Государственное образовательное учреждение
высшего профессионального образования
**«Томский государственный университет
систем управления и радиоэлектроники»**

ТЕМАТИЧЕСКИЙ РЕФЕРАТИВНЫЙ СБОРНИК № 21-1

“Radar Waveform Processing”
(«Обработка РЛ сигналов»)

Журнальные публикации

Источник: *Digital Library IEEEXplore*
Язык: *английский*
Глубина поиска: *2001 – 2011 гг.*
Дата формирования: *март 2011 г.*
Составитель: *В.И. Карнышев*

Томск – 2011

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"Low-Power Technique for SRAM-Based On-Chip Arbitrary-Waveform Generator"

A low-power technique for a static random-access memory (SRAM)-based on-chip arbitrary-waveform generator (AWG) is proposed for two types of analog-signal-processing applications: multiresolution spectrum sensing and matched filter. The SRAM has an embedded address generator to limit the operation in a sequential-access mode of the AWG. Then, the power consumption of the AWG is analyzed according to the operation modes in multiresolution and multiwaveform spectrum-sensing functions. The low-power technique reduces power by 18% of the SRAM and the address generator and by about 2.2% of the entire AWG at a 1.8-V supply voltage. The AWG is fabricated in a 0.18-μm CMOS technology and demonstrates a chirp signal and a Daubechies wavelet with a 45-dBc spurious-free dynamic range and a cross-correlation factor of 0.96-0.988 with ideal signals. [J1]

"Multiobjective Optimization of OFDM Radar Waveform for Target Detection"

We propose a multiobjective optimization (MOO) technique to design an orthogonal-frequency-division multiplexing (OFDM) radar signal for detecting a moving target in the presence of multipath reflections. We employ an OFDM signal to increase the frequency diversity of the system, as different scattering centers of a target resonate variably at different frequencies. Moreover, the multipath propagation increases the spatial diversity by providing extra "looks" at the target. First, we develop a parametric OFDM radar model by reformulating the target-detection problem as the task of sparse-signal spectrum estimation. At a particular range cell, we exploit the sparsity of multiple paths and the knowledge of the environment to estimate the paths along which the target responses are received. Then, to estimate the sparse vector, we employ a collection of multiple small Dantzig selectors (DS) that utilizes more prior structures of the sparse vector. We use the $\ell 1$-constrained minimal singular value ($\ell 1$-CMSV) of the measurement matrix to analytically evaluate the reconstruction performance and demonstrate that our decomposed DS performs better than the standard DS. In addition, we propose a constrained MOO-based algorithm to optimally design the spectral parameters of the OFDM waveform for the next coherent processing interval by simultaneously optimizing two objective functions: minimizing the upper bound on the estimation error to improve the efficiency of sparse-recovery and maximizing the squared Mahalanobis-distance to increase the performance of the underlying detection problem. We provide a few numerical examples to illustrate the performance characteristics of the sparse recovery and demonstrate the achieved performance improvement due to adaptive OFDM waveform design. [J2]

"Fast monostatic radar cross section computation using Maehly approximation"

The method of moments (MoM) in conjunction with the best uniform rational approximation is applied to predict monostatic radar cross section (RCS) pattern from a few pattern value calculations. Numerical results for three-dimensional arbitrarily shaped perfectly electric conductor objects are considered. Good agreement between the proposed technique and the exact solution is observed. Compared with the asymptotic waveform evaluation (AWE) technique, the proposed technique is accurate in much broader angular domains. [J3]

"Wideband MIMO Systems: Signal Design for Transmit Beampattern Synthesis"

The usage of multi-input multi-output (MIMO) systems such as a MIMO radar allows the array elements to transmit different waveforms freely. This waveform diversity can lead to flexible transmit beampattern synthesis, which is useful in many applications such as radar/sonar and biomedical imaging. In the past literature most attention was paid to receive beampattern design due to the stringent constraints on waveforms in the transmit beampattern case. Recently progress has been made on MIMO transmit beampattern synthesis but mainly only for narrowband signals. In this paper we propose a new approach that can be used to efficiently synthesize MIMO waveforms in order to match a given wideband transmit beampattern, i.e., to match a transmit energy distribution in both space and frequency. The synthesized waveforms satisfy the unit-modulus or low peak-to-average power ratio (PAR) constraints that are highly desirable in practice. Several examples are provided to investigate the performance of the proposed approach. [J4]

"Adaptive OFDM Radar for Target Detection in Multipath Scenarios"

