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# ТЕМАТИЧЕСКИЙ РЕФЕРАТИВНЫЙ СБОРНИК № 28-1

## “Polarimetric Radar Systems”
## («Поляриметрические РЛ системы»)

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# ТЕМАТИЧЕСКИЙ РЕФЕРАТИВНЫЙ СБОРНИК № 28-1

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### "Polarimetric Decomposition Over Glacier Ice Using Long-Wavelength Airborne PolSAR"

In recent years, there has been increased interest in using synthetic aperture radar (SAR) to study and monitor glaciers and ice sheets for glaciological and climate change research. However, due to the medium's complexity, SAR backscattering from ice remains poorly understood, including the relative importance of scattering from surface and volume layers and also dependences on frequency and glacier zone. Extreme weather conditions can result in quickly changing surface conditions influencing backscatter signatures while leaving the underlying volume of interest unchanged. Surface and volume components must thus be separated in order to infer information regarding the properties of the ice volume. This paper describes a three-component scattering model to decompose polarimetric SAR (PolSAR) images of glacier ice. Total backscatter is modeled as the incoherent summation of surface, volume, and sastrugi (wind-induced feature) components. The proposed model adapts and extends the Freeman and Durden decomposition for an ice volume scenario in which the volume is a dielectric medium. Forms of the model for both random and oriented volumes are considered, and a new oriented sastrugi component is introduced which is able to explain backscatter behavior between different winter scenes. Validation is performed with airborne PolSAR data at L- and P-band collected using the E-SAR system of the German Aerospace Center over the Austfonna ice cap in Svalbard, Norway, as part of the ICESAR campaign. [J1]

### "A Foreground/Background Separation Framework for Interpreting Polarimetric SAR Images"

In this letter, we present a novel foreground/background separation (FBS) framework for interpreting polarimetric synthetic aperture radar (PolSAR) images. The FBS framework takes the spatial relations between pixels into consideration and incorporates the advantages of pairwise dissimilarity-based grouping schemes. The FBS method can separate specific targets and objects from the background, which is essential in an interpretation system. Multiple FBS operations can be integrated to interpret PolSAR images, flexibly fusing various inherent features of PolSAR data. Several PolSAR data sets are used to verify the proposed approach. [J2]

### "An Internal Calibration Scheme for Polarimetric Synthetic Aperture Radar System"

Two important aspects of internal calibration of polarimetric synthetic aperture radar are discussed, i.e., system gain calibration and individual transmit/receive module (TRM) calibration. System gain variation is measured, utilizing the internal calibration loop. A dual-channel TRM gain and phase calibration is carried out using orthogonal phase coding, where a signal of individual TRM is phase encoded according to a set of orthogonal codes in order to be separated from the composite calibration signal of all TRMs. Calibration results are developed both theoretically and through simulation in the case of TRM failure. Error introduced by phase-shifter toggling inaccuracy is discussed. A cross talk model is used to investigate the effect of imperfect isolation between the two polarization channels of each TRM on the calibration error. [J3]

### "Combination of Direct and Double-Bounce Ground Responses in the Homogeneous Oriented Volume Over Ground Model"

Complex interferometric coherence expressions for the homogeneous (random or oriented) volume-over-ground model are originally derived in a simplified way by neglecting one of the two possible contributions of the ground response: direct return from the ground surface or double-bounce interaction with stems or trunks. The influence of these depends on both system and scene parameters, and in many cases, none of them should be ignored a priori. Therefore, a more general formulation accounting for the simultaneous presence of both ground contributions should be developed. This letter derives this formulation and analyzes the combined effect of both ground returns on the complex coherences. In addition, the implications for a subsequent inversion procedure based on this model are also discussed. [J4]

### "Linear Feature Detection in Polarimetric SAR Images"

Recently, the use of linear features for processing remote-sensing images has shown its importance in applications. Unfortunately, traditional linear feature detection methods rely heavily on the image's local information which makes them vulnerable to the presence of noise in the image. This problem becomes particularly difficult for synthetic aperture radar (SAR) image applications where SAR images are corrupted by speckle noise. In order to overcome this problem, we propose a novel method that processes the polarimetric synthetic aperture radar (Pol-SAR) images by combining the multiscale image analysis with polarimetric information in a new fashion. A two-scale approach is adopted here. On a coarse level, the coarse regions of the linear features are extracted by a curvelet transform from a speckle noise reduced image obtained by the polarimetric whitening filter. On a fine level, we develop a fuzzy polarimetric detector to accurately locate the linear features inside the regions. The effectiveness of the proposed method is demonstrated using simulated Pol-SAR data acquired from both EMISAR and Convair-580 systems. [J5]

## "Analysis of polarimetric techniques using high-resolution polarimetry data in an automatic target recognition context"

In recent years, large numbers of radar images are collected but there is neither time nor enough manpower to go through each collected image. Researchers in the automatic target recognition (ATR) field have developed automated algorithms and tools to analyse each image and obtain higher recognition rate and fewer false alarms but there is still a need for improvement in these aspects. In this study, we have investigated various polarimetric and non-polarimetric techniques and recommended the best ATR approach among those analysed for higher recognition rate and least false alarm rate. The experimental results show that self-organising map (SOM) feature extraction technique with a two-dimensional Fourier transform (2DFFT) algorithm has a better classification rate and a lower false alarm rate. The classifier used here was AND Corporation's holographic neural technology (UNeT) classifier. The SOM technique using |HH|, |HV| and |W| achieved 98.9% correct classification over the detected targets and reduced the false alarm rate to 8.2%. An ATR system trained with both target and not-a-target class data produced a lower false alarm rate compared with ATR systems trained with target samples alone. This study will help in selection of appropriate methods for future ATR system implementations. In addition, it will assist image analysts (IAs) in choosing appropriate techniques and training datasets to perform their operational tasks. [J6]

## "Pedestal height for sea oil slick observation"

In this study fully polarimetric synthetic aperture radar (SAR) measurements are employed for sea oil slick observation. The co-polarised signature is read in terms of sea surface scattering mechanism with and without surface slicks and it is shown to be sensitive to the presence of sea oil slicks. A model, which relates the pedestal of the polarisation signature to the presence of surface slicks, is developed and successfully tested on L-band ALOS-PALSAR, C-band RADARSAT-2 and C-band SIR-C/X-SAR full-polarimetric SAR data. Experiment results show that polarisation signature, and its pedestal height, can be successfully exploited for both observing sea oil slicks and distinguishing them from weak-damping properties look-alikes. [J7]

## "Rao and wald tests design of polarimetric multiple-input multiple-output radar in compound-gaussian clutter"

In high-resolution radars or at low gazing angles, the clutter is more satisfied in the compound-Gaussian model. Meanwhile, the polarisation diversity can be exploited to enhance the detection performance. Motivated by extending the detection problem of multiple-input multiple-output radar to such cases, this study mainly addresses the adaptive detectors design with an unknown covariance matrix based on Rao and Wald criterions. The two-step design strategy is adopted. Three estimation strategies of covariance with secondary data, such as sampled covariance matrix (SCM), normalised sampled covariance matrix (NSCM) and fixed point estimation (FPE) matrix, are introduced to make derived receivers fully adaptive. A thorough performance assessment is given by several numerical examples, the results of which show that Rao and Wald tests can provide good detection performance in even spikier clutter, and the polarimetric diversity can also be exploited to improve the detection performance. Meanwhile, the FPE strategy is more suitable to implement the adaptive detection algorithms, and the adaptive loss is completely acceptable in practical applications. [J8]

## "Target Recognition by Means of Polarimetric ISAR Images"

Automatic target recognition (ATR) is generally the reason why inverse synthetic aperture radar (ISAR) imaging systems are employed. Moreover, the use of fully polarimetric radar systems in radar imaging applications such as SAR and ISAR has enhanced both image quality and classification capabilities. The authors propose a novel technique for ATR using polarimetric ISAR (Pol-ISAR) images. The proposed method is based on a model matching approach. Results are obtained that show the effectiveness of such a technique. [J9]

## "Validation of the ASAR Global Monitoring Mode Soil Moisture Product Using the NAFE'05 Data Set"

The Advanced Synthetic Aperture Radar (ASAR) Global Monitoring (GM) mode offers an opportunity for global soil moisture (SM) monitoring at much finer spatial resolution than that provided by the currently operational Advanced Microwave Scanning Radiometer for the Earth Observing System and future planned missions such as Soil Moisture and Ocean Salinity and Soil Moisture Active Passive. Considering the difficulties in modeling the complex soil-vegetation scattering mechanisms and the great need of ancillary data for microwave backscatter SM inversion, algorithms based on temporal change are currently the best method to examine SM variability. This paper evaluates the spatial sensitivity of the ASAR GM surface SM product derived using the temporal change detection methodology developed by the Vienna University of Technology. This evaluation is made for an area in southeastern Australia using data from the National Airborne Field Experiment 2005. The spatial evaluation is made using three different types of SM data (station, field, and airborne) across several different scales (1-25 km). Results confirmed the expected better agreement when using point (Rstation= 0.75) data as compared to spatial (RPLMR, 1 km= 0.4) data. While the aircraft-ASAR GM correlation values at 1-km resolution were low, they significantly improved when averaged to 5 km (RPLMR, 5 km= 0.67) or coarser. Consequently, this assessment shows the ASAR GM potential for monitoring SM when averaged to a spatial resolution of at least 5 km. [J10]

## "Transitions in the polarimetric radar scattering properties of the sea surface"

The wide variability of sea surface conditions is reflected in a corresponding variability in sea clutter characteristics; moreover, these characteristics manifest a strong dependence on radar parameters such as frequency, waveform and polarisation. Ideally, radar systems should adapt their parameters to the prevailing sea conditions and viewing geometry so as to optimise performance. In practice this is seldom done, in large part because most radar systems have very limited capability to adapt, but also because the rules that might guide the adaptation process are not yet clearly established. Where an appreciable change in radar parameters or viewing geometry would yield only a slight change in clutter severity and a commensurately modest improvement in radar performance, there is little incentive to adapt. On the other hand, if there are sharp transitions in clutter properties as some radar parameter is varied, then exploitation of the transition may be highly advantageous. This study presents the results of a search for transitions in polarimetric X-band sea clutter, focusing on the dependence on scattering geometry. Experiments were conducted to study clutter variation with elevation angle and azimuth with respect to wind direction. The results demonstrate that transitions exist, that they can be surprisingly sharp, and that the consequences for target detectability may be significant. [J11]

## "Identification and analysis of sea radar clutter spikes"

In recent times, considerable advances have been made on analysing low grazing angle radar sea clutter in the gigahertz frequency range. In this work, a set of coherent and polarimetric sea clutter data is analysed focusing on the statistical and spectral properties of the spikes, whatever is the physical phenomenon that generates them. Using three sea spike defining parameters, the spike amplitude, the minimum spike width and the minimum interval between spikes, it is possible to identify the spiking events from the background. This work shows a sample of results from a statistical and spectral analysis of a set of sea spikes selected from the radar returns, focusing on their Doppler properties, the spike duration and the temporal interval between spikes. [J12]

## "C-Band Polarimetric Backscattering Signatures of Newly Formed Sea Ice During Fall Freeze-Up"

A study of the polarimetric backscattering response of newly formed sea ice types under a large assortment of surface coverage was conducted using a ship-based C-band polarimetric radar system. Polarimetric backscattering results and physical data for 40 stations during the fall freeze-up of 2003, 2006, and 2007 are presented. Analysis of the copolarized correlation coefficient showed its sensitivity to both sea ice thickness and surface coverage and resulted in a statistically significant separation of ice thickness into two regimes: ice less than 6 cm thick and ice greater than 8 cm thick. A case study quantified the backscatter of a layer of snow infiltrated frost flowers on new sea ice, showing that the presence of the old frost flowers can enhance the backscatter by more than 6 dB. Finally, a statistical analysis of a series of temporal-spatial measurements over a visually homogeneous frost-flower-covered ice floe identified temperature as a significant, but not exclusive, factor in the backscattering measurements. [J13]

## "Segmentation and Classification of Polarimetric SAR Data Using Spectral Graph Partitioning"

A new approach for segmentation and classification of polarimetric synthetic aperture radar (POLSAR) data is proposed based on spectral graph partitioning. Since automated analysis techniques are often challenged due to

the noisy properties of POLSAR data, human experts are employed to aid in the interpretation of such data in an operational setting. Humans can improve the performance of segmentation and classification of POLSAR data, because their vision system can apply cognitive skills that are not easy to incorporate into an automated system. The motivation for this paper is to incorporate some of these human perceptual skills into the computer algorithms. A framework that has recently emerged in computer vision for solving grouping problems with perceptually plausible results-spectral graph partitioning-is customized for POLSAR data. Segmentation is performed using the contour information in a region-based setting with the aid of spatial proximity. This is followed by a classification step performed through graph partitioning based on similarities of the mean coherence matrices obtained for each segment. Using the proposed approach, the results achieved are superior to the Wishart classifier. Automated parameter selection procedures are under development. This framework also suggests a way to accommodate different representations of polarimetric data and combine them with other information sources (e.g., optical imagery and digital elevation models). [J14]

## "Interferometric Synthetic Aperture Radar (SAR) Missions Employing Formation Flying"

This paper presents an overview of single-pass interferometric Synthetic Aperture Radar (SAR) missions employing two or more satellites flying in a close formation. The simultaneous reception of the scattered radar echoes from different viewing directions by multiple spatially distributed antennas enables the acquisition of unique Earth observation products for environmental and climate monitoring. After a short introduction to the basic principles and applications of SAR interferometry, designs for the twin satellite missions TanDEM-X and Tandem-L are presented. The primary objective of TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurement) is the generation of a global Digital Elevation Model (DEM) with unprecedented accuracy as the basis for a wide range of scientific research as well as for commercial DEM production. This goal is achieved by enhancing the TerraSAR-X mission with a second TerraSAR-X like satellite that will be launched in spring 2010. Both satellites act then as a large single-pass SAR interferometer with the opportunity for flexible baseline selection. Building upon the experience gathered with the TanDEM-X mission design, the fully polarimetric L-band twin satellite formation Tandem-L is proposed. Important objectives of this highly capable interferometric SAR mission are the global acquisition of three-dimensional forest structure and biomass inventories, large-scale measurements of millimetric displacements due to tectonic shifts, and systematic observations of glacier movements. The sophisticated mission concept and the high data-acquisition capacity of Tandem-L will moreover provide a unique data source to systematically observe, analyze, and quantify the dynamics of a wide range of additional processes in the bio-, litho-, hydro-, and cryosphere. By this, Tandem-L will be an essential step to advance our understanding of the Earth system and its intricate dynamics. Enabling technologies and techniques are described in detail. An ou--tlook on future interferometric and tomographic concepts and developments, including multistatic SAR systems with multiple receivers, is provided. [J15]

## "Coherency Matrix Estimation of Heterogeneous Clutter in High-Resolution Polarimetric SAR Images"

This paper presents an application of the recent advances in the field of spherically invariant random vector (SIRV) modeling for coherency matrix estimation in heterogeneous clutter. The complete description of the polarimetric synthetic aperture radar (POLSAR) data set is achieved by estimating the span and the normalized coherency independently. The normalized coherency describes the polarimetric diversity, while the span indicates the total received power. The main advantages of the proposed fixed-point (FP) estimator are that it does not require any a prioriinformation about the probability density function of the texture (or span) and that it can directly be applied on adaptive neighborhoods. Interesting results are obtained when coupling this FP estimator with an adaptive spatial support based on the scalar span information. Based on the SIRV model, a new maximum-likelihood distance measure is introduced for unsupervised POLSAR classification. The proposed method is tested with both simulated POLSAR data and airborne POLSAR images provided by the Radar Ae?? roporte?? Multi-Spectral d'Etude des Signatures system. Results of entropy/alpha/anisotropy decomposition, followed by unsupervised classification, allow discussing the use of the normalized coherency and the span as two separate descriptors of POLSAR data sets. [J16]

