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ТЕМАТИЧЕСКИЙ РЕФЕРАТИВНЫЙ СБОРНИК № 9-1

“Radar Target Classification”
(«Классификация РЛ целей»)

Журнальные публикации

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ТЕМАТИЧЕСКИЙ РЕФЕРАТИВНЫЙ СБОРНИК № 9-1

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"Target localisation for distributed multiple-input multiple-output radar and its performance analysis"

This study considers the problem of target localisation with a coherent processing technique for distributed multiple-input multiple-output radar systems. To enable the coherent processing technique, dual-frequency transmitters are employed to eliminate the stochastic phases of complex fading coefficients, which are caused by target angular fluctuations. And then a two-step procedure is introduced to accomplish the target localisation. In the first step, the amplitudes of the complex fading coefficients are estimated. In the second step, the target position is obtained using the MUSIC algorithm with modified target steering vector. With the amplitudes estimated, the target localisation performance is improved. The Cramer-Rao bound (CRB) for target localisation accuracy is derived with precise knowledge of radar positions. The CRB is shown to be inversely proportional to the frequency difference between the transmitted signals. With the radar positions uncertainty, the average asymptotic performance of the proposed method is given. Finally, numerical examples are given to validate the proposed method and the theoretical analyses. [J1]

"Coherence, Polarization, and Statistical Independence in Cloude-Pottier's Radar Polarimetry"

The Cloude-Pottier radar polarimetry paradigm, which is understood as the spectral decomposition theorem of the target coherency matrix plus the classification technique based on the triad of parameters given by entropy, alpha angle, and anisotropy, has become a very well-established methodology for treating high-resolution polarimetric radar images, particularly those obtained with synthetic aperture radar (SAR) sensors. This methodology is revisited here from the standpoint of the coherence and polarization theory and their mutual relationship, in the light of the interest aroused once again after Wolf's article on this subject in 2003. Despite its success in terms of acceptance by the SAR community, the Cloude-Pottier paradigm relies on the arguable assumption that different scattering mechanisms can be separated by diagonalizing the aforementioned coherency matrix and then assigning each corresponding eigenvector to one of the independent scattering mechanisms. Our main statement in this paper is that the coherency matrix illustrates the behavior of the target from the point of view of polarization and not of full coherence, which would justify this assumption, even if only partially. Therefore, it is not rigorous to identify each eigenvector of this decomposition with a distinct scattering mechanism. Cloude and Pottier argue that the eigendecomposition of the coherency matrix outperforms other target decomposition theorems due to its uniqueness. It is also suggested that this very uniqueness, together with the orthogonality of the eigenvectors, supports the injective mapping between scattering mechanisms and eigenvectors that was first assumed based on statistical independence. With the aim of providing a comprehensive overview of the problem, we discuss some important concepts with regard to both field and target coherency matrices. In addition, we revise the concepts of entropy, alpha angle, and anisotropy as defined by the aforementioned authors, which are-- also a central part of this paradigm and which have played an important role in SAR image classification since its introduction. Again, some disagreement is found with the meaning of these parameters as they have been discussed so far. [J2]

"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. [J3]

"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. [J4]

"Feature for Distinguishing Propeller-Driven Airplanes from Turbine-Driven Airplanes"

A novel feature for distinguishing propeller-driven airplanes from turbine-driven airplanes is proposed: the absolute difference between the Euclidean lengths of the amplitude spectrums of two neighboring high-resolution range profiles (HRRP). A preclassification method based on the proposed feature is also presented. Experimental results for measured data verify the efficiency of the proposed feature. [J5]

"Altitude Measurement Based on Beam Split and Frequency Diversity in VHF Radar"

A new beam split altitude interferometry based on altitude diversity and frequency diversity for very high frequency (VHF) radar is proposed in this paper. As opposed to microwave radar, VHF radar has a wide beam which is usually split when ground reflection occurs. The reflected wave which is coherent with the direct wave will always be contained in the target echo. In this paper, several antennas of different heights are utilized. Owing to the certain relationship among the phases of the split beams, the elevation region where the targets are located can be determined using the phases of echoes. Using "amplitude-comparison" of echoes from various antennas to get the normalized error signals, the elevation of the target can be obtained by looking it up in the error signal table. The effect of roughness on the altitude measurement accuracy is also analyzed. The real data processing on flat and slope terrains testifies to the validity of the proposed method. The altitude measurement precision, especially in low-elevation regions, is greatly improved by using frequency diversity. [J6]

"Reducing the Waveform Cross Correlation of MIMO Radar With Space-Time Coding"

Multiple-input-multiple-output (MIMO) radar is attractive for target detection, parameter identification, and target classification due to diversity of waveform and perspective. However, the mutual interference among the waveforms may lead to performance degradation in resolving spatially close returns. In this paper, we consider the use of space-time coding (STC) to mitigate the waveform cross-correlation effects in MIMO radar. First, it turns out that a joint waveform optimization problem can be decoupled into a set of individual waveform design problems. Second, a number of monostatic waveforms can be directly used in a MIMO radar system, which offers flexibility in waveform selection. We provide conditions for the elimination of waveform cross correlation, and discuss four kinds of space time codes. In addition, we also extend the model to partial waveform cross-correlation removal based on waveform set division. Numerical results demonstrate the effectiveness of STC in MIMO radar for waveform decorrelation. [J7]

"Optimal Waveform Design for Improved Indoor Target Detection in Sensing Through-the-Wall Applications"

This paper deals with waveform design for improved detection and classification of targets behind walls and enclosed structures. The target impulse response is incorporated in an optimum design of the transmitted waveform which aims at maximizing the signal-to-interference and noise ratio (SINR) at the receiver output. The interference represents signal-dependent clutter which, along with the wall, degrades the receiver performance compared to the free-space and zero-clutter case. Computer simulations show sensitivity of the optimum waveform to target orientation but depict an SINR enhancement over chirped waveform radar emissions at all aspect angles. Numerical electromagnetic modeling is used to provide the impulse response of typical indoor stationary targets, namely, tables, chairs, and humans. [J8]

"Correcting Airborne Laser Scanning Intensity Data for Automatic Gain Control Effect"

The intensity data recorded by airborne laser scanning (ALS) systems are useful for several applications, e.g., automatic point classification, change detection, and environmental studies. Before the intensity values can be used for any specific application, it has to be calibrated for atmospheric effect, range, energy loss, and incidence

angle. Some ALS systems use automatic gain control (AGC). AGC is useful for getting laser returns even from low-reflectance surfaces (e.g., dark roofs), but it also changes the recorded intensity during the data acquisition, even within one surface type. This means that the same asphalt road might have totally different intensity values depending on the surrounding environment, which has affected the state of the AGC level. Therefore, it is important to correct the intensity values to neglect the effect of AGC in order to be able to get a normalized intensity value, which is only affected by the target characteristics. A first approach to correct the intensity values for AGC is reported in this letter. The same area was flown with AGC on and off, which allowed the modeling to take place. The results showed that the model produces values that agreed with an R2of 0.76 to the intensities obtained when AGC was turned off. [J9]

"Automatic algorithm for inverse synthetic aperture radar images recognition and classification"

The authors propose an algorithm for automatic aircraft categories that is models classification from inverse synthetic aperture radar (ISAR) images that use pulse reflection shape and Doppler shifts of parts of aircraft that are in any maneuver that introduces rotation to the target. The authors artificially generated five different categories of ISAR aircraft using computer simulations and tested these simulated ISAR aircraft images of the airplanes defined by size and shape that are flying in a prescribed holding pattern. The authors investigate in what parts of the holding pattern the ISAR reflections provide information that makes it possible to identify to which of the five categories an aircraft in the holding pattern belongs. The obtained results show that it is possible in most parts of the holding pattern to successfully classify the various aircraft targets. [J10]

"InSAR Coherence-Decomposition Analysis"

The phase coherence in synthetic aperture radar interferometry is often used in classification algorithms to detect possible temporal changes of the imaged terrain. However, in mountain areas, the interferometric coherence is also sensitive to the slight variations of the acquisition geometry. In this letter, we propose a very simple but effective method to separate the temporal decorrelation from the geometrical one. Assuming the imaged terrain can be modeled as a distributed target, the geometrical coherence can be estimated by exploiting a topographic model and the sensor acquisition parameters. The discrepancy between the geometrical coherence and the observed one can then be ascribed to temporal changes. Moreover, in presence of pointlike targets, the hypothesis of distributed terrain is no longer valid, and higher values of the observed coherence with respect to the synthetic geometrical one can be used to detect such targets. The proposed approach allows then in mountain areas the following conditions: (1) a simple and very fast rough estimation of the temporal coherence, and (2) the identification of pointlike targets using just two images. The method has been applied and tested in the Badong (China) site using European Remote Sensing satellite tandem data. [J11]

"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. [J12]

"Polarimetric Characterization and Temporal Stability Analysis of Urban Target Scattering"

This paper studies the polarimetric-dispersion properties of urban targets and their evolution along time in terms of the geometrical configuration. The relations between target geometry and the scattering behavior have been defined through the analysis of large stacks of simulated images. Scattering maps and synthetic aperture radar (SAR) images have been synthesized with the numerical tool GRaphical Electromagnetic COmputing SAR for different qualitative models of two real buildings. Ground-based SAR (GB-SAR) data acquired in a subsidence measurement campaign has been used to assess the simulator's realism. These data have permitted the identification of the critical simulation parameters and their range of recommended values for realistic simulations. In the context of very high resolution images, the results derived from this study may be crucial for making progress in urban-image postprocessing. As the different resolution cells comprise few scattering centers showing a quasi-deterministic scattering behavior, nonprobabilistic models based on target's geometry seem more suited for scattering modeling. In these models, the geometry-scattering (GS) links precisely inferred from simulated images can be very important. In addition to change detection and land classification, GS models may help in improving the interpretation of subsidence results with differential interferometry. Certainly, new

processing algorithms can be developed exploiting the available scattering data with more physical sense. In addition, they can take more advantage of the fine resolution and polarimetric capabilities of the new sensors, like TerraSAR-X or RADARSAT-2. [J13]

"Model-based sea mine classification with synthetic aperture sonar"

The quality and effectiveness of sensor information provided by mine-hunting autonomous underwater vehicles (AUVs) equipped with high-resolution sonars has improved drastically in recent years. In parallel, data rates have significantly increased resulting in information overload. Automatic target recognition (ATR) is regarded as a solution for this problem. This study describes a specific ATR technique based on model matching for application to high-resolution data. A sonar model for generation of high-resolution synthetic aperture sonar (SAS) images is described and applied both as database generator and classification. The performance of the model matching, which is attained by correlation and stochastically, is evaluated using a large data set covering the variety expected in mine-hunting operations. The model-based features generated in this way are able to reach an acceptable classification performance. The article is concluded with one real data example, which is easily classified when training with the simulated database. Further work is next aimed to confirm performance on real data. [J14]

"Multiple-Input Multiple-Output Radar for Lesion Classification in Ultrawideband Breast Imaging"

This paper studies the problem of applying multiple-input multiple-output (MIMO) radar techniques for lesion classification in ultrawideband (UWB) breast imaging. Ongoing work on this topic has suggested that benign and malignant masses, which usually possess remarkable architectural differences, could be distinguished by exploiting their morphology-dependent UWB microwave backscatter. We have previously approached this problem by deriving the complex natural resonances of the late-time target response, where the damping factors vary with the border profiles of anomalies. In this paper, we investigate the potential advantage of MIMO radar to enhance the resonance scattering phenomenon in breast tissue discrimination. MIMO radar can choose freely the probing signals transmitted via its antennas to exploit the independence between signals at the array elements, thereby enhancing the performance of target classification. Based on the observed damping factors and the receiver operating characteristics at different classifiers, which correspond to various diversity paths in the MIMO radar system, two data-fusion rules are proposed for robust lesion differentiation. Finally, numerical examples are provided to demonstrate the efficacy of the proposed imaging technique. [J15]

"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. [J16]

"Radar Micro-Doppler Signature Classification using Dynamic Time Warping"

This paper describes the first feasibility study using dynamic time warping (DTW) to classify the micro-Doppler signature (mu-DS) for radar automatic target recognition (ATR). Real radar data has been used in the testing, and the performance of the DTW classifier has been benchmarked against the conventional k-nearest neighbour (k-NN) algorithm. The basic theory behind the mu-DS is introduced, and aspects of the phenomenon that could cause difficulties for classifiers are highlighted. We explain how DTW can cope with these difficulties and achieve successful classification of three target classes. A correct classification rate exceeding 0.8 has been achieved, leading to the conclusion that this technique shows considerable promise for application in radar ATR systems. [J17]

"Generic Centralized Multi Sensor Data Fusion Based on Probabilistic Sensor and Environment Models for Driver Assistance Systems"

Modern driver assistance and safety systems are using a combination of two or more sensors for reliable tracking and classification of relevant road users like vehicles, trucks, cars and others. In these systems, processing and fusion stages are optimized for the properties of the sensor combination and the application requirements. A change of either sensor hardware or application involves expensive redesign and evaluation cycles. In this contribution, we present a multi sensor fusion system which is implemented to be independent of both sensor hardware properties and application requirements. This supports changes in sensor combination or application requirements. Furthermore, the environmental model can be used by more than one application at the same time. A probabilistic approach for this generic fusion system is presented and discussed. [J18]

"Improving Discrimination of Savanna Tree Species Through a Multiple-Endmember Spectral Angle Mapper Approach: Canopy-Level Analysis"

Differences in within-species phenology and structure are controlled by genetic variation, as well as topography, edaphic properties, and climatic variables across the landscape, and present important challenges to species differentiation with remote sensing. The objectives of this paper are as follows: 1) to evaluate the classification performance of a multiple-endmember spectral angle mapper (SAM) classification approach in discriminating ten common African savanna tree species and 2) to compare the results with the traditional SAM classifier based on a single endmember per species. The canopy spectral reflectance of the tree species (Acacia nigrescens, Combretum apiculatum, Combretum imberbe, Dichrostachys cinerea, Euclea natalensis, Gymnosporia buxifolia, Lonchocarpus capassa, Pterocarpus rotundifolius, Sclerocarya birrea, and Terminalia sericea) was extracted from airborne hyperspectral imagery that was acquired using the Carnegie Airborne Observatory system over Kruger National Park, South Africa, in May 2008. This study highlights three important phenomena: 1) Intraspecies spectral variability affected the discrimination of savanna tree species with the SAM classifier; 2) the effect of intraspecies spectral variability was minimized by adopting the multiple-endmember approach, e.g., the multiple-endmember approach produced a higher overall accuracy (mean of 54.5% for 20 bootstrapped replicates) when compared to the traditional SAM (mean overall accuracy = 20.5%); and 3) targeted band selection improved the classification of savanna tree species (the mean overall percent accuracy is 57% for 20 bootstrapped replicates). Higher overall classification accuracies were observed for evergreen trees than for deciduous trees. [J19]

"One-Dimensional Frequency-Domain Features for Aircraft Recognition from Radar Range Profiles"

To extract effective one-dimensional frequency-domain features from high-resolution radar range profiles, the differential power spectrum (DPS) and the product spectrum, which were originally proposed for the speech signal processing, are introduced to the radar target recognition community. Through differentiating the power spectrum with respect to frequency, we obtained the DPS, which is translation invariant. The DPS can preserve the spectral information contained in the range profiles. The product spectrum is defined as the product of the power spectrum and the group delay function. Thus, it can combine the information contained in the magnitude spectrum and phase spectrum of the range profiles and then carry more details about the shape of the aircrafts. In the classification phase, an optimal choice can be determined by implementing six different training algorithms of multilayered feed-forward neural network. The range profiles were measured by using the two-dimensional backscatters distribution data of four different scaled aircraft models. Simulations were demonstrated to evaluate the classification performance with the DPS and the product spectrum-based features. The simulation results have shown that both DPS and product spectrum-based features are effective for the automatic target recognition (ATR) of aircrafts. [J20]

"Interference Cancellation and Signal Direction Finding with Low Complexity"

We propose a novel beamforming algorithm for a three-element system that suppresses an interference signal while still being able to measure a target's interferometer phases. Unlike most direction-of-arrival (DOA) estimation algorithms, our algorithm does not use a grid search. Instead the estimates result from a closed-form solution, a great advantage in time-sensitive applications. The derivation of the algorithm is presented, and its statistical performance is examined with simulations. Additionally, our numerical results demonstrate that our algorithm is capable of achieving more reliable DOA estimates than those found with the well-known multiple signal classification (MUSIC) algorithm. Finally, a radar signal processing example is presented. [J21]