We develop methods for detecting a moving target in the presence of multipath reflections, which exist, for example, in urban environments. We take advantage of the multipath propagation that increases the spatial diversity of the radar system and provides different Doppler shifts over different paths. We employ a broadband orthogonal frequency division multiplexing (OFDM) signal to increase the frequency diversity of the system as different scattering centers of a target resonate variably at different frequencies. To overcome the peak-to-average power ratio (PAPR) problem of the conventional OFDM, we also use constant-envelope OFDM (CE-OFDM) signaling scheme. First, we consider a simple scenario in which the radar receives only a finite number of specularly reflected multipath signals. We develop parametric measurement models, for both the OFDM and CE-OFDM signaling methods, under the generalized multivariate analysis of variance (GMANOVA) framework and employ the generalized likelihood ratio (GLR) tests to decide about the presence of a target in a particular range cell. Then, we propose an algorithm to optimally design the parameters of the OFDM transmitting waveform for the next coherent processing interval. In addition, we extend our models to study the aspects of temporal correlations in the measurement noise. We provide a few numerical examples to illustrate the performance characteristics of the proposed detectors and demonstrate the achieved performance improvement due to adaptive OFDM waveform design. [J5]

"Exploiting MIMO SAR Potentialities With Efficient Cross-Track Constellation Configurations for Improved Range Resolution"

In this paper, an innovative technique is presented for synthetic aperture radar (SAR) ground range resolution improvement using multiple transmit and receive platforms with adequate cross-track displacement. Using orthogonal waveforms, which occupy the same bandwidth in the range frequency domain, for the different platforms of the constellation, a multiple-input-multiple-output SAR system is configured. The proposed technique allows one to achieve a maximum theoretical range resolution improvement factor that is significantly greater than the number of operating SAR sensors by jointly exploiting both mono- and bistatic acquisitions. This can be exploited to obtain a ground range resolution that is much higher than the resolution corresponding to the frequency bandwidth transmitted by the single platform. After illustrating the proposed technique and its system requirements, a simulated data set is used to show the effectiveness of the proposed approach. [J6]

"A Novel Radar Waveform for Monostatic Ionosonde"

Monostatic radar, whether using interpulse or intrapulse coded pulse trains, will suffer from the blind zones caused by eclipsing. This letter proposes a novel biphase interpulse coded radar waveform using diverse Pulse Repetition Intervals (PRIs) instead of a consistent PRI within each coherent processing interval (CPI). This waveform can achieve long unambiguous range, high-range resolution and high Doppler resolution without blind zones, and is specially suitable for a monostatic ionosonde. [J7]

"Instrumental CWLFM High-Range Resolution Radar in Millimeter Waveband for ISAR Imaging"

This paper shows a High-Range Resolution (HRR) Radar prototype development, transmitting in millimeter-wave band. The waveform selected to be used is the continuous-wave linear frequency modulation (CWLFM), which allows, at the same time, good range resolution, moderate unambiguous doppler range and reasonable operational range taking into account that high-frequency band is used. The radar prototype looks for High-Range Resolution (HRR) characteristics as well as flexibility, in order to obtain the best Inverse Synthetic Aperture Radar (ISAR) images possible depending on the applications and targets involved. That is, depending on the speed and target's trajectories, some radar features, such as transmitted bandwidth, modulator frequency or sampling frequency, play a key role in obtaining the best possible results while using lowest electrical requirements. [J8]

"Radar Sensor Network Using a Set of New Ternary Codes: Theory and Application"

In the radar sensor network (RSN), the interferences among different radar sensors can be effectively reduced when waveforms are properly designed. In this paper, we perform some theoretical studies on coexistence of phase coded waveforms in the RSN. We propose a new ternary codes-optimized punctured zero correlation zone sequence-pair set (ZCZPS)-and analyze their properties. Applying the new ternary codes and equal-gain combination technique to the RSN, we study the detection performance versus different numbers of radar sensors under the different conditions. The simulation results show that the RSN using our optimized punctured ZCZPS performs better than the RSN using the same number of common codes such as the Gold codes and much better than the single radar system no matter whether or not the Doppler shift is considered. [J9]

"Diversity Gain for MIMO Neyman-Pearson Signal Detection"

For a multiple-input multiple-output (MIMO) system adopting the Neyman-Pearson (NP) criterion, we initially derive the diversity gain for a signal-present versus signal-absent scalar hypothesis test statistic and also for a vector signal-present versus signal-absent hypothesis testing problem. For a MIMO radar system with Mtransmit and Nreceive antennas, used to detect a target composed of Qrandom scatterers with possibly non-Gaussian reflection coefficients in the presence of possibly non-Gaussian clutter-plus-noise, we consider a class of test statistics, including the optimum test for Gaussian reflection coefficients and Gaussian clutter-plus-noise, and apply the previously developed results to compute the diversity gain. It is found that the diversity gain for the MIMO radar system is dependent on the cumulative distribution function (cdf) of the reflection coefficients while being invariant to the cdf of the clutter-plus-noise under some reasonable conditions requiring certain moments of the magnitude of the processed clutter-plus-noise be bounded. If the noise-free received waveforms, due to target reflection, at each receiver span a space of dimension $M' \leq M$, the largest possible diversity gain is controlled by the value of $\min(NM', Q)$ and the lowest order power in an expansion, about zero, of the cdf of the magnitude squared of a linear transformed version of the reflection coefficient vector. It is shown that the maximum possible diversity gain in any given scenario can be achieved without employing orthogonal waveforms. [J10]