## "Bistatic Scattering of GPS Signals Off Arctic Sea Ice"

This paper evaluates the potential of a global positioning system (GPS) bistatic radar for the retrieval of information concerning the presence and condition of sea ice cover. For this purpose, the permittivityand roughnessof a ground scattering target at L-band are extracted from reflected GPS waveforms collected from an airborne platform using the Kirchhoff approximation for the surface cross section. The retrieved GPS estimates are then evaluated against collocated measurements of surface roughness obtained from a lidar profiler and a reference classification of sea ice types inferred from a multisensor data set that includes polarimetric microwave emissions, RADARSAT backscatter, and Moderate Resolution Imaging Spectroradiometer infrared/visible

imagery. [J17]

## "Polarimetric MIMO Radar With Distributed Antennas for Target Detection"

Multiple-input-multiple-output (MIMO) radar systems with widely separated antennas enable viewing the target from different angles, thereby providing spatial diversity gain. Polarimetric design of the transmit waveforms based on the properties of the target scattering matrix provides better performance than transmitting waveforms with only fixed horizontal or vertical polarizations. We propose a radar system that combines the advantages of both systems by transmitting polarized waveforms from multiple distributed antennas, in order to detect a point-like stationary target. The proposed system employs 2-D vector sensors at the receivers, each of which measures the horizontal and vertical components of the received electric field separately. We design the Neyman-Pearson detector for such systems. We derive approximate expressions for the probability of false alarm (PFA) and the probability of detection (PD). Using numerical simulations, we demonstrate that optimal design of the antenna polarizations provides improved performance over MIMO systems that transmit waveforms of fixed polarizations over all the antennas. We also demonstrate that having multiple widely separated antennas gives improved performance over single-input-single-output (SISO) polarimetric radar. We also demonstrate that processing the vector measurements at each receiver separately gives improved performance over systems that linearly combine both the received signals to give scalar measurements. [J18]

## "Analysis of the KK-distribution with medium grazing angle sea-clutter"

Robust maritime surveillance with radar requires an accurate description of the backscatter from the sea. An estimated probability distribution of the backscatter is commonly used to determine the threshold for separating targets from clutter at a given false alarm rate. Data collected at medium to high grazing angles by the Defence Science Technology Organisation (DSTO) Ingara fully polarimetric X-band radar demonstrate that the commonly used K-distribution is not always adequate for modelling the probability distribution. This is especially the case for the horizontal polarisation and in regions of high backscatter where target detection can be a problem. An alternative proposed as a more accurate model in this region is known as the KK-distribution. The analysis presented in this study describes this model with the addition of multiple looks and a thermal noise component to produce greater accuracy in the mean and underlying shape. The threshold required to achieve a constant false alarm rate is then studied and compared with the K-distribution. [J19]

## "Experimental research of unsupervised Cameron/maximum-likelihood classification method for fully polarimetric synthetic aperture radar data"

In this study, experimental research on classification is applied to fully polarimetric data in X-band from China. Considering the amplitude and phase error between H and V channels in the system, the authors firstly correct the error in original data. The authors also deduce the formula of Cameron's classification method for the real data in our study. Then Cameron's method is used to initially classify the site image. Finally, the initial classification map defines training sets for the maximum-likelihood (ML) classifier. The advantages of this method are the automated classification and interpretation of each class based on the scattering mechanism. The experiment demonstrates the feasibility of the proposed approach, which dramatically improves the X-band data classification result compared with the Cameron method and H/Γ,Bï/MLmethod. [J20]

## "A Scatterometer System for Laboratory Study of Polarimetric Electromagnetic Signatures of Icy Hydrometeors"

Radar sensors with dual-polarization capability allow a better understanding and characterization of weather hazards, particularly hydrometeor particles. The knowledge of natural polarimetric hydrometeor scattering signatures, on the other hand, has been limited in theoretical calculations, simulations, and radar measurements. In this paper, an experimental approach was designed with the assistance of a controlled laboratory environment. An advanced vector network analyzer-based scatterometer system has been developed in harmony with an environmentally monitored anechoic chamber with special configurations for hydrometeor measurements. The polarimetric radar cross section (RCS) of various natural and man-made icy hydrometeor samples is measured across wide X-band frequencies and compared with theoretical modeling results. The dual-polarization radar variables and hydrometeor melting parameters are derived from the RCS measurements with interesting observations obtained. The described technology and results serve as the basis of a new hydrometer microphysics knowledge base for hydrometeor classification processing in the next-generation multichannel dual-polarized hazard monitoring radars. [J21]

## "RADARSAT-2 and Coastal Applications: Surface Wind, Waterline, and Intertidal Flat Roughness"

RADARSAT-2 is a follow-up to RADARSAT-1 and is an all weather Earth observation satellite with fully polarimetric imaging capability. The synthetic aperture radars (SARs) onboard both RADARSATs are C-band imaging radars and they are well suited for Earth's ecosystem monitoring and maritime surveillance, because of the near polar orbit and their unique all weather imaging capability, independent of solar illumination. In this paper, RADARSAT-2 is first introduced and several applications of various modes of SAR data to coastal zone problems are discussed, including the coastal surface wind, waterline mapping, and polarimetric SAR data inversion for topographic and geological parameters of tidal flats. Coastal zones, the important interface between the land and the ocean, where a large proportion of the world's population inhabits, continuously change and evolve. The dynamic interaction of coastal winds, coupled with the coastal waves and currents, continuously erode rocks and land mass, and move and deposit various sediments on a continuous basis, along with the tides. Estimation of wind speeds and directions in coastal areas are empirically formulated and can further be improved with the available fully polarimetric data from RADARSAT-2. The water line mapping critically depends on the SAR frequency, or the wavelength of the SAR data used, and RADARSAT-2 SAR data using C-band should map waterlines more accurately than the longer wavelength L- or P-band SAR systems. The roughness parameters and partial information on the tidal flat compositions can be obtained from fully polarimetric SAR data. Some results obtained from NASA AIRSAR(2000) L-band data and RADARSAT-2(2008) C-band data do not fully agree with field measurements and further investigation is in progress. The inversion of polarimetric SAR data is a very complex problem and critically depends on the SAR signal frequency and model functions. RADARSAT-2 is an imaging radar, which is very flexible and powerfu--l tool for potential coastal zone applications. Key RADARSAT-2 features and potential coastal zone application capabilities are also briefly reviewed. [J22]

## "Nonlinear Calibration of Polarimetric Radar Cross Section Measurement Systems"

Polarimetric radar cross section measurement systems are characterized by polarimetric system parameters εhand εv. These parameters can be measured by use of rotating dihedrals. The full polarimetric dataset as a function of the angle of rotation can be analyzed with a nonlinear set of calibration equations to yield the system-parameter complex constants and the four polarimetric-calibration amplitudes. These amplitudes appropriately reproduce the system's drift, and very accurately satisfy a drift-free system-configuration criterion. The results indicate that the nonlinear approach is better than the previously studied linear approach, which yielded system parameters that were seriously distorted by system drift. [J23]

## "Finding Underground Targets by Means of Change-Detection Methods in Huynen Spaces"

A different and useful approach is presented for detecting new events in a scene, such as the presence or absence of landmines or perhaps the movement of people, vehicles, or structures. The approach rests on the radar examination of an area several times, once, before there are targets present, and the other (or others) after. The change detection algorithm notices if there are any changes after the first view. In the present approach the prospective target is represented, not in terms of three complex elements of a scattering matrix, but in terms of phenomenologically-based Huynen parameters. Each element of the Huynen parameter set conveys a different type of physical and geometrical attribute about the scatterers, thus the potential for significant false-alarm mitigation is increased. We provide results of the application of this approach on fully polarimetric signatures of simulated pairs of buried cylindrical targets. These results indicate the following. 1) Huynen parameters are more effective for change detection than the scattering matrix elements because of their ability to generate higher unambiguous autocorrelation peaks and fewer dominating cross-correlation curves. 2) A large number of symmetries are observed in the plots of the Huynen parameters for both one and two buried cylinders. These symmetries may eventually lead to further classification insights. 3) By using standard Prony methods, relevant resonance frequencies are extracted from the parameter plots, from which the height of either one of the cylinders is estimated. 4) The diameter of either cylinder can also be obtained by a simple procedure based on ray-tracing and time delays. Numerical calculations substantiate all the above assertions. [J24]

## "Improved Estimators of Faraday Rotation in Spaceborne Polarimetric SAR Data"

Spaceborne polarimetric synthetic aperture radar systems operating at lower frequencies, such as P-band, are significantly affected by Faraday rotation (FR). A new set of FR estimators is derived from the off-diagonal terms in the measured covariance matrix of a distributed target. These estimators have a phase ambiguity of period, instead of /2 as for the published estimators, and this ambiguity can be completely resolved for arbitrarily large values of FR using total electron content maps derived from Global Navigation Satellite System measurements. Simulations show that one of the new estimators has particularly high resistance to system noise and channel amplitude imbalance but greater sensitivity to channel phase imbalance than the published estimators. Hence, the expected values of residual system distortion after calibration may affect the choice of estimator. [J25]

## "Indoor 3D Full Polarimetric Bistatic Spherical Facility for Electromagnetic Tests"

A new indoor facility for electromagnetic measurements has been developed and built at the Detectability and Electronic Warfare Laboratory, INTA, Spain. The system was designed to extend the previous capabilities so that not only monostatic but also bistatic radar cross section (RCS) tests could be easily conducted. Due to limited space, far-field radar cross sections in the system are restricted to small targets, but this layout will allow the researchers to investigate ReS near-field-to-far-field transformations. The system was also conceived to be versatile enough to carry out other tests, such as near-field antenna measurements, material-absorption measurements, and electromagnetic characterization of materials. The paper describes the novel concept behind the facility, and presents some preliminary measurement results on different applications. [J26]

## "Aspect segmentation and feature selection of radar targets based on average probability of error"

Through statistical estimation by a non-parametric model, a fused polarimetric and resonant return from the radar target is modelled as a function of the target aspect angle. The outcome of this type of modelling is a set of non-parametric density estimates, which are then used to represent this target in a multi-dimensional probability space. These densities within this probability space can be well separated and therefore utilised to make decision rules to identify targets of interest. The return set to be modelled is the average power set associated with spectral bands centred on the target natural resonant frequencies. This return set is mapped into density set using a Gaussian kernel function; subsequently, the density set will be considered as the target radar feature set of interest. To decrease density overlapping between respective densities of different targets, a criterion based on the Bayesian error is employed; first, to bisect the aspect global range into smaller sectors, and second, to select discriminative features that can minimise the average probability of error between the targets respective features. The results show that two targets with similar resonant frequencies can be separated by the Bayesian error criterion based on the proposed features. A simple likelihood ratio test had more than 80% success down to 20%dB of signal-to-noise ratio. [J27]

## "Polarimetric SAR image fusion using nonnegative matrix factorisation and improved-RGB model"

Since different polarimetrie channels have different dynamical ranges, nonnegative matrix factorisation (NMF) is explored for fusing polarimetric SAR (PolSAR) data in a single colour image. The data of the three polarimetric channels (HH, HV and VV) with total power (TP) data is fully utilised to implement the NMF, and the choice of normalised factors for different polarimetric channels based on the same probability is applied, which produces an improved-RGB model. Combining the improved-RGB model with NMF, this approach brings in fusion images with higher spatial resolution and the power component preserved. [J28]

## "Scatterers characterisation in radar imaging using joint time-frequency analysis and polarimetric coherent decompositions"

Classical radar imaging generally considers targets as set of isotropic independent sources with a constant response in the measured frequency band. Nevertheless, new radar capabilities, in terms of signal bandwidth and angular excursion, may challenge this bright point model. Studies based on multidimensional time-frequency (TF) analysis, describing the angular and frequency behaviour of a scene-s reflectivity, showed that some scatterers may have anisotropic and dispersive responses. Polarisation diversity is an interesting additional source of information in radar imaging, and provides indicators closely linked to some geometric and electromagnetic properties of the observed objects. In this study, a fully polarimetric TF analysis is proposed for radar imaging (SAR, ISAR) that characterises the anisotropic and dispersive behaviour of the polarimetric response of deterministic targets. This method is based on the hyper-image concept, which describes the response of scatterers as a function of the observation angle, the emitted frequency and polarimetric canonical behaviours. Polarimetric hyper-images point out that non-stationary behaviours can be related to physical properties of the target (geometrical shape, relative orientation) and allow a better understanding of the scattering mechanisms. This polarimetric hyper-image representation is then used to detect non-stationary scatterers and to classify their behaviour. [J29]

## "Bistatic SAR experiment with the Ingara imaging radar"

Synthetic aperture radar (SAR) operation in a bistatic configuration not only offers various advantages over its now well-established monostatic counterpart but also poses various challenges. As part of a research programme into the potential benefits and challenges of bistatic SAR, the Ingarafully polarimetric X-band airborne imaging radar system, developed and operated by the Australian Defence Science and Technology Organisation, was upgraded to conduct experimental SAR data collections in a bistatic geometry. Initial trials of the new bistatic SAR system were conducted between December 2007 and April 2008: these involved operation

of the existing airborne radar in a fine-resolution (600 MHz bandwidth) circular spotlight-SAR mode, in conjunction with a newly developed fully polarimetric stationary ground-based bistatic receiver. These experimental trials produced a set of fully polarimetric simultaneously collected monostatic and bistatic SAR data, collected over a wide range of bistatic angles. Results from a preliminary analysis of the data have been encouraging: focussed fine-resolution imagery has been obtained, indicating the successful maintenance of synchronisation and phase stability between the independent airborne and ground-based systems. Furthermore, interferometric coherence has been demonstrated between single-pass simultaneously collected monostatic and bistatic images from the airborne and ground-based receivers, and between repeat-pass bistatic images from the ground-based receiver collected some 100 min apart. This study gives an overview of the Ingarabistatic SAR system, discusses the experiments and data processing and presents initial experimental results. [J30]

## "Iterative Bayesian Retrieval of Hydrometeor Content From X-Band Polarimetric Weather Radar"

Dual-polarized weather radars are capable to detect and identify different classes of hydrometeors, within stratiform and convective storms, exploiting polarimetric diversity. Among the various techniques, a model-supervised Bayesian method for hydrometeor classification, tuned for S- and X-band polarimetric weather radars, can be effectively applied. Once the hydrometeor class is estimated, the retrieval of their water content can also be statistically carried out. However, the critical issue of X-band radar data processing, and in general of any attenuating wavelength active system, is the intervening path attenuation, which is usually not negligible. Any approach aimed at estimating hydrometeor water content should be able to tackle, at the same time, path attenuation correction, hydrometeor classification uncertainty, and retrieval errors. An integrated iterative Bayesian radar algorithm (IBRA) scheme, based on the availability of the differential phase measurement, is presented in this paper and tested during the International H2O Project experiment in Oklahoma in 2002. During the latter campaign, two dual-polarized radars, at S- and X-bands, were deployed and jointly operated with closely matched scanning strategies, giving the opportunity to perform experimental comparisons between coincident measurements at different frequencies. Results of the IBRA technique at X-band are discussed, and the impact of path attenuation correction is quantitatively analyzed by comparing hydrometeor classifications and estimates with those obtained at S-band. The overall results in terms of error budget show a significant improvement with respect to the performance with no path attenuation correction. [J31]

## "Algorithm for estimating co-polarised phase-difference using radiative transfer method and comparison with measurements"

A simple algorithm for estimating the co-polarised phase-difference of polarimetric radar backscatters from vegetated surfaces is proposed. The algorithm is verified by polarimetric scatterometer measurements of wetland rice fields at 5.3 GHz. It is also shown that the measured degrees of correlation of the rice fields are quite sensitive to incidence angle and the rice age. [J32]

## "Compact polarimetric SAR interferometry"

The authors discuss the role and performance of compact polarimetry in SAR interferometry. The considered SAR architecture transmits either a linearly polarised wave oriented at 45Г‚В° or a circularly polarised one, and receives at horizontal and vertical polarisation. Two polarimetric acquisitions are combined in an interferometric image, characterised by a polarimetric and interferometric (POLINSAR) covariance matrix. The expression of the covariance matrix for compact polarimetry is derived and the relationship between compact and full polarimetric covariance matrices is discussed. On the basis of symmetry properties of geophysical media, the authors propose a reconstruction algorithm of the full polarimetric information from a compact polarimetric dataset. The algorithm allows the assessment of compact POLINSAR and the comparison between the two compact configurations. The authors consider forested areas and compare the interferometric degree of coherence measured at different polarisations by compact polarimetry and full polarimetry. The study shows that the degree of coherence from a compact polarimetric architecture carries enough information for POLINSAR applications, such as forest parameters retrieval, if the symmetry properties are satisfied. Airborne data acquired by the DLR E-SAR sensor over the Traunstein forest are used to illustrate the results. [J33]