"Permutation Method for ICA Separated Source Signal Blocks in Time Domain"

A new permutation method for ICA (independent component analysis)- based blind separation is presented. The objective here is to concatenate ICA separated signals in adjacent time blocks. The proposed method utilizes the

associativity in column vectors of an estimated mixing matrix and a tracking filter. It has advantages of no required array calibration, efficient computation, and real time updatability. These superiorities are highly beneficial for radar or communication system type applications. Furthermore it is shown, by an experiment using radio wave signals, that the proposed permutation algorithm successfully permutes the separated signal blocks. [J22]

"Radar Micro-Doppler Signature Analysis with HHT"

Radar micro-Doppler signature analysis of vibrating targets with the joint time-frequency methods can provide useful information for target detection, classification, and recognition. We employ a well-known method for nonlinear and nonstationary signals, Hilbert-Huang transform (HHT) as a new approach in micro-Doppler analysis. Simulation and experimental results show that it can achieve better performance than the traditional Cohen's class time-frequency methods. [J23]

"Human motion estimation with multiple frequency modulated continuous wave radars"

Human motion estimation is an important issue in automotive, security or home automation applications. Radar systems are well suited for this because they are robust, are independent of day or night conditions and have accurate range and speed domain. The human response in a radar range-speed-time measurement behaves like an extended target where legs and arms coincide. A mutually non-coherent radar sensor network makes it possible to estimate additional information of the extended target response. To keep the system low cost the network uses commercial off-the-shelf (COTS) radar sensors without synchronisation of frequency or phase between the radar sensors. This article presents the results of human motion estimation with a mutually non-coherent radar sensor network. The calibration, radar processing, parameter estimation and classification of extended human objects are described. The swinging and rotating moving body parts give elliptical shapes in the differential range-speed responses. A model fit gives the legs and arms parameters on which classification is possible. [J24]

"Polarimetric Scattering Similarity Between a Random Scatterer and a Canonical Scatterer"

In this letter, we propose a novel parameter to measure the scattering similarity between a random scatterer and a canonical scatterer. Compared with the similarity parameter proposed by Yang, the novel parameter not only has some advantages, such as its independence of the spans of a coherence matrix, but also can be applied directly in the case of a random scatterer made up of multiscattering centers. As an example, the novel parameter is adopted to extract some scattering characteristics of a target. With the full polarimetric L-band airborne synthetic aperture radar data, we illustrate the veracity of the novel parameter in measuring scattering similarity and its application in terrain classification. [J25]

"Collaborative mobile target imaging in UWB wireless radar sensor networks"

Wireless sensor networks (WSN) have thus far been used for detection and tracking of static and mobile targets for mission critical surveillance applications. However, detection and tracking do not suffice for a complete and accurate target classification. In fact, surveillance target imaging yields the most valuable information. Current techniques mainly aim to provide images of static environment in a sensor network. Nevertheless, imaging of mobile targets requires networked and collaborative detection, tracking and imaging capabilities. With this regard, ultra-wideband (UWB) radar technology stands as a promising approach for networked target imaging due to its unique features such as having no line-of-sight (LoS) requirement. However, UWB wireless radar sensor network (WRSN) is yet to be developed for imaging of mobile targets. In this paper, an architecture and a new collaborative mobile target imaging (CMTI) algorithm for WRSN are presented. The objective is to efficiently obtain an accurate image of mobile targets based on the collaborative effort of deployed radar sensor nodes. CMTI enables detection, tracking and imaging of mobile targets as a complete WRSN solution. Performance evaluations reveal that CMTI yields high quality radar image of mobile targets inWRSN with very low communication overhead regardless of the target shape and velocity. [J26]

"Phenomenological Vessel Scattering Study Based on Simulated Inverse SAR Imagery"

This paper presents a study on the origin of the dominating scattering mechanisms observed in polarimetric synthetic aperture radar (SAR) images of ships. The study has been made by using numerical simulations, which have been carried out with a radar cross section (RCS) prediction tool (GRaphical Electromagnetic COmputing) and a SAR simulator. Extensive series of simulations has been run for realistic 3-D geometrical models of ships with various sizes. Different radar parameters, aspect angles, and sea surface states have been considered in the scenario. Data analysis with coherent target decompositions has indicated characteristic polarimetric signatures for particular ships within a specific range of viewing angles. This happens at highly oblique

incidences where the responses appear to be less sensitive to changes in the operating frequency and bearing angles. Under such conditions, ship scattering can be schematized by the distribution of a set of guide scatterers with high RCS. Their positions and polarimetric characteristics are quantitatively summarized in a new feature vector, which has been proposed to be the basis for classification algorithms. Key ideas about this vector are presented at the end of this paper, jointly with some examples related to three different ships. Recent publications have shown that they can be successfully cast within a new unsupervised vessel classification scheme. [J27]

"Gabor Filter Approach to Joint Feature Extraction and Target Recognition"

This paper presents a new approach of improving automatic target recognition (ATR) performance by tuning adaptively the Gabor filter. The Gabor filter adopts the network structure of two layers, and its input layer constitutes the adaptive nonlinear feature extraction part, whereas the weights between output layer and input layer constitute the linear classifier. From the statistic property of high-resolution range profile (HRRP), its extracted nonstationarity degree of features is tracked to extract the discriminative features of Gabor atoms. Two experimental examples show that the Gabor filter approach with simple structure has higher recognition rate in radar target recognition from HRRP as compared with several existing methods. [J28]

"Mine Classification With Imbalanced Data"

In many remote-sensing classification problems, the number of targets (e.g., mines) present is very small compared with the number of clutter objects. Traditional classification approaches usually ignore this class imbalance, causing performance to suffer accordingly. In contrast, the recently developed infinitely imbalanced logistic regression (IILR) algorithm explicitly addresses class imbalance in its formulation. We describe this algorithm and give the details necessary to employ it for remote-sensing data sets that are characterized by class imbalance. The method is applied to the problem of mine classification on three real measured data sets. Specifically, classification performance using the IILR algorithm is shown to exceed that of a standard logistic regression approach on two land-mine data sets collected with a ground-penetrating radar and on one underwater-mine data set collected with a sidescan sonar. [J29]

"Phase of Target Scattering for Wetland Characterization Using Polarimetric C-Band SAR"

Wetlands continue to be under threat, and there is a major need for mapping and monitoring wetlands for better management and protection of these sensitive areas. Only a few studies have been published on wetland characterization using polarimetric synthetic aperture radars (SARs). The most successful results have been obtained using the phase difference between HH and VV polarizations, phiHH- phiVV, which has shown promise for separating flooded wetland classes. Recently, we have introduced a new decomposition, the Touzi decomposition, which describes target scattering type in terms of a complex entity, the symmetric scattering type. Huynen's target helicity is used to assess the symmetric nature of target scattering. In this paper, the new complex-scattering-type parameters, the magnitude alphasand phase Phialphas, are investigated for wetland characterization. The use of the dominant-scattering-type phase Phialphasmakes it possible to discriminate shrub bogs from poor (sedge or shrub) fens. These two classes cannot be separated using phiHH- phiVV, or the radiometric scattering information provided by alphas, the Cloude alpha, the entropy H, and the multipolarization HH-HV-VV channels. phialphas, which cannot detect deep (45 cm below the peat surface) water flow in a bog, is more sensitive to the shallower (10-20-cm) fen beneath water, and this makes possible the separation of poor fens from shrub bogs. Phialphasalso permits the discrimination of conifer-dominated treed bog from upland deciduous forest under leafy conditions. Target helicity information is exploited to introduce a new parameter, the target asymmetry. The latter is shown very promising for detection of forest changes between leafy and no-leaf conditions. The analysis of low-entropy marsh scattering showed that both the scattering-type magnitude and phas--e alphasand Phialphas, respectively, as well as the maximum polarization intensity of the dominant scattering m, are needed for a better understanding of marsh complex scattering mechanisms. The unique information provided by the new roll-invariant decomposition parameters are demonstrated using repeat-pass Convair-580 polarimetric C-band SAR data collected in June and October 1995 over the RAMSAR Mer Bleue wetland site near Ottawa (Canada). [J30]

"RKHS Bayes Discriminant: A Subspace Constrained Nonlinear Feature Projection for Signal Detection"

Given the knowledge of class probability densities, aprioriprobabilities, and relative risk levels, Bayes classifier provides the optimal minimum-risk decision rule. Specifically, focusing on the two-class (detection) scenario, under certain symmetry assumptions, matched filters provide optimal results for the detection problem. Noticing that the Bayes classifier is in fact a nonlinear projection of the feature vector to a single-dimensional statistic, in

this paper, we develop a smooth nonlinear projection filter constrained to the estimated span of class conditional distributions as does the Bayes classifier. The nonlinear projection filter is designed in a reproducing kernel Hilbert space leading to an analytical solution both for the filter and the optimal threshold. The proposed approach is tested on typical detection problems, such as neural spike detection or automatic target detection in synthetic aperture radar (SAR) imagery. Results are compared with linear and kernel discriminant analysis, as well as classification algorithms such as support vector machine, AdaBoost and LogitBoost. [J31]

"Large Margin Feature Weighting Method via Linear Programming"

The problem of feature selection is a difficult combinatorial task in machine learning and of high practical relevance. In this paper, we consider feature selection method for multimodally distributed data, and present a large margin feature weighting method for k-nearest neighbor (kNN) classifiers. The method learns the feature weighting factors by minimizing a cost function, which aims at separating different classes by large local margins and pulling closer together points from the same class, based on using as few features as possible. The consequent optimization problem can be efficiently solved by linear programming. Finally, the proposed approach is assessed through a series of experiments with UCI and microarray data sets, as well as a more specific and challenging task, namely, radar high-resolution range profiles (HRRP) automatic target recognition (ATR). The experimental results demonstrate the effectiveness of the proposed algorithms. [J32]

"Statistical analysis of the zero-phase method for aligning noisy high-resolution radar signals"

Automatic target recognition using high-range resolution radars is a difficult task. Variations in the distance to the target cause circular shifts of the received signal, and most of the classification algorithms are very sensitive to shifts over the input signal. This fact makes the alignment of each signal prior to any classification stage very important. Here the alignment of noisy signals using the zero phase method is studied. In order to evaluate the performance of the alignment method, a theoretical analysis of the sensitivity to noise of this alignment method is carried out. As a result, an analytical expression that predicts the error of the alignment method is obtained. The validity of this expression is also confirmed by experimental results. A database of high-range resolution radar profiles containing patterns belonging to six different targets has been used, and a comparative study of the sensitivity to noise estimated using the profiles of the database and predicted by the analytical expression is carried out. The results demonstrate that the proposed analytical expression is useful to analyse the sensitivity to noise of the zero-phase alignment method for medium and high signal-to-noise ratio values. [J33]

"Analysis by Wavelet Frames of Spatial Statistics in SAR Data for Characterizing Structural Properties of Forests"

Spatial statistics (texture) in SAR backscatter data of forested areas bears information on structural and geometric properties that could be useful in mapping forest extent, species type, and stages of regeneration or degradation. Based on a previously published theoretical approach in deriving texture measures from SAR data using wavelet frames, experiments are reported that aim to characterize, from a purely observational point of view, wavelet texture measures' sensitivity with respect to target structural properties and SAR configurations. Suitable analytical tools are introduced to represent dependences in the combined space-scale-polarization domain through signatures that condense information in graphical form. Moreover, class separability, afforded by wavelet texture measures in a supervised classification setting and based on the Fischer linear discriminant analysis, is considered. This paper focuses on two structurally different forest types (tropical rain forest in the Central Africa Congo Floodplain and mixed-species wooded savanna in Queensland, Australia) and uses data from orbital radars, particularly from the Japanese Advanced Land Observing Satellite Phased Arrayed L-band Synthetic Aperture Radar. The analysis indicated that textural information from spatial statistics can provide, in some cases, better class separability in forest mapping with respect to one-point statistics, although spatial resolution in texture products is reduced. However, dependences of texture measures on the polarization state are detected, particularly in forests where a greater diversity of scattering mechanisms occurs. [J34]

"Polarization Symmetric Scatterer Metric Space"

The coherent polarization scattering matrix decomposition presented in Cameron et al. brought attention to the importance of Symmetric Scatterer Space, the space of scattering matrices corresponding to symmetric scatterers. Each symmetric scatterer scattering matrix can be associated with a complex number z, the scatterer-type parameter, where |z| les 1. A distance measure, d(z1, z2), was defined on Symmetric Scatterer Space providing a means of comparing scattering matrices. It will be demonstrated that Symmetric Scatterer Space is a metric space with metric d(z1, z2). A new mapping of the Unit Disc representation of Symmetric Scatterer Space to a sphere is also presented along with a metric on the sphere, ds(thetas1, phi1; thetas2, phi2), that is equivalent to the metric d(z1, z2) on the Unit Disc. [J35]

"Exploitation of Ship Scattering in Polarimetric SAR for an Improved Classification Under High Clutter Conditions"

This paper evaluates the potentialities of polarimetric ship scattering for basing classification methods that provide reasonable performance within cluttered scenes. Both simulated and airborne polarimetric synthetic aperture radar (SAR) images have been used to validate the conclusions of a previous phenomenological study. Numerical simulations have been carried out with GRECOSAR, a polarimetric interferometric SAR simulation tool that is able to process highly complex targets with a fast and accurate radar-cross-section prediction module. A representative set of scenarios has been defined, which includes various realistic ship models, sea states, and imaging geometries. In all of them, a two-scale sea surface model precisely accounting for sea-ship interaction and sea clutter has been added. The analysis of different images has shown that, with an adequate spatial resolution, ships may be characterized by a particular spatial arrangement and polarization state distribution of dominant scattering centers. This feature has allowed one to propose a new classification algorithm, which shows a promising behavior after various preliminary tests. In this paper, the performance of this technique is further evaluated with realistic clutter. The results show that robust classification is possible even in highly cluttered scenes if quad-pol imagery is available. On the contrary, in low clutter conditions, the usage of less restrictive solutions, like circular dual-pol schemes, is feasible and may still get an acceptable performance. [J36]

"Lessons for Radar"

Echolocating mammals such as bats, whales and dolphins have been using waveform diversity for over 50 million years. Synthetic systems such as sonar and radar have existed for fewer than 100 years. Given the extraordinary capability of echolocating mammals it seems self-evident that designers of radar (and sonar) systems may be able to learn lessons that may potentially revolutionize current radar-based capability leading to truly autonomous navigation, collision avoidance, and automatic target classification. Echolocating mammals have been little studied in relation to the operation of radar and sonar systems. In this article, we introduce a range of strategies employed by bats and consider how these might be exploitable in the radar systems of tomorrow. Specifically, we concentrate on the functions necessary for autonomous navigation. Echolocating mammals are known to vary their waveforms via modification to the pulse-repetition frequency (PRF), also known to biologists as pulse-repetition rate (PRR), power, and frequency content of their transmitted waveforms. This has enabled them to evolve highly sophisticated orientation techniques and the ability to successfully forage for food. Moreover, recent developments in technology mean that it is now possible to replicate these parametric variations in synthetic sensing systems such as radar and sonar. [J37]

"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. [J38]

"Helicopter Classification with a High Resolution LFMCW Radar"

Helicopter classification using a high resolution linear frequency modulated continuous wave (LFMCW) radar is addressed. A blade echo modelling for this radar system is derived, taking into account that the stop-and-go assumption is not longer applicable. The standard classification schemes based on the L/N-quotient and the evenness of the number of blades are easily reproduced in this high resolution context, although two main advantages are added: a high pulse repetition frequency (PRF) to acquire the Doppler bandwidth is no longer necessary, and the time for which we receive returned signal from the target may be maximized. On the other hand, a characteristic critical classification problem, for which the standard approaches do not properly work, is presented. Two classification schemes are proposed for this situation, the first one based on coherent matched masks and the second one based on incoherent masks where a robustness parameter has also been defined. Identification probabilities as a function of the signal-to-noise ratio (SNR) are obtained in order to characterize the performance of both techniques. Real data validate both the derived model and the proposed classification

algorithms. [J39]

"Classification of primary radar tracks using gaussian mixture models"

Classification of primary surveillance radar tracks as either aircraft or non-aircraft is critical to a number of emerging applications, including airspace situational awareness and collision avoidance. Substantial research has focused on target classification of pre-processed radar surveillance data. Unfortunately, many non-aircraft tracks still pass through the clutter-reduction processing built into the aviation surveillance radars used by the federal aviation administration. This paper demonstrates an approach to radar track classification that uses only post-processed position reports and does not require features that are typically only available during the pre-processing stage. Gaussian mixture models learned from recorded data are shown to perform well without the use of features that have been traditionally used for target classification, such as radar cross-section measurements. [J40]