"Locating a weak change using diffuse waves: Theoretical approach and inversion procedure"

We describe a time-resolved monitoring technique for heterogeneous media. Our approach is based on the spatial variations of the cross-coherence of diffuse waves acquired at fixed positions but at different dates. The technique applies to all kind of waves, provided that waveforms can be acquired with a sampling frequency much larger than the wave frequency. To locate and characterize a weak change that occurred between successive acquisitions, we use a maximum likelihood approach combined with a diffusive propagation model. We characterize this technique, locating a weak change using diffuse waves, called LOCADIFF, with the aid of numerical simulations. In several illustrative examples, we show that the change can be located with a precision of a few wavelengths and that its effective scattering cross-section can be retrieved. We investigate how the accuracy and precision of the method depends on the number of source-receiver pairs, on the time window used to compute the cross-correlation and on the errors in the propagation model. Applications can be found in nondestructive testing, seismology, radar, and sonar location. [J11]

"An adaptive filtering algorithm for blind waveform estimation in diffuse multipath channels"

The use of spatial filtering is considered to isolate a single propagation mode of an unknown narrowband signal received as a superposition of multipath components by a sensor array for the purpose of source waveform estimation. In the problem addressed, multipath propagation from source to receiver occur due to diffuse scattering from a number of distinct but extended regions of an irregular medium rather than ideal specular reflection. The combined presence of diffuse scattering and array calibration uncertainties may cause the spatial signatures of the incident distributed signal modes to deviate significantly from the plane-wave array manifold. Furthermore, the temporal signature of the waveform to be recovered may also be quite arbitrary, with no known deterministic or statistical properties that can be utilised for multipath separation. The lack of knowledge regarding the propagation channel, array manifold and source waveform poses a major challenge for the task at hand. This study proposes a new blind spatial filtering technique, referred to as the generalised estimation of multipath signals (GEMS) algorithm, which can effectively separate distributed signal modes for accurate source waveform estimation. This algorithm actually exploits the presence of multipath propagation and wavefront distortions as the basis for signal separation. The performance of GEMS is compared with two benchmark signal-copy procedures using real data from an experimental finite impulse response single-input multiple-output high frequency (HF) system. [J12]

"Ground-based radar interferometer for tracking fast approaching targets"

This study describes the design and initial evaluation of a radar that detects and tracks a fast approaching target in a short-range application. In some radar applications, tracking durations less than 1 s and 3D tracking accuracy of a few tens of centimetres are required. To satisfy these requirements, a radar interferometer is proposed to simultaneously detect and track a target. A frequency-modulated continuous wave (FMCW) waveform is chosen and a method of separating clutter from a valid signal is developed to obtain very precise range information. In the tracking algorithm, a least squares (LS) filter is adopted because of its fast computing speed and good convergence characteristics to a steady state. This system is constructed using an open architecture approach, with a direct digital synthesiser, a field programmable gate array (FPGA) and a digital signal processor (DSP) as core components. The radar system was evaluated through real field testing. The test results showed that the proposed radar and tracking methods are able to estimate very accurate target positions in real field testing. [J13]

"Novel range profile synthesis algorithm for linearly stepped-frequency modulated inversed synthetic aperture radar imaging of remote manoeuvring target"

For inversed synthetic aperture radar (ISAR) imaging of remote manoeuvring targets via linearly stepped-frequency modulated waveform, a digital stretch technique and a phase coherence compensation method are proposed to achieve highresolution range profile (HRRP) synthesis. By using this digital stretch technique, the sampling rate can be dramatically reduced and thus the data amount can be significantly decreased. Since the motion estimation error is inevitable for conventional parameters estimation methods, the residual Doppler will give rise to the phase discontinuity at the juncture between the neighbouring sub-pulses, which may blur the HRRP to some extent. A phase coherence compensation method is proposed to further eliminate the phase difference. Owing to the adaptively and convenience for residual Doppler compensation of the proposed method, a good HRRP can be obtained by means of time-domain sub-pulses synthesis technique. Finally, a well-focused ISAR image can be achieved after the conventional range alignment and autofocusing. Experimental results confirm the effectiveness of the proposed methods. [J14]

"Pareto-optimal radar waveform design"