## "ESA'S POLarimetric Airborne Radar Ice Sounder (POLARIS): design and first results"

The Technical University of Denmark has developed and tested a P-band ice sounding radar for European Space Agency (ESA). With the recent by the International Telecommunication Union (ITU) allocation of a radar band at 435 MHz, increased interest in space-based sounding of the Earth s ice caps has been encountered. ESA s POLarimetric Airborne Radar Ice Sounder (POLARIS) is intended to provide a better understanding of P-band scattering and propagation through ice sheets and to verify novel surface clutter suppression techniques in preparation for a potential space-based ice sounding mission. POLARIS is a nadir-looking, fully polarimetric

radar featuring aperture synthesis, a multi-aperture antenna for surface clutter suppression and a large dynamic range based on a shallow/deep sounding approach. The system is installed in a De Haviland DHC-6 Twin Otter aircraft, and in May 2008, a proof-of-concept campaign was conducted in Greenland. This study outlines the design and implementation of the system, and based on first results it is concluded that in the central dry snow zone of Greenland, POLARIS can resolve shallow and deep internal ice layers, penetrate the thickest ice encountered and detect the bedrock. [J34]

## "Polarimetric Dual-Baseline InSAR Building Height Estimation at L-Band"

This letter generalizes a multibaseline interferometric synthetic aperture radar (InSAR) signal model to the polarimetric scenario. Based on this formulation, two high-performance spectral analysis techniques are adapted to process multibaseline Pol-InSAR observations. These new methods enhance the height estimation of scatterers by calculating optimal polarization combinations and allow the determination of their physical characteristics. Applying the proposed algorithms to urban environments, the building layover problem is analyzed by means of polarimetric dual-baseline InSAR measurements: the ground and building height are estimated. The techniques are validated using dual-baseline Pol-InSAR data acquired by DLR's Experimental SAR (E-SAR) system over Dresden city. [J35]

## "A Comparison of the Impact of QuikScat and WindSat Wind Vector Products on Met Office Analyses and Forecasts"

Several studies have demonstrated that retrievals of wind vectors from the WindSat polarimetric radiometer are of sufficient quality to be considered for assimilation in operational numerical weather prediction models. In this paper, WindSat data are used in a state-of-the-art global meteorological analysis and forecasting system. Each wind vector contains a directional ambiguity and so is assimilated in a similar way to that of scatterometer data. The forecast impact of using analyses containing information from WindSat data was investigated for a period during August and September of 2005, when a large number of tropical cyclones were present. Forecast errors were reduced in the surface pressure fields, and the average improvement across the forecast range was found to be 1.0%. This is comparable to the improvement of 1.1% found in the same fields when winds were assimilated from the QuikScat scatterometer. The impact on tropical cyclone tracks in the forecasts was also studied. The scatterometer improved (reduced) the track errors markedly by 25% in the analyses. When impacts across the forecast range out to five days were also included, the improvement was found to be 8%. In contrast, the assimilation of WindSat data improved the analysis track errors by 7%, although this figure was found to be 10% across the complete forecast range. [J36]

## "Polarimetric SAR Internal Calibration Scheme Based on T/R Module Orthogonal Phase Coding"

Two important aspects of internal calibration of polarimetric synthetic aperture radar (SAR) are discussed, i.e., individual transmit/receive module (TRM) calibration and system gain calibration. The system has a general structure utilizing a phased array antenna composed of dual-channel TRMs. TRM gain and phase calibration is carried out using orthogonal phase coding (OPC). The signal of the individual TRM is phase-encoded according to a set of orthogonal codes to be separated from the composite calibration signal. OPC uses 1 bit of a digital phase-shifter for encoding, without the need for additional encoding hardware. Performance of the method is examined. Calibration results are developed both theoretically and through simulation in case of TRM amplifier or phase-shifter failure. Zero-padding is used to eliminate calibration error of the first TRM. A crosstalk model is proposed to investigate the effect of imperfect isolation between the two polarization channels of each TRM, and a way to reduce this error is also given. At last, system path gain variation is measured utilizing the internal calibration loop. The OPC method has an accuracy of 0.2 dB for gain and better than 2deg for phase, with 10-dB signal-to-noise ratio and perfect isolation between the two polarization channels. The error due to imperfect isolation is usually small and can be ignored. The simple way to detect TRM malfunction is verified through simulation, and it is also in accordance with TerraSAR-X in-orbit calibration outcomes. The proposed OPC method is shown to be an effective way of internally calibrating TRMs of a phased array antenna. [J37]

## "Comparison of Compact Polarimetric Synthetic Aperture Radar Modes"

Compact polarimetry is a technique that allows construction of pseudo quad-pol information from dual-polarization synthetic aperture radar (SAR) systems. Compact polarimetry showed promise of being able to reduce the complexity, cost, mass, and data rate of a SAR system while attempting to maintain many capabilities of a fully polarimetric system. In this paper, we study different transmit/receive configurations to determine which polarimetric configurations allow for superior reconstruction of the fully polarimetric data. We discuss modifications of the original reconstruction algorithm proposed by Souyris, which show potential to better reconstruct fully polarimetric data. [J38]

## "Measurements of Faraday Rotation Using Polarimetric PALSAR Images"

For spaceborne synthetic aperture radar (SAR) systems operating at L-band frequencies or lower, the ionosphere may have a significant impact on the SAR images. The largest effect at L-band is caused by Faraday rotation (FR). Several studies have modeled the effect of FR and/or devised models to measure and correct FR. With the launch of the fully polarimetric L-band system Phased Array-type L-band SAR (PALSAR), it has become possible to test both models and measurement techniques on real SAR data. In this letter, the quality of calibrated polarimetric PALSAR data is assessed, and FR is measured. It is found that residual crosstalk and channel imbalance are small in the PALSAR data. Two methods are used to measure FR, the first using in-scene distributed targets and the second using large trihedrals. The two methods show very good agreement. The measurements are compared with values of the total electron content using a linear model. It is found that the model and measurements are in good agreement, with a root-mean-square error of 0.3degor 15% of the mean FR angle. [J39]

## "Target Estimation, Detection, and Tracking"

In this article, we explore the adaptive design of radar polarization waveforms for optimal performance, when the statistical properties of the target and clutter are unknown. We focus on a closed-loop system that sequentially estimates the target and clutter scattering parameters, and then uses these estimates to select the polarization of the subsequent waveforms. We demonstrate that the radar system performance is significantly improved when the polarization of the transmitted signal is optimally and adaptively selected to match the polarimetric aspects of the target and environment. In particular, we provide an overview of our recent results showing that the adaptive design of the radar signal polarization enables achieving optimal performance in several operating modes, including detection, estimation, and tracking. [J40]

## "Calibration of Polarimetric PALSAR Imagery Affected by Faraday Rotation Using Polarization Orientation"

For spaceborne polarimetric synthetic aperture radar (SAR), it is important to ensure the removal of both polarimetric system distortion and the effect of Faraday rotation. This paper proposes a new calibration method to derive the system distortion using polarization orientation (PO) induced in built-up areas and applies to Phased-Array-Type L-Band SAR (PALSAR) calibration. Faraday rotation is corrected by the circular-polarization-based method from the distortion matrix (DM)-calibrated data. The derived DMs do not coincide with those by the Japan Aerospace Exploration Agency (JAXA), but our calibration results compare well to JAXA's results in PO angles and calibrator's responses. The two results satisfy polarimetric calibration requirements, and the cross-polarized isolation improves by more than 5 dB after Faraday rotation correction following DM calibration-even in the case of small Faraday rotation (-2deg to -0.5deg). The proposed method is robust to noise and is useful when using an area of mixed polarimetric response for calibration. This method is also applicable to a large crosstalk system and the case of large Faraday rotation. [J41]

## "Verification of Polarimetric Calibration Method Including Faraday Rotation Compensation Using PALSAR Data"

The spaceborne Phased Array L-band Synthetic Aperture Radar (PALSAR) needs polarimetric calibration in order for PALSAR data to be utilized for various applications such as geophysical analysis. In case of a PALSAR system using L-band, the Faraday rotation (FR) effect, which rotates the polarization plane of radio waves, becomes a problem when full-polarimetric observation data are used, such as target classification using polarization synthesis. Therefore, we need to estimate and remove both antenna distortion matrices and the FR effect. In this paper, we propose a polarimetric calibration method taking both channel imbalance and crosstalk of receiving and transmitting antennas and FR effect into consideration using two reference reflectors, namely, polarization preserving reflector and polarization rotating one. Then, we apply our calibration method to PALSAR data and derive antenna distortion matrices and FR angle simultaneously. Our calibration results show that the estimated antenna distortion matrices are almost equal to the calibration results from the Japan Aerospace Exploration Agency and that the estimated FR angle has a reasonable value. [J42]

## "Polarimetric PALSAR Calibration"

Polarimetric Phased-Array-type L-band Synthetic Aperture Radar (PALSAR) system parameters are assessed using data sets collected over several calibration sites. The data collected over the Amazonian rain forest help validate the hypothesis that Faraday rotation is zero near the equator. The analysis of the Amazonian forest data and the response of the corner reflectors deployed there during the PALSAR acquisitions lead to the conclusion that the antenna is highly isolated (better than -35 dB). These results are confirmed using the data collected

over calibration sites located in Sweden and Canada. The 5-m-height corner reflector deployed at the Remningstorp (Sweden) calibration site by Chalmers University of Technology provides accurate measurement of antenna parameters and detection of a (2deg -3deg) Faraday rotation during day-time acquisitions, whereas no Faraday rotation was noted during night-time acquisitions. Small Faraday rotation angles (2deg-3deg) have been measured using acquisitions over the DLR Oberpfaffenhofen and the Ottawa calibration sites. The presence of small but still significant Faraday rotation (2deg-3deg) induces a corner reflector return at the cross-polarization HV and VH that should not be interpreted as the actual antenna crosstalk. These results show that the PALSAR antenna is highly isolated (better than -35 dB), and diagonal antenna distortion matrices (with zero crosstalk terms) can be used for accurate calibration of PALSAR polarimetric data. [J43]

## "Forest Biophysical Parameter Estimation Using L- and P-Band Polarimetric SAR Data"

L- and P-band airborne polarimetric synthetic aperture radar (SAR) data acquired by the RAMSES system over different height maritime pine (Pinus Pinaster Ait.) stands of the Nezer forest (Landes, France) have been evaluated for forest biophysical parameter estimation. A pseudolinear correlation has been brought to evidence at P-band between polarimetric anisotropy and mean tree height, which is also linked to other biophysical parameters in the Nezer forest, meaning that SAR polarimetry constitutes a promising tool for forest parameter retrieval at low frequency. The spatial conditions have been evaluated through the quantification of the impact of signal-to-noise ratio diminution and resolution degradation on the forest height inversion. It has been shown that the inversion accuracy remains acceptable for N Esigma0, representing the noise level of the SAR image, which is lower than -15 dB, and for spatial resolution increasing up to 15 m. [J44]

## "Statistics of the Polarimetric Weibull-Distributed Electromagnetic Wave"

The statistical properties of partially polarized light in Gaussian stochastic plane wave fields have been reported in the literature. In this paper, we examine the statistics of the stochastic plane electromagnetic (EM) wave fields that are Weibull distributed. The polarimetric Weibull-distributed wave is characterized by three parameters: the sum of the intensities of the two electric vector components, the orientation angle that the major axis makes with the reference coordinate system, and the ratio of the minor to the major axis. The joint and marginal probability densities of these random variables are determined as a function of the covariance matrix. The main properties of this important distribution are shown. Then, the statistical properties of the normalized Stokes parameters are described in detail in Weibull-distributed stochastic fields. The joint and marginal probability density functions of the three components of the normalized Stokes parameters are presented. Numerical simulations are operated, which coincide with the theoretical derivations. Comparisons between Gaussian and Weibull stochastic fields have been made. The presented statistics of the Weibull polarimetric wave will be useful to random medium scattering and speckle filtering, which can also be extended to deal with the characterization of the scattering matrix elements in radar polarimetry. [J45]

## "Algebraic Synthesis of Forest Scenarios From Multibaseline PolInSAR Data"

In this paper, a new methodology is proposed for the analysis of forested areas basing on multipolarimetric multibaseline synthetic aperture radar (SAR) surveys. Such a methodology is based on three hypotheses: 1) statistical uncorrelation of the different scattering mechanisms (SMs), such as ground, volume, and ground-trunk scattering; 2) independence of volumetric and temporal coherence losses of each SM on the choice of the polarimetric channel; and 3) invariance (up to a scale factor) of the average polarimetric signature of each SM with respect to the choice of the track. Under these hypotheses, the data covariance matrix can be expressed as a Sum of Kronecker Products, after which it follows that K SMs are uniquely identified by K (K-1) real numbers. This result provides the basis to perform SM separation by employing not only model-based approaches, generally retained in literature but also model-free and hybrid approaches, while yielding the best Least Square solution given the hypothesis of K SMs. It will be shown that this approach to SM separation is consistent with the inversion procedures usually exploited in single-baseline polarimetric SAR interferometry. Experimental validation of this methodology is provided on the basis of the P-band data set relative to the forest site of Remningstorp, Sweden, acquired by German Aerospace Center's E-SAR airborne system in the framework of the European Space Agency campaign BioSAR. [J46]

## "POLSAR Image Analysis of Wetlands Using a Modified Four-Component Scattering Power Decomposition"

It is important to monitor environmental changes of the Earth's cover by remotely sensed data. This paper analyzes seasonal changes of a wetland by a modified polarimetric four-component scattering power decomposition method. The data sets analyzed here are L- and X-band fully polarimetric synthetic aperture radar (POLSAR) data, which have been acquired by the NICT/JAXA airborne polarimetric and interferometric

synthetic aperture radar system in 2004. Since there existed a deficiency in the currently adopted decomposition schemes in that negative powers appear in a few pixels in the image analysis, we modified the approach taking into account physical conditions. It is shown by the modified scheme that the seasonal changes and features of the vegetation near Sakata Lagoon in Niigata, Japan, are observed clearly, demonstrating the utility of POLSAR image analysis for wetland assessments in general. [J47]

## "Classification of Ground Clutter and Anomalous Propagation Using Dual-Polarization Weather Radar"

This paper presents the results of a study designed to classify weather radar clutter echoes obtained from ground-based dual-polarization weather radar systems. The clutter signals are due to ground clutter, sea clutter, and anomalous propagation echoes, which represent sources of error in quantitative radar rainfall estimation. Fuzzy and Bayes classifiers are evaluated as an alternative approach to traditional polarimetric-based methods. Both systems were trained and validated by using C-band dual- polarization radar measurements, and a novel technique is proposed to calculate the texture function to mitigate against the edge effects at the boundaries of precipitation regions. A methodology is presented to extract the membership functions and conditional probability density functions to train the classifiers. The critical success index indicates that the Bayes classifier has, on average, a slightly better performance than the fuzzy classifiers. However, when optimal weighting was applied, the fuzzy classifier gave one of the best performances. The classifiers are sufficiently robust to be used when only single-polarization radar measurements are available. [J48]

## "A Refined GTD Ray System for an Embedded Object and Its Polarimetric Behavior"

A refined ray system based on the geometrical theory of diffraction (GTD) for an object embedded in soil for a monostatic transmitter-receiver alignment is presented. Apart from the investigation of the ldquoclassicalrdquo reflections from the target, creeping waves are also taken into account, and their formalism is presented. The objective of such a ray set is to better understand the different scattering mechanisms, which are presented in the complex scattering framework. In electromagnetic modeling based on GTD, the complex shape of a target is replaced by simpler canonical objects, e.g., facets, cones, wedges, spheres, or cylinders. Here, a cylinder is located in parallel and closely to the plane interface of two dielectric half-spaces. The example of air-soil is taken into account. The numerical results obtained for various directions of incidence are employed to describe the polarimetric characteristics of the diffracted field from grazing to perpendicular incidence to the surface. By representing the diffracted GTD field on the Poincare sphere, the location on the sphere has a one-to-one relationship to the dielectric properties of the soil. The relation can be employed to extract information as the soil moisture. [J49]

