AMPER: Network on Applied Multiparameter Environmental Remote Sensing

An EU Sponsored Resaerch and Training Network

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Dedicated to the memory of late Dr. Ernst Lueneburg

***Abstract*—The EU-sponsored research and training network AMPER deals with state of the art research in the area of multi-parameter polarimetry, duly emphasizing radar engineering, scattering theory, inversion methods, polarimetric theory, propagation and applications. This paper summarises some of the network's scientific achievements. The AMPER partners include: M. Chandra and Alberto Moreira (DLR, Germany), D.H.O Bebbington (Uni. Essex, UK), E. Pottier (Uni. Rennes, France), E. Krogager (DDRE, Denmark), F. Molinet (MOTHESIM, France), J. Fortuny (JRC, Italy), X. Fabregas (UPC, Spain), G. Wanielik and U. Neubert (Uni. Chemnitz, Germany), U. Benz (DEFINIENs, Germany). The EU project officer is Gordana Popovic and the network is coordinated by the lead author (DLR /U. Chemnitz) .**

Keywords: multiprameter polarimetry, inversion methods, propagation effects, sensor development and calibration

I. INTRODUCTION

Network activities fall into three main areas dealing with the sensor systems and base data, the underlying physics and scattering models and parameter retrieval and product generation. Specific objectives for each research area are identified as follows:

Systems - Devising simple, data-based methods for calibrating multi-static polarimetric sensors and enhancing their information-carrying capacity. The approach taken, exploits the use of polarimetric invariants and absolute self-calibrating physical and statistical properties.

Physics - Innovation is sought in various topics: 1. Identification of polarimetric transformation invariants in multistatic mode, 2. Polarimetric scattering models of extended and distributed random target taking into account the coherency properties of the targets, 3. Correcting for propagation-induced errors.

Applications - Optimization of inversion methodology is the main challenge which is addressed by seeking appropriate and new decompositions that also relate to the statistical features arising from eigenvalue analysis.

II. RESEARCH AND TRAINING: RESULTS

A. *SCIENTIFIC HIGHLIGHTS*

In this paper, we shall emphasize the key network scientific achievements to date that have contributed to the advancement of the state of the art. The scientific activities of the network will be detailed under the three main areas described in the previous sections.

1) Systems: Base Data Availability, Robustness and Reliability: The multiparameter and polarimetric database of the network boasts a unique dataset from diverse remote sensing instruments including weather radars and interferometric SAR systems. More specifically, the network database includes measurements of: time series of interferometric radar measurements, polarimetric radar calibration, multistatic-multipath polarimetric signals in mobile communications, and time-series of weather radar echoes. Such datasets represent a useful resource that hitherto was either simply not available, or unprocessed due to lack of undeveloped methodology, or would have been prohibitively expensive to obtain.

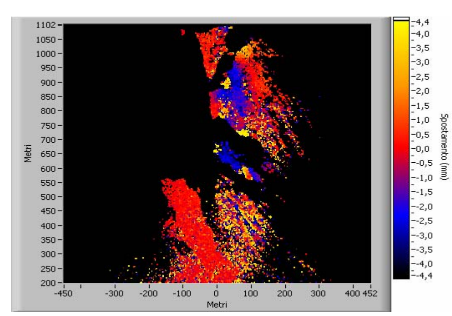

Figure 1. A 5-day Interferogram displaying topographic changes over the slope of the Stromboli volcano (Italy) recorded with JRC's ground based C-band mobile radar system LISA (J. Foruny, private communication) .

Shown in Figure 1 is an example of an interferogram obtained from a series of repeat-pass SAR measurements over the slopes of Stromboli volcano, avalanche test site in Stromboli (Italy).

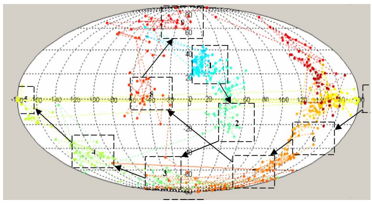

Figure 2. Polarimetric spread of signal received after multipath and multistatic scattering on Poincaré Sphere (G. Wanielik, Pri. Communication)

Such interferometric measurements reveal vital surface-height variations crucial to geophysical monitoring of disaster-prone sites. Summarised in Figure 2 are the first-time polarimetric measurements that provide insight into the polarimetric variability of electromagnetic signals that have undergone multi-path and multi-static scattering. Likewise, in the area of polarimetric weather radars, the network now possesses ready-to-use time-series of polarimetric echoes recorded with dual-channel linear receivers. Such measurements have already enabled testing and development of innovative and new methodologies for monitoring and assessing the atmosphere.

