

## RECENT ADVANCES IN RADAR POLARIMETRY AND POLARIMETRIC SAR INTERFEROMETRY

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

In addition, various closely related topics of (i) acquiring additional and protecting existing spectral windows of the “*Natural Electromagnetic Spectrum (NES)*” pertinent to Remote Sensing; (ii) mitigating against common “*Radio Frequency Interference (RFI)*” and intentional “*Directive Jamming of Airborne & Space borne POL-IN-SAR Imaging Platforms*” are appraised.

**Synopsis:** Radar Polarimetry is a rather difficult and complex multi-disciplinary subject, and it is mired by the fact that the IEEE Standards on Antenna Measurements [104] contain an ill-conceived, if not incorrect definition for the formulation of the polarization descriptors [127, 154]. Many radar engineers try to hold on - at times not aware of the dilemma and more often for not finding a better and correct formulation [24]. Therefore, it was found necessary to expend considerably more efforts on re-assessing the foundations of radar polarimetry, resulting in the finding that there exist several new books, which are using plainly incorrect alternative formulations, which add to the misery. On top of it, there exist five rather different conceptual approaches to radar and optical polarimetry: (1) the standard *Polarization Vector* formulation [4], preferred by most radar engineers as followed in Mott [174] and Yang [299, 300]; (2) an algebraic *Directive Jones Vector* approach, first introduced by Graves [92] and further developed by Lüneburg [153], providing a considerable improvement over the standard method; (3) a *Group-theoretic Polarization vector Approach*, developed by Pottier [196]; (4) a *Spinorial Approach* initiated in quantum-optical analyses, which is more general [170] but not yet fully developed for radar polarimetry as persued by Bebbington [7]; and, (5) a *Quaternion Approach* persued in ellipsometry by Pellat-Finet [138, 139], which is currently being extended by Czyz [55] to radar polarimetry with the aid of the Inversion Point method, derived first by Kennaugh [116, 117] for the Poincaré polarization sphere [194]. Of specific relevance to the latter two approaches is the *Clifford Cl(3) algebra* which is based on a covariant formulation of electrodynamics in terms of *paravectors in the Pauli algebra* [6]. All of these closely interrelated and some mixed descriptions are being further

pursued in collaboration with Lüneburg, Pellat-Finet, Pottier, Bebbington, Mott, Yang, Czyz and others [24]. The following comprehensive review is based on the “*standard polarization vector formulation*”, and reference will be made to alternate formulations when ever the need arises.

## 1. Introduction with Historical Background

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) [13, 17, 21, 24, 57]. 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*’ [116, 103, 192, 193, 86, 35, 24]. The time-dependent behavior 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 [28, 248, 4, 8]. Whereas, this polarization transformation behavior, expressed in terms of the “*polarization ellipse*” is named “*Ellipsometry*” in Optical Sensing and Imaging [4, 28, 29, 37-39, 194, 250]; it is denoted as “*Polarimetry*” in Radar, Lidar/Ladar and SAR Sensing and Imaging [235, 116, 209, 13, 17, 41, 48, 24, 211] - 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 [140, 116, 151, 192, 193], where in *ellipsometry* mainly the “*Forward Scattering Alignment (FSA)*” and in *polarimetry* the “*Back Scattering Alignment (BSA)*” coordinate systems are respectively used, which were rigorously defined by van Zyl and Ulaby [271] in Chapter 2 of Elachi and Ulaby [65] as summarized in [24, 173-175].

**Origins of Polarimetric Matrix Formulations:** With the advent of optical and radar polarization phase control devices, *ellipsometry* advanced rapidly during the Forties (Mueller and Land) [250] with the associated development of mathematical *ellipsometry*, i.e., the introduction of ‘*the 2 x 2 coherent Jones forward scattering (propagation) T [114] and the associated 4 x 4 average power density Mueller (Stokes) propagation M [4] matrices - formulated strictly in a “Forward Scattering Alignment (FSA)” coordinate system [155, 271, 31, 24]*’. *Polarimetry* was developed independently in the late Forties with the introduction of dual polarized antenna technology (Sinclair [235], Kennaugh, et al. [116, 53, 13, 209, 211]) at the Ohio State University, Electro-Science (Antenna) Laboratory, and the sub-subsequent formulation of ‘*the 2 x 2 coherent Sinclair radar back-scattering matrix S and the associated 4 x 4 Kennaugh radar back-scattering power density matrix K - formulated strictly in the “Back Scattering Alignment (BSA)” coordinate system [271, 174, 154]*’, as summarized in detail in Boerner et. al. [24, 56, 173-175]. Since then, *ellipsometry* and *polarimetry* have enjoyed steep advances; and, a mathematically coherent polarization matrix formalism is in the process of being solidified - - in which the lexicographic and the Pauli-based polarimetric phase preserving covariance matrix *C* presentations [44, 45, 150, 179, 258, 259, 37-39, 48] for any polarization basis {A,B} play an equally important role in *ellipsometry* as well as *polarimetry* [37-39, 48, 196].

**Kennaugh’s Optimal Polarization States:** Based on Kennaugh’s original pioneering work [116] on introducing the “*characteristic polarization states*” of the coherent 2x2 Sinclair scattering matrix *S* [235] together with the “*spinorial polarization fork*” expressed in terms of the canonical ‘*co-polarization null state pair*’, Huynen [103, 104] attempted to develop a “*Phenomenological Approach to Radar Polarimetry*”. This basis invariant theory [9,10, 12] had a subtle impact on the steady advancement of *polarimetry* [13, 17, 209, 173, 175, 24] as well as *ellipsometry* by proposing the “*orthogonal (group theoretic) target scattering matrix decomposition*” [116, 103, 104, 40-45, 52, 125, 179, 197, 249, 269] and his own “*characteristic optimal polarization state concept*” together with the Huynen parameters lead to the formulation of the ‘*Huynen Polarization Fork*’ in ‘*Radar Polarimetry*’ [102, 103, 15, 16, 290, 18, 19, 24]. Here, we emphasize that the ‘*Polarimetric Power Density Plots*’ for the reciprocal media symmetric matrix case – more often denoted as the ‘*van Zyl power density signatures [266, 267]*’ - derive directly from the Kennaugh target matrix optimal polarization states [116, 63, 13] and the associated spinorial polarization