"The probabilistic data association filter"

The measurement selection for updating the state estimate of a target's track, known as data association, is essential for good performance in the presence of spurious measurements or clutter. A classification of tracking and data association approaches has been presented, as a pure MMSE approach, which amounts to a soft decision, and single best-hypothesis approach, which amounts to a hard decision. It has been shown that the optimal state estimator in the presence of data association uncertainty consists of the computation of the conditional pdf of the state x(k) given all information available at time k, namely, the prior information about the initial state, the intervening known inputs, and the sets of measurements through time k. It has also been pointed out that if the exact conditional pdf, which is a mixture, is available, then its recursion requires only the probabilities of the most recent association events. The conditions under which this result holds, namely whiteness of the noise, detection, and clutter processes, were presented. The PDAF and JPDAF algorithms, which carry out data association and state estimation in clutter, have been described. A simple example was given to illustrate how the clutter and occasional missed detections can lead to track loss for a standard tracking filter, and how PDAF can keep the target in track under such circumstances. By using the Monte Carlo in a simulated based surveillance as an exampled shown. The numerous applications of the PDAF/JPDAF illustrated in "Real-World Applications of PDAF and JPDAF" show the potential pitfalls of using sophisticated algorithms for tracking in difficult environments as well as how to overcome them. The effect of finite sensor resolution can be a more severe problem than the data association and deserves special attention. [J41]

"Radar target classification method with reduced aspect dependency and improved noise performance using multiple signal classification algorithm"

This study introduces a novel aspect and polarisation invariant radar target classification method based on the use of multiple signal classification (MUSIC) algorithm for feature extraction. In the suggested method, for each candidate target at each designated reference aspect, feature matrices called `MUSIC spectrum matrices (MSMs)` are constructed using the target`s scattered data at different late-time intervals. An individual MSM corresponds to a map of a target`s natural resonance-related power distribution over the complex frequency plane under the chosen aspect angle`late-time interval conditions. The collection of these feature matrices is used first to determine the best late-time interval for optimal feature extraction. Then, the MSM of a target, which are computed over the optimal time interval at all reference aspects, are superposed to obtain the `fused MUSIC spectrum matrix (FMSM)`. The FMSM of a target is its main classifier feature in the proposed method as the aspect dependency of an FMSM is highly reduced because of its multi-aspect construction process. The suggested method is demonstrated for both simple and complex target geometries such as conducting spheres, dielectric spheres and small-scale aircraft targets with high accuracy rates even for low SNR values using feature fusion at only a few different reference aspects. [J42]

"Pitch estimation for non-cooperative maritime targets in ISAR scenarios"

Maritime targets are usually involved in complex motions that complicate the generation of focused inverse synthetic aperture radar (ISAR) images and their scaling in cross-range. By assuming some hypotheses that translate to some restrictions in the maritime surveillance scenario, a signal model for the phase history is derived. This function is calculated here using phase gradient autofocus and can be related to the pitch motion of the ship, which may consequently be estimated. The amplitude and the period of this pitch estimate allow us to select imaging times at which the ISAR images are descriptive for classification purposes. The cross-range scaling of these images is also achieved. Simulated data are used to validate the technique and to evaluate its performance when deviations from the nominal scenario are present. Results obtained with live data acquired by a high-resolution radar confirm the effectiveness of the approach. [J43]

"Multi-feature based automatic recognition of ship targets in ISAR"

This paper deals with the problem of non-cooperative target recognition. Specifically, the aim is the automatic recognition of ship targets from inverse synthetic aperture radar (ISAR) images. For this purpose a new two-step multi-feature based technique is proposed; this technique uses a number of features extracted from the ship radar image and matches these features with those extracted from the images obtained by properly projecting the target models of the classification library. Both cases of a priori known or unknown ship aspect angles are considered: the knowledge of the ship aspect (as available from tracking data) allows the selection of the candidate models on the basis of the matching between the ship and the model length, thus resulting in a performance improvement. Moreover, both single- and multi-frame-based processing techniques are proposed in order to assess the performance improvement achievable when an increasing number of ISAR images are involved in the decision; the fusion strategy adopted for the exploitation of the information from the multiple images is also described. The performance of the overall proposed technique is deeply investigated against simulated data. Results of its application to a set of live ISAR images of a ship target are also provided showing the effectiveness of the proposed approach. [J44]

"Flower classification by bats: Radar comparisons"

In recent years, with the development of high-range resolution radars, the desire to identify targets under all weather and clutter conditions has become of great importance. This is an activity carried out with great success by echo-locating mammals such as nectar feeding bats that are able to detect and select flowers of bat-pollinated plants, even in a dense clutter environment. Herein, data consisting of acoustically-generated high-range resolution profiles of four bat-pollinated flower heads are analysed. Multi-perspective classification performance is assessed and compared with the radar case. There are close parallels that suggest lessons can be learnt from nature. [J45]

"Feature Enhancement of Stripmap-Mode SAR Images Based on an Optimization Scheme"

Based on a nonquadratic-optimization method originally proposed for spotlight-mode SAR image reconstruction, a modification for stripmap-mode SAR images is presented in this letter. This is done by mathematically reformulating the projection kernel and numerically putting it into a form that is suitable for optimization. The performance was evaluated by measures of the target contrast and 3-dB beamwidth using Radarsat-1 data. Results were analyzed and compared with those using minimum-variance and multiple-signal-classification methods. Results demonstrate that the target's features are effectively enhanced and that the dominant scattering centers are well separated using the proposed method. In addition, the image fuzziness is greatly reduced, and the image fidelity is well preserved. The effectiveness of the modification is thus validated. [J46]

"Maritime border control multisensor system"

This focuses on the classification task performed into a multi-sensor system for the coastal surveillance. The system is composed of two platforms of sensors: a land-based platform equipped with a land based radar, an Automatic Identification System (AIS) and an infrared camera (IR); an airborne platform carrying an airborne radar that can operate in a spotlight Synthetic Aperture Radar (SAR) mode, a video camera, and a second IR camera. The tasks performed by the system are the detection, tracking, identification, and classification of multiple targets, the evaluation of their threat level, and the selection of an intervention on them. The classification algorithm implemented inside the system exploits an analytical approach based on the confusion matrix (CM) of the imaging sensors that belong to the system. Some measures of effectiveness (MoE) of the system are evaluated, considering both cases where an ideal error-free classification process and a non-ideal classification process are performed. [J47]

"Automatic Target Recognition by Means of Polarimetric ISAR Images and Neural Networks"

Inverse synthetic aperture radar (ISAR) images are often used for classifying and recognizing targets. Moreover, the use of fully polarimetric ISAR (Pol-ISAR) images enhances classification capabilities. In this paper, the authors propose a novel automatic target recognition (ATR) technique based on the use of fully Pol-ISAR images and neural networks (NNs). In order to reduce the amount of data processed by the classifier, the brightest scattering centers are first extracted by means of the Pol-CLEAN technique, and then, their scattering matrices are decomposed using Cameron's decomposition. A classifier based on the use of multilayer perceptron NN that makes use of the features extracted from the Pol-ISAR images is then implemented. A proof-of-concept test is performed on real data acquired during a controlled experiment in an anechoic chamber. [J48]

"Radar Detection and Classification of Jamming Signals Belonging to a Cone Class"

This paper considers the problem of detecting and classifying a radar target signal and a jamming signal produced by a deception electronic counter measure (ECM) system based on a digital radio frequency memory (DRFM) device. The disturbance is modeled as a complex correlated Gaussian process. The jamming is modeled as a signal belonging to a cone whose axis is the true target signal. Two different approaches are analyzed, based on the adaptive coherent estimator (ACE) and on the generalized likelihood ratio test (GLRT), yielding both to a two-block device. The performance of the two detection/classification algorithms are evaluated, analytically, when possible, and by Monte Carlo simulation. [J49]

"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. [J50]

"A Coherent Model of Forest Propagation- Application to Detection and Localization of Targets Using the DORT Method"

We study the propagation of electromagnetic fields in forest media in a frequency band between 100 and 300 MHz. We develop an exact coherent model in order to compute the electromagnetic field of a received wave after multiple scattering from the elements of the medium, in and outside the forest. We propose simplifications for the model of the forest and approximations for the electromagnetic method to reduce the computing time. We use and simulate a DORT based method to detect and locate a hidden target in the medium. We develop this method to adapt it to a real configuration and we apply it to measurements in anechoic chamber. [J51]

"Data-Level Fusion of Multilook Inverse Synthetic Aperture Radar Images"

Although techniques for resolution enhancement in single-aspect radar imaging have made rapid progress in recent years, it does not necessarily imply that such enhanced images will improve target identification or recognition. However, when multiple looks of the same target from different aspects are obtained, the available knowledge increases, allowing more useful target information to be extracted. Physics-based image fusion techniques can be developed by processing the raw data collected from multiple inverse synthetic aperture radar sensors, even if these individual images are at different resolutions. We derive an appropriate data fusion rule to generate a composite image containing enhanced target shape characteristics for improved target recognition. The rule maps multiple data sets collected by multiple radars with different system parameters on to the same spatial-frequency space. The composite image can be reconstructed using the inverse 2-D Fourier transform over the separated multiple integration areas. An algorithm called the Matrix Fourier Transform is proposed to realize such a complicated integral. This algorithm can be regarded as an exact interpolation such that there is no information loss caused by data fusion. The rotation centers need to be carefully selected to properly register the multiple images before performing the fusion. A comparison of the image attribute rating curve between the fused image and the spatially averaged images quantifies the improvement in the detected target features. The technique shows considerable improvement over a simple spatial averaging algorithm and thereby enhances target recognition. [J52]

"Adaptive fusion framework based on augmented reality training"

A framework for the fusion of computer-aided detection and classification algorithms for side-scan imagery is presented. The framework is based on the Dempster-Shafer theory of evidence, which permits fusion of heterogeneous outputs of target detectors and classifiers. The utilisation of augmented reality for the training and evaluation of the algorithms used over a large test set permits the optimisation of their performance. In addition, this framework is adaptive regarding two aspects. First, it allows for the addition of contextual information to the decision process, giving more importance to the outputs of those algorithms that perform better in particular mission conditions. Secondly, the fusion parameters are optimised on-line to correct for mistakes, which occur while deployed. [J53]

"Time Reversal Imaging by Adaptive Interference Canceling"

We develop the time reversal adaptive interference canceler (TRAIC) time reversal beamformer (TRBF), a new algorithm to detect and locate targets in rich scattering environments. It utilizes time reversal in two stages: (1) Anti-focusing: TRAIC time reverses and then reshapes the clutter backscatter to mitigate the clutter response; (2) Focusing: TRBF time reverses the residual backscatter to focus the radar image on the target. Laboratory experiments with electromagnetic radar data in a highly cluttered environment confirm the superiority of TRAIC-TRBF over conventional direct subtraction (DS) beamform imaging. [J54]

"Breast Tumor Characterization Based on Ultrawideband Microwave Backscatter"

Characterization of architectural tissue features such as the shape, margin, and size of a suspicious lesion is commonly performed in conjunction with medical imaging to provide clues about the nature of an abnormality. In this paper, we numerically investigate the feasibility of using multichannel microwave backscatter in the 1-11 GHz band to classify the salient features of a dielectric target. We consider targets with three shape characteristics: smooth, microlobulated, and spiculated; and four size categories ranging from 0.5 to 2 cm in diameter. The numerical target constructs are based on Gaussian random spheres allowing for moderate shape irregularities. We perform shape and size classification for a range of signal-to-noise ratios (SNRs) to demonstrate the potential for tumor characterization based on ultrawideband (UWB) microwave backscatter. We approach classification with two basis selection methods from the literature: local discriminant bases and principal component analysis. Using these methods, we construct linear classifiers where a subset of the bases expansion vectors are the input features and we evaluate the average rate of correct classification as a performance measure. We demonstrate that for 10 dB SNR, the target size is very reliably classified with over 97% accuracy averaged over 360 targets; target shape is classified with over 70% accuracy. The relationship between the SNR of the test data and classifier performance is also explored. The results of this study are very encouraging and suggest that both shape and size characteristics of a dielectric target can be classified directly from its UWB backscatter. Hence, characterization can easily be performed in conjunction with UWB radar-based breast cancer detection without requiring any special hardware or additional data collection. [J55]

"Equivalence Between Cameron's Unit Disc and PoincarЙ's Sphere for Symmetric Scattering Characterization and Classification"

Scattering type classification represents a significant step toward target classification. Both the surface of Poincare's sphere and Cameron's unit disc have been used separately to represent symmetric scattering matrices and to define classification methods. In this letter, the equivalence of using the surface of Poincare's sphere and Cameron's unit disc in terms of characterization and classification of symmetric scattering types is demonstrated mathematically. [J56]

"Maximum Position Alignment Method for Noisy High-Resolution Radar Target Classification"

In this paper, the alignment of noisy high-resolution radar signals using the maximum position method is studied. The relationship between the shift estimation and the signal-to-noise ratio is considered. As a result, two analytical expressions are obtained that approximate the root-mean-square error of the difference in the shift estimation with and without noise. These two expressions allow us to improve the understanding of the sensitivity to noise of the Maximum Position alignment method. [J57]

"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. [J58]

"Recent developments in detection, imaging and classification for airborne maritime surveillance"

The role of maritime patrol missions is to monitor large oceanic areas. The authors focus on a complete signal-processing sequence from the primary detection of the targets to their classification or recognition from an airborne radar. Contrary to the classical approach in which detection, tracking, imaging and classification are considered separately, here the authors propose an integrated strategy based on a close cooperation among all

of them. Recent developments in high range resolution target detection are presented and their integration in the complete system is discussed to limit false alarms. High-resolution ISAR imaging of ships is then tackled and associated with a feature extraction process and a support vector machine classifier. A set of real data is used to illustrate the imaging and classification results. [J59]

"Analysis of data and model accuracy requirements for target classification using ladar data"

Considerable attention has recently been focused on laser radar (ladar) systems for surveillance applications, because of the richness inherent in the three-dimensional data they collect. Several research groups have looked into the ability to exploit ladar data in automatic or assisted target recognition systems. Designers of practical ladar recognition systems must have answers to very fundamental questions related to the quality and quantity of data required, the fidelity of target models used by the algorithm, and the effects of incorporating prior knowledge. This paper presents implementation guidelines derived from a simulation-based analysis of many such factors that can affect classification accuracy, including measurement noise and corresponding noise model accuracy, number of measured points on target, target model accuracy, target pose error, prior information, and target occlusion. The study includes data from eight vehicles, including seven civilian automobiles of similar size and shape, chosen specifically to result in a "hard" classification problem. Data are simulated under three hypothetical scenarios: 1) a pole-mounted ladar system for monitoring traffic through an intersection; 2) a low-flying helicopter-born ladar system for law enforcement applications; and 3) a low-altitude unmanned aerial vehicle (UAV) for military surveillance applications. [J60]

"Fast Chirplet Transform With FPGA-Based Implementation"

This letter presents a fast chirplet transform (FCT) algorithm, a computationally efficient method, for decomposing highly convoluted signals into a linear expansion of chirplets. The FCT algorithm successively estimates the chirplet parameters in order to represent a broad range of chirplet shapes, including the broadband, narrowband, symmetric, skewed, nondispersive, or dispersive. These parameters have significant physical interpretations for radar, sonar, seismic, and ultrasonic applications. For the real-time application and embedded implementation of the FCT algorithm, an FPGA-based hardware/software co-design is developed on Xilinx Virtex-II Pro FPGA development platform. Based on the balance among the system constraints, cost, and the efficiency of estimations, the performance of different algorithm implementation schemes have been explored. The developed system-on-chip successfully exhibits robustness in the chirplet transform of experimental signals. The FCT algorithm addresses a broad range of applications including velocity measurement, target detection, deconvolution, object classification, data compression, and pattern recognition. [J61]

"Editorial: Signal processing techniques for ISAR and feature extraction"

Inverse synthetic aperture radar (ISAR) is a non-cooperative target recognition technique that has been investigated for target identification by the combat identification (ID) community for the past decade. Recently, ISAR imaging of moving targets has been an area of vigorous research. ISAR imaging is an effective way to acquire high resolution images of targets of interest at long range and as such is an irreplaceable tool in the task of non-cooperative target recognition. Its applications include detection, imaging, and classification of ships and aircraft with airborne, maritime, and land-based radar systems. Being radar-based, this imaging technique can be employed in all weather and day/night conditions. [J62]