This study deals with the problem of Pareto-optimal waveform design in the presence of coloured Gaussian noise, under a similarity and an energy constraint. At the design stage, the authors, determine the optimal radar code according the following criterion: constrained maximisation of the detection performance and constrained minimisation of the Cramer??Rao lower bound (CRLB) on the Doppler estimation accuracy. This is tantamount to jointly maximising two quadratic forms under two quadratic constraints, so that the problem can be formulated in terms of a non-convex multi-objective optimisation problem. In order to solve it, the authors resort to the scalarisation technique, which reduces the vectorial problem into a scalar one using a Pareto weight defining the relative importance of the two objective functions. At the analysis stage, the authors assess the performance of the proposed waveform design scheme in terms of detection performance, region of achievable Doppler estimation accuracy and ambiguity function. In particular, the authors analyse the role of the Pareto weight in the optimisation process. [J15]

"Designing single/multiple sparse frequency waveforms with sidelobe constraint"

Sparse frequency waveform with narrow stopbands sparsely distributed over a wide spectrum band is preferred for many radar and communication systems operating in a highly congested spectrum environment. In this paper, a new method for designing sparse frequency waveform with low range side lobes are proposed. The basic idea is to achieve waveform total performance improvement by minimising a new effective penalty function based on both requirements for the power spectrum density and the range side lobe through an iterative algorithm. The proposed approach is efficient in computation and flexible in designing sparse frequency waveform. Several design examples are also presented to show the validity of the proposed method. An extension to design multiple waveforms for multiple-input multiple-output radar is also presented. [J16]

"Sparse Learning via Iterative Minimization With Application to MIMO Radar Imaging"

Through waveform diversity, multiple-input multiple-output (MIMO) radar can provide higher resolution, improved sensitivity, and increased parameter identifiability compared to more traditional phased-array radar schemes. Existing methods for target estimation, however, often fail to provide accurate MIMO angle-range-Doppler images when there are only a few data snapshots available. Sparse signal recovery algorithms, including many l1-norm based approaches, can offer improved estimation in that case. In this paper, we present a regularized minimization approach to sparse signal recovery. Sparse learning via iterative minimization (SLIM) follows an lq-norm constraint (for 0 <; q≤ 1), and can thus be used to provide more accurate estimates compared to the l1-norm based approaches. We herein compare SLIM, through imaging examples and examination of computational complexity, to several well-known sparse methods, including the widely used CoSaMP approach. We show that SLIM provides superior performance for sparse MIMO radar imaging applications at a low computational cost. Furthermore, we will show that the user parameter qcan be automatically determined by incorporating the Bayesian information criterion. [J17]

"Multiple-input multiple-output radar aperture optimisation"

The authors describe a process for designing low-cost, light-weight antenna apertures for use in multiple-input multiple-output (MIMO) radars. In a MIMO radar system, two or more transmitters emit independent waveforms, with the resulting reflections received by an array of receivers. Recently, MIMO radar has become a subject of great interest. In part, this interest is due to the potential for MIMO techniques to reduce radar weight and cost, while maintaining performance (as compared with conventional radar approaches). However, the size of these

reductions has not yet been quantified. Here, the authors describe a process for designing optimal radar apertures. This process treats the design problem as one of minimising an objective function under performance constraints. The objective function is based upon a first-order model for the relationship between cost (or weight) and performance, and is derived for systems employing active, element-digitised arrays. A systematic process for optimising the aperture's design with respect to this objective function is presented, and equations describing the optimal aperture are derived. These equations provide insight into the optimal relationship between various aperture characteristics, such as the number of transmitters, number of receivers, module power level and virtual array length. [J18]

"Multiple-input multiple-output radar search strategies for high-velocity targets"

The radar detection of high-velocity targets with a multiple-element antenna array is considered. The detection performance of multiple-input multiple-output (MIMO) radar with orthogonal waveforms is compared with that of a radar using a directed beam. An analytical expression for the probability of detection for a radar with a multiple-element array is derived. For high-velocity targets, the decrease in probability of detection because of the longer integration time required for MIMO radar is quantified. It is shown that for lower-velocity targets, sector search using orthogonal waveforms results has similar detection range performance to that of scanning directed beams. For higher-velocity targets, the use of scanning directed beams yields larger detection range. [J19]

"Matched-Illumination Waveform Design for a Multistatic Through-the-Wall Radar System"

We present the matched illumination waveform design for improved target detection in through-the-wall radar imaging and sensing applications. We consider a multistatic radar system for detection of stationary targets with known impulse responses behind walls. The stationary and slowly moving nature of typical indoor targets relaxes the orthogonality requirement on the waveforms, thereby allowing sequential transmissions from each transmitter with simultaneous reception at multiple receivers. The generalization of the matched illumination waveform design concept from a monostatic to a multistatic setting casts the indoor radar sensing problem in terms of multiple-input multiple-output (MIMO) operations and puts in context the offering of MIMO to urban sensing and imaging of targets in enclosed structures. Numerical electromagnetic modeling is used to provide the impulse response of typical behind-the-wall stationary targets, namely tables and humans, for different target orientations and at various incident and reflection angles. Simulation results depict an improvement in the signal-to-clutter-and-noise-ratio (SCNR) at the output of the matched filter receiver for multistatic radar as compared to monostatic operation. [J20]