fork as was shown by Agrawal [1], in Agrawal and Boerner [2], in Xi and Boerner [290] and more recently in Yang [299, 300]. Kennaugh's original studies [116, 117] on "*the characteristic polarization states and its associated polarization fork*" turn out to be the fundamental canonical axioms of both *ellipsometry* and *polarimetry* from which other canonical ellipsometric and polarimetric descriptors may be derived – provided the fully polarimetric complex Jones  $T$  [114] and Sinclair  $S$  [235] scattering matrices are measured most accurately. This can now be achieved in real time also in *ellipsometry* with the implementation of the "*Chipman Instantaneous Multi-spectral Stokes Parameter Measurement Cube*" allowing eight simultaneous spectral line recordings of each set of the sixteen Stokes parameters [38, 60, 151, 190], i. e. fully polarimetric imagery in any basis  $\{A, B\}$  can now be achieved also in optics across the entire optical spectrum by direct conversion of the Mueller  $M$  into the Jones  $T$  matrix [4, 24, 31, 151, 224], which presents a "*quantum leap*" in *ellipsometric metrology*.

**Polarimetric Contrast Optimization:** Next to defining the "*Optimal Polarization State Concept*", as expressed in terms of the "*Spinorial Polarization Fork*" [7] - first introduced by Kennaugh [116, 117] in terms of the "*Co-polarization Null Pair*" and the associated "*Polarization Power Density Signatures*" [1, 2; 266, 267], another set of important polarimetric radar descriptors are the "*Optimal Polarimetric Contrast Enhancement Coefficients (opcec)*" [16, 19]. For the Sinclair  $S$  matrix [235] these were first derived by Kozlov [131], and for the Kennaugh  $K$  matrix by Ioannidis and Hammers [113], and the complete set of *opcec* for the three basic radar scattering matrices and the covariance matrices [249] were derived by Boerner, Mott, et al [16, 17, 19, 129, 130, 173, 175, 251, 298] in closed form solution for any general polarization basis  $\{A, B\}$ . Whereas the optimal polarization states are basis invariant [290, 15], the *opcec* coefficients are not [128, 250]. This is desirable in order for comparing critical texture boundaries within POL-SAR images which need to be presented in different polarization bases [15, 16] depending on the most suitable basis for optimization. These *opcec* algorithms have been applied most successfully to both polarimetric radar for target versus clutter separation [17, 209], and in POL-SAR imaging for target detection, recognition and identification (DRI) in dynamic background clutter [249, 294]. However, the resulting covariance matrix *opcec* – like all other POL-SAR image processing algorithms [14, 20, 129, 130] - suffer from speckle and noise reduction [140-148, 253-257], which must first be removed by implementing the pertinent polarimetric Lee-Wishart speckle and noise reduction filters [71-76, 140, 142]. When applied to different polarization bases, the *opcec* coefficients may reveal specific target features otherwise not readily distinguishable from interfering background clutter, and especially in the case of high resolution polarimetric radar and SAR applications [249].

**Matrix Decompositions:** 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., [37-39, 87, 151] measured in a '*chain matrix arrangement* [226], i.e., *multiplicatively placing one optical decomposition device after the other*'. This behavior can most elegantly be described by a quaternion formulation as shown by Pellat-Finet [188, 189] owing to the ellipsometric Stokes parameter measurement arrangement. The ongoing perfection of Chipman's "*Instantaneous Multi-spectral Stokes Parameter Measurement Cube*" [38, 60, 151, 190] may soon replace the cumbersome time-consuming '*classical ellipsometric metrology*' [4, 28, 31, 37-39, 151, 250] so that various algorithms derived in radar polarimetry can directly be applied. In *polarimetry*, the Sinclair, the Kennaugh, as well as the covariance matrix decompositions [40-45, 52, 16, 177, 196-198, 258, 259, 227, 308] are based on a group-theoretic series expansion in terms of the principal orthogonal radar calibration targets [40-52, 125, 178, 179, 196-198, 253, 257] 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 arrangements of the associated scattering matrices [135-137, 291]; leading to various canonical target feature mapping [32, 33, 135-137, 42-52, 81] and sorting as well as scatter-characteristic decomposition theories [52, 196-198]. In addition, polarization-dependent speckle and noise reduction play an important role in both *ellipsometry* and *polarimetry* [140-148, 253-257, 291]. The implementation of all of these novel methods will fail unless one is given fully calibrated scattering matrix information which applies to each of the complex elements of the Jones and Sinclair matrices. This places stringent requirements on the calibration [79, 80, 217, 218, 284, 285, 274] of the polarimetric radar data takes inferring that the highest possible dynamic range – at the order of "*about 0.1 dB in amplitude*" and "*1° in polarimetric phase*" - must be



accepted [3, 66-70, 124]. In addition, it is most desirable to develop POL-IN-SAR Imaging systems with sufficient resolution ( $1\text{m}^2$  achievable) in order to discern the finer scattering structure of complex scattering scenarios [11, 12], in which case polarimetry attains even higher relevance and cannot be disregarded, which applies to every radar-band not excluding the X-Band [24].

**Supervised and Unsupervised SAR Feature Sorting:** Very remarkable improvements above classical [209] “*non-polarimetric*” radar target detection, recognition and discrimination, and identification were made [13, 17, 32, 33, 173, 175, 24] especially with the introduction of the covariance matrix optimization procedures of Tragl [258, 259], van Zyl et al. [269-279, 208, 122, 123], Novak et al. [125, 178, 130, 234, 249], Lüneburg [152, 261, 308], Cloude [42-43], and of Cloude and Pottier [44, 45, 52, 196-198]. Special attention must however be placed on the nature of the polarimetric distribution functions, when reducing the four-dimensional to the three-dimensional covariance matrices for the reciprocal symmetric scattering matrix  $S$  case [91, 199], which must be normal multi-variate distribution functions [89, 90]. Very remarkable is the Cloude-Pottier “*Polarimetric Entropy (H), Anisotropy (A), Feature-Angle ( $\alpha$ ) Parametric Decomposition*” [44, 45, 52, 196-198] because it allows for unsupervised target feature interpretation [196-198, 146, 52] as shown for the multiband case by Ferro-Famil et al [71-76]. Using various classifiers obtained from fully polarimetric (scattering matrix  $S$ ) target feature synthesis [44, 45, 52, 71-76, 196-198, 253-257], polarization contrast optimization, [16, 18, 131, 113, 251, 126, 128] and polarimetric entropy/anisotropy classification [196-198, 71-76] very considerable progress was made in interpreting and analyzing POL-SAR image features [24]. This includes the reconstruction of ‘*Digital Elevation Maps (DEMs)*’ directly from ‘*POL-SAR Covariance-Matrix Image Data Takes*’ [228-230, 143, 148] next to the familiar method of DEM reconstruction from cross-track and along-track IN-SAR Image data takes [24]. In all of these techniques, it must be strongly re-emphasized that well calibrated polarimetric scattering matrix data takes of high dynamic range are becoming an essential pre-requisite without which little can be achieved [3, 66-70].