"Imaging Simulation of Bistatic Synthetic Aperture Radar and Its Polarimetric Analysis"

Employing the 3-D mapping and projection algorithm (MPA), an imaging simulation of bistatic synthetic aperture radar (BISAR) observation over a complex scenario is developed. Based on the explicit expression of the point target response of stripmap BISAR imaging, raw data are efficiently generated from the scattering map precalculated by MPA. Some examples of BISAR image simulation are studied. The polarimetric characteristics of a BISAR image are then discussed. It is found that some typical polarimetric parameters such as Cloude's alpha, beta and gamma and might become unable to describe the scattering mechanism under bistatic observation. A transform of unified bistatic polar bases for a BISAR image is proposed. The parameters alpha, beta and gamma and are modified to retain the property of orientation independence in the bistatic circumstance. Analysis of simulated images shows that the redefined alpha, beta and gamma and after the unified bistatic polar bases transform well describe different scattering mechanisms in BISAR imaging. It provides a primary tool for BISAR image interpretation and terrain classification. [J63]

"High-Resolution Through-the-Wall Radar Imaging Using Beamspace MUSIC"

The MUSIC algorithm is a high-resolution direction finding technique which has been successfully applied to enhance radar imaging in inverse synthetic aperture radar (ISAR). Although this signal subspace-based method

has proven effective when dealing with point targets and high signal-to-noise ratio (SNR), it may fail to work when directly applied to extended targets or target returns of low SNR. The Beamspace MUSIC (BS-MUSIC), in which the MUSIC algorithm is applied to multiple beams, is capable of locating spatially extended targets in low SNR environments. In this paper, we consider BS-MUSIC as an image formation method for indoor radar imaging problems and sensing through-the-wall applications. We compare BS-MUSIC performance to conventional beamforming and element-space MUSIC. Imaging results, using both synthesized and real data, demonstrate the advantages of the proposed algorithm in depicting targets behind walls. [J64]

"Ultra-wideband radar noise reduction for target classification"

The authors describe a calibration procedure for ultra-wideband (UWB) radar systems in order to measure the frequency-dependent transfer function or radar cross-section, respectively, of objects with a high computational efficiency. The benefit of using UWB pulses is that only one measurement is required for covering several GHz. However, the signal processing steps contain a deconvolution operation producing spike artefacts. They were successfully removed by the calculation of frequency-dependent signal-to-noise ratio and a following Wiener filtering. The proposed method was verified by some elementary targets of which the size of the objects were determined. [J65]

"Experimental investigation of selective localisation by decomposition of the time reversal operator and subspace-based technique"

The approaches of the active time reversal (TR) selective localisation based on the decomposition of the time reversal operator (DORT) and the TR multiple signal classification (MUSIC) location are presented. The waveguide experiment describes in detail the procedure of active TR location and shows that (i) the extended target could have multiple distinguishable eigenstates, unlike point-like targets in which one target corresponds to one eigenstate; (ii) the selective location can be achieved by means of the standard TR location in the presence of the suspended and bottom objects; (iii) compared with the standard TR location, TR MUSIC location based on signal subspaces performs better in locating non-resolved targets and has lower sidelobe levels to locate the extended target. Finally, the approach of acquiring the TR operator via array probing by weighting Hadamard-Walsh functions (to produce orthogonal beams) is discussed. The experimental result shows that the ambiguity surfaces of the standard TR location and the TR MUSIC location are greatly improved with this approach. [J66]

"Statistical CLEAN Technique for ISAR Imaging"

Inverse synthetic aperture radar (ISAR) images are frequently used in target classification and recognition applications. Some classifiers often require features that can be more easily obtained by extracting scattering centers from ISAR data rather than by reconstructing ISAR images. An available method for scattering center extraction, namely, the CLEAN technique, was proposed in a recent paper by Yang et al. In this paper, an improvement of this CLEAN technique is proposed that introduces a new method for detecting scattering centers. The proposed technique is based on a Gaussianity test, and its effectiveness is first theoretically proven and then tested on real data. Moreover, a comparison with the technique proposed by Yang et al. is shown. [J67]

"Sea-Ice Deformation State From Synthetic Aperture Radar Imagery-Part I: Comparison of C- and L-Band and Different Polarization"

In this paper, we present a quantitative comparison of L- and C-band airborne synthetic aperture radar imagery acquired at like- and cross-polarizations over deformed sea ice under winter conditions. The parameters characterizing the deformation state of the ice are determined at both radar bands and at different polarizations. The separation of deformed and level ice is based on a target detection technique. The threshold is set such that image pixels with intensities equal to or larger than the highest 2% of the level-ice intensity distribution are classified as deformed ice, independent of the radar configuration and ice conditions. Optical imagery of sufficient quality for comparison is available only in a very few cases. To characterize the deformation state, the areal fraction of deformation features and the average distance between these features are evaluated. The values obtained for both parameters are very sensitive to the radar frequency. Aeral fractions are larger, and average distances are smaller at L-band than at C-band because of the much higher intensity contrast between the deformed and level ice at L-band. The differences between polarizations at one radar band are smaller but not always negligible. In comparison to optical images, it was observed that deformed-ice areas can be distinguished from level ice over their whole length and extension at L-band, whereas at C-band, often, only prominent parts are visible. [J68]

"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. [J69]

"Bayesian Analysis of Lidar Signals with Multiple Returns"

Time-correlated single photon counting and burst illumination laser data can be used for range profiling and target classification. In general, the problem is to analyze the response from a histogram of either photon counts or integrated intensities to assess the number, positions, and amplitudes of the reflected returns from object surfaces. The goal of our work is a complete characterization of the 3D surfaces viewed by the laser imaging system. The authors present a unified theory of pixel processing that is applicable to both approaches based on a Bayesian framework, which allows for careful and thorough treatment of all types of uncertainties associated with the data. We use reversible jump Markov chain Monte Carlo (RJMCMC) techniques to evaluate the posterior distribution of the parameters and to explore spaces with different dimensionality. Further, we use a delayed rejection step to allow the generated Markov chain to mix better through the use of different proposal distributions. The approach is demonstrated on simulated and real data, showing that the return parameters can be estimated to a high degree of accuracy. We also show some practical examples from both near and far-range depth imaging. [J70]

"Radar target classification using doppler signatures of human locomotion models"

The problem of target classification for ground surveillance Doppler radars is addressed. Two sources of knowledge are presented and incorporated within the classification algorithms: 1) statistical knowledge on radar target echo features, and 2) physical knowledge, represented via the locomotion models for different targets. The statistical knowledge is represented by distribution models whose parameters are estimated using a collected database. The physical knowledge is represented by target locomotion and radar measurements models. Various concepts to incorporate these sources of knowledge are presented. These concepts are tested using real data of radar echo records, which include three target classes: one person, two persons and vehicle. A combined approach, which implements both statistical and physical prior knowledge provides the best classification performance, and it achieves a classification rate of 99% in the three-class problem in high signal-to-noise conditions. [J71]

"Automatic target recognition using multi-diversity radar"

The information content of radar target signatures is a key aspect for automatic target recognition. The role of high-range resolution is investigated as a function of the illuminating wavelength. The classification performance is evaluated using (i) full-scale 2D inverse synthetic aperture radar images obtained from a stepped-frequency chirp modulation radar system and (ii) the corresponding sub-spectra of the target reflectivity function forming lower resolution images at differing centre frequencies. The classification performance as given by different combinations of RF frequencies are also evaluated and compared with the coherent reconstruction from the full bandwidth. Finally, the classification results are also computed using multiple aspects to sense the target. In this way, classification performance as function of diversity space is examined. [J72]

"A Self-Initializing PolInSAR Classifier Using Interferometric Phase Differences"

This paper describes an unsupervised classifier for polarimetric interferometric synthetic aperture radar (PolInSAR) data. Expectation maximization is used to estimate class parameters that maximize the likelihood of observations in an input data set for a given number of classes. Polarimetric information, in the form of coherency matrices, and interferometric information, in the form of complex coherences, are taken into account. Differences in interferometric phase across different polarization states are explicitly modeled to make the classifier sensitive to the vertical structure of the scene under observation, and the distribution over such phase

differences is introduced. The classifier is self-initializing, in that it does not rely on decompositions or thresholds. Classification results obtained for real polarimetric interferometric data are presented and discussed. [J73]

"Polarimetric Analysis of Bistatic SAR Images From Polar Decomposition: A Quaternion Approach"

This paper focuses on polar decomposition, which is based on the quaternion formalism, in single-look and multilook synthetic aperture radar polarimetry. Polar decomposition is used to decompose a bistatic or monostatic polarimetric scattering matrix into a product of a Hermitian matrix (boost) and a unitary matrix (rotation). After an overview of polar decomposition principle and quaternion properties, coherent (single-look complex) and incoherent (multilook) polar decompositions are discussed. In single-look polar decomposition, we introduce the boost parameter and the rotation parameter with the purpose of classifying scattering mechanisms of different natures. New relationships between these geometrical parameters and the scattering matrix elements are obtained. We also briefly reexamine the standard coherent polarimetric target decomposition algorithms in the light of quaternions. Next, an original use of polar decomposition for incoherent polarimetric imaging is proposed, which leads to the definition of the multilook boost parameter and of the degree of polarization dispersion. Subsequently, a new approach is presented, which consists in decomposing the scattering matrix into boost and rotation components before vectorization, then in averaging to generate boost and rotation coherency matrices separately. This leads to new inferred parameters: the boost and rotation entropies, and the concurrent dominant scattering mechanisms. The link between these new parameters and standard polarimetric invariants from the Cloude and Pottier decomposition is discussed. Eventually, the multilook extension of polar decomposition may allow this to be applied to the classification of remote sensing data. In this framework, a set of five parameters reducing to four in the monostatic case can be considered. [J74]

"Supervised target detection and classification by training on augmented reality data"

A proof of concept for a model-less target detection and classification system for side-scan imagery is presented. The system is based on a supervised approach that uses augmented reality (AR) images for training computer added detection and classification (CAD/CAC) algorithms, which are then deployed on real data. The algorithms are able to generalise and detect real targets when trained on AR ones, with performances comparable with the state-of-the-art in CAD/CAC. To illustrate the approach, the focus is on one specific algorithm, which uses Bayesian decision and the novel, purpose-designed central filter feature extractors. Depending on how the training database is partitioned, the algorithm can be used either for detection or classification. Performance figures for these two modes of operation are presented, both for synthetic and real targets. Typical results show a detection rate of more that 95% and a false alarm rate of less than 5%. The proposed supervised approach can be directly applied to train and evaluate other learning algorithms and data representations. In fact, a most important aspect is that it enables the use of a wealth of legacy pattern recognition algorithms for the sonar CAD/CAC applications of target detection and target classification [J75]

"Angular Dependence of -Distributed Sonar Data"

Backscattered signal statistics are widely used for target detection and seafloor characterization. The K-distribution shows interesting properties for describing experimental backscattered intensity statistics. In addition to the fact that its probability distribution function accurately fits actual sonar data, it advantageously provides a physical interpretation linked to the backscattering phenomenon. Sonar systems usually record backscattered signals from a wide angular range across the ship's track. In this context, previous studies have shown that backscatter statistics strongly depend on the incidence angle. In this paper, we propose an extension of previous works to model the angular evolution of the K-distribution shape parameter. This evolution is made clear and analyzed from experimental data recorded with two sonar systems: a 95-kHz multibeam echosounder and a 110-kHz sidescan sonar. Model fitting with data backscattered from six seafloor configurations shows the improvement provided by our extension as compared to two previous models [J76]

"Adaptive boosting for SAR automatic target recognition"

The paper proposed a novel automatic target recognition (ATR) system for classification of three types of ground vehicles in the moving and stationary target acquisition and recognition (MSTAR) public release database. First MSTAR image chips are represented as fine and raw feature vectors, where raw features compensate for the target pose estimation error that corrupts fine image features. Then, the chips are classified by using the adaptive boosting (AdaBoost) algorithm with the radial basis function (RBF) network as the base learner. Since the RBF network is a binary classifier, the multiclass problem was decomposed into a set of binary ones through the error-correcting output codes (ECOC) method, specifying a dictionary of code words for the set of three possible classes. AdaBoost combines the classification results of the RBF network for each binary problem into a code word, which is then "decoded" as one of the code words (i.e., ground-vehicle classes) in the specified

dictionary. Along with classification, within the AdaBoost framework, we also conduct efficient fusion of the fine and raw image-feature vectors. The results of large-scale experiments demonstrate that our ATR scheme outperforms the state-of-the-art systems reported in the literature [J77]

"Discriminating real objects in radar imaging by exploiting the squared modulus of the continuous wavelet transform"

New technique based on continuous wavelet transform (CWT) for classifying objects in synthetic aperture radar (SAR) imaging is presented. The CWT allows to analyse two-dimensional SAR images to highlight the frequency and angular behaviour of the scatterers. This technique allows to build a SAR hyperimage, that is, a four-dimensional data cube which represents for each spatial location (x, y) of the scatterer in the image, its frequency and angular energy behaviour. When analysing different targets, objects or areas in SAR images, it has been recently observed that some scatterers belonging to a same class of objects could have similar frequency and angular energy responses. The previous observations have motivated the determination to exploit these energy responses to discriminate these objects. This discrimination is performed by frequency and angular correlations between the response of a particular scatterer (measured) and those of all the scatterers in the SAR image. Some examples of discrimination from real SAR data are presented and show an interest of the method for target classification and recognition for SAR imaging [J78]

"Development of a Tunable Multiband UWB Radar Sensor and Its Applications to Subsurface Sensing"

Development of a new tunable multiband ultra-wideband (UWB) radar sensor is presented. The UWB sensor integrates the transmitter, receiver, and antennas completely in a single package using microwave integrated circuits and operates over multiple pulse durations or frequency bands. The sensor can transmit pulses with duration varying from 450 to 1170 ps and peak power from 200 to 400 mW and can detect signals with a conversion gain of 6.5-9.5 dB and a dynamic range of 50dB over a 5.5-GHz RF bandwidth. It has a range resolution of around 1 in. The sensor performs well through tests of various samples, demonstrating its success for subsurface sensing. The multipulse/multiband feature allows the sensor to achieve both fine-range resolution and long operating range and enhanced target detection and classification [J79]

"Target Scattering Decomposition in Terms of Roll-Invariant Target Parameters"

The Kennaugh-Huynen scattering matrix con-diagonalization is projected into the Pauli basis to derive a new scattering vector model for the representation of coherent target scattering. This model permits a polarization basis invariant representation of coherent target scattering in terms of five independent target parameters, the magnitude and phase of the symmetric scattering type introduced in this paper, and the maximum polarization parameters (orientation, helicity, and maximum return). The new scattering vector model served for the assessment of the Cloude-Pottier incoherent target decomposition. Whereas the Cloude-Pottier scattering type alpha and entropy H are roll invariant, beta and the so-called target-phase parameters do depend on the target orientation angle for asymmetric scattering. The scattering vector model is then used as the basis for the development of new coherent and incoherent target decompositions in terms of unique and roll-invariant target parameters. It is shown that both the phase and magnitude of the symmetric scattering type should be used for an unambiguous description of symmetric target scattering. Target helicity is required for the assessment of the symmetry-asymmetry nature of target scattering. The symmetric scattering type phase is shown to be very promising for wetland classification in particular, using polarimetric Convair-580 synthetic aperture radar data collected over the Ramsar Mer Bleue wetland site to the east of Ottawa, Ontario, Canada [J80]

"SAR Polarimetry to Observe Oil Spills"

A study on sea oil spill observation by means of polarimetric synthetic aperture radar (SAR) data is accomplished. It is based on the use of a polarimetric constant false alarm rate filter to detect dark patches over SAR images. Then, the target decomposition theorem is exploited to distinguish oil spills and look-alikes. Experiments are conducted on polarimetric SAR data acquired during the SIR-C/X-SAR mission on October 1994. The data were processed and calibrated at the Jet Propulsion Laboratory, National Aeronautics and Space Administration. Results show that the new polarimetric approach is able to assist classification [J81]

"MIMO radar waveform design based on mutual information and minimum mean-square error estimation"

This paper addresses the problem of radar waveform design for target identification and classification. Both the ordinary radar with a single transmitter and receiver and the recently proposed multiple-input multiple-output

