Issue on "Computational Infrastructure: Toward the Twenty-first Century", Communications of the

ACM (Association for Computing Machinery) Vol. 40(11), November 1997

[130] Smith, J. A., and S. M. Goltz, "A Thermal Exitance and Energy Balance Model for Forest Canopies", IEEE Trans. GRS Vol 32(5), pp. 1060-1066, Sept. 1994

[131] Smith, J.A., J.R. Ballard, Jr., J.A. Pedelty, "Effect of Three-Dim. Canopy Architecture on Thermal Infrared Existence", OPT. ENG.-36(1), pp. 3039-3100, Nov. 97

[132] Smith, P. H and J. van Rosendale, Guest Editors, Data and Visualization Corridors - - report on the 1998 DVC Workshop Series, CAL-TECH Inst. Press, 1998.

[133] SPIE Conferences on Imaging Spectrometry : "I Orlando Apr 95", "II Denver Aug 96", "III San Diego Jul 97", "IV San Diego Jul 98" (http://www.spie.org)

[134] Stimson, G.W., Introduction to Airborne Radar - 2nd Rev. Ed., SciTech Publ., Inc., Medham N.J, 1998

[135] Sullivan, R A. Nichols, R. Rawson, C. Haney, F. Darreff and J. Schanne Jr., "Polarimetric X/C/L-Band SAR", Proceedings of the 1988 IEEE National Radar Conference, Ann Arbor, MI, pp. 9-14, 1988.

[136] Swindell, W., Polarized Light, Halsted Press (John Wiley & Sons), Stroudsburg, PA: 423 p., 1975

[137] Tapley, I., "Using Radar Polarimetry for Mapping for Regolith Geology in Australia", Proceedings of the US-AU PACRIM Significant Results Workshop, MHPCC, Kihei, Maui, HI, 1999 August 24 - 26 (10 pages)

[138] Touzi R., R. St-Jean, and Y. Crevier, Taking the speckle out of SAR: the Gamma filter, Remote Sensing in Canada, Vol. 23, No. 3, Dec. 1995.

[139] Touzi R. and A. Lopes, Analysis of Speckle Filtering in Polarimetric SAR Imagery, IEEE Trans. Geoscience Rem. Sens., Vol. 32, No. 5, pp. Sep. 1994

[140] Touzi R. and A. Lopes, Statistics of the Stokes parameters and of the complex coherence parameters in one-look and multi-look speckle fields, IEEE Trans. Geoscience Rem. Sens., Vol. 34, No. 2, pp. 519-531, March 1996

[141] Touzi R., A. Lopes, J. Bruniquel , and P. Vachon, "Unbiased estimation of the coherence for SAR Imagery", IEEE Trans. Geoscience Rem. Sens.,Vol. 37, No. 1, jan. 1999

[142] Touzi R., "On the use of polarimetric SAR data for ship detection", Proc. of the IGARSS'99 Symp., pp. 812-814, Hamburg, Germany, July 1999.

[143] Touzi R., A. Lopes, J. Bruniquel , and P. Vachon, "Unbiased estimation of the coherence for SAR Imagery", IEEE Trans. Geoscience Rem. Sens.,Vol. 37, No. 1, jan. 1999

[144] Tragl, K. "Polarimetric Radar Back-scattering from Reciprocal Random Targets", IEEE Trans. GRS-28(5), pp. 856 - 864, Sept. 1990 (see Dr. - Ing. Thesis, 1989).

[145] Treuhaft, R. N and P. R. Sequeira, "The Vertical Structure of Vegetated Land Surfaces from Interferometric and Polarimetric Radar", Radio Science, Vol.xx(y), 1999/2000(?), accepted for publication.

[146] Treuhaft, R N, S R Cloude,"The Structure of Oriented Vegetation from Polarimetric Interferometry", IEEE Transactions Geoscience and Remote Sensing, Vol 37/2, No. 5, p 2620, September 1999

[147] Treuhaft, R. N., S. N. Madsen, M. Moghaddam, and J. J. van Zyl, "Vegetation Characteristics and Surface Topography from Interferometric Radar," Radio Science, 31, p. 1449-1485, 1996.

[148] Treuhaft, R. N., "Estimating Vegetation Parameters from Interferometric and Polarimetric Radar Using Physical Scattering Models," URSI General Assembly, Toronto, August 1999 (invited)

[149] Treuhaft, R. N., S. Hensley, B. E. Law, P. R. Siqueira, "Estimating Forest Vertical Structure from Multialtitude, Fixed-Baseline Radar Interferometric and Polarimetric Data," IGARSS99, Hamburg, July 1999 (invited)

[150] Ulaby, F. T. and C. Elachi, Editors, Radio Polarimetry for Geo-science Applications, Artech House, Inc., Norwood, MA, 1990, 364p.