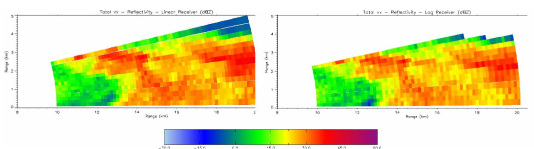

Figure 3. Cloud reflectivities obtained from time-series data of polarimetric echoes recorded with linear receivers (left) at DLR and compared with the corresponding reflectivity signature obtained from the standard logarithmic receivers (right). P. Tracksdorf, Pri. Communication.

Shown in Figure 3 is an example of cloud reflectivities obtained from the above mentioned time-series data. This signature is compared with the corresponding reflectivity signature obtained from the standard logarithmic receivers. The agreement between the two sets of data has introduced a new standard of calibration of the linear echoes.

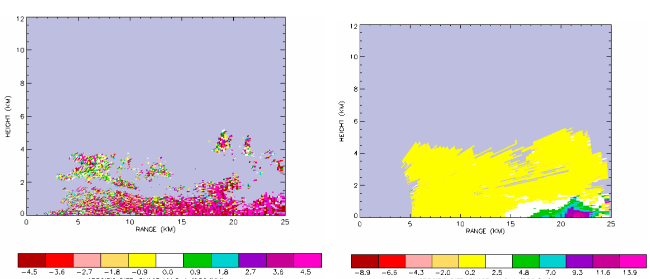

Figure 4. On the left is the noisy differential propagation phase signature obtained from V/H – basis and on the right is the specific differential propagation phase obtained after the S- Matrix measurements were processed to remove Doppler phase from the 'raw' data recorded with DLR's polarimetric weather radar (T. Otto, Pri. Communication).

Another key data base feature was the successful development and implementation of a two-stage algorithm that (a) corrects for phase discontinuities generated by the phase-noise in the neighbourhood of Nyquist limits and (b) smoothes out the residual random phase-noise. Shown in Figure 4 is an example of how this technique enables the retrieval of specific differential phase (KDP) from the noisy raw data in its original form. Such measurements are believed to be most crucial to the state-of-the-art monitoring of precipitation, particularly in flood-disaster management. The collective data pool, open to all partners, represents a rather unique and highly valuable data resource available anywhere within the communities. It may also be noted that the data bank exploits the latest techniques of self-consistent radar calibrations that ensure the highest degree of data robustness.

Development of polarimetric calibration methodologies:

The main strategy used in the development of calibration methodologies was to identify and exploit self-consistencies and self-calibrating measurements derived from the underlying physics of the very own raw radar data. For instance, the results shown in Figure 4 afford one such example of a processed quantity that yields a method for actively calibrating operational weather radars because such differential co-polar propagation phases are absolute physical effects that themselves do not require calibration. This methodology for obtaining a reference quantity towards calibration forms a sound groundwork for considering the design of PARC (polarisation-active radar calibrators) devices. In the area of polarimetric and interferometric SAR calibration, a complete multi-step algorithm has been similarly developed. This method uses to advantage scattering reciprocity for the symmetrisation of cross-polar channels and balancing the S-matrix channels. For the absolute-phase calibration in SAR measurements, the application of one or more trihedrals inside the target area has been considered. Likewise, the classical theory of phase error minimisation based on high and low frequency spectral partition was successfully implemented, particularly in the case of high coherency SAR measurements. These developments provide groundwork for investigating the relationship between coherence and phase errors and the development of a polarimetric interferometric data generator, using uncorrelated Gaussian data together with the Cholesky factorisation of the covariance matrix. Finally, key developments have been noted in the identification of invariance properties of bi-static scattering. In this regard, new insight into the coordinate-free representation of bi-static measurements has been developed, using projective geometry for representing polarisation states. This methodology portrays a polarisation state as a point on the line on the projective plane corresponding to its wave vector and it imposes a linear 1:1 relationship between incident and scattered waves.

$$M_{ab} = m_a n_b + n_a m_b - \frac{1}{2}\left(m_c \Omega^{cd} n_d\right)\Omega_{ab}$$

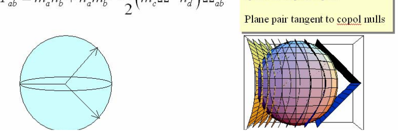

Figure 5. The coherent polarimetric optimisation problem corresponds to a linear combination of sphere and plane-pair in the geometric formulation, exploiting quadric surface representation. The equation gives a decomposition of the Kennaugh matrix (D.H.B. Bebbington, Pri. Communication).