**Scattering Matrix Format and Speckle plus Noise Reduction:** In most cases the ‘*Multi-look SAR Image Data Take Formatting*’ [61] suffices also for completely polarized SAR image algorithm implementation [61, 65, 268, 270, 305]. However, in the sub-aperture polarimetric studies [76, 139], 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*’ [24]. Of course, for SLC-formatted Image data, in particular, speckle filtering must be applied always [140-148, 253-257]. Implementation of the ‘*Lee Filter*’ for speckle reduction in polarimetric SAR image reconstruction [140], and of the Wishart distribution [287, 241, 89, 90] for improving image feature characterization have further contributed toward enhancing the interpretation and display of high quality SAR Imagery [140-148, 71-76], 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* [3, 70] or of the currently planned *TERRA-SAR* [70] - - from a ‘*Fully Polarimetric, Well-calibrated Scattering-Matrix-SAR System with exceedingly high dynamic range*’, - - like *RADARSAT-2* [3, 242] or of *JERS-2 (ALOS)* [66-70]. Using poorly or badly calibrated POL/IN-SAR Image data takes with poor dynamic range - like those of the early quasi-polarimetric SAR imaging platforms - is also not sufficient and strongly detracts from recognizing the truly superior performance capabilities of ‘*fully polarimetric POL-IN-SAR Imaging*’ [24, 140-148, 40-52, 253-257, 71-76, 106].

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

Thus, whereas ‘*hyper-spectral optical radiometry*’ will provide high resolution characterization of scattering surface parameters - *subject to the skin depth* - with appreciable penetration only for a rather limited number of transparent media [87, 212, 236, 237, 240]; it lacks manageable coherent phase information and strongly depends on the heterogeneous and dispersive propagation medium such as non-transparent meteorological scatter, smog, smoke and other atmospheric pollution. So, it provides [2212, 240, 236, 237, 282] very useful direct ‘*hyper-spectral*’ indicators of the vegetative cover and of surface chemical pollutants [240]. 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*” [37, 107-112, 240] – being desirable mainly for vegetation canopy assessment.

Whereas, hitherto in most of the hyper-spectral optical remote sensing techniques polarization effects were in general totally neglected [240], 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 [28, 38, 126, 173, 283] in dependence of relative sensor versus scatterer versus source (sun) position. This very early discovery of ellipsometry by Arago [126, 173, 283] seems to have been either forgotten or been disregarded altogether [126, 215, 24, 37-39]. An environmental effect similar to the ‘*Arago Sphere*’ dependence also applies throughout the optical (FUV-VIS-FIR) down to the millimeter wavelength region within which atmospheric particle scattering is effective [212, 30, 58, 96]. As regards microwave polarimetric remote sensing similar phenomena hold true in that leaves, buds and flowers as well as branches of most vegetation species are re-orienting themselves in a phylo-taxic sensitive manner towards the illuminating sun location; resulting in an Arago-type behavior. This very important aspect of the “*diurnally and hourly changing relative observer – sun – foot print constellation*” has been disregarded hitherto in most microwave polarimetric radar and SAR measurement analyses [24]. Complete polarimetric sensor and transceiver technology must henceforth be incorporated into future designs [37-39, 60, 85, 190] of both optical and microwave passive and active imaging systems.

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 scalar (non-polarimetric) hyper-spectral information are at their best rather misplaced [24, 107-113, 95] unless fully polarimetric sensor design [288, 289, 37-39, 60, 85, 190] is being rapidly developed also for the extended optical spectral regime for both active and passive remote sensing. This implies the instantaneous acquisition - not the consecutive time-consuming classical *ellipsometric measurements* - of the Stokes parameters [37-39, 60, 85, 190, 246] for the instantaneous reconstruction of the ‘*Stokes Reflection (defined in the FSA coordinate system [271, 153-155, 173-175])*’ or the ‘*Kennaugh Back-scattering matrix (defined in the BSA coordinate system)*’ [271, 65, 264, 305, 24], which has now been accomplished in principle also in ellipsometry by Chipman et al. [37-39, 60, 151, 190].

And, “*all-weather, day and night*” sensing and imaging is a capability which only ‘*radar*’ can provide [245, 24, 30, 58, 191] and not “*Hyper-spectral FIR-VIS-FUV Radiometric Imagery*” [96]; hence, full attention is paid in the following to ‘*EWB (HF-VHF-UHF-SHF-EHF) POL-IN/TOMO-SAR*’ sensing and imaging [24-27, 175, 66-70]. However, we need to re-emphasize that for obtaining the hitherto best estimates on biomass parameters requires acquisition of fully polarimetric and polarimetric-interferometric extra-wideband imagery across the entire electromagnetic spectrum within which vegetation is responsive [66-70, 107-112, 95], i. e., from the FUV to the HF spectral bands. These multi-band imaging data sets require to be fused across the entire pertinent electromagnetic spectrum [107-112, 120] within which the pertinent remote sensing observing spectral windows need to be protected and safeguarded [27].

### 3. HF - EHF Radar and SAR Polarimetry and Interferometry

With increasing wavelength from the EHF (sub-millimeter) via UHF (cm/m) to HF (deca-meter) regimes, the radar imaging process becomes less dependent on the meteorological propagation parameters [30, 58, 150] but more so on parametric target orientation/fine structure/resonance effects [116, 102, 103, 12, 13, 41, 1, 2, 266, 135, 196, 184, 72, 207, 93, 244]; and it possesses increasing polarization dependent penetration capabilities into semi-transparent volumetric under-burden with associated decreasing image resolution [34, 96, 107-113, 95, 304]. 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)*’ [105, 263, 264, 276] but of more sophisticated coherent and fully polarimetric (scattering matrix) POL-SAR [24] as well as fully coherent cross-track and along-track Interferometric (dual coherent sensor pair) IN-SAR (or IF-SAR) systems have become feasible [5, 88, 157, 158, 162, 163, 172, 303, 307]. From ever increasing accumulating experience, it is safe to conjecture that ‘*Non-polarimetric and Non-interferometric SAR Imaging*’ is ever so steadily on its way out, and that the IN-SAR Systems also need

to become fully polarimetric *POL-IN-SAR Imaging Systems* [46-51, 183-185, 24]. This “*quantum leap towards complete physical realizability*” must and will be achieved during this decade – similar to progressing from “*Classical X-Ray-Shadow-graphy*” toward “*functional Magnetic Resonant Imaging (fMRI)*”.