"Transmit Subaperturing for MIMO Radars With Co-Located Antennas"

We present a transmit subaperturing (TS) approach for multiple-input multiple-output (MIMO) radars with co-located antennas. The proposed scheme divides the transmit array elements into multiple groups, each group forms a directional beam and modulates a distinct waveform, and all beams are steerable and point to the same direction. The resulting system is referred to as a TS-MIMO radar. A TS-MIMO radar is a tunable system that offers a continuum of operating modes from the phased-array radar, which achieves the maximum directional gain but the least interference rejection ability, to the omnidirectional transmission based MIMO radar, which can handle the largest number of interference sources but offers no directional gain. Tuning of the TS-MIMO system can be easily made by changing the configuration of the transmit subapertures, which provides a direct tradeoff between the directional gain and interference rejection power of the system. The performance of the TS-MIMO radar is examined in terms of the output signal-to-interference-plus-noise ratio (SINR) of an adaptive beamformer in an interference and training limited environment, where we show analytically how the output SINR is affected by several key design parameters, including the size/number of the subapertures and the number of training signals. Our results are verified by computer simulation and comparisons are made among various operating modes of the proposed TS-MIMO system. [J21]

"Signal Processing for Passive Radar Using OFDM Waveforms"

Passive radar is a concept where illuminators of opportunity are used in a multistatic radar setup. New digital signals, like digital audio/video broadcast (DAB/DVB), are excellent candidates for this scheme, as they are widely available, can be easily decoded to acquire the noise-free signal, and employ orthogonal frequency division multiplex (OFDM). Multicarrier transmission schemes like OFDM use block channel equalization in the frequency domain, efficiently implemented as a fast Fourier transform, and these channel estimates can directly be used to identify targets based on Fourier analysis across subsequent blocks. In this paper, we derive the exact matched filter formulation for passive radar using OFDM waveforms. We then show that the current approach using Fourier analysis across block channel estimates is equivalent to the matched filter, based on a piecewise constant assumption on the Doppler-induced phase rotation in the time domain. We next present

high-resolution algorithms based on the same assumption: first we implement MUSIC as a 2-D spectral estimator using spatial smoothing; then we use the new concept of compressed sensing to identify targets. We compare the new algorithms and the current approach using numerical simulation and experimental data recorded from a DAB network in Germany. [J22]

"Iterative Adaptive Approaches to MIMO Radar Imaging"

Multiple-input multiple-output (MIMO) radar can achieve superior performance through waveform diversity over conventional phased-array radar systems. When a MIMO radar transmits orthogonal waveforms, the reflected signals from scatterers are linearly independent of each other. Therefore, adaptive receive filters, such as Capon and amplitude and phase estimation (APES) filters, can be directly employed in MIMO radar applications. High levels of noise and strong clutter, however, significantly worsen detection performance of the data-dependent beamformers due to a shortage of snapshots. The iterative adaptive approach (IAA), a nonparametric and user parameter-free weighted least-squares algorithm, was recently shown to offer improved resolution and interference rejection performance in several passive and active sensing applications. In this paper, we show how IAA can be extended to MIMO radar imaging, in both the negligible and nonnegligible intrapulse Doppler cases, and we also establish some theoretical convergence properties of IAA. In addition, we propose a regularized IAA algorithm, referred to as IAA-R, which can perform better than IAA by accounting for unrepresented additive noise terms in the signal model. Numerical examples are presented to demonstrate the superior performance of MIMO radar over single-input multiple-output (SIMO) radar, and further highlight the improved performance achieved with the proposed IAA-R method for target imaging. [J23]

"Signaling Strategies for the Hybrid MIMO Phased-Array Radar"

The hybrid MIMO phased array radar (HMPAR) is a notional concept for a multisensor radar architecture that combines elements of traditional phased-array radar with the emerging technology of multiple-input multiple output (MIMO) radar. A HMPAR comprises a large number, MP, of T/R elements, organized into M subarrays of P elements each. Within each subarray, passive element-level phase shifting is used to steer transmit and receive beams in some desired fashion. Each of the M subarrays are in turn driven by independently amplified phase-coded signals which could be quasi-orthogonal, phase-coherent, or partially correlated. Such a radar system could be used in an airborne platform for concurrent search, detect, and track missions. This paper considers various signaling strategies which could be employed in the notional HMPAR architecture to achieve various objectives quantified by transmit beampatterns and space-time ambiguity functions. First, we propose a method to generate multiple correlated signals for uniform linear and rectangular arrays that achieve arbitrary rectangular transmit beampatterns in one and two dimensions, while maintaining desirable temporal properties. Examples of the range of transmit beampatterns possible with this technique are illustrated for an array of MP=900 elements, arranged using different values of M and P. Then the space-time, or MIMO, ambiguity function that is appropriate for the HMPAR radar system is derived. Examples of ambiguity functions for our signals using a one-dimensional HMPAR architecture are given, demonstrating that one can achieve phased-array-like resolution on receive, for arbitrary transmit beampatterns. [J24]

