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Extra Wideband Polarimetry, Interferometry and Polarimetric Interferometry in Synthetic Aperture Remote Sensing

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SUMMARY 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 (single platform: 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 accuracy. Then, by either designing *Multiple Dual-Polarization Antenna POL-IN-SAR systems* or by applying advanced *POL-IN-SAR image compression techniques,* it will result in *POL-arimetric TOMO-graphic (Multi-Inter-ferometric) SAR* or *POL-TOMO-SAR Imaging*. This is of direct relevance to local-to-global environmental background validation, stress assessment and stress-change monitoring of the terrestrial and planetary covers.
key words: *polarimetry, interferometry, polarimetric interferometry, synthetic aperture radar (SAR)*

1. Introduction

Both Optical [8], [17], [28] and Radar [3], [6], [42], [49] Imaging have matured considerably, and the benefits of using one imaging modality over the other are discussed frequently [17], [42], [35], [36], [24], [15]. For example, *Hyper-spectral Optical (FIR-VIS-FUV) Radiometric Imaging* [17], [9], [u-01 to u-09] 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 [6], [35], [36], [24], [w-01 to w-12]. 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 [43]. 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 [6], [5], [10], [34], [40], [20], [60]; 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 [6], [42], [9], [21] in remote sensing [v-01 to v-18]. 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 [10]–[13], [6], [21], [52] and bio-mass assessment tasks - as will be discussed in the following; and may be assessed by visiting the web-sites listed in the last page, specifically [w-01 to w-12].

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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 [21], [48], [42]; 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 [17], [42], [48], [35] 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*" [17], [42], [48]. 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 [6], [42], [35], [36] in dependence of relative sensor versus scatterer versus source (sun) position. This seems to have been either forgotten or been disregarded altogether [43], [35], [36]. This *Arago Sphere* dependence [35], [36] also applies throughout the optical (FUV-VIS-FIR) down to the millimeter wavelength region within which atmospheric particle scattering is effective [24], [42]. Consequently, complete polarimetric sensor and transceiver technology must be incorporated into future designs [9], [17]. 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 [6], [42], [21] 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 [10]–[13], [54], [61], [60].

And, *all-weather, day and night* sensing and imaging is a capability which only *radar* can provide [49], [34], [22], [20] and not *Hyper-spectral FIR-VIS-FUV Radiometric Imagery* [42]; hence, full attention is paid in the following to *EWB (HF-VHF-UHF-SHF-EHF) POL-IN/TOMO-SAR* sensing and imaging [6], [42], [11], [41], [43], [52], [w-09/11/12].

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 [20], [22], [1], [10]–[13], [9], [30], [38], [52]; and it possesses increasing polarization dependent penetration capabilities into semi-transparent volumetric under-burden with associated decreasing image resolution [6], [21], [38]. 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)* [53], [46] but of more sophisticated coherent and fully polarimetric (scattering matrix) POL-SAR [6] as well as fully coherent Interferometric (dual coherent sensor pair) IN-SAR (or IF-SAR) systems have become feasible [2], [31], [32]. 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* [38], [41], [11], [w-09/11/12], [v-02], [v-03], [v-04], [v-17].

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

In classical radar, i.e. "*amplitude-only radar*" [49], 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 [2], [31], [32], [46], [47], but not the polarization information of the electromagnetic vector wave - scatterer interrogation process [3], [6], [11], [33]; 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 [11], [41]. Provided that coherent two-dimensional complex-valued phase-unwrapping can fully be achieved [2], [31], [32], the IN-SAR information, derived from such interferometric complex image data sets [38], [11], [41], 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. [6]. 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 [2], [6], [31], [32], [42], [w-09], [v-02 to v-10].

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) [43], [35], [36], [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* [22], [20], [6], [53], [34]. 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 [1], [60], [25], [16]. Whereas, this polarization transformation behavior, expressed in terms of the "*polarization ellipse*" is named "*Ellipsometry*" in Optical Sensing and Imaging [9], [10], [17], [50], it is denoted as "*Polarimetry*" in Radar, Lidar/Ladar and SAR Sensing and Imaging [22], [20], [1], [10], [34]–[36] - 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 [22], [6], [50]. 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* 2×2 *coherent Jones forward scattering (propagation) and the associated* 4×4 *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. [22], [34], [6], [5]), and the sub-sequent formulation of *the* 2×2 *coherent Sinclair radar back-scattering matrix and the associated* 4×4 *Kennaugh radar back-*