## "Adaptive Polarized Waveform Design for Target Tracking Based on Sequential Bayesian Inference"

In this paper, we develop an adaptive waveform design method for target tracking under a framework of sequential Bayesian inference. We employ polarization diversity to improve the tracking accuracy of a target in the presence of clutter. We use an array of electromagnetic (EM) vector sensors to fully exploit the polarization information of the reflected signal. We apply a sequential Monte Carlo method to track the target parameters, including target position, velocity, and scattering coefficients. This method has the advantage of being able to handle nonlinear and non-Gaussian state and measurement models. The measurements are the output of the sensor array; hence, the information about both the target and its environment is incorporated in the tracking process. We design a new criterion for selecting the optimal waveform one-step ahead based on a recursion of the posterior Cramer-Rao bound. We also derive an algorithm using Monte Carlo integration to compute this criterion and a suboptimal method that reduces the computation cost. Numerical examples demonstrate both the performance of the proposed tracking method and the advantage of the adaptive waveform design scheme. [J50]

## "Polarimetric Detection of Targets in Heavy Inhomogeneous Clutter"

Polarization diversity has proved to be a useful tool for radar detection, especially when discrimination by Doppler effect is not possible. In this paper, we address the problem of improving the performance of polarimetric detectors for targets in heavy inhomogeneous clutter. First, we introduce a new polarimetric radar model that includes the realistic dependence of the clutter reflections on the transmitted signal. Then, we develop a polarimetric detection test that is robust to inhomogeneous clutter. We run this polarimetric test against synthetic and real data to assess its performance in comparison with existing polarimetric detectors. Finally, we propose a polarimetric waveform-design algorithm to further improve the target-detection performance. A numerical analysis is presented to demonstrate the potential performance improvement that can be achieved

with this algorithm. [J51]

## "Application of Bispectrum Estimation for Time-Frequency Analysis of Ground Surveillance Doppler Radar Echo Signals"

A microwave coherent homodyne and polarimetric ground surveillance Doppler radar is employed for collecting the radar returns from moving objects. Nonstationary nonlinearly frequency-modulated and multicomponent backscattered signals are analyzed and described as a sum of Doppler frequency-shifted polynomial chirp-like components. Instantaneous frequencies corresponding to the radiation backscattered by the different parts of a moving spatially distributed object are extracted from the time-varying bimagnitude estimates of transient sample sequences separated from the total received signal by a sliding window and projected into the time-frequency (TF) domain. Experimental investigations demonstrate a clean recovery of evolutionary phase-coupled harmonics for such targets as a swinging metallic sphere or a walking human. The computed TF distributions can be used in radar automatic target recognition systems to retrieve new data for the classification and recognition of ground moving objects. [J52]

## "Information Theory-Based Approach for Contrast Analysis in Polarimetric and/or Interferometric SAR Images"

We propose a new approach for evaluating the contribution of the different channels of polarimetric and interferometric synthetic aperture radar (PolInSAR) images. For that purpose, we demonstrate that the Bhattacharyya distance between the probability density functions of neighboring regions in the image provides an efficient scalar contrast measure. We show that the analysis of this contrast measure allows one to precisely characterize the contribution of each channel for different system configurations, including intensity, polarimetric, and interferometric images. We illustrate this approach using a real synthetic aperture radar image to compare several polarimetric system architectures. Since PolInSAR imaging configurations can correspond to complex and expensive systems, the proposed method can be helpful in system imaging optimization. [J53]

## "Evaluation and Bias Removal of Multilook Effect on Entropy/Alpha/Anisotropy in Polarimetric SAR Decomposition"

Entropy, alpha, and anisotropy (H/alpha/A) of the polarimetric target decomposition have been an effective and popular tool for polarimetric synthetic aperture radar (SAR) image analysis and for a geophysical parameter estimation. However, multilook processing can severely affect the values of these parameters. In this paper, a Monte Carlo simulation is used to evaluate and remove the bias generated by the multilook effect on these parameters for various media composed of grassland, forest, and urban returns. Due to insufficient averaging, entropy is underestimated, and anisotropy is overestimated. We also found that the bias in the alpha angle can be either underestimated or overestimated depending on scattering mechanisms. Based on simulation results, efficient bias removal procedures have been developed. In particular, the entropy bias can be precisely corrected, and the amount of correction is independent of the radar frequency and SAR systems. Data from L-band Advanced Land Observing Satellite/phased array type L-band SAR, German Aerospace Research Center (DLR)/enhanced SAR, Jet Propulsion Laboratory (JPL)/airborne SAR, and X-band polarimetric and interferometric SAR are used for demonstration in this paper. [J54]

## "Forest Height Inversion Using High-Resolution P-Band Pol-InSAR Data"

In this paper, a high-resolution P-band Pol-InSAR data set acquired by the airborne RAMSES system over pine forest stands of different height is investigated. A significant penetration depth in all the polarimetric channels and a wide range of polarimetric phase center heights are observed, attesting of an interaction of the radar waves with different forest structural elements. The main objective of this paper concerns forest height inversion at P-band. First, forest-modeling assumptions are evaluated using aprioriinformation, such as ground-level and forest height measurements. The full extend of the forest height is shown to be responsible of the volume decorrelation, and a significant orientation effect is clearly identified over the highest stands. As a consequence, the Oriented Volume over Ground model (OVoG) is determined to be the most appropriated model for the forest height inversion. At P-band, the ground contribution is present in all the polarimetric channels due to the important penetration at this frequency. To overcome this difficulty, a time-frequency optimization method based on sublook decomposition is developed to separate the pure ground and canopy contributions, allowing forest height estimation with OVoG with an rms error on the order of 2 m. In the last section of this paper, a sensitivity analysis of the inversion with respect to two important system parameters, the signal-to-noise ratio and the resolution, is presented, leading to a discussion on the inversion robustness in spaceborne conditions, where these system parameters are the most deteriorated as compared to airborne configurations. [J55]

## "Measurements and inferences of raindrop canting angles"

The canting angle distribution of raindrops derived separately from a 2D video disdrometer and from an S-band advanced polarimetric radar are presented. In the former case, measurements were made in both natural and artificial rain. The canting angles showed a symmetric distribution about 0deg with a standard deviation (sigmabeta) of 7deg-8deg in low wind conditions and 12deg in moderate wind conditions. In the radar-based estimates, the histogram of sigmabetaderived from data obtained during a light stratiform rain event with embedded convection shows the mode to be around 7deg, with a significant positive skewness. Around 16% of occurrences exceeded 10deg and 3.3% exceeded 15deg. [J56]

## "Polarimetric ISAR autofocusing"

Interest in polarimetric inverse synthetic aperture radar (ISAR) systems has been growing because of their capability to provide extra information about the imaged target compared with single polarisation ISAR systems. Target classification and recognition can be improved by exploiting full polarisation ISAR images. Moreover, full polarisation can be exploited for improving image formation and in particular image autofocusing. Two novel image autofocusing techniques are defined by extending two well-known single polarisation autofocusing techniques, namely the image contrast-based autofocus and image entropy-based autofocus. A performance analysis is carried out by comparing the results obtained by using the extended and the original autofocusing techniques. [J57]

## "The Compact Polarimetry Alternative for Spaceborne SAR at Low Frequency"

In spaceborne synthetic aperture radar (SAR), a single-polarization on-transmit offers twice the swath width compared to full polarization. This is linked to SAR system design issues, and, without getting into the technical details deserving by themselves a full paper, we can just mention the swath characteristics of ALOS PALSAR (the Advanced Land Observing Satellite, Phased Array L-Band Synthetic Aperture Radar), reducing from 70 km for the dual-pol mode to 30 km for the full polarization mode. The reduced coverage in the full polarization mode has a harmful impact on the revisit time, which is always a major drive for the Earth-observing community. The options chosen up to now for dual-pol system designs (or single-polarization on-transmit) rely on a linear polarization on-transmit [either horizontal (H) or vertical (V)], with two orthogonal polarizations on-receive. Souyris and Raney in earlier papers proposed more pertinent alternatives for the selection of the transmit polarization leading to a better characterization of the scattering mechanisms. In this paper, the analysis is pursued in more depth by including the effect of the ionosphere on the wave propagation and extending the applications to polarimetric interferometry SAR (PolInSAR). A compact mode is developed where the transmit polarization is circular, whereas the only constraint on the two receiving polarizations is independence. Indeed, the choice of the polarizations of the two receive channels does not matter, as any polarization on-receive can be synthesized from these two measurements. This is, however, not the case for the unique transmit polarization. At a low frequency, where the ionosphere has a significant effect, the circular transmit polarization is the only sensible option, as it provides an effective constant polarization as seen by the scattering surface. This is an essential condition for a meaningful multitemporal analysis. Both the polarimetric SAR applications and the PolInSAR appl--ications in the context of this compact polarimetry (CP) mode are explored. A pseudocovariance matrix can be reconstructed following Souyris' proposed approach for distributed targets and is shown to be very similar to the full polarimetric (FP) covariance matrix. The reconstruction of the cross-polarized Sigma0 is shown to be reliable and to have very low sensitivity to Faraday rotation. A PolInSAR vegetation height inversion for P-band is presented and applied to the CP data with a level of performance that is similar to the one derived from FP (a 1.2-m root-mean-square height error on the ONERA Airborne radar (RAMSES) data over the Landes Forest). A procedure is developed to correct for the ionospheric effects for the PolInSAR acquisition in the FP or CP mode and is assessed on the data simulated from an airborne acquisition. The results demonstrate that the technique is efficient and robust. The calibration of CP data is identified as an important challenge to be solved, and some clues are provided to address the problem. [J58]

## "Measurement and Characterization of Entropy and Degree of Polarization of Weather Radar Targets"

To date, few polarimetric weather radars have exhibited the capability to measure full scattering matrices. In contrast, in the synthetic aperture radar (SAR) community, considerable experience has been gained in dealing with complete scattering matrices and their statistical behavior. This paper aims to place weather radar parameters in a wider context in order to exploit more general concepts like target decomposition theorems and polarization basis transformations. Entropy, which is a fully polarimetric variable derived from the Cloude-Pottier decomposition, and the degree of polarization, which is derived from Wolf's coherence matrix, are the subject of this paper. The theoretical analysis carried out in the first part is checked against fully polarimetric data from

POLDIRAD, which is the german aerospace center research weather radar. The entropy and the degree of polarization are compared with the copolar correlation coefficient in order to understand whether they can add value to radar meteorological investigations. Because the degree of polarization is available to conventional dual-polarization coherent systems, it is important to assess its potential for operational use. [J59]

## "Stokes Antenna Temperatures"

The growing importance of polarimetric radiometers has led to the need for a detailed theory for Stokes antenna temperatures. In this paper, we provide a full Stokes vector formulation of an antenna temperature that accounts for the entire antenna pattern, which includes polarization mixing in the main-beam and sidelobe effects. To derive the Stokes antenna temperatures, we follow the conventional methods in the Earth remote sensing literature while relying on a coherency algebra approach from radio astronomy. Connections and parallels to the conventional approaches are noted along the way. We also introduce generalizations of beam efficiency and cross polarization for use with polarimetric radiometers. These provide important metrics in the design of future systems. [J60]

## "Atmospheric Artifact Compensation in Ground-Based DInSAR Applications"

In this letter, a coherence-based technique for atmospheric artifact removal in ground-based (GB) zero-baseline synthetic aperture radar (SAR) acquisitions is proposed. For this purpose, polarimetric measurements acquired using the GB-SAR sensor developed at the Universitat Politecnica de Catalunya are employed. The heterogeneous environment of Collserola Park in the outskirts of Barcelona, Spain, was selected as the test area. Data sets were acquired at X-band during one week in June 2005. The effects of the atmosphere variations between successive zero-baseline SAR polarimetric acquisitions are treated here in detail. The need to compensate for the resulting phase-difference errors when retrieving interferometric information is put forward. A compensation technique is then proposed and evaluated using the control points placed inside the observed scene. [J61]

## "Fitting a Two-Component Scattering Model to Polarimetric SAR Data From Forests"

Two simple scattering mechanisms are fitted to polarimetric synthetic aperture radar (SAR) observations of forests. The mechanisms are canopy scatter from a reciprocal medium with azimuthal symmetry and a ground scatter term that can represent double-bounce scatter from a pair of orthogonal surfaces with different dielectric constants or Bragg scatter from a moderately rough surface, which is seen through a layer of vertically oriented scatterers. The model is shown to represent the behavior of polarimetric backscatter from a tropical forest and two temperate forest sites by applying it to data from the National Aeronautic and Space Agency/Jet Propulsion Laboratory's Airborne SAR (AIRSAR) system. Scattering contributions from the two basic scattering mechanisms are estimated for clusters of pixels in polarimetric SAR images. The solution involves the estimation of four parameters from four separate equations. This model fit approach is justified as a simplification of more complicated scattering models, which require many inputs to solve the forward scattering problem. The model is used to develop an understanding of the ground-trunk double-bounce scattering that is present in the data, which is seen to vary considerably as a function of incidence angle. Two parameters in the model fit appear to exhibit sensitivity to vegetation canopy structure, which is worth further exploration. Results from the model fit for the ground scattering term are compared with estimates from a forward model and shown to be in good agreement. The behavior of the scattering from the ground-trunk interaction is consistent with the presence of a pseudo-Brewster angle effect for the air-trunk scattering interface. If the Brewster angle is known, it is possible to directly estimate the real part of the dielectric constant of the trunks, a key variable in forward modeling of backscatter from forests. It is also shown how, with a prioriknowledge of the forest height, an estimate for th- e attenuation coefficient of the canopy can be obtained directly from the multi-incidence-angle polarimetric observations. This attenuation coefficient is another key variable in forward models and is generally related to the canopy density. [J62]

## "Performance analysis of passive low-grazing-angle source localization in maritime environments using vector sensors"

We consider the problem of passive estimation of source direction-of-arrival (DOA) and range using polarization-sensitive sensor arrays, when the receiver array and signal source are near the sea surface. The scenario of interest is the case of low-grazing-angle (LGA) propagation in maritime environments. We present a general polarimetric signal model that takes into account the interference of the direct field with the field reflected from smooth and rough surfaces. Using the Cramer-Rao bound (CRB) and mean-square angular error (MSAE) bound, we analyze the performance of different array configurations, which include an electromagnetic vector sensor (EMVS), a distributed electromagnetic component array (DEMCA), and a distributed electric dipole array

(DEDA). By computing these bounds, we show significant advantages in using the proposed diversely polarized arrays compared with the conventional scalar-sensor arrays. [J63]

## "Microwave Observatory of Subcanopy and Subsurface (MOSS): A Mission Concept for Global Deep Soil Moisture Observations"

The Microwave Observatory of Subcanopy and Subsurface (MOSS) is a mission concept for a spaceborne synthetic aperture radar (SAR) system that provides global observations of soil moisture under substantial vegetation cover (exceeding 20 kg/m2) and at useful depths (1-5 m). The concept was developed and a number of new required technologies were demonstrated through a National Aeronautics and Space Administration Earth Science Technology Office Instrument Incubator Program project. This very high frequency (VHF)/ultrahigh frequency (UHF) polarimetric SAR is designed to provide 7-10-day observations of soil moisture at 1-km resolution. The rapid repeat cycle mandates swath widths in the range of 300-400 km, which must be realized by a 30-m-long antenna. Conventional array implementations would result in a mass of more than 4000 kg, whereas with the technology proposed and demonstrated in this project, the total antenna mass is less than 500 kg. The antenna concept is a dual-stacked patch array feed illuminating a 30-m mesh reflector to synthesize the long apertures and achieve the wide swath. The feed system prototype was fabricated and its performance demonstrated. Other major project components were: (1) system-level SAR and mission design; (2) demonstration of science data and products, using a tower-based VHF/UHF radar; (3) spacecraft and mesh reflector antenna mechanical design; (4) developing mitigation strategies for ionospheric effects; and (5) assessing frequency interference effects. Experimental science data were generated from the tower radar for soil moisture profiling in Arizona and for forest penetration in Oregon. The soil moisture products were demonstrated through an integrated inversion-processing algorithm. This paper summarizes the results from the MOSS project and demonstrates the feasibility of the spaceborne mission. [J64]