[151] Ulaby, F. T., R. K. Moore, and A. K. Fung, Microwave Remote Sensing, Vols. 1- 3, Addison Wesly, Reading, MA, 1981, 2184p

[152] Verdi, J.S., R. Lee, P.R. Kersten, S.K Krasznay, D.R. Statter, and W-M. Boerner, Comparative Analysis of Polarimetric SAR Image Exploitation Algorithms For Environmental Stress-Change Monitoring, Proc. IGARSS-99 (06-28_07-02), E05_5, Hamburg, Germany, July, 1999

[153] Waring, R.H. and S.W. Running, Forest Ecosystems - Analysis and Multiple Scales, Acad. Press, 2nd Ed., Harcourt Brace & Co., San Diego CA, 1998

[154] Waterman, T. H., Polarization Sensitivity by {Marine Animals}, pp. 281-469, Chap. 3, in H. Autrum, ed., Comparative Physiology and Evolution of Vision in Invertebrates, Part B: Invertebrate Visual Centers and Behavior I, Springer Verlag, NY, 1981, 469p.

[155] Waterman, T. H., 'Navigational Potential of E-Vector Pol-Sensing by Marine Animals', Keynote Paper, Radar Polarimetry, Proc. SPIE-1748, pp. 2 - 10, 1993

[156] Wilson E.O., '*The Diversity of Life*', Norton, New York, 1999

[157] Xi, A-Q and W-M. Boerner, "Determination of the Characteristic Polarization States of the

target scattering matrix [S(AB)] for the coherent Monostatic and Reciprocal Propagation Space Using the Polarization Transformation Ratio Formulation", JOSA-A/2, 9(3), pp. 437-455, 1992.

[158] Yamaguchi, Y., T. Nishikawa, M. Sengoku, W-M. Boerner and H.J. Eom, "Fundamental Study on Synthetic Aperture FM-CW Radar Polarimetry", IEEE Trans. Comm., vol. S77-B, no. 1, pp. 73-80, January 1994

[159] Yamaguchi, Y., T. Nishikawa, M. Sengoku and W-M. Boerner, "Two-Dimensional and Full Polarimetric Imaging by a Synthetic Aperture FM-CW Radar", IEEE Trans. GRS, Vol. 33, no. 2, pp. 421-427, March 1995

[160] Yamaguchi, Y., Y. Takayanagi, W-M. Boerner, H.J. Eom and M. Sengoku, "Polarimetric Enhancement in Radar Channel Imagery", IEICE Trans. Communications, vol. E78-B, no. 1, pp. 45-51, Jan 1996

[161] Yang, J., Y. Yamaguchi, H. Yamada, M. Sengoku, S. Lin, "Stable Decomposition of Mueller Matrix", IEICE Trans. Comm., vol. E81-B(6), pp. 1261-1268, June 1998

[162] Yang, J., Yoshio Yamaguchi, Hiroyoshi Yamada, "Co-null of targets and co-null Abelian group," Electronics Letters, vol.35, no.12, pp.1017-1019, June 1999.

[163] Yang, J., Yoshio Yamaguchi, Hiroyoshi Yamada, Masakazu Sengoku, Shi -Ming Lin, Optimal problem for contrast enhancement in polarimetric radar remote sensing, J-IEICE Trans. Commun., vol.E82-B, no.1, pp.174-183, Jan. 1999

[164] Zebker, H.A, and R.M. Goldstein, "Topographic Mapping from Interferometric Synthetic Aperture Radar Observations", J. Geo. Res., Vol. 91, pp. 4993-4999, 1986.

[165] van Zyl, J.J. On the Importance of Polarization in Radar Scattering Problems, Ph.D. thesis, California Institute of Technology, Pasadena, CA, December 1985.

[166] van Zyl, J.J., H. Zebker, and C. Elachi, "Imaging Radar Polarization Signatures: Theory and Application", Radio Science, vol. 22, no. 4, pp. 529-543, 1987.

[167] van Zyl, J.J. "Application of Cloude's Target Decomposition Theorem to Polarimetric Imaging Radar Data", SPIE Proceedings (H. Mott, W-M Boerner eds.), Vol. 1748, San Diego, CA, 23-24 July 1992.

[168] van Zyl, J.J., and J.S. Hjelmstad, 'Interferometry in Remote Sensing', State of the Art Review (1996 - 1999), Proceedings of the URSI-GA-99, Toronto, Ontario, Canada, Special Issue, Radio Science,Vol. 35, 2000, 12 p.