scattering power density matrix, as summarized in detail in Boerner et al. [6]. 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 [10]–[13], [29], [30], [6], [39], [40] play an equally important role in *ellipsometry* as well as *polarimetry* [9], [17], [50], [28]. Based on Kennaugh's original pioneering work [22], Huynen [20] developed a "*Phenomenological Approach to Radar Polarimetry*," which had a subtle impact on the steady advancement of *polarimetry* [43] as well as *ellipsometry* by developing the "*orthogonal (group theoretic) target scattering matrix decomposition*" [20], [11], [39], [40], [10]–[13], [52], [29] and characteristic optimal polarization state concepts, which lead to the formulation of the *Huynen Polarization Fork* in *Radar Polarimetry* [20], [54], [1], [16], [57], [58], [60]. 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 [35], [36], [16], [11].

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., [9], [11], [17], [50] 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 [5], [10]–[13], [52], [29], [30], [39], [40] 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 [25], [6]; leading to various canonical target feature mapping [11]–[13], [25], [39], [40], [26], [27] and sorting as well as scatter-characteristic decomposition theories [39], [40], [29], [30]. In addition, polarization-dependent speckle and noise reduction play an important role in both *ellipsometry* and *polarimetry* [6], [26], [27], [52]. 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 strictly be accepted [52], [26], [27], [6].

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 Novak et al. [37] Lüneburg et al. [29], [30], Cloude [11], and of Cloude and Pottier [12], [13]. Special attention must be placed on the Cloude-Pottier Polarimetric Entropy (H) [39], [40], [12], [13], Anisotropy (A), Feature-Angle (α) parametric decomposition because it allows for unsupervised target feature interpretation [39], [40], [26], [27]. Using the various fully polarimetric (scattering matrix) target feature synthesis [39], [40], [51], [52], [25], [35], [36], [6], polarization contrast optimization, [6], [34]–[36], [57], [58] 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* [44], [45], [39], [40], [6], [51] 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* [6]. 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 [26], [27], [51], again requiring fully calibrated *SLC formatted POL-IN-SAR Image data takes*. This distinguishes the limited use of a *Multi-Amplitude-Polarization SAR* - like the ENVISAT or of the currently planned TERRA-SAR - from a *Fully Polarimetric, Well-calibrated Scattering-Matrix-SAR*, - like RADARSAT-2 or of ALOS-PALSAR. 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* [51], [38], [11], [52]. This is now being realized also with the upgraded AIR/TOP-SAR imaging system [52], [v-02], [w-09].

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* [4], [6], [9], [35], [36], [17], [48], [w-01 to w-12]; and, especially in *Chapter 5 on "Polarimetry in Radar Remote Sensing: Basic and Applied Concepts"* [6] of Volume 2 , *Principles and Applications of Imaging Radar* in the Third Edition of the *Manual of Remote Sensing* [42].

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* [49], [53], [46]; with standard (scalar) *Radar Interferometry* the spatial (range/in depth) structure may be resolved, from which *Digital Elevation Maps (DEMs)* can be reconstructed [2], [31], [32]. 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 [21], [52]. Although, IN-SAR enables the recovery of *Digital Elevation Maps*; without polarimetry [2], [31], [32], it will be difficult to discern - in all cases - the source orientation/location of the scattering mechanisms [10], [38], [44], [45]. Without the full implementation of POL-IN/TOMO-SAR imagery [41], [33], 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 [52], [41]. Many more additional studies of the kind executed by Treuhaft, Cloude, et al., as reported in [52], [41], [33], 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 [6]. In order to satisfy the correct implementation of Maxwell's equations fully [3]–[6], it is necessary - in all cases - to incorporate fully coherent polarimetric (scattering matrix) POL-SAR [6], [42], [43] and especially "*Polarimetric-Interferometric Synthetic Aperture Radar (POL-IN-SAR)*" imaging methods [10]–[13], [38], [41], [33], [v-04], [v-05], [v-02].

4. 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 [11], [13], [38]. This novel optimization procedure requires the acquisition of *highly accurate, well calibrated,* fully polarimetric (scattering matrix), *SLC-formatted POL-IN-SAR image data sets* [6]. In addition, several different complementing DEM extraction methods [44], [45] 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 [2], [31], [32] - derived from IN-SAR, it is possible to generate two DEMs [31], [32], [38], [13] directly from the 3×3 covariance matrices of the two separate fully polarimetric sensor data sets as well as various additional ones from the 6×6 POL-IN-SAR correlation matrix optimization procedure [11], [38] for the reciprocal 3×3 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 [13], [38], [41]. 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 [11], [6], [38], [41]. 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 [11], [38], [41], [33]. 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* [11], [52], [6], [38], [41], [w-01 to w-12], [v-01 to v-18].