"Performance of MIMO Radar With Angular Diversity Under Swerling Scattering Models"

The performance of statistical multiple-input multiple-output (MIMO) radar configurations that use distributed antennas is analyzed in this paper. Statistical MIMO radars exploit angular diversity to mitigate the impact of radar cross section (RCS) fluctuations. The fluctuations can be modeled with the Swerling scattering model consisting of four different cases with either fast or slow target RCS fluctuations. In this paper, the performance of different statistical MIMO radar configurations is compared in the different Swerling cases. Both target detection and direction of arrival estimation tasks are considered. We derive the optimal test statistics for target detection for non-orthogonal waveforms in all the Swerling cases in single-pulse as well as multi-pulse scenarios. We derive a closed-form density function for the test statistics under null and alternate hypotheses in the Swerling cases 1 and 2. For orthogonal waveforms in cases 3 and 4, the density function is given as a convolution involving a transcendental function. A suboptimal detector having a closed-form density function in cases 3 and 4 when the waveforms are orthogonal is introduced as well. In the direction finding task, confidence bounds of the squared estimation error of the different configurations are compared. The comparison is done in terms of the confidence bounds as the Cramer-Rao bounds are not defined for all the cases and configurations. The pros and cons of the angular diversity and each radar configuration are pointed out in different fluctuation scenarios. [J25]

"Optimal Joint Target Detection and Parameter Estimation by MIMO Radar"

We consider multiple-input multiple-output (MIMO) radar systems with widely spaced antennas. Such antenna

configuration facilitates capturing the inherent diversity gain due to independent signal dispersion by the target scatterers. We consider a new MIMO radar framework for detecting a target that lies in an unknownlocation. This is in contrast with conventional MIMO radars which break the space into small cells and aim at detecting the presence of a target in a specified cell. We treat this problem through offering a novel composite hypothesis testing framework for target detection when 1) one or more parameters of the target are unknown and we are interested in estimating them, and 2) only a finitenumber of observations are available. The test offered optimizes a metric which accounts for both detection and estimation accuracies. In this paper, as the parameter of interest we focus on the vector of time-delays that the waveforms undergo from being emitted by the transmit antennas until being observed by the receive antennas. The analytical and empirical results establish that for the proposed joint target detection and time-delay estimation framework, MIMO radars exhibit significant gains over phased-array radars for extended targets which consist of multiple independent scatterers. For point targets modeled as single scatterers, however, the detection/estimation accuracies of MIMO and phased-array radars for this specific setup (joint target detection and time-delay estimation) are comparable. [J26]

"MIMO Radar Waveform Constraints for GMTI"

Ground moving-target indication (GMTI) provides both an opportunity and challenge for coherent multiple-input multiple-output (MIMO) radar. MIMO techniques can improve a radar's angle estimation and the minimum detectable velocity (MDV) for a target. However, the challenge of clutter mitigation places significant constraints on MIMO radar waveforms. In this paper, the loss of target return because of clutter mitigation (signal-to-noise ratio (SNR) loss) is the driving performance metric. The ideal, orthogonal repeated-pulse waveform is shown not to exist. Pulse-to-pulse time-varying waveforms, such as Doppler-division multiple access (DDMA), are shown to offer SNR loss performance approaching ideal MIMO systems. [J27]

"Compressed Synthetic Aperture Radar"

In this paper, we introduce a new synthetic aperture radar (SAR) imaging modality which can provide a high-resolution map of the spatial distribution of targets and terrain using a significantly reduced number of needed transmitted and/or received electromagnetic waveforms. This new imaging scheme, requires no new hardware components and allows the aperture to be compressed. It also presents many new applications and advantages which include strong resistance to countermesasures and interception, imaging much wider swaths and reduced on-board storage requirements. [J28]

"Source Localization and Sensing: A Nonparametric Iterative Adaptive Approach Based on Weighted Least Squares"