**Classical Amplitude-Only Radar & SAR, and “Scalar” IN-SAR Imaging:** In classical radar, i.e. “*amplitude-only radar*” [245, 209], mainly the energy of the returned pulse is utilized; and in basic imaging radar, it is the Doppler phase information in addition [187]. Interferometric SAR (IN-SAR) exploits fully the phase and Doppler information [5, 29, 158, 172, 212, 303-307], but not the polarization information of the “*electromagnetic vector wave - scatterer interrogation process*” [8, 11-14, 172]; 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 [184, 207, 244]. Distinction needs to be made between cross-track and along-track interferometry [5, 158, 172], and there exist now several airborne multi-modal SAR Imaging platforms that support both systems – such as the NASA-JPL AIR/TOP-SAR [106, 121, 122], the DLR E-SAR [223], the ONERA RAMSES SAR [70], and we refer to pertinent papers presented at recent expert meetings for additional details [66-70]. Provided that coherent two-dimensional complex-valued phase-unwrapping can fully be achieved [5, 158, 172, 200-204], the IN-SAR information, derived from such interferometric complex image data sets [121, 122, 277, 278], 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 with single platform cross-track interferometers [5, 158, 172, 160-163, 210, 303, 306, 307]; ocean currents with single platform along-track interferometers [5, 106, 141]; and by implementing repeat-pass polarimetric SAR Interferometers it is possible to determine vegetative growth patterns and environmental stress assessment, etc. [96, 107-112, 95, 280, 307]. Thus, the amplitude and coherent phase but not its intrinsic polarization information that electromagnetic wave interrogation can recover, is fully utilized in IN-SAR imaging, and here we refer to the wide body of technical reviews on various aspects [5, 158, 172, 200-204, 307].

**Polarimetric Doppler Radar Meteorology:** Here, we need to refer to the decisive advances made in “*Polarimetric Radar Meteorology*” during the past two decades as reviewed for example in Mueller and Chandra [176], McCormick and Hendry [168, 169], Doviak and Zrnicek [58], also in Boerner et al. [13]; and more recently in “*Polarimetric Doppler Radar Meteorology*” for the assessment of global as well as dynamic micro-cloud meteorological structures in Bringi and Chandrasekar [30]. Of specific interest are the polarimetric weather radar techniques, which were initiated during the early 1980ies [1,2], subsequently advanced with the *UIUC/CSU-CHILL Meteorological Polarimetric Doppler Radar* facility [176, 30], and then by Ryzhkov [213, 214, 247], Zrnicek [309], Doviak [58, 59] and others [247, 281] at NOAA-ETL-NSSL in Norman, OK; by Matrosov and Kröpfl [164-166] at NOAA-ETL, and by Wheeler, Vivekanandan et al. [281] at NCAR in Boulder; at DLR in Oberpfaffenhofen [119, 227], and more recently elsewhere [100]. Ground-based Polarimetric Doppler Radar technology was rapidly advanced at Norman, OK so that the forthcoming generation of NEXRAD weather radars will become fully polarimetric (scattering matrix) Doppler radar systems – preferably at the S-Band [59] – so that severe storms, down-bursts, tornadoes and also cyclones may be more accurately assessed and predicted. This in itself represents a true “*quantum leap*” in the advancement of radar polarimetry, which is complemented by the dramatic recent advances of “*Passive Polarimetric Microwave Cloud Radiometry*” – covering the upper microwave to sub-millimeter wave bands [123] – accomplished at NOAA-ETL in Boulder [150, 83, 84].

However, the existing SAR signal compression techniques do not lend themselves readily for implementation to airborne and/or space borne imaging of dynamic weather phenomena – whether for standard amplitude-only or fully polarimetric SAR imaging systems [30, 58]. Yet, several MTI-imaging signal processing techniques could possibly be extended for the imaging and micro-cloud analysis of dynamically moving hydrometeor cells and structures, which may eventually lead to applicable hybrid Polarimetric MTI-SAR Imaging from air and space of local to global weather phenomena [203]. There is still a lot to be accomplished during the next decades before these technologies [118, 134, 202-205] can be implemented as to be shown next.

**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*’ [245, 263]; with standard (scalar) ‘*Radar Interferometry*’ [5, 158, 171, 200, 201] the spatial (range/in depth) structure may be resolved, from which ‘*Digital Elevation Maps*’ can be reconstructed [5, 87, 88, 158, 172, 307]. However, neither method is complete in that POL-SAR by itself does not provide information on where in elevation the scattering processes take place; and non-polarimetric IN-SAR or military (non-polarimetric) air-borne imaging radar cannot infer the elevation from which the scatter comes [260, 261] – irrespective of driving up the resolution – and therefore not providing the desired information about the vertical structure of vegetation and underburden. Here, we emphasize that with increasing resolution, polarization dependence becomes all the more pertinent; and that there exists a threshold level above which polarimetric IN-SAR becomes absolutely necessary and prevalent. Although, IN-SAR enables the recovery of ‘*Digital Elevation Maps (DEMs)*’, without polarimetry [5, 156-158, 172, 210, 306, 307] it will be difficult to discern - *in most cases* - the source orientation/location of the scattering mechanisms [46-51, 184, 185, 205-207, 243, 244]. Without the full implementation of POL-IN/TOMO-SAR imagery [205-207], it will be difficult or close to impossible to discern the tree-top canopy from that of the understore, thicket under-burden or of the layered soil and sub-surface under-burden, i. e. discern the vertical structure of vegetation and semi-transparent underburden [260, 261]. Many more additional studies of the kind executed by Imhoff, Smith, Treuhaft, Cloude, et al., as reported in [3, 66-70], are required to establish fully the capabilities of one method as compared to the other, and to their integral POL-IN-SAR implementations. However, in order to be able to fully interpret scattering mechanisms of vegetation in areas with non-planar topography, the distinct topography must be known *a priori*, in that subtle changes in the polarimetric response are introduced by the local slopes [273], an effect which is exploited directly by the POL-DEM reconstruction method of Schuler, Lee et al. [228-230, 143, 148].