(MIMO) radar are considered. A random target impulse response is used to model the scattering characteristics of the extended (nonpoint) target, and two radar waveform design problems with constraints on waveform power have been investigated. The first one is to design waveforms that maximize the conditional mutual information (MI) between the random target impulse response and the reflected waveforms given the knowledge of transmitted waveforms. The second one is to find transmitted waveforms that minimize the mean-square error (MSE) in estimating the target impulse response. Our analysis indicates that under the same total power constraint, these two criteria lead to the same solution for a matrix which specifies the essential part of the optimum waveform design. The solution employs water-filling to allocate the limited power appropriately. We also present an asymptotic formulation which requires less knowledge of the statistical model of the target [J82]

"Consistency Analysis of Subsurface Fracture Characterization Using Different Polarimetry Techniques by a Borehole Radar"

We present a fully polarimetric borehole radar in conjunction with radar polarimetry, Pauli decomposition, and H-alpha decomposition techniques to carry out physical characterization of subsurface fractures. Further tests are needed to validate the applicability of radar polarimetry analysis for physical characterization of subsurface targets. Toward this goal, we present the implementation of two other decomposition techniques, namely: (1) the Durden-Freeman decomposition and (2) polarimetric anisotropy parameter methods, in the context of previous research and examine the consistency of results using various polarimetric decomposition techniques. While results from the radar polarimetry decomposition were found to depend greatly upon the kind of physical or mathematical models, these techniques seem to provide comparable performances in terms of fracture characterization and classification. [J83]

"Unsupervised Classification of Scattering Mechanisms in Polarimetric SAR Data Using Fuzzy Logic in Entropy and Alpha Plane"

The eigenvalue-eigenvector-based approach for understanding the scattering mechanisms of polarimetric synthetic aperture radar (POLSAR) data leads to noisy classification results due to arbitrarily fixed zone boundaries in the H/alpha macr plane. In this paper, a new classification scheme that can address the inherent vagueness of class boundaries in the H/alpha macr plane was tested in order to improve the unsupervised classification of the microwave scattering mechanism by introducing concepts related to fuzzy sets. A 2-D fuzzy membership function was developed for the fuzzification of the 2-D H/alpha macr plane. The proposed fuzzy H/alpha macr classifier is composed of three steps: fuzzification of the H/alpha macr plane, iterative refinement of membership degrees using the c-means algorithm, and defuzzification for the final decision process. The performance of this new approach for the L-band NASA/Jet Propulsion Laboratory's Airborne SAR data obtained during the PACRIM-II experiment was shown to be consistently improved. This new classification technique can be applied to POLSAR data without any a priori information. The fuzzification of the zone boundaries can be further applied to the interpretation of the POLSAR data, e.g., multifrequency classification, retrieval of bio- and geophysical parameters, etc. In order to propose another implementation of the fuzzy boundary representation, we exploited the combination of the H/alpha macr state space and anisotropy information. [J84]

"Application of the Deflection Criterion to Classification of Radar SAR Images"

An original application of the weighted deflection is proposed for radar target classification by quadratic filters. An explicit formulation of optimal filters is derived. We analyze the impact of the weighting parameter on real data recognition and show that performances are better when the deflection coincides with the Fisher ratio. [J85]

"Radar target classification using multiple perspectives"

The problem of radar target classification is examined for the case when more than one perspective or viewing angle of the target is available to the sensor. Using full-scale target signature measurements as the source data, it is shown how, for the first time, multiple perspectives enhance the classification performance. Indeed this is the case even if only one additional perspective is available for exploitation. Further, we explore the classification performance both as a function of the number of perspectives and of the signal to noise ratio. Three approaches to high range resolution profile multi-perspective classification have been implemented. This removes any possible bias that could be introduced by a single individual classifier. The results show, for all three, a consistent improvement in the classification performance, as the number of perspectives is increased. The techniques employed also provide considerable insight into the classification process highlighting the degree of complexity of this extremely challenging problem. [J86]

"Minimax Robust MIMO Radar Waveform Design"

We consider the problem of minimax robust waveform design for multiple-input multiple-output (MIMO) radar based on mutual information (MI) and minimum mean-square error (MMSE) estimation for target identification and classification. Recognizing that a single, precise characterization of target power spectral density (PSD) is rare in practice, we assume the PSD lies in an uncertainty class of spectra bounded by known upper and lower bounds, which markedly relaxes the required target a priori knowledge. Based on this band model, we develop minimax robust waveforms for MIMO radar under both MMSE and MI criteria. These robust waveforms bound the worst-case performance at an acceptable limit, and also could insure performance will be sufficiently good for any PSD in the uncertainty class. Our findings also indicate that the MI and MMSE criteria lead to different minimax robust waveform solutions, which is in contrast to the case of the perfectly known target PSD [J87]

"Introduction to the issue on adaptive waveform design for agile sensing and communication"

The 18 papers in this issue focus on the following areas: waveform design; adaptive waveform design; surveillance and classification in radar; multiple-input multiple-output (MIMO) radar systems; and wireless communications. [J88]

"Bounding the performance of sidescan sonar automatic target recognition algorithms using information theory"

Modern sidescan sonars provide the ability to image the seafloor with increasingly high resolution. With this comes a corresponding increase in complexity of determining the performance of the sensor, with focus shifting from simple signal detection theory to assess the capability for automatic target recognition (ATR) algorithms to discriminate between different objects based on the shape of the projected acoustic shadows on the seafloor. This paper uses information theory to place bounds on the performance of ATR algorithms which use features based on an object's shadow as a classification cue. Information is used to compute different bounds on the performance of any classification method. The technique is applied to a simple classification task namely to discriminate between circular and square shapes. The effect of sensor characteristics, such as contrast and resolution, are computed. An example is given where the bounds on performance for a sidescan sonar with given characteristics under some environmental conditions are computed. The performance is then analysed as a function of the shapes being classified by changing the circular shape to a superellipse. Although high-frequency imaging sonar is examined here, the method could be applied to other types of monochromatic imagery that contains multiplicative noise. [J89]

"Demining sensor modeling and feature-level fusion by Bayesian networks"

A method for obtaining the Bayesian network (BN) representation of a sensor's measurement process is developed so that the problems of sensor fusion and management can be approached from a unified point of view. Uncertainty, reliability, and causal information embedded in the sensor data are used to build the BN model of a sensor. The method is applied to model ground-penetrating radar, electromagnetic induction, and infrared sensors for humanitarian demining. Structural and parameter learning algorithms are employed to encode relationships among mine features, sensor measurements, and environmental conditions in the BN model. Inference is used to estimate target features in the presence of heterogeneous soil and varying environmental conditions. A multisensor fusion technique operating on BN models is developed to exploit the complementarity of the sensor measurements. Through the same approach, a BN classifier is obtained to estimate the target typology. The BN models and classifier also compute so-called confidence levels that quantify the uncertainty associated with the feature estimates and the classification decisions. The effectiveness of the approach is demonstrated by implementing these BN tools for the detection and classification of metal and plastic landmines that are characterized by different shape, size, depth, and metal content. Through BN fusion, the accuracy of the feature estimates is improved by up to 64% with respect to single-sensor measurements, and the number of objects that are both detected and classified is increased by up to 62%. [J90]

"Detecting and characterising returns in a pulsed ladar system"

A new multi-spectral laser radar (ladar) system based on the time-correlated single photon counting, time-of-flight technique has been designed to detect and characterise distributed targets at ranges of several kilometres. The system uses six separated laser channels in the visible and near infrared part of the electromagnetic spectrum. The authors present a method to detect the numbers, positions, heights and shape parameters of returns from this system, used for range profiling and target classification. The algorithm has two principal stages: non-parametric bump hunting based on an analysis of the smoothed derivatives of the photon count histogram in scale space, and maximum likelihood estimation using Poisson statistics. The approach is demonstrated on simulated and real data from a multi-spectral ladar system, showing that the return parameters can be estimated to a high degree of accuracy. [J91]

"Orientation angle preserving a posteriori polarimetric SAR calibration"

Fully polarimetric synthetic aperture radar (SAR) data analysis has found wide application for terrain classification, land-use, soil moisture, and ground cover classification. Critical to all analyses and applications is accurate calibration of the relative amplitudes of and phases between the various polarimetric channels. Here we propose an a posteriori method imposing only the weakest of constraints, scattering reciprocity, on the polarimetric data. Calibration parameters are self-consistently estimated from full 4Ч4 polarimetric covariance matrices. Whilst the complete set of calibration parameters is underdetermined, we give several reasonable heuristic methods to provide a complete calibration. Stronger constraints reduce the number of independent parameters and provide an overdetermined set of equations but at a cost-the loss of polarimetric fidelity when the underlying assumptions are violated. Without recourse to in situ calibration targets, the extent of the polarimetric distortion that results from polarimetric calibration remains unknown. We apply our new method to simulated data, anechoic chamber data and polarimetric SAR imagery. We also present comparisons with alternate calibration methods and different approximate solutions of the new technique. [J92]

"Scattering-model-based speckle filtering of polarimetric SAR data"

A new concept in polarimetric synthetic aperture radar (POLSAR) speckle filtering that preserves the dominant scattering mechanism of each pixel is proposed in this paper. The basic principle is to select pixels of the same scattering characteristics to be included in the filtering process. To achieve this, the algorithm first applies the Freeman and Durden decomposition to separate pixels into three dominant scattering categories: surface, double bounce, and volume, and then unsupervised classification is applied. Speckle filtering is performed using the classification map as a mask. A single-look or multilook pixel centered in a 9 Ч 9 window is filtered by including only pixels in the same and two neighboring classes from the same scattering category. This filter is effective in speckle reduction, while perfectly preserving strong point target signatures, and retains edges, linear, and curved features in the POLSAR data. The effect of speckle filtering on scattering characteristics, such as entropy, anisotropy, and alpha angle, will be discussed. [J93]

"An organizational coevolutionary algorithm for classification"

Taking inspiration from the interacting process among organizations in human societies, a new classification algorithm, organizational coevolutionary algorithm for classification (OCEC), is proposed with the intrinsic properties of classification in mind. The main difference between OCEC and the available classification approaches based on evolutionary algorithms (EAs) is its use of a bottom-up search mechanism. OCEC causes the evolution of sets of examples, and at the end of the evolutionary process, extracts rules from these sets. These sets of examples form organizations. Because organizations are different from the individuals in traditional EAs, three evolutionary operators and a selection mechanism are devised for realizing the evolutionary operations performed on organizations. This method can avoid generating meaningless rules during the evolutionary process. An evolutionary method is also devised for determining the significance of each attribute, on the basis of which, the fitness function for organizations is defined. In experiments, the effectiveness of OCEC is first evaluated by multiplexer problems. Then, OCEC is compared with several well-known classification algorithms on 12 benchmarks from the UCI repository datasets and multiplexer problems. Moreover, OCEC is applied to a practical case, radar target recognition problems. All results show that OCEC achieves a higher predictive accuracy and a lower computational cost. Finally, the scalability of OCEC is studied on synthetic datasets. The number of training examples increases from 100 000 to 10 million, and the number of attributes increases from 9 to 400. The results show that OCEC obtains a good scalability. [J94]

"GMM-based target classification for ground surveillance Doppler radar"

An automatic target recognition (ATR) algorithm, based on greedy learning of Gaussian mixture model (GMM) is developed. The GMMs were obtained for a wide range of ground surveillance radar targets such as walking person(s), tracked or wheeled vehicles, animals, and clutter. Maximum-likelihood (ML) and majority-voting decision schemes were applied to these models for target classification. The corresponding classifiers were trained and tested using distinct databases of target echoes, recorded by ground surveillance radar. ML and majority-voting classifiers obtained classification rates of 88% and 96%, correspondingly. Both classifiers outperform trained human operators. [J95]

"On the Usage of GRECOSAR, an Orbital Polarimetric SAR Simulator of Complex Targets, to Vessel Classification Studies"

This paper presents a synthetic aperture radar (SAR) simulator that is able to generate polarimetric SAR (POLSAR) and polarimetric inverse SAR data of complex targets. It solves the electromagnetic problem via high-

frequency approximations, such as physical optics and the physical theory of diffraction, with notable computational efficiency. In principle, any orbital monostatic sensor working at any band, resolution, and operating mode can be modeled. To make simulations more realistic, the target's bearing and speed are considered, and for the particular case of vessels, even the translational and rotational movements induced by the sea state. All these capabilities make the simulator a powerful tool for supplying large amounts of data with precise scenario information and for testing future sensor configurations. In this paper, the usefulness of the simulator on vessel classification studies is assessed. Several simulated polarimetric images are presented to analyze the potentialities of coherent target decompositions for classifying complex geometries, thus basing an operational algorithm. The limitations highlighted by the results suggest that other approaches, like POLSAR interferometry, should be explored [J96]

"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 [J97]

"Target Classification and Remote Sensing of Ocean Current Shear Using a Dual-Use Multifrequency HF Radar"

In this paper, we describe a high-frequency (HF) radar capable of multifrequency operation over the HF band for dual-use application to ship classification and mapping ocean current shear and vector winds. The radar is based on a digital transceiver peripheral component interconnect (PCI) card family that supports antenna arrays of four to 32 elements with a single computer, with larger arrays possible using multiple computers and receiver cards. The radar makes use of broadband loop antennas for receive elements, and a number of different possibilities for transmit antennas, depending on the operating bandwidth desired. An option exists in the choice of monostatic or multistatic operation, the latter providing the ability to use several transmit sites, with all radar echo signal reception and processing conducted at a single master receiver site. As applications for such a multifrequency radar capability, we show measurement and modeling examples of multiple frequency HF radar cross section (RCS) of ships as an approach to ship target classification. Results of using 32 radar frequencies to measure the fine structure in ocean current vertical shear are also shown, providing evidence of one edge of a 1-3-m deep uniform flow masked at the surface by wind-driven current shear in a different direction. Other applications of current-shear measurements, such as vector wind mapping and volumetric current estimation in coastal waters, are also discussed [J98]

"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 [J99]

"Nonlinear and linear combination of multi-frequency signals for radar target classification; verification of basic relations"

First Page of the Article [J100]

"Automatic ground target classification using forward scattering radar"

Experimental study is undertaken of the feasibility of forward scattering radar (FSR) and its application to automatic ground target classification. The radar itself, fundamental theoretical analysis, target recognition algorithm and the target's classification subsystem are introduced. For target recognition, the effect of shadow inverse synthetic aperture radar is used. The radar experimental set-up and experimentation results are discussed. For classification, a system is proposed, which extracts features from the radar measurements by using Fourier transform and principle component analysis and uses a nearest neighbour classifier. Speed estimation in FSR is also introduced. By analysing 850 experimentally obtained car signatures, the performance of the system is evaluated and the effectiveness of the system is confirmed. The limitations of the work and its future are also discussed [J101]

"Efficient classification of ISAR images"

In this paper, we propose a method to classify inverse synthetic aperture radar images from different targets. Our approach can provide efficient features for classification by the combined use of a polar mapping procedure and a well-designed classifier. The resulting feature vectors are able to meet the requirements that efficient features should have: invariance with respect to rotation and scale, small dimensionality, as well as highly discriminative information. Typical experimental examples of the proposed method are provided and discussed. [J102]

"Radar HRRP target recognition based on higher order spectra"

Radar high-resolution range profile (HRRP) is very sensitive to time-shift and target-aspect variation; therefore, HRRP-based radar automatic target recognition (RATR) requires efficient time-shift invariant features and robust feature templates. Although higher order spectra are a set of well-known time-shift invariant features, direct use of them (except for power spectrum) is impractical due to their complexity. A method for calculating the Euclidean distance in higher order spectra feature space is proposed in this paper, which avoids calculating the higher order spectra, effectively reducing the computation complexity and storage requirement. Moreover, according to the widely used scattering center model, theoretical analysis and experimental results in this paper show that the feature vector extracted from the average profile in a small target-aspect sector has better generalization performance than the average feature vector in the same sector when both of them are used as feature templates in HRRP-based RATR. The proposed Euclidean distance calculation method and average profile-based template database are applied to two classification algorithms [the template matching method (TMM) and the radial basis function network (RBFN)] to evaluate the recognition performances of higher order spectra features. Experimental results for measured data show that the power spectrum has the best recognition performance among higher order spectra. [J103]

"Integration of optical and radar classifications for mapping pasture type in Western Australia"