Array processing is widely used in sensing applications for estimating the locations and waveforms of the sources in a given field. In the absence of a large number of snapshots, which is the case in numerous practical applications, such as underwater array processing, it becomes challenging to estimate the source parameters accurately. This paper presents a nonparametric and hyperparameter, free-weighted, least squares-based iterative adaptive approach for amplitude and phase estimation (IAA-APES) in array processing. IAA-APES can work well with few snapshots (even one), uncorrelated, partially correlated, and coherent sources, and arbitrary array geometries. IAA-APES is extended to give sparse results via a model-order selection tool, the Bayesian information criterion (BIC). Moreover, it is shown that further improvements in resolution and accuracy can be achieved by applying the parametric relaxation-based cyclic approach (RELAX) to refine the IAA-APES&BIC estimates if desired. IAA-APES can also be applied to active sensing applications, including single-input single-output (SISO) radar/sonar range-Doppler imaging and multi-input single-output (MISO) channel estimation for communications. Simulation results are presented to evaluate the performance of IAA-APES for all of these applications, and IAA-APES is shown to outperform a number of existing approaches. [J29]

"Noncoherent MIMO Radar for Location and Velocity Estimation: More Antennas Means Better Performance"

This paper presents an analysis of the joint estimation of target location and velocity using a multiple-input multiple-output (MIMO) radar employing noncoherent processing for a complex Gaussian extended target. A MIMO radar with Mtransmit and Nreceive antennas is considered. To provide insight, we focus on a simplified case first, assuming orthogonal waveforms, temporally and spatially white noise-plus-clutter, and independent reflection coefficients. Under these simplifying assumptions, the maximum-likelihood (ML) estimate is analyzed, and a theorem demonstrating the asymptotic consistency, large MN, of the ML estimate is provided. Numerical investigations, given later, indicate similar behavior for some reasonable cases violating the simplifying assumptions. In these initial investigations, we study unconstrained systems, in terms of complexity and energy, where each added transmit antenna employs a fixed energy so that the total transmitted energy is allowed to

increase as we increase the number of transmit antennas. Following this, we also look at constrained systems, where the total system energy and complexity are fixed. To approximate systems of fixed complexity in an abstract way, we restrict the total number of antennas employed to be fixed. Here, we show numerical examples which indicate a preference for receive antennas, similar to MIMO communications, but where systems with multiple transmit antennas yield the smallest possible mean-square error (MSE). The joint Cramer-Rao bound (CRB) is calculated and the MSE of the ML estimate is analyzed. It is shown for some specific numerical examples that the signal-to-clutter-plus-noise ratio (SCNR) threshold, indicating the SCNRs above which the MSE of the ML estimate is reasonably close to the CRB, can be lowered by increasing MN. The noncoherent MIMO radar ambiguity function (AF) is developed in two different ways and illustrated by examples. It is shown for some specif--ic examples that the size of the product MNcontrols the levels of the sidelobes of the AF. [J30]

"Phased-MIMO Radar: A Tradeoff Between Phased-Array and MIMO Radars"

We propose a new technique for multiple-input multiple-output (MIMO) radar with colocated antennas which we call phased-MIMO radar. The new technique enjoys the advantages of the MIMO radar without sacrificing the main advantage of the phased-array radar which is the coherent processing gain at the transmitting side. The essence of the proposed technique is to partition the transmit array into a number of subarrays that are allowed to overlap. Then, each subarray is used to coherently transmit a waveform which is orthogonal to the waveforms transmitted by other subarrays. Coherent processing gain can be achieved by designing a weight vector for each subarray to form a beam towards a certain direction in space. Moreover, the subarrays are combined jointly to form a MIMO radar resulting in higher angular resolution capabilities. Substantial improvements offered by the proposed phased-MIMO radar technique as compared to the phased-array and MIMO radar techniques are demonstrated analytically and by simulations through analyzing the corresponding beam patterns and the achievable output signal-to-noise-plus-interference ratios. Both analytical and simulation results validate the effectiveness of the proposed phased-MIMO radar. [J31]

"Dimensionality Reduction Techniques for Efficient Adaptive Pulse Compression"

Adaptive filtering for radar pulse compression has been shown to improve sidelobe suppression through the estimation of an appropriate pulse compression filter for each individual range cell of interest. However, the relatively high computational cost of full-dimension, adaptive range processing may limit practical implementation in many current real-time systems. Dimensionality reduction techniques are here employed to approximate the framework for pulse compression filter estimation. Within this approximate framework, two new minimum mean square error (MMSE) based adaptive algorithms are derived. The two algorithms are denoted as specific embodiments of the fast adaptive pulse compression (FAPC) method and are shown to maintain performance close to that of full-dimension adaptive processing, while reducing computation cost by nearly an order of magnitude (in terms of the discretized waveform length N). [J32]

"Costas CW frequency hopping radar waveform: peak sidelobe improvement using Golay complementary sequences"

The use of Golay complementary sequences to encode Costas frequency hopping continuous waveforms (CW) in order improve the range (time) sidelobe behaviour of received radar signals compared to classical techniques such as Barker coding is investigated for the first time. Sidelobe reduction is quantified using the aperiodic autocorrelation function and the periodic autocorrelation function. The results are compared with the same frequency hopping waveform encoded with a 13-bit Barker code. The results show that a 16 dB improvement in peak sidelobe performance is achieved over Barker coding using Golay complementary sequences with a code length of only 23and a 26 dB improvement with code length 28. [J33]