## "Polarimetric Calibration Using a Genetic Algorithm"

This letter presents a novel calibration approach to polarimetric synthetic aperture radar using distributed targets with known scattering characteristics. A genetic algorithm with complex-valued encoding is proposed to solve the overdetermined system of nonlinear equations associated with the polarimetric calibration problem. The proposed genetic algorithm is described in detail, and validation of the algorithm is performed by numerical simulations. [J65]

## "Measurement of radar signatures of passenger cars: airborne SAR multi-frequency and polarimetric experiment"

The launch of SAR satellites with high-resolution and dual-receive antenna capabilities opens new possibilities for traffic-monitoring applications on a global scale. Thus, it will be possible to detect cars and measure their speed from the acquired along track interferometric data. The development of vehicle-detection algorithms requires the knowledge of the radar signatures of vehicles, especially under consideration of the geometry of the radar look direction and the vehicle orientation. The radar signatures of the non-moving cars are presented. They are estimated experimentally from airborne E-SAR multi-frequency and polarimetric data, which have been collected during a flight campaign in 2003. Radar signatures are estimated for a considerable part of aspect angles ranging from 0deg to 180deg. The large synthetic aperture length of the E-SAR radar sensor allows the look processing of data and therefore allows an increase of the aspect angle resolution. The radar signature analysis for one type of passenger cars showed that the largest radar cross-section values and thus the greatest chance for high probability of detection are for cars standing in rear and front views of radar beam direction. This holds true for all frequencies and co-polarisations. Radar cross-section values for cross-polarisations and diagonal views are much lower and are therefore less suitable for car detection. The radar signature profile over a considerable range of aspect angles in fine resolution can be used further for the verification of simulation studies and for the performance prediction for traffic monitoring with a coming German TerraSAR-X satellite [J66]

## "MMW Polarimetric Radar Bistatic Scattering From a Random Surface"

This paper explores the nature of bistatic radar scattering from terrain by reporting the results of an investigation involving measurements of the hemispherical pattern of the field scattered by a random soil surface. The measurements were performed by a 35-GHz fully polarimetric radar system with transmitter and receiver modules mounted on separate rotatable arches. The acquired data were analyzed to determine the angular sensitivities of several attributes of the scattered field, including amplitudes and phase differences of the polarized scattering coefficients, and their copolarized and cross-polarized ratios. Generally speaking, the scattering pattern exhibits a weak dependence on the scattering angle thetass(except along the backward

direction and forward specular direction), but it exhibits a strong dependence on the azimuth angle phi, particularly for the cross-polarized components. Much of the dependence is attributed to the vectorial definition of polarization in a standard frame of reference. Comparison of the measured data with calculations based on the second-order physical optics model reveals reasonable overall agreement between theory and observations (typically within 4 dB) [J67]

## "Polarimetric angular smoothing algorithm for an electromagnetic vector-sensor array"

The polarimetric angular smoothing (PAS) technique for coherent direction-of-arrival (DOA) estimation and adaptive beamforming is explored and enriched by taking into account the cross-correlations among the smoothed subarrays and using non-uniform weights. The PAS using annihilating weights is shown to be free of signal cancellation [which occurs in the conventional spatial smoothing (SS) technique for uncorrelated sources] while effectively suppressing coloured noise with unknown Toeplitz covariance matrix, but may be incompetent for DOA estimation. The PAS technique is still shown to be more attractive than the SS scheme in a very difficult situation that the direct signals and the reflecting signals are of very close DOAs. The penalised Toeplitz-block-Toeplitz scheme is further suggested for more thorough source decorrelation with an L-shaped electromagnetic vector-sensor array to gain improved interference suppression. The analytical expression for the mean-squared error of DOA estimates obtained from the weight-PAS pre-processed root-multiple signal classification is derived and analysed. A hybrid DOA estimator incorporating PAS and integrating some existing techniques is also described. Numerical results are finally given. [J68]

## "Variable Precision Two-Channel Phase, Amplitude, and Timing Measurements for Radar Interferometry and Polarimetry"

In this paper, we present a time-domain method for estimating the phase, amplitude, and timing of a test signal, referenced either to a theoretical version of the signal, or to another signal undergoing a similar transformation as the measured signal. The use of time-domain basis for this method allows for its direct application to data samples collected by a digital oscilloscope or a dedicated A/D converter, and precludes the need for conversion into in-phase and quadrature components. The estimation process described in this paper is based on a maximum likelihood formulation, which allows for the estimate performance to be related to errors associated with sampling and is shown to achieve the Cramer-Rao lower bound for variance. Measurements such as the ones described in this paper are important for characterizing interferometric and polarimetric radar systems, as well as for determining the number of observations necessary for achieving a given degree of accuracy in the measurement. By including a statistical description of the estimation process, we enable the ability for using the technique for evaluating hypotheses describing the measurement error model. This last point is critical because it creates a mechanism for accepting or rejecting system model scenarios based on the signal-to-noise ratio and the number of digitized samples. [J69]

## "Evaluation of a New Airborne Microwave Remote Sensing Radiometer by Measuring the Salinity Gradients Across the Shelf of the Great Barrier Reef Lagoon"

Over the last ten years, some operational airborne remote sensing systems have become available for mapping surface salinity over large areas in near real time. A new dual-polarized Polarimetric L-band Multibeam Radiometer (PLMR) has been developed to improve accuracy and precision when compared with previous instrument generations. This paper reports on the first field evaluation of the performance of the PLMR by measuring salinity gradients in the central Great Barrier Reef. Before calibration, the raw salinity values of the PLMR and conductivity-temperature-depth (CTD) differed by 3-6 psu. The calibration, which uses in situ salinity data to remove long-term drifts in the PLMR as well as environmental effects such as surface roughness and radiation from the sky and atmosphere, was carried out by equating the means of the PLMR and CTD salinity data over a subsection of the transect, after which 85% of the salinity values between the PLMR and CTD are within 0.1 psu along the complete transect. From offshore to inshore across the shelf, the PLMR shows an average cross-shelf salinity increase of about 0.4 psu and a decrease of 2 psu over the inshore 20 km at -19deg S (around Townsville) and -18deg S (around Lucinda), respectively. The average cross-shelf salinity increase was 0.3 psu for the offshore 100 km over all transects. These results are consistent with the in situ CTD results. This survey shows that PLMR provided an effective method of rapidly measuring the surface salinity in near real time when a calibration could be made. [J70]

## "Bistatic SAR ATR"

With the present revival of interest in bistatic radar systems, research in that area has gained momentum. Given some of the strategic advantages for a bistatic configuration, and technological advances in the past few years, large-scale implementation of the bistatic systems is a scope for the near future. If the bistatic systems are to

replace the monostatic systems (at least partially), then all the existing usages of a monostatic system should be manageable in a bistatic system. A detailed investigation of the possibilities of an automatic target recognition (ATR) facility in a bistatic radar system is presented. Because of the lack of data, experiments were carried out on simulated data. Still, the results are positive and make a positive case for the introduction of the bistatic configuration. First, it was found that, contrary to the popular expectation that the bistatic ATR performance might be substantially worse than the monostatic ATR performance, the bistatic ATR performed fairly well (though not better than the monostatic ATR). Second, the ATR performance does not deteriorate substantially with increasing bistatic angle. Last, the polarimetric data from bistatic scattering were found to have distinct information, contrary to expert opinions. Along with these results, suggestions were also made about how to stabilise the bistatic-ATR performance with changing bistatic angle. Finally, a new fast and robust ATR algorithm (developed in the present work) has been presented. [J71]

## "UAVSAR: New NASA Airborne SAR System for Research"

NASA's Jet Propulsion Laboratory is currently building a reconfigurable, polarimetric L-band synthetic aperture radar (SAR), specifically designed to acquire airborne repeat track SAR data for differential interferometric measurements. Differential interferometry can provide key deformation measurements, important for studies of earthquakes, volcanoes, and other dynamically changing phenomena. Using precision real-time GPS and a sensor controlled flight management system, the system will be able to fly pre-defined paths with great precision. The expected performance of the flight control system will constrain the flight path to be within a 10 m diameter tube about the desired flight track. The radar will be designed to be operable on a Unpiloted Arial Vehicle (UAV) but will initially be demonstrated on a NASA Gulfstream III. The radar will be fully polarimetric, with a range bandwidth of 80 MHz (2 m range resolution), and will support a 16 km range swath. The antenna will be electronically steered along track to assure that the antenna beam can be directed independently, regardless of the wind direction and speed. Other features supported by the antenna include elevation monopulse and pulse-to-pulse re-steering capabilities that will enable some novel modes of operation. The system will nominally operate at 45,000 feet (13,800 m). The program began as an Instrument Incubator Project (IIP) funded by NASA Earth Science and Technology Office (ESTO). [J72]

## "Bistatic Radar Imaging of the Marine Environment-Part II: Simulation and Results Analysis"

We present a bistatic, polarimetric, and real aperture marine radar simulator (MaRS) producing pseudoraw radar signals. The simulation takes the main elements of the environment into account (sea temperature, salinity, and wind speed). Realistic sea surfaces are generated using a two-scale model on a semideterministic basis to incorporate the presence of ship wakes. Then, the radar acquisition chain (antennas, modulation, and polarization) is modeled, as well as the movements of the sensors, on which uncertainties can be introduced, and ship wakes. The pseudoraw temporal signals delivered by MaRS are further processed using, for instance, bistatic synthetic aperture beamforming. The scene itself represents the sea surface as well as ship wakes. The main points covered here are the scene discretization, the ship wake modeling, and the computational cost aspects. We also present images simulated in various monostatic and bistatic configurations and discuss the results. This paper follows its companion paper, where much of the theory used here is recalled and developed in detail. a bistatic, polarimetric, and real aperture marine radar simulator (MaRS) producing pseudoraw radar signals. The simulation takes the main elements of the environment into account (sea temperature, salinity, and wind speed). Realistic sea surfaces are generated using a two-scale model on a semideterministic basis to incorporate the presence of ship wakes. Then, the radar acquisition chain (antennas, modulation, and polarization) is modeled, as well as the movements of the sensors, on which uncertainties can be introduced, and ship wakes. The pseudoraw temporal signals delivered by MaRS are further processed using, for instance, bistatic synthetic aperture beamforming. The scene itself represents the sea surface as well as ship wakes. The main points covered here are the scene discretization, the ship wake modeling, and the computational cost aspects. We also present images simulated in various--monostatic and bistatic configurations and discuss the results. This paper follows its companion paper, where much of the theory used here is recalled and developed in detail. [J73]

## "Least Squares Estimation of Doppler and Polarimetric Parameters for Weather Targets"

Doppler and polarimetric parameters have shown to be of great utility in weather radar applications. Different measurement schemes have been proposed and implemented to obtain Doppler and polarimetric information of the sensed weather target. To date, none of these methods is capable of providing all polarimetric and Doppler parameters of interest for the whole range of temporal correlation conditions. To obtain all parameters, some of the systems require to assume different hypotheses about the Doppler or polarimetric characteristics of the targets. Failure of the assumed hypotheses leads to unacceptable bias and loss of performance of the estimated parameters. Other methods reach a tradeoff, reducing either the number of polarimetric parameters to be

estimated or the maximum measurable range of Doppler parameters. With respect to polarimetric parameter estimation, it has already been shown that alternate transmission of three different polarizations improves polarimetric parameter estimation through decoupling of temporal and polarimetric effects. In this paper, this measurement system is generalized by means of a new data processing algorithm and a least squares estimation to provide joint estimates of all Doppler and polarimetric parameters for all temporal correlation conditions. No hypotheses are required. In fact, this method provides minimum variance unbiased linear estimates of all elements of the polarimetric covariance matrix. It also allows Doppler parameter estimation within their corresponding maximum measurable ranges, which are determined by the radar base pulse repetition frequency. The performance of Doppler parameter estimates is comparable to that reached by nonpolarimetric systems. Implementation of the method requires transmitting three known polarizations. Moreover, phase shifts between them should be either known or measured. [J74]

## "Surface-Based Polarimetric C-Band Scatterometer for Field Measurements of Sea Ice"

A portable surface-based polarimetric C-band scatterometer for field deployment over sea ice is presented. The scatterometer system, its calibration, signal processing, and near-field correction are described. The near-field correction is shown to be effective for both linear polarized and polarimetric backscatter. Field methods for the scatterometer are described. Sample linear polarized and polarimetric backscatter results are presented for snow-covered first-year sea ice (FYI), multiyear hummock ice, and rough melt pond water on FYI. The magnitude of backscatter signature variability due to system effects is presented, providing the necessary basis for quantitative analysis of field data. [J75]

## "Single-Pass Polarimetric SAR Interferometry for Vessel Classification"

This paper presents a novel method for vessel classification based on single-pass polarimetric synthetic aperture radar (SAR) interferometry. It has been developed according to recent ship scattering studies that show that the polarimetric response of many types of vessels can be described by trihedral- and dihedral-like mechanisms. The adopted methodology is quite simple. The input interferometric data are decomposed in terms of the Pauli basis, and hence, one height image is derived for each simple mechanism. Then, the local maxima of these images are isolated, and a 3-D map of scatters is generated. The correlation of this map with the scattering distribution expected for a set of reference ships provides the final classification decision. The performance of the proposed method has been tested with the orbital SAR simulator developed at Universitat Politecnica de Catalunya. Different vessel models have been processed with a sensor configuration similar to the incoming TanDEM-X system. The analysis of diverse vessel bearings, vessel speeds, and sea states shows that the map of scatters matches reasonably the geometry of ships allowing a correct identification even for adverse environmental conditions. [J76]

## "Robust inversion technique for retrieving soil moisture from multi-polarised backscatter of bare surface"

A robust inversion technique using a genetic algorithm (GA) for retrieving soil moisture content from the multi-polarised radar data of bare soil surfaces is presented. This inversion technique employs a semi-empirical polarimetric backscattering model as a cost function for the GA. Good agreement is found between the values estimated by this inversion technique and those measured in situ. [J77]

## "An evaluation of the potential of polarimetric radiometry for numerical weather prediction using QuikSCAT"

It has been proposed that wind vector information derived from passive microwave radiometry may provide an impact on numerical weather forecasts of similar magnitude to that achieved by scatterometers. Polarimetric radiometers have a lower sensitivity to wind direction than scatterometers at low wind speed but comparable sensitivity at high windspeed. In this paper, we describe an experiment which aimed to determine if an observing system only capable of providing wind direction information at wind speeds over 8 ms-1can provide comparable impact to one providing wind vectors at wind speeds over 2 ms-1. The QuikSCAT dataset used in the experiments has a wide swath and is used operationally by several forecast centers. The results confirm that assimilation of wind vectors from QuikSCAT only for wind speeds above 8 ms-1gives similar analysis increments and forecast impacts to assimilating wind vectors at all wind speeds above 2 ms-1. Measurements from the WindSat five frequency polarimetric radiometer are compared with calculations from Met Office global forecast fields, and this also confirms that WindSat measurement and radiative transfer model accuracy appears to be sufficiently good to provide useful information for numerical weather prediction. [J78]

## "PolInSAR analysis of X-band data over vegetated and urban areas"

This paper investigates the polarimetric and polarimetric interferometric synthetic aperture radar (PolInSAR) information contained in the high-resolution X-band data acquired by the RAMSES airborne SAR system over an area around Avignon, France containing bare surfaces, vegetation, and urban areas. The interferometric coherences are computed over natural and urban areas for all possible baseline copolar polarizations. In the complex plane, the obtained regions of coherence corresponding to most vegetation areas display small angular extents, meaning that if penetration occurs in the foliage, it is shallower than the system height accuracy. To quantify the PolInSAR information, an analysis of the interferometric height accuracy is first performed, and the results are compared with those associated with a theoretical and an empirical model. Concerning vegetation, a 6-m height difference is measured between the different polarimetric phase centers over a sparse pine forest, probably due to the presence of holes in the canopy. Crop study reveals also that wheat-type fields present oriented media properties at X-band due to their vertical structure. Over urban areas, in most cases, building height can be accurately obtained by using Pauli polarimetric phase center information. [J79]