In this study, independent classifications of Landsat Thematic Mapper imagery and Jet Propulsion Laboratory AirSAR were combined to create an integrated classification of pasture and other vegetation types for a study area in the agricultural zone of Western Australia. The resulting classification combines greenness and brightness information from optical data with structure and water content information from synthetic aperture radar (SAR). Field observations of vegetation type, botanical composition, ground cover percentage, wet and dry biomass, canopy height, and soil water content were collected at 34 sites representing a range of pastures, browse shrubs, and crops. An unsupervised version of the Complex Wishart classification procedure, based on preserving scattering characteristics from the Freeman and Durden backscatter decomposition, was applied to the C-, L-, and P-band polarimetric SAR data. The optical classification was carried out using a principle component analysis on the green, red, and near-infrared bands and clustering on the basis of a class centroid distance measure and knowledge of ground targets. These two classification results were then fused together. Assessment of a confusion matrix using the individual sites showed that identification of more uniform, dense, and structurally distinct canopies was better than that of more diverse, sparse, and structurally ambiguous canopies, as the former were better represented by the canopy height attribute used in the SAR classification component. The optical classification enabled correction of SAR misclassification of vegetation due to surface roughness and soil moisture effects, or similar backscatter responses from herbaceous or arboreal canopies. The results show that simplification of vegetation into groups based upon properties with sensitive responses in both the optical and SAR domains, and combination of separate SAR and optical classifications, has potential for improving classification of diverse and heterogeneous herbaceous and browse cover in grazing lands. However, collection of ground calibration data must be at an appropriate spatial scale and include canopy and surface measurements directly related to backscatter mechanisms and spectral sensitivity. [J104]

"Time reversal imaging of obscured targets from multistatic data"

The methods employed in time-reversal imaging are applied to radar imaging problems using multistatic data collected from sparse and unstructured phased array antenna systems. The theory is especially suitable to problems involving the detection and tracking (locating) of moving ground targets (MGT) from satellite based phased array antenna systems and locating buried or obscured targets from multistatic data collected from phased array antenna systems mounted on unmanned aerial vehicles (UAV). The theory is based on the singular value decomposition (SVD) of the multistatic data matrix K and applies to general phased array antenna systems whose elements are arbitrarily located in space. It is shown that the singular vectors of the K matrix together with knowledge of the Green function of the background medium in which the targets are embedded lead directly to classical time-reversal based images of the target locations as well as super-resolution images based on a generalized Multiple-Signal-Classification algorithm recently developed for use with the K matrix. The theory is applied in a computer simulation study of the TechSat project whose goal is the location of MGTs from an unstructured and sparse phased array of freely orbiting antennas located above the ionosphere. [J105]

"Application of feature extraction methods for landmine detection using the Wichmann/Niitek ground-penetrating radar"

Ground-penetrating radar (GPR) has been proposed as an alternative to classical electromagnetic induction techniques for the landmine detection problem. The Wichmann/Niitek system provides a good platform for novel GPR-based antitank mine detection and classification algorithm development due to its extremely high SNR. When the GPR sensor is mounted on a moving vehicle, the target signatures are hyperbolas in a time-domain data record. The goal of this work is to extract useful features that exploit this knowledge in order to improve target detection. The algorithms can be divided into two steps: feature extraction and classification. Preprocessing is also considered to remove both stationary effects and nonstationary drift of the data and to improve the contrast of the desired hyperbolas. The algorithm is evaluated using real data over primarily plastic antitank mines collected with a fielded GPR sensor at a government test site. [J106]

"Real time electromagnetic target classification using a novel feature extraction technique with PCA-based fusion"

This work introduces an efficient technique to design an electromagnetic target classifier whose reference database is constructed using scattered data at only a few aspects. The suggested technique combines a natural-resonance related feature extraction process with a novel, multiaspect feature fusion scheme. First, moderately aspect-variant late-time features are extracted from scattered field of a given candidate target at several different reference aspects using the Wigner transformation to characterize the target's scattered energy distribution over a selected late-time segment of the joint time-frequency plane. Then, these features are fused using the principal component analysis to obtain a single characteristic feature vector that can effectively represent the target of concern over a broad range of aspect angles. The suggested technique is demonstrated to design a classifier that is verified to be highly accurate and robust even in the presence of excessive noise. Due to the computational efficiency of the technique, the classifier needs very small memory space to store the reference information and quite fast lending itself suitable for real-time target classification. [J107]

"Compact polarimetry based on symmetry properties of geophysical media: the pi/4 mode"

We assess the performance of synthetic aperture radar (SAR) compact polarimetry architectures based on mixed basis measurements, where the transmitter polarization is either circular or orientated at 45°(pi/4), and the receivers are at horizontal and vertical polarizations with respect to the radar line of sight. An original algorithm is proposed to reconstruct the full polarimetric (FP) information from this architecture. The performance assessment is twofold: it first concerns the level of information preserved in comparison with FP, both for point target analysis and crop fields classification, using L-band SIRC/XSAR images acquired over Landes forest and Jet Propulsion Laboratory AIRSAR images acquired over Flevoland. Then, it addresses the space implementation complexity, in terms of processed swath, downloading features, power budget, calibration, and ionospheric effects. The polarization uniqueness in transmission of this mixed basis mode, hereafter referred to as the pi/4 mode, maintains the standard lower pulse repetition frequency operation and hence maximizes the coverage of the sensor. Because of the mismatch between transmitter and receiver basis, the power budget is deteriorated by a factor of 3 dB, but it can partly be compensated. [J108]

"Tracking with classification-aided multiframe data association"

In most conventional tracking systems, only the target kinematic information from, for example, a radar or sonar or an electro-optical sensor, is used in measurement-to-track association. Target class information, which is

typically used in postprocessing, can also be used to improve data association to give better tracking accuracy. The use of target class information in data association can improve discrimination by yielding purer tracks and preserving their continuity. In this paper, we present the simultaneous use of target classification information and target kinematic information for target tracking. The approach presented integrates target class information into the data association process using the 2-D (one track list and one measurement list) as well as multiframe (one track list and multiple measurement lists) assignments. The multiframe association likelihood is developed to include the classification results based on the "confusion matrix" that specifies the accuracy of the target classifier. The objective is to improve association results using class information when the kinematic likelihoods are similar for different targets, i.e., there is ambiguity in using kinematic information alone. Performance comparisons with and without the use of class information in data association are presented on a ground target tracking problem. Simulation results quantify the benefits of classification-aided data association for improved target tracking, especially in the presence of association uncertainty in the kinematic measurements. Also, the benefit of 5-D (or multiframe) association versus 2-D association is investigated for different quality classifiers. The main contribution of this paper is the development of the methodology to incorporate exactly the classification information into multidimensional (multiframe) association. [J109]

"Adaptive learning approach to landmine detection"

We consider landmine detection using forward-looking ground penetrating radar (FLGPR). The two main challenging tasks include extracting intricate structures of target signals and adapting a classifier to the surrounding environment through learning. Through the time-frequency (TF) analysis, we find that the most discriminant information is TF localized. This observation motivates us to use the over-complete wavelet packet transform (WPT) to sparsely represent signals with the discriminant information encoded into several bases. Then the sequential floating forward selection method is used to extract these components and thereby a neural network (NNW) classifier is designed. To further improve the classification performance and deal with the problem of detecting mines in an unconstraint environment, the AdaBoost algorithm is used. We integrate the feature selection process into the original AdaBoost algorithm. In each iteration, AdaBoost identifies the hard-to-learn examples and a new set of features which provide the specific discriminant information for these hard samples is extracted adaptively and a new classifier is trained. Experimental results based on measured data are presented, showing that a significant improvement on the classification performance can be achieved. [J110]

"A soft computing approach for rainfall retrieval from the TRMM microwave imager"

A neural network model for rainfall retrieval over ocean from remotely sensed microwave (MW) brightness temperature (BT) is proposed. BT data are obtained from the Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI). The BT values from different channels of TMI over the Pacific Ocean (163° to 177°W and 18° to 34°S) are the input features. The near-surface rainfall rate from the Precipitation Radar (PR) are considered as a target. The proposed model consists of a neural network with online feature selection (FS) and clustering techniques. A K-means clustering algorithm is applied to cluster the selected features. Different networks have been trained to give an instantaneous rainfall rate with all input features as well as with selected features obtained by applying the FS algorithm. It is found that the hybrid network utilizing FS and clustering techniques performs better. The developed network is also validated with two independent datasets on March 14, 2000 over the Atlantic Ocean having stratiform rain and on March 21, 2000 over the Pacific Ocean having both stratiform and convective rain. In both cases, the hybrid network performs well with correlation coefficient improving to 0.78 and 0.81, respectively, in contrast to 0.70 and 0.75 for the network with all features. The rainfall rate retrieved from the hybrid network is also compared with the TMI surface rain rate, and a correlation of 0.84 and 0.75 is found for the two events. The proposed hybrid model is validated with a Doppler Weather Radar, and correlation of 0.52 is observed. [J111]

"Deorientation theory of polarimetric scattering targets and application to terrain surface classification"

Deorientation theory of polarimetric scattering targets is presented. Using a transformation of the target scattering vector, the target orientation is turned to a certain fixed state and polarimetric scattering of the transformed scattering vector shows the prominence of the generic characteristics of the target. A new set of parameters u, v, w, ψ is defined based on a deorientation of the target scattering vector. Numerical simulation of polarimetric scattering of nonspherical particles illustrates the meanings of the parameters u, v, w, ψ and the entropy H. An unsupervised classification scheme of the terrain surfaces is developed, which classifies the terrain surfaces using the set of u., v, H, and analyzes the orientation distribution of each class based on deorientation angle ψ. As examples, a SIR-C polarimetric image over China's Guangdong Hui-Yang district is classified into eight classes and a AirSAR polarimetric image over Canada's Boreal district is orientation-analyzed using our approach of deorientation and four parameters u, v, ψ, and H. [J112]

"A joint compression-discrimination neural transformation applied to target detection"

Many image recognition algorithms based on data-learning perform dimensionality reduction before the actual learning and classification because the high dimensionality of raw imagery would require enormous training sets to achieve satisfactory performance. A potential problem with this approach is that most dimensionality reduction techniques, such as principal component analysis (PCA), seek to maximize the representation of data variation into a small number of PCA components, without considering interclass discriminability. This paper presents a neural-network-based transformation that simultaneously seeks to provide dimensionality reduction and a high degree of discriminability by combining together the learning mechanism of a neural-network-based PCA and a backpropagation learning algorithm. The joint discrimination-compression algorithm is applied to infrared imagery to detect military vehicles. [J113]

"Target classification approach based on the belief function theory"

A theoretical framework is presented for target classification based on the belief theory on the continuous space. The proposed approach is applicable when class-conditioned densities of feature/attribute measurements are known only partially, as subjective models of a potential "betting" behaviour. Prior class probabilities may also be unknown. Numerical examples are provided to illustrate how the proposed approach is more cautious in decision making and produces very different results from those obtained using the Bayesian classifier. [J114]

"A Classification Approach Based on SVM for Electromagnetic Subsurface Sensing"

In clearing terrains contaminated or potentially contaminated by landmines and/or unexploded ordnances (UXOs), a quick wide-area surveillance is often required. Nevertheless, the identification of dangerous areas (instead of the detection of each subsurface object) can be enough for some scenarios/applications, allowing a suitable level of security in a cost-saving way. In such a framework, this paper describes a probabilistic approach for the definition of risk maps. Starting from the measurement of the scattered electromagnetic field, the probability of occurrence of dangerous targets in an investigated subsurface area is determined through a suitably defined classifier based on a support vector machine. To assess the effectiveness of the proposed approach and to evaluate its robustness, selected numerical results related to a two-dimensional geometry are presented. [J115]

"Approach to object classification using dispersive scattering centres"

The dispersive scattering centre (DSC) model characterises high-frequency backscatter from radar objects as a finite sum of localised scattering geometries distributed in range. These geometries, along with their locations, can be conveniently used as features in a one-dimensional automatic object recognition algorithm. The DSC model's type and range parameters correspond to geometry and distance features according to the geometric theory of diffraction (GTD). To demonstrate the viability of feature extraction based on the DSC model's range and type parameters, a typical object classification experiment was performed. The experimental data contained direct range radar measurements of four model fighter aircraft of similar size and shape at 0° elevation and 0°-30° azimuth. After implementing DSC model feature extraction on these data, a fully-connected two-layer neural net obtained over 98% classification accuracy. In addition, DSC model feature extraction gave an approximately 85% reduction in the number of required features when compared to the numerous range bin magnitudes used in template matching techniques. [J116]

"Pattern recognition of multiple signals from ground penetrating radar for metal and plastic objects"

The author describes methods for pattern recognition of multiple time signals of embedded targets in water or soil. The received time signals are investigated using characteristic features of metal and plastic pipes in water for better detection of plastic and for soil with noisy signals. The classification of time signals is done by statistical signal parameters, ARMAX, Prony modelling, a new difference vector method of the model transfer function H(z) in the coefficient vector feature space, principal component analysis (PCA), and the classification (more than the estimation or identification) of radar targets via complex frequencies (CNR-complex natural resonances) of these multiple time signals. [J117]

"Super-resolution imaging for point reflectors near transmitting and receiving array"

This paper presents subsurface imaging techniques using the well-known MUSIC algorithm to localize point reflectors in cross-borehole radar arrangements. Radar signals received by a spatial array have to be decorrelated, in general, as a preprocessing step when the MUSIC algorithm is implemented. Since most of the decorrelation techniques are based on planar wave incidence model, it is difficult to apply the decorrelation

technique for signals from radar targets in the near field of the array. In this paper, we introduce a decorrelation technique with transmitting and receiving array for targets near the array and apply the MUSIC algorithm for estimating the two dimensional position of the point targets in crosshole tomographic measurement. Further, an expanded version of the algorithm to eliminate the direct wave is also derived. Simulation results show that this method offers much higher resolution and accuracy than the conventional diffraction stack method. The paper also discusses the relationship between the SNR ratio and the minimum target separation to be resolved. [J118]

"Investigation of broadband electromagnetic induction scattering by highly conductive, permeable, arbitrarily shaped 3-D objects"

Operating as low as tens of hertz and as high as hundreds of kilohertz, new broadband electromagnetic induction (EMI) sensors have shown promise for classification of unseen buried metallic objects. The three-dimensional (3-D) and bodies-of-revolution (BOR) numerical studies reported here are designed to explain key scattering sensitivities that may either be useful in or may limit object classification capability. The target is excited either by a spatially uniform oscillating primary magnetic field or by the oscillating field from a loop antenna. The problem is formulated in terms of Poison's equation for scalar potential outside the object, where conductivity and electric field values are low and consequent conduction currents are generally negligible. The Helmholtz equation for vector potential applies inside the highly conducting and permeable object. In both regions, the electromagnetic phenomena of interest are magneto-quasi-static (MQS). The simulation algorithm uses the method of auxiliary sources (MAS), with auxiliary magnetic charges and auxiliary magnetic current elements distributed on auxiliary surfaces. These surfaces generally conform to but do not coincide with physical surfaces, providing extraordinarily efficient and accurate 3-D solutions. Comparisons to available analytical solutions and experimental data validate the solutions. The simulations and data illuminate broadband MQS scattering phenomenology for both magnetic and nonmagnetic metallic objects. Distinctive sensitivities are shown and signature effects analyzed relative to the scatterer's shape and aspect ratio, orientation, sharp points and edges, finite wall thickness in hollow bodies, and compound structure in which a geometrically complex body consists of a number of distinct sections, e.g., fins. [J119]

"Automatic target classification of slow moving ground targets in clutter"

A new approach is proposed which will allow air-to-ground target classification of slow moving vehicles in clutter. A wideband space-time adaptive (STAP) filter architecture, based on subbanding, is developed and coupled with a one dimensional template-based minimum mean squared error (MMSE) classifier. The performance of this STAP/ATC (automatic target classification) algorithm is quantified using an extensive simulation. The level of residual clutter afforded by various filter configurations and the associated incremental improvement in ATC performance is quantified, revealing the potential for realizable hardware and software implementations to achieve acceptable ATC performance. [J120]

"Design and application of quadratic correlation filters for target detection"

We introduce a method for designing and implementing quadratic correlation filters (QCFs) for shift-invariant target detection in imagery. The QCFs are a quadratic classifier that operates directly on the image data without feature extraction or segmentation. In this sense, the QCFs retain the main advantages of conventional linear correlation filters while offering significant improvements in other respects. Not only is more processing required to detect peaks in the outputs of multiple linear filters, but choosing a winner among them is an error prone task. On the other hand, all channels in a QCF work together to optimize the same performance metric and produce a combined output that leads to considerable simplification of the postprocessing scheme. In addition, QCFs also yield better performance than their linear counterparts for comparable throughput requirements. Two different methods for designing basis functions that optimize the QCF performance criterion are presented. An efficient architecture for implementing QCFs is discussed along with a case study of the proposed approach for detecting targets in LADAR imagery. [J121]