Enhancing radar-channel / information-channel capacity:

An experimental set-up for monitoring polarimetric properties of signals, concurrently in two orthogonally polarized horizontal and vertical channels, has been successfully developed and implemented. Such studies, now under way, have provided a wealth of data that will directly help to identify adaptive polarimetric methods for either increasing the channel isolation (thus permitting higher channel diversity) or optimizing the detectability of received signals. An example of such measurements is given in figure 2. Such data sets provide direct information required for designing next-generation radar and communication systems using polarisation diversity as a means of generating higher channel capacity.

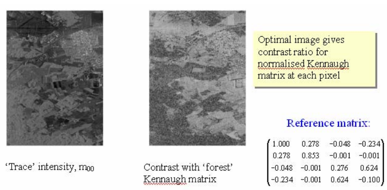

Figure 6. The optimal image on the right gives the contrast ratio for normalised Kennaugh matrix at each pixel (D. Bebbington, pri. Comm.)

Physics – Scattering and Propagation Models

Unambiguous definition of S-matrix measurements and transformations:

The unambiguous definition of polarimetric transformations and a generalized description of S-matrices were brought into context through the development of a consistent and unifying theoretical framework developed from fundamental physical principles. The so-developed unifying approach uses projective geometry to formulate the concept of optimal polarisations in characterising complex polarimetric data. Shown in Figure 6 is an example that illustrates how the application of projective geometry, exploited in the aforementioned optimal polarisation approach, translates the coherent optimisation problem into a geometric scenario of tangent planes located on the Poincaré quadric surface. The concept of optimal polarisations, regardless of the polarimetric scattering scenario (multi-static or bi-static), represents a useful way of reducing polarimetric images to data-characterising scalar components.

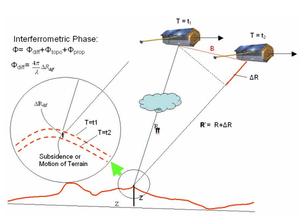

Figure 7. A SAR measurement scenario displaying aspects of interferometric, bistatic, topographic and propagation effects that can influence SAR echoes (A. Danklmayer, Pri. Communication).

This innovative approach differs from the classical approach in that it exploits the theory of quadric surfaces in projective geometry and successfully establishes that all optimisation problems can be reduced to polynomial problems which can be solved to obtain useful solutions in the key areas of polarimetric contrast and classification. Rather importantly, the optimal ratios that can be obtained under this approach are independent of any polarisation bases (D. H. O. Bebbington, private communication). Summarized and reemphasized in Figure 6 is an example of an optimal image (obtained from a sextic polynomial solution) that shows optimised contrast ratio for normalised Kennaugh matrix at each pixel of a SAR image recorded with DLR's ESAR system.

Scattering and propagation formulations:

Propagation effects, we note, essentially represent non-unitary transformations that introduce additional differential amplitudes and phases to the radar-measured S-matrices. Investigations were undertaken to quantify differential propagation effects by exploiting the direct measurement of accumulated differential propagation phases by coherent radars. Such measurements enable a relatively model-free estimation of differential attenuation. Shown in figure 4 is an example of specific differential propagation phase image processed from S-matrix mode measurements made with the DLR polarimetric weather radar. This methodology for estimating propagation effects is equally implementable in multi-static or bi-static radar scenarios. Interplay between propagation effects, backscattering and bi-static geometry, in a SAR measurement, is illustrated in Figure 7. Analysis of such scenarios, using the know-how gained in the network, directly enables the analysis of such a situation.

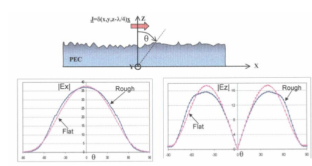

Figure 8. Example of a dipole over a Gaussian rough surface of correlation: $\sigma = 0.2\lambda$ Correlation length : $L_x = L_y = \lambda$. The curves give the average far field on the $z = 0$ plane (F. Molinet, Pri. Communication).