[169] van Zyl, J.J., "An Overview of the Analysis of Multi-frequency Polarimetric SAR Data", Proceedings of the US-AU PACRIM Significant Results Workshop, MHPCC, Kihei, Maui, HI, 1999 August 24 - 26 (10 pages)

[170] Zakharov, A.I., L.E.Nazarov, "Classification of the forests types based on the textural analysis of SIR-C SAR images", Earth Research from Space, 1998, n2, pp. 102-109., in Russian

[171] Zakharov, A.I., P.V.Tugarinov, "Research of the dynamics of the sea ice covers near Antarctic coast based on the ALMAZ-1 SAR data", Radiotekhnika, 1998, n12, pp.63-67., in Russian

[172] Zakharov A.I., Kucheryavenkova I.L, "On the quality of forest types classification using SIR-C/X SAR polarimetric data at various observation angles", Proceedings of CEOS SAR Workshop, Netherlands, 1998, WPP-138, pp. 97-100.

[173] Turpin, T. M, P. Woodford, C. Price, J. L. Lafuse, S. M. Evanko, and L. C. Phillips, "ImSyn: Optoelectronic Product for Image Synthesis and Correlation,", Proc. SPIE-**XXXX**, pp. uvw - xyz, Lake Tahoe CA, March 1997

16. PERTINENT WEB SITES: (http://.....)

POL-SAR-Imaging (see Kramer : [44] & [71, Vol. 1[ )

[w-01] ONR-IFO-NICOP: http://www.ehis.navy.mil/

[w-02] EU-TMR-RP:http://www.dlr.de/ne-hf/projects/TMR, e-m: tmr-network@dlr.de

[w-03] IGARSS-99: http://www.igarss.org

[w-04] ERIM-IARSCE:http://www.erim-int.com/CONF/4th_airborne/intro.html

[w-05] RADAR-99: http://www-rad99.enst-bretagne.fr or e-m: s.e.e@wanadoo.fr

[w-06] IEEE-AESS-Radar Systems Panel: http://www.aeroconf.org

[w-07] SPIE-AM&E: http://www.spie.org/web/oer/september/sep99/spiescene.html

[w-08] URSI-GA-99: http://www.nrc.cal/confserv/ursi99/welcome.html

[w-09] NASA-JPL AIRSAR: http://airsar.jpl.nasa.gov or http://southport.jpl.nasa.gov

[w-10] USA-A&S-MI-LAB/RDECHSMSMMS: http://smaplab.ri.uah.edu/HMSM

[w-11] ESA-CEOS: http://www.estec.esa.nl/CONFANNOUN/99b02

[w-12] EU-SAR: http://www.dlr.de/ne-hf/eusar2000/

POL-IN-SAR IMAGING PLATFORMS

[v-01] GEOSAR: southport.jpl.nasa.gov

[v-02] AIR-SAR: airsar.jpl.nasa.gov

[v-03] ERIM-SARS: www.erim-int.com

[v-04] ESAR: www.dlr.de/NE-HF/projects/ESAR , AEROSENSING: http://www.op.dlr.de/aerosensing

[v-05] PI-SAR: www.crl.go.jp

[v-06] EMISAR: www.dcrs.dk/DCRS

[v-07] RAMSES: www.onera.fr/english.html

[v-08] CARABAS: www.foa.se/eng/carabas.html

[v-09] PHARUS: neonet.nlr.nl/tno-fel

[v-10] HUTRAD: www.space.hut.fi

[v-11] SRTM:www-radar.jpl.nasa.gov/srtm/index.html

[v-12] SRTM-DLR:www.dlr.de/NEHF/projects/SRTM

[v-13] RADARSAT: www.ccrs.nrcan.gc.ca/globesar2

[v-14] ERS-1/2: earth1.esrin.esa.it/ERS/

[v-15] JERS-1: www.eoc.nasda.go.jp

[v-16] ENVISAT-1: envisat.estec.esa.nl/

[v-17] ADEOS: www.nasda.go.jp/index_e.html

[v-18] COMMERCIAL: www.spaceimaging.com

HYPERSPECTRAL OPTICAL IMAGING PLATFORMS

[u-01] JPL AVIRIS: makalu.jpl.nasa.gov/aviris.html

[u-02] GSFC: ltpwww.gsfc.nasa.gov/ltp/ltp_projects.html

[u-03] VCL: essp.gsfc.nasa.gov/vcl/

[u-04] SLICER: ltpwww.gsfc.nasa.gov/eib/slicer.html

[u-05] EO-1: eo1.gsfc.nasa.gov/

[u-06] ASAS: asas.gsfc.nasa.gov/asashome.html

[u-07] NASA-MASTER: http://masterweb.jpl.nasa.gov

[u-08] NASA-MODIS&ASTER: http://ltpwww.gsfc.nasa.gov/MODIS/MAS

[u-09] USA-AS-MI-LAB, REDSTONE ARSENAL: http://www.tec.army.mil

COLLABORATORIUM TERRA DIGITALIS

[t-01] TERRA-DIGITALIS: http://www.digitalearth.net.cn/de99.htm

[t-02] T-D-B, TERRA-DIGITALIS BAIKALUM: http://pipeline.swan.ac.uk/siberia

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