"Radar detection and preclassification based on multiple hypothesis"

This work presents a single-scan-processing approach to the problem of detecting and preclassifying a radar target that may belong to different target classes. The proposed method is based on a hybrid of the maximum a posteriori (MAP) and Neyman-Pearson (NP) criteria and guarantees the desired constant false alarm rate (CFAR) behavior. The targets are modeled as subspace random signals having zero mean and given covariance matrix. Different target classes are discriminated based on their different signal subspaces, which are specified by their corresponding projection matrices. Performance is investigated by means of numerical analysis and Monte Carlo simulation in terms of probability of false alarm, detection and classification; the extra signal-to-noise power ratio (SNR) necessary to classify once target detection has occurred is also derived. [J122]

"Some radar imagery results using superresolution techniques"

The key problem in any decision-making system is to gather as much information as possible about the object or the phenomenon under study. In the case of the radar targets, frequency and angular information is integrated to form a radar image, which has very high information content. Salient features can then be extracted in order to characterize or to classify radar targets. The quality of the reconstructed image is mainly related to the resolution performed by the radar system both in slant range and in cross range. The Fourier-based reconstruction methods are fast and robust, but they are limited in resolution and dynamic range. Subspace eigenanalysis based methods, such as multiple signal classification (MUSIC) or estimation of signal parameters by rotational invariance techniques (ESPRIT), are able to provide superresolution and to accurately recover the scattering center locations even for a small number of correlated samples. The aim of the paper is to present some results of our ongoing research on the application of these techniques for radar imagery. [J123]

"Comments on "Joint target tracking and classification using radar and ESM sensors" (Digest)"

For original paper see Challa and Pulford (2001). Joint target tracking and classification (JTC) filter was presented in the above mentioned paper. A comment is made here to point out that JTC filter has no advantage over interacting multiple model (IMM) filter from a theoretical viewpoint. [J124]

"A note on microwave guided propagation in the case of anomalous dispersion"

A group velocity greater than that of light, in propagation through dispersive media, was theoretically predicted by Brillouin. We present a simple experiment of propagation in a waveguide, where an externally introduced absorption band originates anomalous dispersion and acts as a dispersive medium. As expected, the group velocity was greater than the light speed. [J125]

"Effect of AR model-based data extrapolation on target recognition performance"

A data extrapolation method is applied to improve the performance of a target recognition scheme based on the central moments of one-dimensional range profiles. We adopt the autoregressive (AR) model to extrapolate the radar cross section data of a target in order to expand the measured data window. It is shown that the resulting high resolution range profiles can enhance target recognition capability, providing a more accurate recognition performance than the multiple signal classification range profile for moderate signal-to-noise ratio SNR ranges. Furthermore, the effects of the AR model-based data extrapolation on target recognition accuracy are carefully analyzed and investigated. [J126]

"Texture and speckle statistics in polarimetric SAR synthesized images"

We investigate in this paper the one-point statistical properties of the backscattered power derived by polarization synthesis of polarimetric synthetic aperture radar (SAR) observations. In particular, we focus our attention on the normalized second moment of intensity and its dependency on the polarization state. For the analysis of this dependency, a novel graphical representation-an extension of the polarization response-is introduced: the polarimetric texture signature. The second moment of backscattered power characterizes statistically the variation of the radar signal due to speckle and the underlying radar cross section. The classical texture product model with a scalar radar reflectivity implies that the normalized second moment of intensity does not depend on the polarization state. However, such dependency is found in experimental observations, a fact that calls for further investigation of the phenomenon. Considering at first speckle statistics for homogeneous areas having no texture, it is demonstrated that correlation among the single-look speckle patterns, which are added on an intensity basis in a multilook operation, is responsible for a weak polarization dependency of the normalized second moment. Concerning the textural properties, a new model is proposed-the mixture model-where it is assumed that polarimetrically diverse scattering mechanisms contribute to the total return from an ensemble of resolution elements. Numerical simulations are used to reconstruct the texture signatures according to the mixture model, starting from simple assumptions related to scattering processes from natural targets. It is found that the polarimetric texture signature can be an interesting discriminator of weak targets against clutter, when only polarimetric diversity and not radiometric diversity plays a role. The effects predicted by the theory are confirmed by experimental analysis of polarimetric data acquired by the Jet Propulsion Laboratory AIRSAR sensor. Finally a classification scheme based on the polarimetric texture signature is proposed. [J127]

"Multi-mode ENVISAT ASAR interferometry: techniques and preliminary results"

The paper focuses on the interferometric capabilities of current and future SAR systems, like ENVISAT, RADARSAT-2, etc. The authors introduce a technique to obtain interferometric surveys by combining two images, coming from any SAR mode, together with a digital elevation mode (DEM). The DEM is exploited during

the interferogram generation to provide, at one time, effective noise removal and compensation for the topographic-dependent fringes. The final product is a 'differential' (topography-compensated) interferogram to be used for monitoring over landslides, upswelling, etc. An innovative technique is also discussed to estimate local coherence maps, to be used for classification and change detection. Such a technique exploits windows whose shapes and sizes adapt locally to the target features, to attain at one time the highest resolution and the best statistical confidence. Finally, applications involving the various ENVISAT ASAR modes are discussed. [J128]

"Robust Doppler classification technique based on hidden Markov models"

A classification algorithm is presented that uses hidden Markov models (HMMs) to carry out recognition between three classes of targets: personnel, tracked vehicles and wheeled vehicles. It exploits the time-varying nature of radar Doppler data in a manner similar to techniques used in speech recognition, albeit with a modified topology, to distinguish targets with different Doppler characteristics. The algorithm was trained and tested on real radar signatures of multiple examples of moving targets from each class, and the performance was shown to be invariant to target speed and orientation and was able to be generalised with respect to variants within a class. [J129]

"Netted radar sensing"

Future radar applications are beginning to stretch monostatic radar systems beyond their fundamental sensitivity and information limits. Networks of smaller radar systems can offer a route to overcome these limitations; for example, networks of radar sensors can counter stealth technology whilst simultaneously providing additional information for improved target classification. More generally, multiple independent sensors can provide an energetically more efficient collector of radar scatter. The relative merits of non-coherent and coherent networks are introduced and the balance between increased performance, complexity, and cost is discussed. [J130]

"Two-dimensional scattering center extraction based on multiple elastic modules network"

The concept of scattering centers on a target is commonly used for radar signature modeling and data compression, as well as target recognition. In particular, two-dimensional (2-D) scattering centers are useful features in automatic target recognition, which uses a synthetic aperture radar system, because they are directly related to physical scattering mechanisms and also have small dimensionality. We propose a new technique for estimating 2-D scattering centers using radar data in the frequency-aspect domain. The technique first estimates one-dimensional scattering centers at several aspects, and the multiple elastic modules network optimization is exploited to find 2-D locations and amplitudes of the target's scattering centers. Experimental results illustrate that the proposed method is efficient not only for estimating 2-D scattering centers on the target but also in computation. [J131]

"Iterated wavelet transformation and signal discrimination for HRR radar target recognition"

This paper explores the use of wavelets to improve the selection of discriminant features in the target recognition problem using high range resolution (HRR) radar signals in an air to air scenario. We show that there is statistically no difference among four different wavelet families in extracting discriminatory features. Since similar results can be obtained from any of the four wavelet families and wavelets within the families, the simplest wavelet (Haar) should be used. We use the box classifier to select the 128 most salient pseudo range bins and then apply the wavelet transform to this reduced set of bins. We show that by iteratively applying this approach, the classifier performance is improved. We call this the iterated wavelet transform . The number of times the feature reduction and transformation can be performed while producing improved classifier performance is small and the transformed features are shown to quickly cause the performance to approach an asymptote. [J132]

"A new polarimetric classification approach evaluated for agricultural crops"

Statistical properties of the polarimetric backscatter behavior for a single homogeneous area with constant radar reflectivity are described by the Wishart distribution or its marginal distributions. These distributions do not necessarily well describe the statistics for a collection of homogeneous areas of the same class because of variation in, for example, biophysical parameters. Using Kolmogorov-Smirnov (KS) tests of fit, it is shown that, for example, the Beta distribution is a better descriptor for the polarimetric correlation, and the log-normal distribution for the backscatter level. An evaluation is given for a number of agricultural crop classes, grasslands, and fruit tree plantations at the Flevoland test site, using an AirSAR (C-, L- and P-band polarimetric) image from July 3, 1991. A new reversible transform of the covariance matrix into backscatter intensities will be introduced in order to describe the full polarimetric target properties in a mathematically alternative way, allowing for the development of simple, versatile, and robust classifiers. Moreover, it allows for polarimetric image segmentation using conventional approaches. The effect of azimuthally asymmetric backscatter behavior on the classification

results is discussed. Several models are proposed, and results are compared with results from the literature for the same test site. It can be concluded that the introduced classifiers perform very well, with levels of accuracy for this test site, with 14 cover types, of 90.4% for C-band, 88.7% for L-band, and 96.3% for the combination of C- and L-band. [J133]

"Correction to 'Robust Doppler classification technique based on hidden Markov models'"

In the original paper (see ibid., vol.150, no.1, p.33-6, Feb. 2003) a novel technique based on hidden Markov models (HMM) for Doppler classification was presented and performance was reported for a 3-class problem. It was proposed that a HMM model using a cyclic topology would be suited to representing the time varying Doppler signatures observed for moving targets. The paper concluded that the problem was adequately modelled with a HMM algorithm using a cyclic topology with 9 states. At the time of the production of the paper it was believed that the HMMs were using all 9 states to explain the data within each data file that was being classified. However, results obtained subsequent to the publication of the paper show that the models were, for the most part, fitting any given test data file to a single state. The 9 states were being used to explain different data files and thus the system was behaving effectively as a Gaussian mixture based classifier. [J134]

"Automatic spectral target recognition in hyperspectral imagery"

Automatic target recognition (ATR) in hyperspectral imagery is a challenging problem due to recent advances of remote sensing instruments which have significantly improved sensor's spectral resolution. As a result, small and subtle targets can be uncovered and extracted from image scenes, which may not be identified by prior knowledge. In particular, when target size is smaller than pixel resolution, target recognition must be carried out at subpixel level. Under such circumstance, traditional spatial-based image processing techniques are generally not applicable and may not perform well if they are applied. The work presented here investigates this issue and develops spectral-based algorithms for automatic spectral target recognition (ASTR) in hyperspectral imagery with no required a priori knowledge, specifically, in reconnaissance and surveillance applications. The proposed ASTR consists of two stage processes, automatic target generation process (ATGP) followed by target classification process (TCP). The ATGP generates a set of targets from image data in an unsupervised manner which will subsequently be classified by the TCP. Depending upon how an initial target is selected in ATGP, two versions of the ASTR can be implemented, referred to as desired target detection and classification algorithm (DTDCA) and automatic target detection and classification algorithm (ATDCA). The former can be used to search for a specific target in unknown scenes while the latter can be used to detect anomalies in blind environments. In order to evaluate their performance, a comparative and quantitative study using real hyperspectral images is conducted for analysis. [J135]

"Bayesian gamma mixture model approach to radar target recognition"

This paper develops a Bayesian gamma mixture model approach to automatic target recognition (ATR). The specific problem considered is the classification of radar range profiles (RRPs) of military ships. However, the approach developed is relevant to the generic discrimination problem. We model the radar returns (data measurements) from each target as a gamma mixture distribution. Several different motivations for the use of mixture models are put forward, with gamma components being chosen through a physical consideration of radar returns. Bayesian formalism is adopted and we obtain posterior distributions for the parameters of our mixture models. The distributions obtained are too complicated for direct analytical use in a classifier, so Markov chain Monte Carlo (MCMC) techniques are used to provide samples from the distributions. The classification results on the ship data compare favorably with those obtained from two previously published techniques, namely a self-organizing map and a maximum likelihood gamma mixture model classifier. [J136]

"Time-frequency analysis for plastic landmine detection via forward-looking ground penetrating radar"

Time-frequency analysis techniques are used for buried plastic landmine detection with a forward-looking ground penetration radar (GPR) system. Several time-frequency distributions are considered to characterise and interpret the scattering phenomena of both targets and clutter. An ambiguity function based detector is also presented, which employs principal component analysis and feature selection for data dimensionality reduction and linear discriminant analysis for signal classification. Experimental results based on the SRI (Stanford Research Institute) experimentally measured forward-looking GPR data are presented, showing a significant detection performance improvement over the conventional detector [J137]

"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. [J138]

"Classification of audio radar signals using radial basis function neural networks"

Radial basis function (RBF) neural networks are used to classify real-life audio radar signals that are collected by a ground surveillance radar mounted on a tank. Currently, a human operator is required to operate the radar system to discern among signals bouncing off tanks, vehicles, planes, and so on. The objective of this project is to investigate the possibility of using a neural network to perform this target recognition task, with the aim of reducing the number of personnel required in a tank. Different signal classification methods in the neural net literature are considered. The first method employs a linear autoregressive (AR) model to extract linear features of the audio data, and then perform classification on these features, i.e, the AR coefficients. AR coefficient estimations based on least squares and higher order statistics are considered in this study. The second approach uses nonlinear predictors to model the audio data and then classifies the signals according to the prediction errors. The real-life audio radar data set used here was collected by an AN/PPS-15 ground surveillance radar and consists of 13 different target classes, which include men marching, a man walking, airplanes, a man crawling, and boats, etc. It is found that each classification method has some classes which are difficult to classify. Overall, the AR feature extraction approach is most effective and has a correct classification rate of 88% for the training data and 67% for data not used for training. [J139]

"High-resolution time-frequency distributions for manoeuvring target detection in over-the-horizon radars"

A novel high-resolution time-frequency representation method is proposed for source detection and classification in over-the-horizon radar (OTHR) systems. A data-dependent kernel is applied in the ambiguity domain to capture the target signal components, which are then resolved using root-MUSIC based coherent spectrum estimation. This two-step procedure is particularly effective for analysing a multicomponent signal with time-varying complex time-Doppler signatures. By using the different time-Doppler signatures, important target manoeuvring information, which is difficult to extract using other linear and bilinear time-frequency representation methods, can be easily revealed using the proposed method [J140]

"Coaxial range measurement-current trends for mobile robotic applications"

The useful environmental interaction of a mobile robot is completely dependent on the reliable extraction of information from its immediate surroundings. A review of some of the most commonly used coaxial, active sensing methods in robotics is presented. A coaxial sensor results if the transmitter and receiver are geometrically arranged in a coaxial manner. Certain advantages of such configurations are discussed. First, optical sensors, in which a controlled light signal is transmitted, are reviewed with respect to their applicability to mobile robotics. An overview of the literature describing light detection and ranging (LIDAR) systems for range measurement in robotics is given. A review of mobile robot research using sound navigation and ranging (SONAR) is presented where processing algorithms are demonstrated for the correct interpretation of ultrasonic data recorded in indoor environments. Ultrasonic wave reflection is generally dominated by specular reflections. Methods for the interpretation of SONAR data, for correct target classification, and, hence, range estimation are given, based on the acoustic reflection mechanism [J141]

"Characterisation of objects and general ocean phenomena by use of target adaptive multifrequency multistatic matched illumination acoustics"

Through modelling and detailed experimental investigations there exists in most cases a considerable amount of a priori information about the target and the background scene. Some of the signatures are very dominant and

specific in nature, and some are less so and may overlap signatures related to other targets or background clutter. The authors investigate phenomena of interest in the maximum number of signature domains and present the basic matched illumination sonar concept. Subsequently they illustrate a set of specific application areas with emphasis on classification of submerged objects and their wakes against a background of gravity waves, internal waves and turbulence. Some experimental results displaying the capability of the technique are presented [J142]

"Measured and predicted synthetic aperture radar target comparison"

The DARPA Image Understanding program publicly released measured and predicted synthetic aperture radar (SAR) targets were compared by means of correlation. The training set consisted of three classes (BMP-2, T-72, and BTR-70) at 17 deg depression and 233 azimuths. The test set consisting of seven different serial-numbered targets at 15 deg depression was tested at 196 azimuths. After segmentation and normalization, each test image was correlated with all the training images to generate correlation and classification statistics. Measured correlation scores were higher and more consistent for same serial number training than variant training. The average in-class (0.837) and between-class (0.734) means for measured correlations were higher than both the average in-class (0.707) and between-class (0.675) means for predicted correlations; however, the corresponding variances for in-class (0.056) and between-class (0.048) predicted correlations were higher than in-class (0.026) and between-class (0.036) measured variances. The measured training data declared the target correctly almost 100% of the time; the T-72 and BTR-70 model-predicted data declared the target correctly 80% of the time. The correlation scores varied approximately sinusoidally with aspect. Correlation plots between a single orientation target and the entire training sets showed that a target was highly correlated at both the correct aspect angle and the correct angle rotated 180 deg [J143]