So, speaking strictly in terms of Maxwell’s equations, ‘*amplitude-only SAR*’ and ‘*Scalar IN-SAR*’ can only apply either to 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 [24]. In order to satisfy the correct implementation of Maxwell’s equations fully [8, 11-13], it is necessary - *in all cases* - to incorporate fully coherent polarimetric (scattering matrix) POL-SAR [116, 117, 102, 103, 24, 215] and especially ‘*Polarimetric-Interferometric Synthetic Aperture Radar (POL-IN-SAR)*’ imaging methods [46-51, 184, 185, 205-207].

#### 4. Polarimetric Multiple Baseline SAR Operations

During the past decade several diverse multiple baseline SAR operations were developed for both airborne and space borne platform implementation – for single [184] and multiple passes [207, 244]. Here, the most essential ones – not addressing multi-sensor data fusion of existing commercial or defense imaging platforms - are summarized:

**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 introduced first by Cloude and Papathanassiou [46-51, 184, 185]. This novel optimization procedure requires the acquisition of *highly accurate, well calibrated*, fully polarimetric (*scattering matrix*), *SLC-formatted POL-IN-SAR image data sets* collected with systems of high dynamic range. 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 [5, 158, 172, 303, 307] - derived from IN-SAR - it is possible to generate two DEMs [228-230] 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 [184] 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 [46, 47, 49, 106, 203]. This provides the additional benefit of obtaining ‘*co-registered textural/orientational + spatial three-dimensional POL-IN-DEM information*’. Most recently Cloude and Papathanassiou [51] extended this technique for extracting vertical vegetation distribution together with vegetation height and non-planar ground topology by implementation of multiple polarization interferograms [273, 51] obtained either from multi-pass overflights and/or simultaneous multi-band POLINSAR imaging – which presents definitely a “*quantum leap*” forward in multimodal POL-IN/TOMO-SAR technology.

Another approach was recently developed by Yamada and Yamaguchi, which is based on the ESPRIT algorithm [292, 293], which made possible the comparison of various partially versus fully polarimetric approaches in various different polarization bases. Stebler recently investigated multi-band and multiple repeat-pass fully polarimetric SAR image data sets, and further analyzed above cited methods [243, 244]. 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 [24, 108-110, 112]. 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 of highest possible dynamic range* become available; and its development has only just begun [205, 223, 243]. This basic requirement cannot be re-emphasized sufficiently often and strong enough.

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* [205, 223]. 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 [49, 260, 261, 107, 112] by utilizing simultaneously the ‘*canopy-gap scaling method*’, first introduced in *Optical Hyper-spectral Mapping* [236, 237]. Indeed, multi-band ‘*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. [12, 13, 24, 41-52, 140-148, 184, 205-207].

**Polarimetric SAR Tomography:** Because the ‘*twin-antenna-interferometer POL-D-IN-SAR optimization method*’ [106, 47, 184] at narrow band operation allows formally the delineation only of three spatially - in vertical extent - separated scattering layers, characterized by polarimetrically unique scattering mechanisms [260, 261], 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) or in series next to each other (along-track and cross-track) resulted in a “*Polarimetric Tomographic SAR*” Imaging system with “*Moving Target Imaging (MTIm)*” capabilities. This was demonstrated with the DLR E-SAR so that a ‘*POL-TOMO-SAR*’ imaging system was synthesized [205-207, 243, 244]. These *Moving Target Imaging* capabilities might also be used for ocean current environmental monitoring and assessment [238].

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 within heterogeneous layers below the clutter canopies; and embedded in inhomogeneous layered under-burden. This represents a good example on what we can definitely not achieve merely by implementing ‘*EO-Hyper-spectral Imagery*’ – whether scalar or polarimetric.

**Extension to Polarimetric SAR Holography:** 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*’ [11-18, 231], i.e., the full recovery of three-dimensional closed bodies embedded in heterogeneous, multi-layered scattering scenarios [205-207]. 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 [260, 261]. Full polarimetric multi-baseline, multi-sensor interferometry (*POL-IN/TOMO-SAR*) - which can now be synthesized by air-borne multi-altitudinal polarimetric interferometry [205-207] - will result in improved accuracy. It will allow the treatment of more complicated realistic inverse scattering models than the fundamentally “*stripped-down*” analytic models, which must currently be implemented for non-polarimetric and also for most of single-band POL-SAR twin-interferometric sensing and imaging [24]. The development of these modes of high resolution, fine-structure stress-change imaging and three-dimensional DEM mapping techniques are of direct and immediate relevance to wide-area, dynamic battle-space and ‘*homeland security*’ surveillance as well as to local-to-global environmental background measurement and validation, stress assessment, and stress-change monitoring of the terrestrial covers [24-26, 260]. **The price to be paid is high in that:**

- (i) 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; must possess a very high dynamic range;
- (ii) 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.

Yet, in retrospect, the exorbitant costs are justifiable because of the immense gains made. Similar to the early negative predictions of the MRI (Magnetic Resonance Imaging) technology in radiology because of its initially exuberantly high costs and exceedingly high technical demands on its operators, the cost per Imaging Platform will steadily decrease yet requiring well educated radar physicist as operators - opening up never anticipated additional fields of applications. For example, with the ongoing rapid development it will enable the provision - for every flying platform (helicopter, aircraft, UAV, missile, etc.) - of such a holistic sensor facility operable in real time.

**Design of Mission-Oriented Multi-Sensor Imaging Platforms:** However, in order to realize the implementation of such highly demanding multi-sensor technologies [29, 30, 24, 58, 203], 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 – desirable on one and the same sensor platform. Considering that there was no truly mission-oriented new ‘*Multi-purpose SAR IMAGING AIRCRAFT PLATFORM*’ designed [132] 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 ‘*homeland security surveillance*’ as well as the environmental background validation, environmental stress-assessment and stress-change monitoring missions - world-wide [16, 20-27]. Just to make use of existing air-borne platforms of opportunity; e.g., the B-707 for the non-polarimetric AWACS, the carrier-based clumsy E-2C Hawkeye for the non-polarimetric APS-145, the P-3 Orion for the NAWC UWB-POL-IN-SAR [231], the DC-8 for the AIR/TOP-SAR [106], etc. [223], is no longer sufficient; because EWB/UWB fully polarimetric POL-SAR Multi-SAR-Interferometers cannot tolerate any platform generated 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 and UAVs, etc.