## "Polarimetric Ka-band backscattering measurements at grazing-angle extremes"

Polarimetric millimeter-wave backscattering data has been measured in true operational environments for perpendicular illumination and for grazing angles below one degree. Manmade objects, such as vehicles and light poles, were found to give a 5-10 dB lower response for vertical polarization, and the cross-polarized returns were about 10-20 dB below the reference level obtained with horizontal polarization. Forest and soil backscattering showed similar characteristics of -7 to -9 dB (vertical) and -14 to -17 dB (cross-polar). An anomaly was observed for horizontally transmitted/vertically received data, where gravel soil showed only about 2 dB attenuation compared to the co-polar reference level. The dynamic variations of mobile target signals at different polarizations indicated that millimeter-wave cross-polarized returns call for high transmitter power if true polarimetric target classification is attempted. Close-to-ground radars seem to benefit from multipath and thus from using horizontal polarization if only maximum range is defined. Variations in the cross-polarized echo amplitudes of moving manmade objects were found to be within 3-5 dB of their typical mean values [J80]

## "Statistical analysis of measured polarimetric clutter data at different range resolutions"

This paper deals with the statistical modelling of radar backscattering from sea surface at low-grazing angles in high resolution radar systems. High-resolution polarimetric data at different range resolutions (60, 30, 15, 9 and 3 m) are analysed to highlight the differences in clutter statistical behaviour due to changes of resolution and/or polarisation. The clutter data were recorded by the IPIX radar of McMaster University in Grimsby, Ontario, Canada [J81]

## "Radar Polarimetry Analysis Applied to Single-Hole Fully Polarimetric Borehole Radar"

A fully polarimetric borehole radar system using four combinations of dipole and slot antennas was developed to acquire fully polarimetric data sets in drilled boreholes. First, to implement radar polarimetry analysis, a processing scheme suitable for analyzing a single-hole reflection data set acquired by the system is presented. This processing consists of antenna-characteristic compensation, migration for image reconstruction, and time-frequency analysis for single-frequency data set construction. Two polarimetric target decomposition methods, namely: 1) Pauli decomposition and 2) eigenvector-based decomposition, are applied to characterize the scattering problem of the subsurface fractures. The Pauli decomposition method provided important radar polarimetry information of fractures, and the eigenvector-based decomposition method made a significant contribution to understanding the scattering mechanisms from different fractures with different properties. Furthermore, information about fracture classification can be obtained by analysis of the H-alpha distribution provided by eigenvector-based decomposition of local radar image regions. The potential of polarimetric target decomposition techniques to fracture characterization is shown, which, in turn, provides valuable information about water permeabilities of fractures in hydrogeological studies [J82]

## "Investigations on the polarimetric behavior of a target near the soil"

The polarimetric behavior of the diffracted field from an object located close to the ground is investigated for a varying incidence angle. Here, the field is described by the geometrical theory of diffraction in accordance to its asymptotic formulas (krarrinfin). As a result, a ray system composed of 13 different rays was implemented for the monostatic case by applying the principle of Fermat. The different spatial and creeping waves give a physical insight in the mechanisms involved in the entire scattering process. By varying the angle from perpendicular to grazing incidence 0deg-90deg, geometrical surface shadow boundaries are present for the backscattered field. At such boundaries, the spatial waves are replaced by their corresponding creeping waves, leading to a strong attenuation. The diffracted field for look angles related to the transition zones has a characteristic polarimetric behavior, which can be represented on the Poincare sphere. The typical locations on the sphere can be

exploited to get information about the geometrical parameters of the target and its height above the ground [J83]

## "Implementation of fully polarimetric random noise radar"

A heterodyne correlation receiver technique has been developed for coherent processing of backscatter data acquired by a radar system transmitting ultrawideband (UWB) random noise waveforms. In such a receiver, the reflected signal is correlated with a time-delayed and frequency-shifted version of the transmitted waveform, which is able to provide the phase of the reflected waveform. We describe the implementation of fully polarimetric capability in a coherent random noise radar system operating in the ultrahigh frequency (UHF) range designed for foliage penetration (FOPEN) applications. Using this implementation, the polarimetric response of various foliage targets has been characterized. [J84]

## "Slicks detection on the sea surface based upon polarimetric SAR data"

This letter proposes a generalized-likelihood ratio test-based edge detector to be fed by possibly polarimetric synthetic aperture radar (SAR) data. It can be used to detect dark spots on the sea surface and, hence, as the first stage of a system for identification and monitoring of oil spills. The proposed constant false alarm rate (CFAR) detector does not require secondary data (namely pixels from a slick-free area); remarkably, a preliminary performance assessment, carried out by resorting to real SAR recordings, shows that it guarantees detection capabilities comparable to those of previously proposed polarimetric CFAR detectors (which though make use of secondary data). The preliminary performance assessment also seems to indicate that processing polarimetric data does not ensure improved detection capabilities. [J85]

## "Interference suppression in synthesized SAR images"

Radio interferences are becoming more and more an important source for image degradation in synthetic aperture radar (SAR) imaging. Especially at longer wavelengths, interferences are often very strong, and their suppression is required during data processing. However, at shorter wavelengths, interferences are often not obvious in the image amplitude, and filtering is not performed in an operational way. Nevertheless, interferences might significantly degrade the image phase, and the estimation of sensitive parameters like interferometric coherence or polarimetric descriptors becomes imprecise. Interference suppression is usually performed on the raw data, which are in most cases not available to the end-user. In this letter, a new interference suppression method for focused SAR images is proposed. Its performance is tested on interferometric repeat-pass data acquired by the German Aerospace Agency's experimental SAR system (E-SAR) at L-band. [J86]

## "Fully polarimetric measurements of brightness temperature distributions with a quasi-optical radiometer system at 90 GHz"

The thermal microwave radiation of our natural and man-made environment contains many objects with fully polarimetric information. Based on this assumption a quasi-optical imaging radiometer system was designed and realized for the determination of the complete Stokes vector. To demonstrate the system performance, the beam quality was verified by measurements and a polarimetric calibration procedure was developed. Measurements on selected objects have been carried out to demonstrate the polarimetric effects primarily of the third and fourth component of the Stokes vector. The measured results indicate new possible applications for remote sensing and material testing. [J87]

## "Radiative transfer model for microwave bistatic scattering from forest canopies"

A bistatic forest scattering model is developed to simulate scattering coefficients from forest canopies. The model is based on the Michigan Microwave Canopy Scattering (MIMICS) model (hence called Bi-MIMICS) and uses radiative transfer theory, where the first-order fully polarimetric transformation matrix is used. Bistatic radar systems offer advantages over monostatic radar systems because of the additional information provided by the diversity of the geometry. By simulating the forest canopy scattering from multiple viewpoints, we can better understand how the forest scatterers' shape, orientation, density, and permittivity affect the canopy scattering. Bi-MIMICS is parametrized using selected forest stands with different canopy compositions and structure. The simulation results show that bistatic scattering is more sensitive to forest biomass changes than backscattering. Analyzing scattering contributions from different parts of the canopy gives us a better understanding of the microwave's interaction with the tree components. The ground effects can also be studied. Knowledge of the canopy's bistatic scattering behavior combined with additional synthetic aperture radar measurements can be used to improve forest parameter retrievals. The simulation results of the model provide the required information for the design of future bistatic radar systems for forest sensing applications. [J88]

## "A compact dual-polarized multibeam phased-array architecture for millimeter-wave radar"

A broad-band dual-polarized phased array is presented, which allows for independent beam control of the vertical and horizontal polarization with multibeam scanning in azimuth and elevation. The system is based upon a compact tray architecture with element spacing of 0.6λ. Using stereolithography, a miniature dual-polarized waveguide front end was fabricated, which provides a low-loss transition to the microstrip phase-shifting circuitry. A p-i-n diode switch followed by a low-noise amplifier is implemented for each tray to allow for the electronically controlled beam scanning with a 49° field of view. The phased array demonstrates broad-band characteristics from 34 to 40 GHz with better than 20-dB cross-polarization signal discrimination. [J89]

## "Effect of multiple scattering on the phase signature of wet subsurface structures: applications to polarimetric L- and C-band SAR"

We propose a two-layer integral equation model (IEM) model including multiple-scattering terms to reproduce the phase signature of buried wet structures that we observed on L-band synthetic aperture radar (SAR) images. We have good agreement between the extended (single+multiple scattering) IEM model and previous results obtained using a single-scattering IEM model combined with finite-difference time-domain simulations. We show that the multiple scattering not only significantly influences the copolarized phase difference but can also be related to the soil moisture content. In order to assess the validity of our extended model, we performed radar measurements on a natural outdoor site and showed that they could be fairly well fitted to the extended model. A parametric analysis presents the dependence of the copolarized phase difference on roughness parameters (rms height and correlation length) and radar parameters (frequency and incidence angle). Our study also shows that the phase signature should allow detection of buried wet structures down to a larger depth for C-band (3.8 m) than for L-band (2.6 m). This signature could then be used to map subsurface moisture in arid regions using polarimetric SAR systems. [J90]

## "Statistical Assessment of Eigenvector-Based Target Decomposition Theorems in Radar Polarimetry"

The performance of quantitative remote sensing based on multidimensional synthetic aperture radars (SARs), and polarimetric SAR systems in particular, depends strongly on a correct statistical characterization of the data, i.e., on a complete knowledge of the effects of the speckle noise. In this framework, the eigendecompostion of the covariance or coherency matrices and the associated$H/underlinealpha/A$decomposition have demonstrated the potential for quantitative estimation of physical parameters. In this paper, we present a detailed study of the statistics associated with this decomposition. This analysis requires the introduction of mathematical tools that are not well known in the remote sensing community. For this reason, we include a review section to present them. Using this work, we then present an expression for the probability density function of the sample eigenvalues of the covariance or coherency matrix. The availability of this expression allows a complete study of the separated sample eigenvalues, as well as, the entropy H and the anisotropy A. As demonstrated, all these parameters must be considered as asymptotically nonbiased with respect to the number of looks. In order to reduce the biases for a small number of averaged samples, a novel estimator for the eigenvalues is proposed. The results of this work are analyzed by means of simulated and real airborne SAR data. This analysis permits us to determine in detail the effects of the number of averaged samples in the estimation of physical information in radar polarimetry. [J91]

## "Calibration of linearly polarized polarimetric SAR data subject to Faraday rotation"

A model for linearly polarized fully polarimetric backscatter measurements is used, incorporating the effects of system noise, channel amplitude, phase imbalance, crosstalk, and Faraday rotation. A step-by-step procedure is outlined for correction (or calibration) of fully polarimetric data subject to Faraday rotation, to recover the true scattering matrix. The procedure identifies steps for crosstalk removal and correction of channel imbalances that are robust in the presence of Faraday rotation. The final steps in the procedure involve a novel strategy for estimation and correction of Faraday rotation. Three approaches to estimate the (one-way) Faraday rotation angle Ω directly from linear (quad-) polarized synthetic aperture radar (SAR) backscatter data obtained by a spaceborne SAR system are described. Each approach can initially be applied to the signature of any scatterer within the scene. Sensitivity analyses are presented that show that at least one of the measures can be used to estimate Ω to within ±3° to 5°, with reasonable levels of residual crosstalk, noise floor, channel amplitude, and phase imbalance. Ambiguities may be present in the estimates of Ω of ±npi/2-the impact of this is discussed, and several approaches are suggested to deal with this possibility. The approach described in this paper is relevant for future L-band spaceborne SARs and removes one key obstacle to the deployment of even longer wavelength SARs (e.g., an ultrahigh frequency or P-band SAR) in Earth orbit. [J92]

## "A phase signature for detecting wet subsurface structures using polarimetric L-band SAR"

In this paper, we investigate the ability of L-band synthetic aperture radar (SAR) systems to penetrate soils to retrieve information about subsurface wet structures. Our experiment site, the Pyla dune, is a bare sandy area allowing high radar penetration and known to have large wet subsurface structures (paleosoils) at varying depths. Buried paleosoils, which act as moisture tanks, are detectable with radar, since they present a high permittivity due to their water content. By analyzing airborne polarimetric SAR data, we established that a phase signature is correlated to the buried wet palesoils: a phase difference of 23° between the horizontal (HH) and vertical (VV) channels was clearly observed. It allows detection of the paleosoil down to a larger depth (5.2 m) than when only considering HH and HV amplitude signals (3.5 m). In order to confirm this result, field measurements were performed that led to the same observed phase difference. We could fit our observations to the semiempirical model proposed by Oh and Sarabandi, and we reproduced the observed phenomenon using a two-layer integral equation method (IEM) model of the Pyla dune, which was completed by finite-difference time-domain (FDTD) numerical simulations. We show that the soil moisture significantly influences the radar response in terms of phase difference between the copolarized modes. Our study also shows that the single-scattering IEM model reproduces the observed phase difference fairly well for a natural outdoor site when combined to FDTD simulation results. This phase signature could be used as a new tool to map subsurface moisture in arid regions. [J93]

## "Exploration of factors limiting biomass estimation by polarimetric radar in tropical forests"

Direct inversion of radar return signals for forest biomass estimation is limited by signal saturation at medium biomass levels (roughly 150 ton/ha for P-band). Disturbing factors such as forest structural differences-and, notably, at low biomass levels, terrain roughness, and soil moisture variation-cause further complications. A new and indirect inversion approach is proposed that may circumvent such problems. Using multifrequency polarimetric radar the forest structure can be assessed accurately. Ecological relationships link these structures with biomass levels, even for high biomass levels. The LIFEFORM model is introduced as a new approach to transform field observations of the complex tropical forest into input files for the theoretical UTARTCAN polarimetric backscatter model. The validity of UTARTCAN for a wide range of forest structures is shown. Backscatter simulations for a wide range of forest structures, terrain roughness, and soil moisture clearly show the limitations of the direct approach and the validity of the proposed indirect approach up to very high levels of biomass. [J94]

## "Polarization diversity detection of distributed targets in compound-Gaussian clutter"

We deal with the problem of polarimetric detection of compound-Gaussian clutter with unknown distributed targets in covariance matrix. Since no uniformly most powerful (UMP) detector exists for the problem at hand, we devise and assess two classes of suboptimum receivers. The former contains two detectors, designed according to the Wald and the generalized likelihood ratio tests, which resort to secondary data, free of signal components and with the same covariance structure of the cells under test, for estimating the clutter spectral properties. The latter contains a detector which achieves adaptivity without exploiting the training set All the decision rules ensure the constant false alarm rate (CFAR) property with respect to the texture statistics but they are not theoretically CFAR with respect to the disturbance covariance matrix. Finally, we present simulation results, based also on real clutter data, showing that the Wald test receiver achieves in general a better detection performance and a stronger robustness than its counterparts. [J95]

## "Development of a ground-based polarimetric broadband SAR system for noninvasive ground-truth validation in vegetation monitoring"

We have developed a ground-based polarimetric broadband synthetic aperture radar (SAR) system for noninvasive ground-truth validation in polarimetric SAR remote sensing of terrestrial vegetation cover. This system consists of a vector network analyzer, one dual-polarized antenna, and an antenna positioner. It can be operated in a frequency range from 50 MHz to 20 GHz, with a scanning aperture of 20 m in the horizontal and 1.5 m in the vertical direction. Tests carried out with standard reflectors showed that the polarimetric measurement capabilities of this system are satisfactory. Using the polarimetric ground-based SAR (GB-SAR) system, we carried out measurements on a specific vegetation cover pertinent to the remote sensing of forested regions within Sendai City, consisting of three different kinds of trees common within the Kawauchi Campus of Tohoku University. Measurements were collected in spring, summer, and autumn. Three-dimensional (3-D) polarization-sensitive images were reconstructed from the acquired data. Analysis of the 3-D polarimetric images of each measurement found differences (at times strong differences) among the polarization signatures. There were stronger reflections in all of the HH, VH, VV images in the second (summer) measurement, especially in the VH image, due to the substantial growth of branches and leaves in summer. This ground-truth validation system provided valuable information about the scattering mechanisms of the three trees selected for analysis in

different seasons, which can be detected by broadband polarimetric ground-based SAR measurements. The experimental results demonstrate the excellent polarimetric performance of the newly developed SAR imaging system, which should find many useful and immediate applications in noninvasive ground-truth validation of diverse terrestrial vegetation covers. [J96]

