From Airborne Via Drones to Space-Borne Polarimetric-Interferometric SAR Environmental Stress- Change Monitoring – Comparative Assessment of Applications

Wolfgang-Martin Boerner (1)

[1]UIC-ECE Communications, Sensing & Navigation Laboratory
900 W. Taylor St., SEL (607) W-4210, M/C 154
CHICAGO IL/USA-60607-7018
Email: wolfgang.m.boerner@uic.edu

Motoyuki Sato (2), Yoshio Yamaguchi & Hiroyoshi Yamada (3), Wooil Moon (4),Laurent Ferro-Famil & Eric Pottier (5), Andreas Reigber (6), Shane R. Cloude (7), Alberto Moreira (8), Tom Lukowski & Ridha Touzi (9)
2. TU-CNEAS-SATOLAB, Sendai; 3. NU-FEIN-YYHYLAB, Niigata; 4. SNU-SEES-ESI, Seoul; 5. UR1-IETR-SAPHIR, Rennes; 6. TUB-P&C, Berlin; 7. AEL, Cupra; 8. DLR-HR,Oberpfaffenhofen; 9.CCRS, Ottawa

Abstract: Very decisive progress was made in advancing fundamental POL-IN-SAR theory and algorithm development during the past decade. This was accomplished with the aid of airborne & shuttle platforms supporting single-to-multi-band multi-modal POL-SAR and also some POL-IN-SAR sensor systems, which will be compared and assessed with the aim of establishing the hitherto not completed but required missions such as tomographic and holographic imaging. Because the operation of airborne test-beds is extremely expensive, aircraft platforms are not suited for routine monitoring missions which is better accomplished with the use drones or UAVs. Such unmanned aerial vehicles were developed for defense applications, however lacking the sophistication of implementing advanced forefront POL-IN-SAR technology. This shortcoming will be thoroughly scrutinized resulting in the finding that we do now need to develop most rapidly POL-IN-SAR drone-platform technology especially for environmental stress-change monitoring with a great variance of applications beginning with flood, bush/forest-fire to tectonic-stress (earth-quake to volcanic eruptions) for real-short-time hazard mitigation. However, for routine global monitoring purposes of the terrestrial covers neither airborne sensor implementation - aircraft and/or drones - are sufficient; and there-fore multi-modal and multi-band space-borne POL-IN-SAR space-shuttle and satellite sensor technology needs to be further advanced at a much more rapid phase. The existing ENVISAT with the forthcoming ALOS-PALSAR, RADARSAT-2, and the TERRASAT will be compared, demonstrating that at this phase of development the fully polarimetric and polarimetric-interferometric modes of operation must be viewed and treated as preliminary algorithm verification support modes and at this phase of development are still not to be viewed as routine modes.

Keywords: Polarimetric and Interferometric Synthetic Aperture Radar, Airborne and Space-borne SAR Imaging, Environmental Stress Change Imaging.

1. Introduction

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 and also for wetland assessment and monitoring. 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. 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*; and* (ii) mitigation against common *"Radio Frequency Interference (RFI)"* and intentional *"Directive Jamming of Airborne & Space borne POL-IN-SAR Imaging Platforms"* are appraised

2. Historical Development of Radar Polarimetry and Interferometry

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). Where there are abrupt or gradual changes in the index of refraction (or permittivity, magnetic permeability, and conductivity), the polarization state of a narrow-band (single-frequency) wave is transformed, and the electromagnetic "*vector wave*" is re-polarized. When the wave passes through a medium of changing index of refraction or when it strikes an object such as a radar target and/or a scattering surface and it is reflected; then, characteristic information about the reflectivity, shape and orientation of the reflecting body can be obtained by implementing '*polarization control*'. The 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. Whereas, this polarization transformation behavior, expressed in terms of the "*polarization ellipse*" is named "*Ellipsometry"* in Optical Sensing and Imaging; it is denoted as *"Polarimetry*" in Radar, Lidar/Ladar and SAR Sensing and Imaging - using the ancient Greek meaning of "*measuring orientation and object shape*". Thus, *ellipsometry* and *polarimetry* are concerned with the control of the coherent polarization properties of the optical and radio waves, respectively; where in *ellipsometry* mainly the *"Forward Scattering Alignment (FSA*)" and in *polarimetry* the *"Back Scattering Alignment (BSA)*" coordinate systems are respectively used.

3. SAR Polarimetry and 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'*; with standard (scalar) '*Radar Interferometry'*, the spatial (range/in depth) structure may be resolved, from which '*Digital Elevation Maps'* can be reconstructed. However, neither method is complete in that POL-SAR by itself does not provide 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 – irrespective of driving up the resolution – and therefore not providing the desired information about the vertical structure of vegetation and under burden. 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 it will be difficult to discern - *in most cases* - the source orientation/location of the scattering mechanisms. In addition, without the full implementation of POL-IN/TOMO-SAR imagery with a highly enlarged window of depression angles, 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.

4. 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 – desirable on one and the same sensor platform. Considering that there was no truly mission-oriented new '*Multi-purpose SAR IMAGING AIRCRAFT PLATFORM'* designed since that of the P-3 Orion sub-marine hunting platforms of the late Fifties, it is a timely and highly justifiable request to our forward looking, visionary Planning Offices of DOD, NASA (HQT.-JPL), DOC (USGS+NOAA), NATO, ESA, NASDA, etc., to place top priority on this long overdue demand of having access to the '*ideal imaging platforms'* required to execute both the military wide area '*homeland security surveillance'* as well as the environmental background validation, environmental stress-assessment and stress-change monitoring missions - world-wide. Just to make use of existing air-borne platforms of opportunity; 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.

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. 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. This is strictly required in order to recover - *next to material bio-mass parameters* - canopy versus sub-canopy versus understore, 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. 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. Similarly, for more accurate and verifiable estimation of soil moisture and roughness, and of snow water equivalence 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.

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. Whereas, for a dense virgin equatorial rain forest with huge trees of highly conductive hard-wood, the UWB (10 - 1000 MHz) regime is required, etc. 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. 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.

6. Conclusions

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. 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.

References

[1] W-M. Boerner, Recent Advances in Extra-Wide-Band Polarimetry, Interferometry and Polarimetric Interferometry in Synthetic Aperture Remote Sensing, and its Applications, IEE Proc.-Radar Sonar Navigation, *Special Issue of the EUSAR-02,* vol. 150, no. 3, June 2003, pp. 113-125

[2] Boerner, W-M., et al., (Guest Eds.), 1981, IEEE Transactions on the Antennas & Propagation Society, vol. 29(2), Special Issue, Inverse Methods in Electromagnetics, (417 p.) [Also see: Boerner, W-M. et al, "Polarization dependence in electromagnetic inverse problems", ibid, pp. 267-271].

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

[4] Boerner, W-M., H. Mott, E. Lüneburg, C. Livingston, B. Brisco, R. J. Brown and J. S. Paterson with contributions by S.R. Cloude, E. Krogager, J.S. Lee, D.L. Schuler, J. J. van Zyl, D. Randall P. Budkewitsch and E. Pottier, 1998, *"Polarimetry in Radar Remote Sensing: Basic and Applied Concepts"*, Chapter 5 (pp. 271-357, + 12 image plates) in F.M. Henderson, and A.J. Lewis, (eds.), *Principles and Applications of Imaging Radar*, vol. 2 of *Manual of Remote Sensing*, (ed. R.A. Reyerson), Third Edition, John Willey & Sons, New York, 940 p, ISBN: 0-471-29406-3.