For one thing, the utilization of UAVs is not the most cost saving approach for the development of novel multi-modal, multi-band POL-IN-SAR imaging sensor systems; whereas, they indeed may provide the desired modicum of operation for routine environmental remote sensing and ‘*homeland security*’ monitoring

tasks in desolate regions. 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 developing the ideal set of low/medium/high-altitude versus small/medium/large-sized imaging platforms also for satisfying the urgent and realistic needs of ‘*homeland security surveillance*’.

## 5. Polarimetric Implementation Scenario for Multi-static Space IN-SAR Micro-Satellites

One of the most challenging new ideas in the field of radar remote sensing in the last years was the implementation of passive and/or active SAR test systems on board of micro-satellites [159-163]. Its realization will provide a more flexible and significantly more cost-efficient generation of radar remote sensing sensors in space. However, apart from the financial incentive and flexibility in terms of imaging geometry, resolution, and timing, such sensor configurations allow also the extension of the possible observation vector, and consequently the information content of the acquired data to be substantially enlarged. From this point of view, the most promising - *and complementary* - approaches to extend the observation vector at a single frequency is by introducing interferometric baseline and polarization diversity.

**Multi-static Interferometric Considerations:** There are several proposed scenarios for the position and movement of the micro-satellites relative to each other on an elliptical mini-orbit regarding the acquisition of multiple baselines, allowing at the same time along and across-track interferometry. Last but not least, the availability of a sufficient large number of micro-satellites (or clusters of them) will open the door for multi-static interferometry, leading towards tomographic data acquisition, providing direct imaging of the penetrated distributed volume including occluded targets [133]. However, the second promising way to extend the observation vector is by introducing polarization diversity. Regarding high resolution sensors operating at higher frequencies, point scatterers are characterized by a strongly polarization-dependent behavior. This vital – *hitherto often poorly appreciated information an electromagnetic vector wave always provides* - can be utilized for identification and evaluated for an accurate classification of the scatterer as well as for extracting physical information about it. Our “*Collaboratorium Terra Digitalis Polarimetrici et Interferometrici*” [22, 23] has decisively contributed towards the rapid advancement of these intrinsic information capabilities inherent in electromagnetic vector (polarization) wave target interrogation.

**Polarimetric Considerations:** There are different possibilities regarding the implementation of a polarimetric operational mode in a micro-satellite based multi-static remote sensing concept. The attractive advantage is the fact that not all micro-satellites have to be equipped with polarimetric transmitter and receiver paths. For example, one of the micro-satellites within a cluster can be used as a transmitter of two orthogonal polarizations while the rest of the micro-satellites in the cluster can be passive, receiving - *in synchronization with the transmitter* - in the two orthogonal polarizations. Such an operational scenario allows for the acquisition of coherent multi-static scattering matrix  $S$  data without having a fully polarimetric system, and combines the advantages of passive reception operation with significantly increased information content. Depending now on the relative positioning of the receiver satellites to each other, alternatively multi-static polarimetry, polarimetric interferometry and / or polarimetric super-resolution acquisition modes can be achieved and operated in a flexible way. Opportune off-the-shelf hardware and straight-forward instrument steering design can initially avoid a critical increase of the hardware, weight and volume as well as an expansion of the mission costs; although ideally an entirely new class of navigational devices need to be developed rapidly with rigor, which makes use of EO down-sizing [64, 262] wherever possible.

**The European Cart-wheel Passive Receiving (SAR) Satellite Cluster (3 to 6) System Design** is for example laid out as to be able to join up with existing or shortly to be launched multi-band active SAR satellite systems; for example the RADARSAT-2 with fully polarimetric C-Band SAR; the ALOSAR (JERS-2) with fully polarimetric L-Band SAR; the ENVISAT (ERS-3) with partially polarimetric (unfortunately

with poorly polarimetric correlated channels) C-Band SAR; the TERRASAT with both fully polarimetric L-Band and partially, but well correlated polarimetric X-Band SAR [70]. The question on which band is suited for what kind of geo-environmental imaging & monitoring mission depends on the application, but the proper choice can now be well substantiated. This differs quite a lot from the rather restricted US HighTechSAR21 [159] configuration of active mono-(non)-polarimetric high resolution SAR satellites operating at X-Band.

## 6. Optimal Utilization and Protection of the Electromagnetic Spectrum in Remote Sensing

The demands on additional frequency bands for radar and SAR remote sensing is steadily increasing [27], resulting in various collisions of the remote sensing with other user communities of the electromagnetic spectrum [180]. Because the safeguarding against such collisions is absolutely pertinent to the development of POL-IN/TOMO-SAR technology, these aspects need to be addressed here.

**Need for EWB (Hyper-Band) POL-IN-SAR Imaging in Environmental Monitoring:** 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 [24, 34, 95, 107-112, 149, 182]. This is strictly required in order to recover - *next to material bio-mass parameters* - canopy versus sub-canopy versus understory, 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 across 10 (100) MHz to 100 (10) GHz becomes all the more necessary and essential [25]. 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 a different choice of multiple-to-wide-band POL-IN-SAR imaging platforms, not necessarily operated at one and the same band and at one fixed altitude, for optimal performance within the HF/VHF{(10)100 MHz} to EHF (100 GHz) regime [24]. Similarly, for more accurate and verifiable estimation of soil moisture and roughness [62, 82, 93, 94, 167, 181], and of snow water equivalence [232, 233, 296, 294] such multi-band and multi-altitudinal POL-IN/TOMO-SAR implementations become essential. Here, we emphasize the need for the rapid advancement of these integrated POL-IN-SAR Imaging techniques in order for advancing the still overall poorly performing bio-mass estimation algorithms, which still lack such vital capabilities [95, 120, 107-112, 263].