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 [52], [21] by utilizing simultaneously the *canopy-gap scaling method,* first introduced in *Optical Hyper-spectral Mapping* [52], [21], [48]. Indeed, *POL-SAR Interferometry* opened a huge treasure chest of novel modeling methods for an unforeseen large number of hitherto unapproachable problems of environmental stress-change validation and interpretation [10]–[13], [39], [40], [38], [41].

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 [6], [21]. 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 [6], [35], [36]. 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 [58]–[67] 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 [17]. For most semi-dense to dense forests of the temperate zones, the EWB VHF/UHF/SHF (600–5000 MHz) regime may be optimal [21]. 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. 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 [53]. 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 [53] 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 [4], [v04], [w-09], [v-05], [v-16], [v-17].

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 [w-01], [w-07], [w-11], [v-03/04].

6. Allocation of Additional SAR Imaging Frequency Bands

In order to secure the required frequency windows within the ELF (HF/VHF) to EHF (UHF-SHF) 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 (CRAF)* in a unified, concerted effort [14]. 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 [4], [42], [35], [36]. 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 [17]. It is *densely over-packing* the "*commercially appropriated frequency windows*" plus "*encroaching into neighboring scientific bands*" [w-11], [w-07], [w-01].

We must follow the successful example of the *International Radio Astronomic Research Community* [14], 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 unabating 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* [11], [38], [41], [52] at narrow band operation allows formally the delineation only of three spatially - in vertical extent - separated scattering surfaces, characterized by polarimetrically unique scattering mechanisms [38], [52], 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 [33], [41] 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 [v-04]. 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 by implementing *EO-Hyper-spectral Imagery* [52], [u-01 to u-09].

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* [11], [6], [38], [40], i.e., the full recovery of three-dimensional bodies embedded in heterogeneous, multi-layered scattering scenarios. 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 [52]. Full polarimetric multi-baseline, multi-sensor interferometry *(POL-IN/TOMO-SAR)* - which can now be synthesized by air-borne multi-altitudinal polarimetric interferometry [41] - 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 [6]. 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 [6], [43]. 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/holographic imaging capabilities [2], [4], [6], [11], [38], [41]. 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. 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, CRL, 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 [6]. 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, the DC-8 for the AIR/TOP-SAR, etc., is no longer sufficient; 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," generated platform designs (see pertinent web-pages: v-01 to v-18). 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.

9. 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* [6] as well as *Synthetic Aperture Sonar (SAS)* multi-sensor technology [18], [19], [46], [47] 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. Because of the close relations among image digital and analytical processing techniques for *UWB SAR* [18], [19], [46], [47] 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*" [36] 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 - of these multi-sensor technologies for the increasingly more complex problems of environmental stress-change monitoring in littoral coastal surf zones, of continental wetlands [6], [23], and of the receding glacial ice fields.

10. Preservation of Digital SAR Image Information [URLs: t-01, t-02]

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 [8]. 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* [7], [t-01], [t-02] 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 [8], [7], [w-01].

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 [7]. 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 historical records (evidence) may be lost irretrievably for ever [8].

11. 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* 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 Sects. 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 [6], and for Baikal Lake, Siberia, the "*Collaboratorium Terra Digi-*

talis Baikalum," respectively [7], [6], [w-01], [w-02], [t-01], [t-02].

The recent *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 [w-01], [w-02], [w-09], [w-11], [u-01], [t-01], [t-02] - in particular like the "*CEOS Collaboratory*" - as summarized in the *Report on Polarimetric & Interferometric Polarimetry of Friday, 1999 October 25* [w-11].

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

POL-SAR-Imaging

[w-01] ONR-IFO-NICOP: www.ehis.navy.mil/
[w-02] EU-TMR-RP: www.dlr.de/ne-hf/projects/TMR
[w-03] IGARSS-99: www.igarss.org
[w-04] ERIM-IARSCE: www.erim-int.com/CONF/4th_airborne/intro.html
[w-05] RADAR-99: www-rad99.enst-bretagne.fr
[w-06] IEEE-AESS-Radar Systems Panel: www.aeroconf.org
[w-07] SPIE-AM&E: www.spie.org/web/oer/september/sep99/spiescene.html
[w-08] URSI-GA-99: www.nrc.cal/confserv/ursi99/welcome.html
[w-09] NASA-JPL AIRSAR: airsar.jpl.nasa.gov or southport.jpl.nasa.gov
[w-10] USA-A&S-MI-LAB/RDECHSMSMMS: smaplab.ri.uah.edu/HMSM
[w-11] ESA-CEOS: www.estec.esa.nl/CONFANNOUN/99b02
[w-12] EU-SAR:www.dlr.de/ne-hf/eusar2000/