## "Phase coded pulse Doppler and continuous wave 77 GHz radar measurement and analysis facility"

A new and unique millimetre wave radar capability is described. A coherent quasi-monostatic 77 GHz polarimetric short range phase coded pulse Doppler (PCPD) radar is integrated with a coherent monostatic 77 GHz co-polar continuous wave (CW) fast event radar data capture facility to provide unparalleled functionality in a single unit. The PCPD radar, originally designed for the short range radar measurement of vehicles travelling at velocities up to 200 m/s, is shown to offer significant additional benefits beyond original expectations. Results showing the complex Doppler from a rotating target and illustrating the PCPD system capabilities are presented. The CW radar, configured to measure objects travelling at velocities up to 2000 m/s, is also shown to be a useful asset. System verification tests and measurement results for Browning gun firings of spinning high velocity metallic spheres and cubes are discussed. Evidence has also been provided suggesting that the velocity of a small flat facetted projectile, fired from a Browning gun, can be estimated from radar measurements of spin rate given a priori knowledge of the rifling characteristics of the Browning gun. [J97]

## "Fitting a statistical model to SIR-C SAR images of the sea surface"

A suite of statistical procedures aimed at assessing to what extent polarimetric and/or multifrequency synthetic aperture radar (SAR) images of the sea surface can be modeled in terms of spherically invariant random vectors and matrices (SIRVs and SIRMs) is presented. The proposed tests assume that images can be described by resorting to the compound-Gaussian model, but do not require any a priori knowledge about the actual first-order probability density function (pdf) of the texture. The tests have also been used to analyze three data sets from STR-C/X-SAR missions. [J98]

## "On the use of permanent symmetric scatterers for ship characterization"

The symmetric scattering characterization method (SSCM) has been recently introduced for high-resolution characterization of certain targets under coherent conditions. SSCM is based on the Poincarer' sphere representation, which supports a high-resolution decomposition of symmetric target scattering, as well as assessment and validation of the backscatter coherence. In this paper, the SSCM is investigated for ship characterization using Convair-580 polarimetric synthetic aperture radar (SAR) data. It is shown that the target Poincarer' parameters permit identification of dominant scatterers with a significant symmetric scattering component. The polarization orientation angle of these quasi-symmetric scatterers is used to derive an estimate of the ship's pitch angle, under certain conditions. The effect of SAR system focus setting errors and Doppler centroid mistracking on the SSCM performance is investigated. It is shown that the SSCM is sensitive to the system focus setting and Doppler centroid shift. The first-order effects of these errors can be removed prior to the application of the SSCM method. [J99]

## "Doppler measurements of smooth and rough surface high frequency scattering from spinning steel cylinders"

Preliminary measurement results gathered using a fully coherent 77GHz phase coded pulse Doppler polarimetric radar and investigating the electromagnetic signatures of electrically large spinning steel cylinders are presented. New and novel results showing the Doppler contributions due to dynamic rough and smooth surface scattering effects are discussed and analysed. In the latter case, significant sideband conversion occurs together with a rapid fall off in the power density spectrum. Future work is proposed and discussed. A fuller analysis of these preliminary results and further results was presented. [J100]

## "Development of a ground-based radar for scattering measurements"

A ground-based C-band scatterometer system has been constructed at the Multimedia University, Malaysia. This is an inexpensive FM-CW radar that was efficiently constructed from a combination of commercially available components and in-house fabricated circuitry. The system has full polarimetric capability for determining the complete backscattering matrix of a natural target. It will be used to conduct in-situ backscatter measurements on Earth terrain, such as vegetation fields, forests, and soil surfaces. This paper presents the system design and the evaluation results of the scatterometer system. The system was tested at a football field. A metal sphere was used as the calibration target. The backscattering matrices of an 8" trihedral corner reflector and of a 4" Ч 8"

dihedral corner reflector were measured. The dihedral was rotated at different angles to provide different sets of polarimetric data. The results were compared with the theoretical values to verify the effectiveness of the calibration technique. The external calibration and internal calibration procedures, as well as the approach used in measuring the relative phase response, are discussed. [J101]

## "Radar imaging of moving targets in foliage using multifrequency multiaperture polarimetric SAR"

Because of the low signal-to-clutter ratio, it is a difficult problem to detect and image moving targets in foliage. In this paper, a multifrequency multiaperture polarimetric synthetic aperture radar (MFMA POLSAR) system is proposed for imaging of moving targets in foliage. The MFMA POLSAR extends the multifrequency antenna array SAR (MF-SAR) system to multiple polarizations. Full polarization is used in MFMA POLSAR to achieve an optimal polarization adaptive to the environment such that the images obtained by different apertures are of the best coherence that is used to obtain the highest accuracy of the phase estimation. It is also shown that the MFMA POLSAR cannot only accurately locate both the slow and the fast moving targets but also reveal moving targets in foliage. [J102]

## "High-resolution measurements of scattering in wheat canopies-implications for crop parameter retrieval"

Polarimetric X- and C-band measurements by the University of Sheffield ground-based synthetic aperture radar (GB-SAR) indoor system provide three-dimensional images of the scattering processes in wheat canopies, at resolutions of around a wavelength (3-6 cm). The scattering shows a pronounced layered structure, with strong returns from the soil and the flag leaves, and in some cases a second leaf layer. Differential attenuation at horizontal (H) and vertical (V) polarization, due to the predominantly vertical structure of the wheat stems, gives rise to marked effects. At both C and X bands, direct return from the canopy exceeds the soil return at large incidence angles for VV polarization, but is comparable to or less than the soil return in all other cases. At HV, the apparent ground return is probably due to a double-bounce mechanism, and volume scattering is never the dominant term. Direct sensing of the crop canopy is most effective at X band, VV, and large incidence angles, under which conditions the return is dominated by the flag leaf layer. Field measurements with the outdoor GB-SAR system suggest, however, that for sensitivity to biomass and reduced susceptibility to disturbances by rainfall, a two-channel C-band system operating at a medium range of incidence angles is preferred. [J103]

## "Volume decorrelation resolution in polarimetric SAR interferometry"

Volume decorrelation is a phenomenon affecting the synthetic aperture radar (SAR) interferometric coherence images in the presence of forests or buildings. 'Resolving' this effect could lead to an estimation of the height of the observed distributed scatterers. An empirical method is suggested to distinguish volume decorrelation due to random volumes (such as trees) and stationary distributed targets (such as man-made artifacts) when polarimetric SAR data are used. [J104]

## "Classified pixel-based windowing algorithm for polarimetric SAR speckle filtering"

Two main purposes of synthetic aperture radar (SAR) speckle filtering are the preservation of the edge sharpness and the suppression of the speckle noise. However, most of the existing filtering techniques suppress the speckle noise while smearing edges. This problem is partly solved by using nonsquare windows, but it can also generate large errors in many applications. A new windowing algorithm that can overcome the defects of the nonsquare window, by discriminating the edges more precisely with a preliminary terrain classification result, is proposed. [J105]

## "A calibration method for fully polarimetric microwave radiometers"

A technique for absolute end-to-end calibration of a fully polarimetric microwave radiometer is presented. The technique is based on the tripolarimetric calibration technique of Gasiewski and Kunkee, but is extended to provide a means of calibrating all four Stokes parameters. The extension is facilitated using a biaxial phase-retarding microwave plate to provide a precisely known fourth Stokes signal from the Gasiewski-Kunkee (GK) linearly polarized standard. The relations needed to determine the Stokes vector produced by the augmented standard are presented, and the effects of nonidealities in the various components are discussed. The application of the extended standard to determining the complete set of radiometer constants (the calibration matrix elements) for the National Oceanic and Atmospheric Administration Polarimetric Scanning Radiometer in a laboratory environment is illustrated. A calibration matrix inversion technique and error analysis are described, as well. The uncertainties associated with practical implementation of the fully polarimetric standard for spaceborne wind vector measurements are discussed relative to error thresholds anticipated for wind vector retrieval from the U.S. National Polar-Orbiting Environmental Satellite System. [J106]

## "Subsurface imaging in south-central Egypt using low-frequency radar: Bir Safsaf revisited"

We present the capabilities of low-frequency radar systems to sound the subsurface for a site located in south-central Egypt, the Bir Safsaf region. This site was already intensively studied since the SIR-A and SIR-B orbital radars revealed buried paleodrainage channels. Our approach is based on the coupling between two complementary radar techniques: the orbital synthetic aperture radar (SAR) in C and L bands (5.3 and 1.25 GHz) for imaging large-scale subsurface structures, and the ground-penetrating radar (GPR) at 500 and 900 MHz for sounding the soil at a local scale. We show that the total backscattered power computed from L-band SAR and 900-MHz GPR profiles can be correlated, and we combined both data to derive the geological structure of the subsurface. GPR data provide information on the geometry of the buried scatterers and layers, while the analysis of polarimetric SAR data provides information on the distribution of rocks in the sedimentary layers and at the interface between these layers. The analysis of 500-MHz GPR data revealed some deeper structures that should be detected by lower frequency SARs, such as a P-band system. [J107]

## "Polarimetric speckle reduction using multi-texture maximum likelihood method"

A new speckle reduction approach, which estimates texture parameters simultaneously by the method of maximum likelihood under the assumption of multi-texture, is proposed. Comparison with the polarimetric whitening filter (PWF) shows that this approach preserves the polarimetric properties and reduces the couple between polarimetric channels. [J108]

## "Polarimetric SAR speckle noise model"

Synthetic aperture radar (SAR) data are affected by speckle noise, originated by the SAR system's coherent nature. The problem of speckle noise in one-dimensional (1-D) data is already solved, as speckle has a multiplicative characteristic. SAR polarimetry represents an extension to multidimensional data by the use of polarization wave diversity. As a consequence of the existence of a correlation degree between the SAR images, the 1-D speckle noise model cannot be extended to multidimensional SAR data. This paper is devoted to present a completely new speckle noise model for the complex covariance matrix describing polarimetric SAR data in the distributed scatterers case. As is shown, this new model is able to identify which are the noise mechanisms in all the covariance matrix elements. The speckle noise model is validated by using real L-band polarimetric data acquired with the German E-SAR sensor. [J109]

## "Multitemporal/multiband SAR classification of urban areas using spatial analysis: statistical versus neural kernel-based approach"

In this paper, we derive two techniques for the classification of multifrequency/multitemporal polarimetric SAR images, based respectively on a statistical and on a neural approach. Both techniques are especially designed to exploit the spatial structure of the observed scene, thus allowing more stable classification results. Such techniques are useful when looking at medium- to large-scale features, like the boundaries between urban and nonurban areas. They are applied to a set of SIR-C images of a urban area, to test their effectiveness in the identification of the different classes that compose the observed scene. A lower and an upper bound to the classification performance are introduced to characterize their limits. They correspond respectively to pixel-by-pixel classification and to the joint classification of the pixels belonging to the different classes identified in the ground truth. The results achieved with the two approaches are quantitatively analyzed by comparing them to the ground truth. Moreover, a hybrid approach is presented, where the homogeneous regions identified through statistical segmentation are classified using a neurofuzzy technique. Finally, a quantitative analysis of the results achieved with all the proposed techniques is carried out, showing that their classification performance is much higher than the lower bound and reasonably close to the upper bound. This is a consequence of their effectiveness in the exploitation of the spatial information. [J110]

## "Analysis of multistatic configurations for spaceborne SAR interferometry"

Spaceborne bistatic and multistatic SAR configurations are an attractive approach to acquire along-track and cross-track interferograms on a global scale. An efficient realisation of such systems may be achieved by a set of low-cost, passive receivers onboard a constellation of microsatellites which simultaneously record the backscattered signals transmitted by a conventional spaceborne radar. The authors introduce several multistatic SAR configurations suitable for global single-pass interferometry and discuss their advantages and limitations. The achievable interferometric performance is analysed in detail, taking into account thermal noise, block adaptive quantisation, range and azimuth ambiguities, and geometric decorrelation for both surface and random volume scatterers. Based on the estimated interferometric phase errors, the relative height accuracies for three

illuminators (PALSAR, ASAR, TerraSAR-X) are derived. The achievable height accuracies are of the order of 2 m for PALSAR and ASAR, and of the order of 1 m for TerraSAR-X. However, it turns out that for vegetated areas, volume decorrelation may become a limiting factor for configurations with large interferometric baselines. These restrictions can be overcome by making the interferometric configuration fully polarimetric and/or increasing the number of available baselines. [J111]

## "A radar cross-section model for power lines at millimeter-wave frequencies"

The knowledge of radar backscatter characteristics of high-voltage power lines is of great importance in the development of a millimeter-wave wire detection system. In this paper, a very high-frequency technique based on an iterative physical optics approach is developed for predicting polarimetric radar backscattering behavior of power lines of arbitrary strand arrangement. In the proposed scattering model the induced surface current is obtained using the tangent plane approximation in an iterative manner where the first-order current, obtained from the incident wave, is used as the source for the second-order current and so on. The approximation is valid for frequencies where the cable strand diameter is on the order of or larger than the wavelength. It is shown that the copolarized backscatter is dominated by the contribution from the first-order PO currents, whereas the cross-polarized backscatter is generated by the second- and higher order PO currents. Using this model, the effects of radar antenna footprint, surface irregularities, and cable sag (when suspended between towers) on radar backscatter are studied. To verify the validity of the proposed model, theoretical results are compared at 94 GHz with experimental results and are found to be in good agreement. [J112]

## "The use of fully polarimetric information for the fuzzy neural classification of SAR images"

Presents a method, based on a fuzzy neural network, that uses fully polarimetric information for terrain and land-use classification of synthetic aperture radar (SAR) image. The proposed approach makes use of statistical properties of polarimetric data, and takes advantage of a fuzzy neural network. A distance measure, based on a complex Wishart distribution, is applied using the fuzzy c-means clustering algorithm, and the clustering result is then incorporated into the neural network. Instead of preselecting the polarization channels to form a feature vector, all elements of the polarimetric covariance matrix serve as the target feature vector as inputs to the neural network. It is thus expected that the neural network will include fully polarimetric backscattering information for image classification. With the generalization, adaptation, and other capabilities of the neural network, information contained in the covariance matrix, such as the amplitude, the phase difference, the degree of polarization, etc., can be fully explored. A test image, acquired by the Jet Propulsion Laboratory Airborne SAR (AIRSAR) system, is used to demonstrate the advantages of the proposed method. It is shown that the proposed approach can greatly enhance the adaptability and the flexibility giving fully polarimetric SAR for terrain cover classification. The integration of fuzzy c-means (FCM) and fast generalization dynamic learning neural network (DLNN) capabilities makes the proposed algorithm an attractive and alternative method for polarimetric SAR classification. [J113]

## "Change detection for thematic mapping by means of airborne multitemporal polarimetric SAR imagery"

The paper addresses the detection of changes in multitemporal polarimetric radar images, focusing on small objects and narrow linear features. The images were acquired at C- and L-band by the airborne EMISAR system. It is found that the radar intensities are better suited for change detection than the correlation coefficient and the phase difference between the co-polarized channels. In the case of linear features, there is no obvious difference between the C- and L-bands, and slight variations of the flight tracks are acceptable at look angles larger than 35 degrees. Theoretical detection thresholds are evaluated from the statistical distribution of the intensity ratio due to speckle. For the linear features and for urban environments, the observed thresholds are larger than the theoretical predictions. This is interpreted as an effect of radar intensity variations on length scales smaller than the spatial image resolution. The signature of urban areas is very sensitive to deviations between the flight tracks, and the sensitivity is larger at C-band than at L-band. On the other hand, the intensity contrast between buildings and the urban background is smaller at L-band and larger at C-band. For change detection, thresholds may have to be chosen separately for each object class because the intensity ratios of different object classes vary differently as a function of time [J114]

## "Using cross-entropy for polarimetric radar discrimination problem"

Cross-entropy for measuring the difference between two scatterers in the polarimetric radar discrimination problem is introduced. Two cross-entropy measures in favour of one scatterer over another are obtained for two independent probability mass functions that indicate the average scattering mechanism and the scattering randomness [J115]