Indeed, the ideal operational altitudes also differ from one scenario to the other. For most semi-dense to dense forests of the temperate zones, the EWB VHF/UHF/SHF (600 - 5000 MHz) regime may be optimal [107-112]. Whereas, for a dense virgin equatorial rain forest with huge trees of highly conductive hardwood, the UWB (10 - 1000 MHz) regime is required, etc. [109, 110]. Thus, the current choice of frequency bands for bio-mass determination is indeed very limited 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 [212, 263, 264].

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 lies below the nominal P-Band (420 MHz) to well below 10 MHz. Thus, adaptive EWB-POL-IN/TOMO-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 [24, 216] - - embedded in forests, shrubbery, thickets, grasslands [110]; and - in addition - for vegetative canopy plus rugged terrain as well as for atmospheric scatter analyses [30, 58, 83, 84, 123].



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 (10) MHz to 300 (100) GHz, and beyond. In addition, for a reliable and more accurate estimation of biomass parameters, it is definitely necessary to add and include polarimetric hyper-spectral EO wideband FIR-VIS-FUV imagery [107-112].

**Joint Radio Frequency & Optical Repeat-Pass SAR Operations:** Furthermore, whereas most ‘Hyper-spectral Optical Radiometers’ and “Microwave Multi-band Radio-altimeters” 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 laterally displaced imaging platforms - - flying side-by-side, and being fully equipped with Microwave Multi-band (polarimetric) Radio-altimeters and Hyper-spectral Optical plus UWB-POL-IN/TOMO-SAR systems - - is strictly required [205-207, 243, 244]. For example, for the environmental stress-change monitoring within the *Baikal Lake Basin, Siberia* or of the multitude of pertinent Pacific Rim (PACRIM) regions, monitored by the SIR-C/X-SAR Mission-2 [22, 23, 184, 207, 244] as well as the PACRIM-AIRSAR-1/2 measurement campaigns [294, 219, 221, 297], such simultaneous triple platform imaging modes of operation are warranted. By implementing *Differential GPS*, the three platforms could 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 radio-altimeters 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 Image 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 [139, 186]. 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 [22, 23].

The frequency-dependence of the averaged spectral characteristics over a wide frequency band of natural electromagnetic emissions within the Earth’s covers and its surface are not well known – especially not toward the lower end of the spectrum [78, 138]. Its determination becomes ever more hopeless with an increasing civilization unless isolated “**electromagnetic quiet zones (sites)**” are being identified and are being sanctioned as such to becoming permanent ‘**World Natural Heritage Electromagnetic Ground-truthing Quiet Sites**’ by the United Nations. Aeronomists have sought for and identified a few isolated “*electromagnetically quiet sites*” such as the “*Arrival-Heights of Hut-Point-Peninsula on Ross Island, Antarctica*”, and other similar sites for establishing the ‘Average Amplitude/Power-Spectra’, especially for the ULF/ELF/VLF spectral bands. Similarly, one of radio astronomy’s prime goals is to determine the ‘*virgin radio signatures*’ before modern civilization was perturbing it. For technological applications it is essential to know as precisely as ever possible the average characteristics together with reproducible lower and upper (peak-power) bounds within which man-made systems must operate; and within which we need to discover the passive and active environmental remote sensing signatures.

**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 (WHO-WRC’03, Sept./Oct., Geneva, Switzerland)*’ via the pertinent *National Research Councils (NRC), Committees on Radio Frequencies (CoRF)* in a unified, concerted effort [101, 180, 310]. 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 [83, 84, 123], be granted because very little revenue can be collected from remote sensing allocated frequency bands (which are however of utmost priority for securing successful environmental stress change monitoring), the proposal of “*levying a user’s tax for commercial and profit utilization*” of the electromagnetic spectrum needs to be supported strongly. The user’s tax so collected need to be applied directly to supporting basic remote sensing needs across the entire electromagnetic spectrum; and for sustaining natural electromagnetic quiet sites for monitoring the un-perturbed natural planetary and galactic background noise against which the user needs to provide natural radio frequency interference reduction methods.

This trend of reducing the available electromagnetic frequency bands for surveillance and remote sensing indeed represents a very serious, major problem for all of military surveillance and environmental stress-change monitoring [27]. It is 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. The “*natural resource of the electromagnetic spectrum*” 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*’ [54, 187], 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 “*sparse 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.

**User Collision of the “Natural Electromagnetic Spectrum (NES)”**: The user community of the electromagnetic frequency bands within the ULF-band to the FUV-band is rapidly increasing; and the *natural electromagnetic spectrum (NES)* – **one of the most fundamental Resources** - is being overtaxed in providing the required frequency band allocations. This has led to direct confrontations between the active and the passive user groups [27]. The active user group includes the entire terrestrial-space & mobile tele/video-communications industry, tele-navigation including the US GPS (Global Positioning System), the RF GLONASS (GLOBal NAVigation Satellite System), and the EU GNSS (Global Navigation Satellite System) [115], the defense, in future the homeland security and other active remote sensing communities, whose interests among themselves are colliding with increasing frequency because the available spectral bands are not sufficient for satisfying all needs. The passive user group consisting of aeronomy, radio-astronomy and of passive near-field sounding & far-field remote sensing are also colliding because radio-astronomy and in great parts aeronomy are directed outward toward the planetary and galactic space, whereas airborne and shuttle/satellite multi-modal passive and active remote sensing is looking down close-to-nadir on the terrestrial covers, which tends to add to the interference by the active user groups. Furthermore, the rapid increase of expanding narrow-band to ultra-wide-band mobile communication is creating havoc and an unavoidable impasse. Therefore, the entire issue of frequency allocation and radio spectral-band sharing coupled with modern advanced digital techniques, such as digital antenna beam forming, digital coding and correlation plus digital radio frequency interference reduction must be re-addressed.

Although hitherto remote sensing utilization of the electromagnetic spectrum was absolutely not an economically viable and may remain a less profitable venture for a long time to come; we request that an entirely new approach to revenue sharing be adopted. This could mean to levy a surcharge for the use of

“NES” from the commercial users for maintaining and operating the passive and active remote sensing and monitoring bands, which must be considered a justified measure in order to be able to monitor on a permanent un-interrupted time-scale the health of planet Earth; and even the “*Modern Telecommunications Complex*” cannot deny that it relies on the availability of a clean and clear “NES”. We, the passive & active remote sensing community, we must consider ourselves to be therefore given the astute “*Professional Status*” with the innate responsibility of functioning as the “*Pathologists and Radiologists of the Terrestrial and also Planetary Environments*”, and be entrusted to keep a watchful eye on the misuse of the “**Natural Electromagnetic Spectrum (NES)**”, which is indeed to be sanctified as one of the most “**sacred treasures and resources of Planet Earth**”, our planetary system and the universe. However, propagation space pollution of “NES” is not irreversible; and still today measures can be taken to reverse the trend by implementing more efficient spectrum utilization based on advances in digital communications and novel RF interference reduction techniques [27].