Scattering models

Progress was noted in the electromagnetic modelling of a deterministic (man-made) target located near the ground or embedded in the ground for mono-static and bi-static diffraction. Such a model is of vital importance for testing decomposition theorems that permit the separation of a deterministic target from the random process resulting from rough surface contribution.

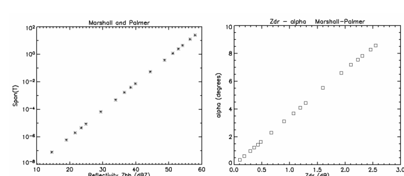

Figure 9. Simulations show a linear relationship between the span of the coherency matrix and the reflectivity on the left side and between α and the differential reflectivity on the right side of the figure. (M. Galletti, Pri. Comm)

These investigations (F. Molinet, private communication) address a problem on which little work has been reported in the past. In these investigations, the Green's function has been analytically derived using the method of perturbations. It has been demonstrated that this Green's function depends on the variance and the correlation function used for describing the random rough surface. The first results, summarised in Figure 8, demonstrate the implemented software that is capable of computing the field radiated by a dipole over a rough surface with different correlation functions (i.e. Gaussian, exponential, etc.). By employing this Green's function, a solution of the Electric Field Equation (EFIE) using the Method of Moments has been developed for a perfectly conducting target. In this way, the classical method has been extended to the stochastic case. Furthermore, it was established that only the inverse of the mean value of the integral operator of the corresponding impedance matrix needs to be calculated in order to derive the zero, first and second order terms of the induced currents and the radiated field, both of which are random variables. Finally, from the calculated diffracted field, the coherency matrix can thus be obtained. The numerical implementation of this final part is currently under development.

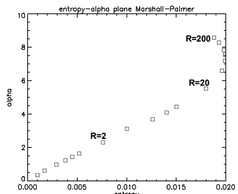

Figure 10. The entropy-alpha plane in dependence of rain-rate R (G. Galletti).

Polarimetric scattering models of distributed and random targets:

An interesting development has demonstrated that the Entropy-Alpha method of Cloude-Pottier for analysing radar measured covariance matrices can be used for estimating rain rates from polarimetric weather radar observations. The simulations summarised in Figures 9 and 10 reveal how a three-parameter characterisation of rain rate can be achieved using the entropy (H), Alpha, and span parameters. This methodology provides a polarimetric parameter (Alpha) that is independent of the mean canting angle.

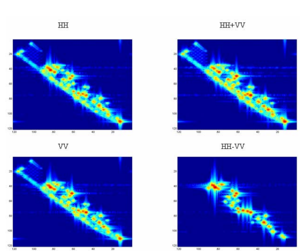

Figure 11. Simulated ISAR images of a ship (E. Krogager, pri comm)

This parameter was demonstrated to be a co-ordinate-free measurement of the conventional differential reflectivity and hence ideally suited for advancing the state of the art for rain rate estimation by radars. Research effort characterising polarimetric scattering from a distributed target (example: a ship) was extensively reported (E. Krogager, private communication) in context of polarimetric decomposition. In this approach, the distributed target was divided into statistically independent targets. By considering polarimetric decompositions, it was shown that an S-matrix contribution from each independent target was completely and coherently separable into a sphere and a dihedral combination. Likewise, it was shown that helix-scattering could be modeled with two appropriately positioned dihedrals separated by $\lambda/8$. Reported studies led to the conclusion that location and behaviour of the effective phase centre depend on the coherent integration resulting from the contributions from the independent scatterers. This, in turn, opens the possibility of employing polarimetric decompositions in order to reduce interference between contributions from different scattering mechanisms. Shown in this context are the simulated ISAR images of a ship summarised in Figure 11.

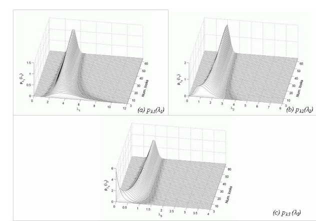

Figure 12. The distributions of the sample eigenvalues for the particular case in which the true eigenvalues are $\{l_1, l_2, l_3\}=\{3,2,1\}$ (C. Lopez/E. Pottier).