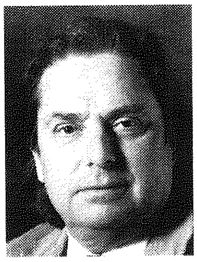
POL-IN-SAR Imaging Platforms

[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] E-SAR: www.dlr.de/NE-HF/projects/ESAR, AEROSENSING: /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

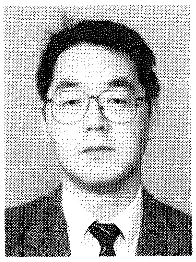
[v-08] CARABAS: www.foa.se/eng/carabas.html
[v-09] PHARUS: neonet.nlr.nl/tno-fel
[v-10] HUTRAD: www.space.hut.fi
[v-11] SRTM: www-radar.jpl.nasa.gov/srtm/index.html
[v-12] SRTM-DLR: www.dlr.de/NEHF/projects/SRTM
[v-13] RADARSAT: www.ccrs.nrcan.gc.ca/globesar2
[v-14] ERS-1/2: earth1.esrin.esa.it/ERS/
[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 Platform
[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: masterweb.jpl.nasa.gov
[u-08] NASA-MODIS&ASTER: ltpwww.gsfc.nasa.gov/MODIS/MAS
[u-09] USA-AS-MI-LAB, REDSTONE ARSENAL: www.tec.army.mil

Collaboratorium TERRA Digitalis
[t-01] TERRA-DIGITALIS: www.digitalearth.net.cn/de99.htm
[t-02] T-D-B, TERRA-DIGITALIS BAIKALUM: pipeline.swan.ac.uk/siberia



Wolfgang-Martin Boerner received his childhood education in Austral-Asia; the Abitur (B. S.) from the August von Platen Gymnasium, Mittelfranken, Germany in 1958; his Dipl. Ing. (M. S. E. E.) degree in Communications & Electromagnetic Wave Engineering from the Technische Universität München, Bavaria, Germany in 1963; and his Ph.D. degree in Electromagnetic Engineering Sciences from the Moore School of Electrical Engineering, The University of Pennsylvania, Philadelphia, PA in 1967. From 1967 to 1968 he was a Research Assistant Engineer with the EECS Radiation Laboratory of the University of Michigan, Ann Arbor, MI. In 1968 he joined the University of Manitoba at Winnipeg, Canada; since 1978 he has been a Professor at the Department of Electrical Engineering & Computer Science, the University of Illinois at Chicago, and Director of its Communications, Sensing and Navigation Laboratory. While at UIC Professor Boerner was awarded the Alexander von Humboldt Senior US Scientist, the Japan Society for the Promotion of Science Senior US Scientist and the US Navy Distinguished Senior Professor awards; and he is a University of Illinois Distinguished Senior Professor - all in recognition for his contributions to the advancements of Electromagnetic Inverse Scattering, Radar Polarimetry and Interferometry. He is a member of numerous international scientific societies; he is a senior member of the Canadian Association of Physicists (CAP), the American Society for Engineering Education (ASEE), the American and the International Societies for Remote Sensing and Photogrammetry (ASRSP & ISRSP); he is Fellow of IEEE (Institute for Electrical and Electronic Engineering), OSA (Optical Society of America), the SPIE (International Society for Applied Optics), AAAS (American Association for the Advancement of Science); he is a registered engineer with VDE (Verein Deutscher Ingenieure), APEM (Association of Professional Engineers of the Province of Manitoba), ISPE & NSPE (Illinois and US National Societies of Professional Engineers); and among others he is a member of the honor societies Sigma Xi, the American and the German Fulbright Associations, and the Alexander von Humboldt Association.



Yoshio Yamaguchi received the B. E. degree in electronics engineering from Niigata University in 1976, and the M. E. and Dr. Eng. degrees from Tokyo Institute Technology in 1978 and 1983, respectively. In 1978, he joined the Faculty of Engineering, Niigata University, where he is a professor. From 1988 to 1989, he was a Research Associate at the University of Illinois, Chicago. His interests are in the field of propagation characteristics of electromagnetic waves in lossy medium, radar polarimetry, microwave remote sensing and imaging. Dr. Yamaguchi is a senior member of IEEE, and a member of the Japan Society for Snow Engineering.