"Efficient radar target recognition using the MUSIC algorithm and invariant features"

An efficient technique is developed to recognize target type using one-dimensional range profiles. The proposed technique utilizes the Multiple Signal Classification algorithm to generate superresolved range profiles. Their central moments are calculated to provide translation-invariant and level-invariant feature vectors. Next, the computed central moments are mapped into values between zero and unity, followed by a principal component analysis to eliminate the redundancy of feature vectors. The obtained features are classified based on the Bayes classifier, which is one of the statistical classifiers. Recognition results using five different aircraft models measured at compact range are presented to assess the effectiveness of the proposed technique, and they are compared with those of the conventional range profiles obtained by inverse fast Fourier transform [J144]

"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 [J145]

"Performance complexity study of several approaches to automatic target recognition from SAR images"

A framework which allows for the direct comparison of alternate approaches to automatic target recognition (ATR) from synthetic aperture radar (SAR) images is described and applied to variants of several ATR algorithms. This framework allows comparisons to be made on an even footing while minimizing the impact of implementation details and accounts for variation in image sizes, in angular resolution, and in the sizes of orientation windows used for training. Alternate approaches to ATR are characterized in terms of the best achievable performance as a function of the complexity of the model parameter database. Several approaches to ATR from SAR images are described and the performance achievable by each for a range of database complexities is studied and compared. These approaches are based on a likelihood test under a conditionally Gaussian model, log-magnitude least squared error, and quarter power least squared error. All approaches are

evaluated for a wide range of parameterizations and the dependence on these parameters of both the resulting performance and the resulting database complexity is explored. Databases for all of the approaches are trained using identical sets of images and their performance is assessed under identical testing scenarios in terms of probability of correct classification, confusion matrices, and orientation estimation error. The results indicate that the conditionally Gaussian approach outperforms the other two approaches on average for both target recognition and orientation estimation, that accounting for radar power fluctuation improves performance for all three methods, and that the conditionally Gaussian approach normalized for power delivers average performance that is equal or superior to all other considered approaches [J146]

"Evolving pattern recognition systems"

A hybrid evolutionary learning algorithm is presented that synthesizes a complete multiclass pattern recognition system. The approach uses a multifaceted representation that evolves layers of processing to perform feature extraction from raw input data, select cooperative sets of feature detectors, and assemble a linear classifier that uses the detectors' responses to label targets. The hybrid algorithm, called hybrid evolutionary learning for pattern recognition (HELPR), blends elements of evolutionary programming, genetic programming, and genetic algorithms to perform a search for an effective set of feature detectors. Individual detectors are represented as expressions composed of morphological and arithmetic operations. Starting with a few small random expressions, HELPR expands the number and complexity of the features to produce a recognition system that achieves high accuracy. Results are presented that demonstrate the performance of HELPR-generated recognition systems applied to the task of classification of high-range resolution radar signals. [J147]

"ATR scheme based on 1-D HRR profiles"

A new automatic target recognition (ATR) scheme based on one-dimensional high range resolution profiles is presented, which features joint range alignment and classification. This method can also be used to form mean- or eigen-templates to further improve the ATR performance. Experimental results are provided to demonstrate the performance of the new algorithm. [J148]

"Identification of ground targets from sequential high-range-resolution radar signatures"

An approach to identifying targets from sequential high-range-resolution (HRR) radar signatures is presented. In particular, a hidden Markov model (HMM) is employed to characterize the sequential information contained in multiaspect HRR target signatures. Features from each of the HRR waveforms are extracted via the RELAX algorithm. The statistical models used for the HMM states are formulated for application to RELAX features, and the expectation-maximization (EM) training algorithm is augmented appropriately. Example classification results are presented for the ten-target MSTAR data set. [J149]

"VHF/UHF radar Part 2: Operational aspects and applications"

For Part 1 see ibid., vol.14, no.2, p.61-72 (April 2002). Low-frequency radars have the potential to counter stealth efforts and detect low-flying targets beyond the horizon. Part 2 of this paper discusses approaches to target classification and the problems of vulnerability to jamming and operation in a densely populated frequency band. The anti-jamming capabilities of VHF radars are analysed based on measurements conducted with the FHR experimental radar LARISSA and it is demonstrated that electromagnetic compatibility (EMC) with other users of the band can be achieved using a spectral signal-shaping technique. The paper is completed by an overview of possible and existing VHF/UHF radar applications [J150]

"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. [J151]

"Seasonal and short-term variability of multifrequency, polarimetric radar backscatter of Alpine terrain from SIR-C/X-SAR and AIRSAR data"

Signatures of glaciated and ice free areas were analyzed from polarimetric SAR data at C-, L-, and P-band and single polarization X-band data. The data base includes an AIRSAR scene from June 25, 1991, and SIR-C/X-SAR images from April and October 1994 (SRL-1 and SRL-2), acquired over the high Alpine test site Цtztal in Austria. The environmental conditions were different at the time of the three experiments. Ground measurements, meteorological observations, and backscattering modeling are the basis for interpreting the backscattering signatures. Seasonal differences are due mainly to the presence or absence of snow and due to changes of its properties. Short term variations of snow conditions can be monitored at C- and X-band. For unglaciated areas, the surface roughness has a dominant influence on backscattering in all seasons. The dependence of the mean backscattering and correlation coefficients on the incidence angle was analyzed. Spectral and depolarization ratios and the magnitude of the HHVV correlation coefficient were selected as components of the multidimensional feature vector for studying the target separability. Good separability was found between the accumulation and ablation areas on the glaciers, whereas on ice-free areas, the dominance of surface roughness limits the discrimination of different surface types. Short-term variations of backscattering have significant impact for the classification of accumulation and ablation areas on glaciers, as verified by comparisons with field data [J152]

"The use of MUSIC algorithm to characterize emissive sources"

This paper applies the MUSIC algorithm to finite-distance sources without omnidirectional radiation patterns to identify their positions and radiation characteristics. This technique can be used to obtain the image of a radiating source and therefore can be successfully utilized in many disciplines such as EMC, biomagnetic data evaluation, geophysical studies. The canonical cases herein discussed may be generalized to define a methodology to localize and characterize emissive sources in the same manner as the radar imaging technique is used for passive reflecting targets [J153]

"A Gabor atom network for signal classification with application in radar target recognition"

A Gabor atom neural network approach is proposed for signal classification. The Gabor atom network uses a multilayer feedforward neural network structure, and its input layer constitutes the feature extraction part, whereas the hidden layer and the output layer constitute the signal classification part. From the physics point of view, it is shown that the time-shifted, frequency-modulated, and scaled Gaussian function is available for a basic model for the signal of high-resolution radar. Two experiment examples show that the Gabor atom network approach has a higher recognition rate in radar target recognition from range profiles as compared with several existing methods [J154]

"Angular superresolution for phased antenna array by phase weighting"

In this paper, a new angular superresolution technique called Phase Weighting Superresolution Method (PWSM) is proposed. The method combines a phase weighting method and a nonlinear spectral estimation algorithm. It is used in conventional phased array radar for improving angle resolution. The motion compensation of radar target and an analysis of influence of component imperfection in the realization of the method are presented. To evaluate the performance of the proposed method, Monte Carlo simulation has been conducted to estimate the root mean square error (RMSE) of the angle estimates and the spatial resolution signal-to-noise ratio (SNR) threshold in the cases of both non-fluctuating targets and fluctuating targets. The simulation results have been compared to those of beam space MUSIC method and the Cramer-Rao lower bound (CRLB). Numerical and experimental results show that good angular superresolution and high estimation accuracy can be achieved provided that the radar pulse repetition time is small enough so that the echoes can be considered sufficiently correlated. For an X band conventional phased array radar with 139 antenna elements, by using PWSM the angular resolution is improved by a factor of 2 when SNR equals 15 dB [J155]

"Wavelet preprocessing for high range resolution radar classification"

We develop a wavelet denoising scheme to aid an automatic target recognition (ATR) system in recognizing aircraft from high range resolution radar (HRR) signatures. A template matching classification technique is used with templates formed from synthetically generated signatures. The goal of the classification system is to achieve classification accuracy equivalent to that obtained with measured HRR signatures. Results suggest that a large portion of HRR signature content is nondiscriminatory. The wavelet denoising process removes the nondiscriminatory information, thereby leading to remarkable increases in classification accuracy. Results are shown for HRR signatures from six aircraft [J156]

"Superresolution HRR ATR with high definition vector imaging"

A new 1-D template-based automatic target recognition (ATR) algorithm is developed and tested on high range resolution (HRR) profiles formed from synthetic aperture radar (SAR) images of targets taken from the Moving and Stationary Target Acquisition and Recognition (MSTAR) data set. In this work, a superresolution technique known as High Definition Vector Imaging (HDVI) is applied to the HRR profiles before the profiles are passed through ATR classification. The new I-D ATR system using HDVI demonstrates significantly improved target recognition compared with previous I-D ATR systems that use conventional image processing techniques. This improvement in target recognition is quantified by improvement in probability of correct classification (PCC). More importantly, the application of HDVI to HRR profiles helps to maintain the same ATR performance with reduced radar resource requirements [J157]

"Radar target identification using one-dimensional scattering centres"

Identification concerning different types of radar targets can be achieved by using various radar signatures, such as one-dimensional (1-D) range profiles, 2-D radar images, and 1-D or 2-D scattering centres on a target. To solve the target identification problem, the authors utilise 1-D scattering centres, which correspond to the highest peaks in the 1-D range profile. The proposed approach obtains scale and translational-invariant features based on the central moments from the distribution of the 1-D scattering centres on the target; these 1-D scattering centres can be extracted from various techniques such as the inverse fast Fourier transform (IFFT), fast root-multiple signal classification (fast root-MUSIC), total least squares-Prony (TLS-Prony), generalised eigenvalues utilising signal subspace eigenvectors (GEESE), and the matrix-pencil (MP) algorithm. The information redundancy contained in these features, as well as their dimensions, are further reduced via the Karhunen-Loeve transform, followed by adequate scaling of the computed central moments. The resulting small dimensional and redundancy-free feature vectors are classified using the Bayes classifier. Finally, this new strategy for radar target identification is demonstrated with data measured in the compact range facility, and the above five different techniques for 1-D scattering centre extraction are compared and investigated in the context of target identification [J158]

"Multiaspect classification of airborne targets via physics-based HMMs and matching pursuits"

Wideband electromagnetic fields scattered from N distinct target-sensor orientations are employed for classification of airborne targets. Each of the scattered waveforms is parsed via physics-based matching pursuits, yielding N feature vectors. The feature vectors are submitted to a hidden Markov model (HMM), each state of which is characterized by a set of target-sensor orientations over which the associated feature vectors are relatively stationary. The N feature vectors extracted from the multiaspect scattering data implicitly sample N states of the target (some states may be sampled more than once), with the state sequence modeled statistically as a Markov process, resulting in an HMM due to the “hidden” or unknown target orientation. In the work presented here, the state-dependent probability of observing a given feature vector is modeled via physics-motivated linear distributions, in lieu of the traditional Gaussian mixtures applied in classical HMMs. Further, we develop a scheme that yields autonomous definitions for the aspect-dependent HMM states. The paradigm is applied to synthetic scattering data for two simple targets [J159]

"Support vector machines for SAR automatic target recognition"

Algorithms that produce classifiers with large margins, such as support vector machines (SVMs), AdaBoost, etc, are receiving more and more attention in the literature. A real application of SVMs for synthetic aperture radar automatic target recognition (SAR/ATR) is presented and the result is compared with conventional classifiers. The SVMs are tested for classification both in closed and open sets (recognition). Experimental results showed that SVMs outperform conventional classifiers in target classification. Moreover, SVMs with the Gaussian kernels are able to form a local “bounded” decision region around each class that presents better rejection to confusers [J160]

"Surface movement radar data processing methods for airport surveillance"

An airport surveillance function operating on surface movement radar (SMR) images is proposed and evaluated. The main contributions presented are the statistical error models of the target centroid and attributes extracted from radar images, developed and applied to the design of its main data processing blocks. Besides a multihypothesis image-to-tracks assignment method, a tracking filter using the extracted orientation and a classification scheme based on target attributes is detailed. The error models confidence and processing methods performance are demonstrated through simulation in representative scenarios [J161]

"Object detection using high resolution near-field array processing"

The authors present an algorithm for the detection and localization of an unknown number of objects buried in a halfspace and present in the near field of a linear receiver array. To overcome the nonplanar nature of the wavefield over the array, the full array is divided into a collection of subarrays such that the scattered fields from objects are locally planar at each subarray. Using the multiple signal classification (MUSIC) algorithm, directions of arrival (DOA) of locally planar waves at each subarray are found. By triangulating these DOAs, a set of crossings, condensed around expected object locations, are obtained. To process this spatial crossing pattern, the authors develop a statistical model for the distribution of these crossings and employ hypotheses testing techniques to identify a collection of small windows likely to contain targets. Finally, the results of the hypothesis tests are used to estimate the number and locations of the targets. Using simulated data, they demonstrate the usefulness and performance of this approach for typical background electrical properties and signal to noise ratios [J162]

"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 [J163]

"Super resolution feature extraction of moving targets"

High range resolution (HRR) moving target indicator (MTI) is becoming increasingly important for many military and civilian applications such as the detection and classification of moving targets in strong clutter background. We consider the problem of extracting the HRR features of moving targets with very closely spaced scatterers in the presence of strong stationary clutter, where the range migration and Doppler frequency are taken into account. A relaxation-based algorithm, which is robust and computationally simple, is proposed to deal with the above problem. Numerical results have shown that the proposed algorithm exhibits super resolution and excellent estimation performance [J164]

"Joint target tracking and classification using radar and ESM sensors"

Bayesian target classification methods using radar and electronic support measure (ESM) data are considered. A joint treatment of target tracking and target classification problems is introduced. First, a method for target classification using radar data and class-dependent kinematic models is presented. Second, a target classification method using ESM data is presented. Then, a Bayesian radar and ESM data fusion algorithm, referred to as direct identity fusion (DIF), for target classification is presented. This algorithm exploits the dependence of target state on target class via the use of class dependent kinematic models but fails to exploit the dependence of target class on target state. We then introduce a method, referred to as joint tracking and classification (JTC), for treating target tracking and classification problems jointly, by exploiting the dependence of target class on target state via flight-envelope-dependent classes and the dependence of target state on target class via class dependent kinematic models. A two-dimensional example demonstrates the relative merits of these methods. It is shown that, while the incorporation of the two-way dependence between target state and class (i.e., JTC) promises some benefits over the method that incorporates only a one-way dependence (i.e., DIF), there are severe filter implementation difficulties for the former. The results also demonstrate that the fusion of information from radar and ESM sensors via the DIF approach results in improvements over classification methods based on either of the individual sensors [J165]

"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 [J166]

"An automatic identification of clutter and anomalous propagation in polarization-diversity weather radar data using neural networks"

Radar polarization measurements have mostly been used to improve rainfall estimation and hydrometeor characterization. The authors extend the use of such measurements to the problem of ground clutter recognition, including the case when this problem is associated with anomalous propagation of the electromagnetic wave. They present a methodology used for recognizing both clutter and meteorological targets. The methodology is based on the knowledge of the scattering properties of the targets, as provided by the polarization measurements and the use of the neural network approach that performs the classification. The results show that if circular polarization is used, the circular depolarization ratio and the degree of polarization are good discriminators of clutter and nonclutter. They have used data from the Alberta polarization diversity radar to build an automatic decision process using a feedforward neural network. After they trained the neural network, they tested the classifier for two common clutter situations: when there is an electromagnetic wave anomalous propagation and when targets from rain are mixed with the clutter close to the radar [J167]

"A new feature vector using selected bispectra for signal classification with application in radar target recognition"

Radially integrated bispectra (RIB), axially integrated bispectra (AIB), and circularly integrated bispectra (CIB) were used as feature vectors of signals, but many bispectra on integration paths may be redundant, and some bispectra are even baneful for signal classification. To avoid these problems, this paper proposes using selected bispectra with the maximum interclass separability as feature vectors of signals. In radar target recognition, range profiles are suitable feature vectors, but they have two main shortcomings: sensitivity to time shift and aspect dependence. Since the selected bispectra of range profiles are translation invariant and can avoid redundant and baneful bispectra as features, they are thus especially suitable for radar target recognition, which is shown by experiments [J168]

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