## "SPRI: simulator of polarimetric radar images"

Simulator of polarimetric radar images (SPRI) consists of a suite of image processing programs for producing realistic millimeter-wave (MMW) radar images artificially on a workstation. The heart of the simulation approach is a polarimetric Rayleigh clutter simulator coupled to a clutter database. The simulator produces high resolution single-look polarimetric images. Hard targets can then be embedded into this clutter map, and the resultant image can be degraded in resolution, number of looks, polarization, etc. to match that which would be observed by a real sensor. Examples of simulated images, and comparisons of these simulations to actual images, are presented. The MMW Clutter Database is the most comprehensive to-date database of over 3500 Mueller matrices for many kinds of terrestrial clutter measured at 35 and 95 GHz, many of which are at incidence angles close to grazing. The database can be accessed via a World Wide Web flexible interface that enables data to be combined in new and unique ways specified by the user, and displayed in either tabular or graphical format. The structure and access procedure to the database are described [J116]

## "Improved target classification using optimum polarimetric SAR signatures"

We present a new method for automatic target/object classification by using the optimum polarimetric radar signatures of the targets/objects of interest. The state-of-the-art in radar target recognition is based mostly either on the use of single polarimetric pairs or on the four preset pairs of orthogonal polarimetric signatures. Due to these limitations, polarimetric radar processing has been fruitful only in the area of noise suppression and target detection. The use of target separability criteria for the optimal selection of radar signal state of polarizations is addressed here. The polarization scattering matrix is used for the derivation of target signatures at arbitrary transmit and receive polarization states (arbitrary polarization inclination angles and ellipticity angles). Then, an optimization criterion that minimizes the within-class distance and maximizes the between-class metrics is used for the derivation of optimum sets of polarimetric states. The results of the application of this approach on real synthetic aperture radar (SAR) data of military vehicles are obtained. The results show that noticeable improvements in target separability and consequently target classification can be achieved by the use of the optimum over nonoptimum signatures [J117]

## "Characterization of target symmetric scattering using polarimetric SARs"

Cameron's coherent target decomposition (CTD) theory and the classification method that Cameron developed for operational use of his CTD are reconsidered. It is shown that Cameron's classification leads to a coarse scattering segmentation because of the large class dispersion that corresponds to a synthetic aperture radar (SAR) system with about ±8-dB channel imbalance. The application of Cameron's method within known SAR radiometric calibration requirements limits the utility of the classification. In addition, Cameron's classification is applied under the implicit assumption on the coherence nature of target scattering, and this might yield erroneous results within areas of noncoherent scattering. A new method, named the symmetric scattering characterization method (SSCM), is introduced to better exploit the information provided by the largest target symmetric scattering component in the context of coherent scattering. The Poincarer' sphere is used as the basis for a more complete representation of symmetric scattering than Cameron's unit disk, thus enabling the SSCM to generate better segmentation of target symmetric scattering with much higher resolution. In order to limit the application of the SSCM to targets of coherent scattering, new methods are developed for assessment and validation of the coherent nature of point and extended target scattering. [J118]

## "An ultrafast wide-band millimeter-wave (MMW) polarimetric radar for remote sensing applications"

With the advent of high-frequency radio frequency (RF) circuits and components technology, millimeter-wave (MMW) radars are being proposed for a large number of military and civilian applications. Accurate and high-resolution characterization of the polarimetric radar backscatter responses of both clutter and man-made targets at MMW frequencies is essential for the development of radar systems and optimal detection and tracking algorithms. Toward this end, a new design is developed for ultrafast, wide-band, polarimetric, instrumentation radars that operate at 35 and 95 GHz. With this new design, the complete scattering matrix of a target (magnitude and phase) can be measured over a bandwidth of 500 MHz in less than 2 μs. In this paper, the design concepts and procedures for the construction and calibration of these radars are described. In addition, the signal processing algorithm and data-acquisition procedure used with the new radars are presented. To demonstrate the accuracy and applicability of the new radars, backscatter measurements of certain points and distributed targets are compared with their analytical radar cross section (RCS) and previously measured σ° values, respectively, and good agreements are shown. These systems, which can be mounted on a precision gimbal assembly that facilitates their application as high-resolution imaging radar systems, are used to determine the MMW two-way propagation loss of a corn field for different plant moisture conditions. [J119]

## "Biophysical forest type characterization in the Colombian Amazon by airborne polarimetric SAR"

Fully polarimetric C-, L-, and P-band data were collected by NASA's AirSAR system in May 1993 at the Araracuara test site, a well-surveyed forest reserve in the center of the Colombian Amazon. The area is characterized by a high diversity of forest types, soil types, and flooding conditions. In this paper a polarimetric classification technique is used to assess AirSAR's potential for forest structural type mapping and, indirectly, forest biophysical characterization. Field observations were made at 23 0.1 ha plots to obtain additional quantitative descriptions on forest structure and ground surface conditions, but also to assess the suitability of existing map legends for synthetic aperture radar (SAR) mapping. It could be shown that a new type of legend leads to physically better interpretable results. it method based on iterated conditional modes is introduced and is shown to yield radar-derived classifications with a high level of agreement with the landscape-ecological map, as well as with the ground observations. The following results may indicate the high level of accuracy obtained: 15 classes can be differentiated, the average radar classification agreement ranges from 68% to 94% (depending on the type of classification and approach), and for only a few classes the agreement is less than 70%. The relation between physical forest structure and polarimetric signal properties is studied explicitly using polarimetric decomposition. A new method is introduced based on the decomposition of polarimetric coherence, instead of power. It is based on simple physical descriptions of the wave-object interaction. The accuracy of the complex coherence estimation is described using the complex Wishart distribution. Thus, several interesting physical relations between polarimetric signal and forest structure can be revealed. The physical limitations of this technique and its relation with sample size are indicated. [J120]

## "Polarimetric adaptive detection of range-distributed targets"

We address the problem of polarimetric adaptive detection of range-spread targets in Gaussian noise with unknown covariance matrix. At the design stage, we model the target echo from each polarimetric channel as a deterministic signal known up to a scaling factor (possibly varying from cell to cell), which accounts for the polarimetric scattering properties of the target. We first show the failure of the generalized likelihood ratio test (GLRT) procedure to deal with this kind of problem, and thus, we propose a fully adaptive detector based on the method of sieves. We also derive the analytical expression for the probability of false alarm and show that the newly introduced receiver can be made bounded constant false alarm rate (CFAR). Finally, we present simulation results highlighting the performance gain that can be achieved by resorting to polarization diversity in conjunction with high resolution. [J121]

## "Single-baseline polarimetric SAR interferometry"

Examines the application of single-baseline polarimetric SAR interferometry to the remote sensing and measurement of structure over forested terrain. For this, a polarimetric coherent scattering model for vegetation cover suitable for the estimation of forest parameters from interferometric observables is introduced, discussed and validated. Based on this model, an inversion algorithm which allows the estimation of forest parameters such as tree height, average extinction, and underlying topography from single-baseline fully polarimetric interferometric data is addressed. The performance of the inversion algorithm is demonstrated using fully polarimetric single baseline experimental data acquired by DLR's E-SAR system at L-band [J122]

## "Reduced bandwidth algorithm for near field imaging of tree targets using synthetic aperture radar"

An imaging algorithm which can generate high resolution near-field synthetic aperture radar images is presented. The algorithm requires only a small fractional bandwidth and is not computationally intensive. Images are produced in a format familiar to the human visual system and provide a more complete characterisation of the polarimetric scattering distribution of a target. A new derivation of the algorithm is presented and its characteristics and limitations are described and formulated. The focusing process is validated by simulations and practical measurements on test targets. Sidelobe reduction is carried out by application of the SVA filtering algorithm. Finally, the technique is applied to the imaging of a small larch tree and the images presented clearly demonstrate the dependency of the target response on the system polarisation [J123]

## "Projection pursuit classification of multiband polarimetric SAR land images"

Results are presented for an experiment utilizing a pastoral land scene with a variety of eight classes, imaged by the NRL dual band (X and L) polarimetric synthetic aperture radar (NUWSAR) at a spatial resolution of 1.2 m. Projection pursuit (PP) statistical analysis tools were applied to a set of simultaneous L-band and X-band fully polarized images (six independent channels) to demonstrate the utility of land classification at high spatial resolution from a light aircraft using SAR. The statistical confusion matrix was used as a quantitative optimization measure of classification. Samples of eight classes from a portion of the scene were used to define a training

set, then PP tools were used for classification. It is clear that L-band and X-band fully polarized data view the classes in a significantly different manner, and each brings independent information to the analysis. These results are not meant to be exhaustive at this time but to demonstrate the utility of applying PP tools to multiband and polarization SAR data and to give an indication of the quality of classification one can achieve with moderately high spatial resolution SAR data using a light plane platform [J124]

## "Adaptive polarimetric target detection with coherent radar. II. Detection against non-Gaussian background"

For pt. I see ibid., vol. 37, no. 4, pp. 1194-1206 (2001).This paper presents the derivation of a polarimetric coherent adaptive scheme to detect a radar target against a non-Gaussian background. This completes the results presented in Part I for the Gaussian background. A Texture Free-Generalized Likelihood Ratio Test (TF-GLRT) detector is derived that exploits the polarimetric characteristics of the received radar echoes to improve the detection performance. The proposed polarimetric detector is shown to have Constant False Alarm Rate (CFAR) when operating against compound-Gaussian clutter with unknown parameters. Its performance is fully characterized by both theoretical analysis and simulation. Moreover, the application to recorded radar data demonstrates the performance improvement achievable in practice [J125]

## "Adaptive polarimetric target detection with coherent radar. I. Detection against Gaussian background"

The derivation of a completely adaptive polarimetric coherent scheme to detect a radar target against a Gaussian background is presented. A previously proposed Generalized Likelihood Ratio Test (GLRT) polarimetric detector is extended to the case of a general number of channels; this exploits the polarimetric characteristics of the received radar echoes to improve the detection performance. Together with the fully adaptive scheme, a model-based detector is derived that has a lower estimation loss. A complete theoretical expression is derived for the detection performance of both proposed polarimetric detectors. They are shown to have Constant False Alarm Rate (CFAR) when operating against Gaussian clutter, but to be sensitive to deviations from the Gaussian statistic. The application to recorded radar data demonstrates the performance improvement achievable in practice [J126]

## "Ultrawide-bandwidth fully-polarimetric ground penetrating radar classification of subsurface unexploded ordnance"

An ultrawide-bandwidth (UWB) ground penetrating radar (GPR) was used to collect fully-polarimetric backscattered data from 10 to 800 MHz using a dual-polarization version of the previously developed dielectric-loaded horn-fed bow-tie (HFB) antenna. Special processing algorithms were developed to extract the polarization, orientation, depth, and length features of the target under investigation. The polarization and resonance features were utilized to discriminate subsurface ordnance from false-alarm objects that do not have elongated bodies. The classification of a specific type of unexploded ordnance (UXO) was also performed using the known length information. The processed results obtained from an initial blind field test show a very encouraging discrimination performance [J127]

## "Polarimetric processing of coherent random noise radar data for buried object detection"

Random noise polarimetry is a new radar technique for high-resolution probing of subsurface objects and interfaces. The University of Nebraska has developed a polarimetric random noise radar system based on the heterodyne correlation technique. Simulation studies and performance tests on the system confirm its ability to respond to phase differences in the received signals. In addition to polarimetric processing capability and the simplified system design, random noise radar also possesses other desirable features, such as immunity from radio frequency interference. The paper discusses the theoretical foundations of random noise polarimetry, and presents examples out of the entire data set collected that demonstrate the usefulness of the image processing and Stokes matrix presentation to enhance target detection using the coherent random noise radar [J128]

## "Discrimination of UXO in soil using broadband polarimetric GPR backscatter"

Polarimetric analysis of ground penetrating radar (GPR) backscatter offers a new means of discriminating subsurface metallic target shapes from one another. Such discrimination is urgently needed to distinguish buried unexploded ordnance (UXO) from other subsurface objects. To illuminate the underlying phenomenology of scattering from objects enveloped in soil, three-dimensional (3D) simulations are performed over a broad frequency band, characteristic of new low frequency GPRs. For moist soil, this means that the subsurface wavelength may range from a fraction of the target size to an order of magnitude larger With a transmitting

antenna representation that produces typical subsurface GPR beam features, combined effects of positional, orientation, and frequency diversity are investigated. Despite long wavelengths, results show distinctive features in reflections obtained from contrasting example target shapes. Full polarimetric analysis suggests the capability for inferring the length of elongated targets, aspect ratio and rotational symmetry, and gross shape along the axis for either elongated or flattened bodies of revolution in problematical orientations [J129]

## "Subsurface structures detection by combining L-band polarimetric SAR and GPR data: example of the Pyla Dune (France)"

The authors investigate the penetration capabilities of microwaves, particularly at L-band, for the mapping of subsurface heterogeneities such as lithology variations, moisture or sedimentary structures. The experiment site, the Pyla Dune, is a bare sandy area allowing high signal penetration and presenting large subsurface structures (paleosoils) at varying depths. Several radar data sets over this area are available. A polarimetric analysis of airborne synthetic aperture radar (SAR) data as web as the ground penetrating radar (GPR) sounding experiment show that subsurface scattering occurs at several places. The SAR penetration depth is estimated by inverting a scattering model for which the subsurface structure geometric and dielectric properties are determined by the GPR data analysis. These results suggest that airborne radar systems in a lower frequency range (P-band) should be able to detect subsurface moisture down to several meters, leading to innovative Earth observation systems for hydrogeology in arid regions [J130]

## "Restoration of polarimetric SAR images using simulated annealing"

Filtering synthetic aperture radar (SAR) images ideally results in better estimates of the parameters characterizing the distributed targets in the images while preserving the structures of the nondistributed targets. However, these objectives are normally conflicting, often leading to a filtering approach favoring one of the objectives. An algorithm for estimating the radar cross-section (RCS) for intensity SAR images has previously been proposed in the literature based on Markov random fields and the stochastic optimization method simulated annealing. A new version of the algorithm is presented applicable to multilook polarimetric SAR images, resulting in an estimate of the mean covariance matrix rather than the RCS. Small windows are applied in the filtering, and due to the iterative nature of the approach, reasonable estimates of the polarimetric quantities characterizing the distributed targets are obtained while at the same time preserving most of the structures in the image. The algorithm is evaluated using multilook polarimetric L-band data from the Danish airborne EMISAR system, and the impact of the algorithm on the unsupervised H-α classification is demonstrated [J131]

## "Effects of the ground surface on polarimetric features of broadband radar scattering from subsurface metallic objects"

Throughout the world, the problem of buried unexploded ordnance (UXO) poses an enormous, persistent, and expensive problem. While UXO generally consists of sizable bodies of ferrous metal and can therefore be detected, with current technology it is extremely difficult to distinguish them reliably from typically widespread pieces of clutter. Thus the problem is one of subsurface discrimination. The authors previous modeling work on scattering of ground penetrating radar (GPR) from metallic objects surrounded by an infinite soil-like medium has suggested the utility of a number of key discriminants in broadband fully polarimetric sensing. In particular, resonance structure, induced field rotation and ellipticity, and bistatic observation of scattered signals were shown to offer key information about target shape and size. The authors investigate the effects on signature features of the proximity of a ground surface to the target, for the common case of shallow burial (<1 m). Overall, their analyses suggest that the key discriminants seen in scattering in an infinite medium survive the complex interactions with the ground surface. In some instances, these revealing signatures appear to be strengthened by the presence of a nearby surface. Multiposition backscatter also allows fundamental inferences about target elongation and symmetry when those cannot be obtained from single position viewing [J132]

## "Polarimetric radar interferometry for improved mine detection and surface clutter rejection"

A recently developed technique, polarimetric radar interferometry, is applied to tackle the problem of the detection of buried objects embedded in surface clutter. An experiment with a fully polarimetric radar in an anechoic chamber has been carried out using different frequency bands and baselines. The processed results show the ability of this technique to detect buried plastic mines and to measure their depth. This technique enables the detection of plastic mines even if their backscatter response is much lower than that of the surface clutter [J133]

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