Applications – Data Analysis and Physical Parameter Retrieval

Optimisation studies in inversion applications:

As already mentioned, the aspect of optimising polarimetric contrast was dealt with in the light of polarimetric transformations. Likewise, optimisation is an important issue in connection with data inversion for parameter retrieval, target recognition, segmentation and classification. A noteworthy point, identified in this regard, was that a multi-dimensional radar system ideally exploits the correlation structure that characterises the data when represented by coherency/covariance matrices. A review of the field of inversion studies in this context indicated that progress beyond the present state of the art requires (i) statistical assessment of eigenvalues-based target decomposition, possibly in conjunction with (ii) a comprehensive treatment of complex multidimensional speckle noise, taking duly into account the multiplicative and additive types of contributions. More specifically, a review of different multidimensional SAR data models was performed in order to derive the statistical properties of the H/A decomposition proposed by Cloude and Pottier. Furthermore, it was identified that the multi-dimensional model for SAR imagery offers the best compromise between applicability and the possibility to derive a useful mathematical model. This approach, using the Wishart probability-density-distribution characterisation, led to the derivation of the joint distribution of the eigenvalues associated with the H/A-decomposition. Summarised in Figure 12 is an example of such a distribution of eigenvalues in dependence of sample size. This knowledge was put to further use in order to develop a correction of the eigenvalue estimates obtained from a small sample size. This correction was developed in the form of an 'asymptotic quasi maximum likelihood estimation' of the true eigenvalues. Results illustrating this correction are summarised in Figure 13. The knowledge of the distribution of eigenvalues thus permits a simple correction of these biases. Interestingly, the derivation of the distribution of eigenvalues (of H/A- decomposition) drew attention to a possible link between the speckle noise and the eigenvalue biases. Clearly, this connection suggests the possibility to seek a unified framework for the analysis of speckle noise that will permit us to determine the accuracy of quantitative estimation of physical parameters and improve the overall estimation efficiency.

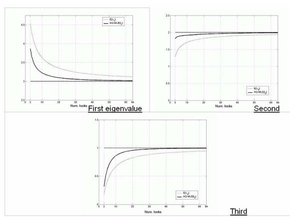

Figure 13. The correction for the sample eigenvalues with an asymptotic quasi maximum likelihood estimation (AQ-MLE) of the true eigenvalues. In the figure it is shown the correction for the particular case in which the true eigenvalues are $\{l_1, l_2, l_3\}=\{3,2,1\}$ (C. Lopez / E. Pottier, pri. Comm).

With regard to practical applications, the development of object-oriented knowledge-based image-analysis-software termed 'eCognition' was set up as an operational system for ENVISAT-ASAR data analysis. This methodology of 'eCognition' exploits multi-dimensional observations (i.e. polarimetric and multitemporal) for obtaining geographical information. Iinterestingly, the developed software is capable of combining different sensing techniques such as SAR, Lidar, Infrared and multi-spectral optical observations. A prototype of this system-integration and the necessary software architecture was successfully developed. Such an 'eCognition' system promises to be a valuable operational tool in crisis management, because it enables the monitoring of maritime oil spills and coastline boundaries. This approach will also allow the mapping of land cover classes.

Polarimetric interferometry for observing random targets:

The application of polarimetric interferometry in remote sensing has internationally turned into a key topic of current interest. The AMPER network, collectively, has access to some of the most unique data sets, tools of analysis and expertise resource in this field. Interferometric/tomographic methods permit the retrieval of scattering variation in height over the planar regions observed with SAR sensors. Time series measurements of 'SAR-data-takes' are thus a valuable tool for identifying structural changes resulting from height variations between the data takes. In this connection, the most frequently exploited observables are the interferometric phases and coherence in dependence of polarisation. The AMPER network has noted state-of-the-art progress in this area.

The coherency images obtained with the LISA system of JRC proved to be a robust indicator of structural changes in the snow cover, mass movement and local discontinuities in snow wetness. Similarly, the analysis of the unique and extensive time series of full polarimetric data on rice crops, in conjunction with state-of-the-art electromagnetic scattering models for rice crops, revealed that optimal height inversion is possible at X-band. A study of interferometric coherence and an assessment of coherent and incoherent methods of processing SAR data was successfully completed and it showed that in some cases coherent techniques may be superior to the commonly applied incoherent techniques (E. Krogager et al.). The study suggests new grounds for further investigations.

ACKNOWLEDGMENT

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