Every effort must be made to guarantee that mankind is protecting the “**Natural unperturbed-by-man Electromagnetic Spectrum**” as a “*Natural Treasure*”, which must be safeguarded against the greedy misuse of the “*International Communication Complex*” In order to fulfill this request, a finite set of isolated “*World Heritage Natural Electromagnetic Quiet Sites*” needs to be identified, so designated, licensed by UNESCO and protected by the UNITED NATIONS. **Passive & Active Remote Sensing must be given MUCH HIGHER PRIORITY**; anything not requiring the open propagation space must be removed, and should be subjected to the existing well developed but highly underused EO fiber communication links. The Telecommunications Complex must be forced to work hard in reducing their reliance on the increase of designated spectral bands for their commercial use, in fact must be enticed/forced to reduce their electromagnetic spectral real-estate by many factors with the focused implementation of efficient digital techniques of spectral bandwidth reduction.

The passive & active Remote Sensing community must adopt ***the high professional stature of being the pathologists and radiologists of the terrestrial and also the planetary environment, and nothing less***. Much improved RFI reduction and mitigation methods must rapidly be advanced because of the increasing needs of an expanding civilization. This implies introduction of standardized signal coding techniques and time-sharing for the use of identical spectral bands. In every respect, the general public ought to be educated about the serious state of pollution of the natural electromagnetic spectrum, and especially our educational systems K12 to Post-Doctoral levels – *all inclusive* – about reducing the undesirable propagation litter! The “*International Remote Sensing Community*” ought to request that the commercial users be levied with a - *say 10% to 15% or even higher surcharge* – solely to be applied to safeguarding the purity – *as far as is physically required* - of the “*Natural Electromagnetic Spectrum*” by providing funds for developing the pertinent “*Remote Sensing & Monitoring Ground-based, Air/Space-borne Sensor Systems*”, including the establishment of “*World Natural Electromagnetic Quiet Sites*”. In other words there has to be a fair distribution of the revenues gained from using “NES”, similar to levying toll-charges and gasoline tax for designing, building and maintaining clean motorways, etc.; there should be charges introduced for utilizing the “*National and International Information Highways*”. In fact, any misuse of the sacred “**Natural Electromagnetic Spectrum (NES)**” ought to be punished by stiff fines; and the intentional and/or careless generation of propagation litter along the “*International Information Highway*” ought to be dealt with similar to fining the ruthless production of refuse litter along our National, State and Local Highways in the US, and elsewhere [27].

**Radio Frequency Interference Reduction and RFI Security Threat Mitigation:** Next to the “*User Collision of NES*”, another equally serious radio interference and jamming problem is threatening not only military plus homeland security surveillance and environmental monitoring from ground [83, 84, 220], in air and space [97], but also environmental stress change monitoring from air and space [69, 70]. The RF sensors affected include polarimetric, interferometric and polarimetric-interferometric antenna arrays, multi-arm spiral and Butler matrix antennas, wideband polarimetric receivers as well as adaptive processing, and so on [252, 286]. Current mitigation techniques for determining the temporal and spatial plus differential temporal and spatial geo-location of one or more - including sparsely and densely distributed clusters of emitting sources – at ground, in air and space – is known as “*Vector Position Finding*”. A large body of methods



were developed in Electronic Signal Warfare [195] – such as the “*Angle-of-Arrival (AOA)*” or the “*Line of Bearing/Position (LOB/LOP)*” of the incoming interfering signal relative to “*true astronomical north*”, and “*magnetic north*” (in case of Faraday rotation correction requirements at radio frequencies at the order of 3MHz and below [302]). In general, this requires several optimally spaced and separated vector receiver locations for computing the exact time and space varying emitter locations via “*Time of Arrival (TOA)*”, “*Differential Time of Arrival (TDOA)*”, and “*Frequency of Arrival (FOA)*” or “*Differential Doppler (DF)*” methods [36, 98, 99] as reviewed most recently in Poisel [195]. Of specific interest is the “***Multiple Signal Classification (MUSIC)***” technique introduced by R. O. Schmidt [225], which is based on an eigenvector/eigenvalue decomposition technique applied to the complex geo-location system transfer matrix, which can also be formulated and computed for the polarimetric, the interferometric and the polarimetric-interferometric radar and SAR cases [99, 225]. This MUSIC algorithm was applied successfully in telecommunications satellite technology for TOA, TDOA, FDOA and several other algorithms derived from DF methods including the formulation of error bounds and cross-ambiguity functions, etc. as reviewed most comprehensively in Poisel [195].

Of specific interest are airborne and space borne RF emitter detection, recognition, identification and differential temporal and spatial geo-location algorithms for stationary and moving RFI and jammer sources [97-99]. In these cases the baselines of the distributed receivers are extremely small and they require adaptive optimization algorithms – over a rather wide frequency band, which in turn requires the development of compact minimum-weight packaging technology [64, 262]. Of interest are hybrid EO-RF conversion as well as EO laser sensor array techniques, which make possible such compact denser packaging. Similar observations also hold for EO-Laser imaging and telecommunication techniques, for which the recently developed “*Optical real time Phase Registration Devices*” will enable to cover the wideband RF and EO wavelength regime while maintaining the desired sensitivity and false alarm rejection requirements for implementing the optimal geolocation algorithms [34, 64, 222, 262].

Therefore, the entire issues of frequency allocation and radio spectral-band sharing - coupled with modern advanced digital techniques, such as digital antenna beam forming, digital coding and correlation - plus digital radio frequency interference reduction as well as RFI threat mitigation must be re-addressed totally and immediately – especially as regards the unavoidable implementation of POL-IN/TOMO-SAR surveillance and remote sensing technology.

## 7. Conclusions

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

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; more emphasis must be placed on the accelerated development of ‘*International Collaboratories*’ [22-24], 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 Polarimetricii et Interferometricii*” as proposed in [22-24].

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