"Efficient Spotlight SAR MIMO Linear Collection Configurations"

We describe how a family of synthetic aperture radar (SAR) platforms flying linearly and transmitting mutually orthogonal waveforms at a common pulse repetition frequency (PRF) constitute a multiple-input multiple output (MIMO) radar system that reduces time spent collecting a SAR image and quantify the efficiency of such sensor configurations. We give efficient collection configurations for up to 15 platforms as well as asymptotically optimally efficient sequences of configurations. [J34]

"Modeling Envisat RA-2 Waveforms in the Coastal Zone: Case Study of Calm Water Contamination"

Radar altimeters have so far had limited use in the coastal zone, the area with most societal impact. This is due to both lack of, or insufficient accuracy in the necessary corrections, and more complicated altimeter signals.

This letter examines waveform data from the Envisat RA-2 as it passes regularly over Pianosa (a 10-km2island in the northwestern Mediterranean). Forty-six repeat passes were analyzed, with most showing a reduction in signal upon passing over the island, with weak early returns corresponding to the reflections from land. Intriguingly, one third of cases showed an anomalously bright hyperbolic feature. This feature may be due to extremely calm waters in the Golfo della Botte (northern side of the island), but the cause of its intermittency is not clear. The modeling of waveforms in such a complex land/sea environment demonstrates the potential for sea surface height retrievals much closer to the coast than is achieved by routine processing. The long-term development of altimetric records in the coastal zone will not only improve the calibration of altimetric data with coastal tide gauges but also greatly enhance the study of storm surges and other coastal phenomena. [J35]

"MIMO-OFDM radar for direction estimation"

Multiple-input-multiple-output (MIMO) radar makes use of orthogonal signals to obtain the phase delay for each transmitting/receiving antenna pair, and thus increasing the accuracy of direction estimation. The previously proposed MIMO radar assumes narrowband signals that guarantee the waveform orthogonality during the signals- transmission, propagation and reception. However, a narrowband system is unstable in target localisation because of the fluctuation of the target-s radar cross section. An MIMO-OFDM radar is proposed for target localisation. It adopts the OFDM technique to simultaneously transmit and receive a set of multiple narrowband orthogonal signals at orthogonal frequencies. A practical model accommodating a physical target is presented to simulate the MIMO-OFDM radar. As an example, a composite target composed of five infinite dielectric cylinders is localised by a four-element uniform linear array. The performance of the MIMO-OFDM radar is investigated by examining the estimation error for different numbers of sub-bands, different signal-to-noise ratios and different target directions. It is demonstrated by simulation that the MIMO-OFDM radar gives more statistically stable estimation by spreading the signal power over a wider spectrum. [J36]

"ISAR Imaging for Avian Species Identification With Frequency-Stepped Chirp Signals"

Imaging an avian target by inverse synthesis aperture radar (ISAR) is a novel and important technological approach of solving the problem of avian detection. However, the ISAR images of birds obtained with the conventional range-Doppler algorithm could be contaminated due to serious micro-Doppler effects, which are generated by the birds' flapping wings. In this letter, a novel imaging method of birds is proposed, which is simple to comprehend and operate, and avoids lots of complications and computation burdens. In the method, the moving status of bird is identified first via finding the variety of moving average values of the cross-correlation coefficient of the adjacent high-resolution range profiles. The usage of moving average values is attributed to the characters of the bird's flapping. The parts of respective flapping spectrogram can then be eliminated, and the parts of the residual spectrogram, i.e., the respective gliding spectrogram, can be connected to prepare for the cross-compression. In this letter, the minimum waveform entropy criterion and genetic algorithm are employed in the spectrogram connection to compensate the phase error. Finally, the feasibility and effectiveness of the methods are verified by simulation results. [J37]

"Code Design for Radar STAP via Optimization Theory"

In this paper, we deal with the problem of constrained code optimization for radar space-time adaptive processing (STAP) in the presence of colored Gaussian disturbance. At the design stage, we devise a code design algorithm complying with the following optimality criterion: maximization of the detection performance under a control on the regions of achievable values for the temporal and spatial Doppler estimation accuracy, and on the degree of similarity with a pre-fixed radar code. The resulting quadratic optimization problem is solved resorting to a convex relaxation that belongs to the semidefinite program (SDP) class. An optimal solution of the initial problem is then constructed through a suitable rank-one decomposition of an optimal solution of the relaxed one. At the analysis stage, we assess the performance of the new algorithm both on simulated data and on the standard challenging the Knowledge-Aided Sensor Signal Processing and Expert Reasoning (KASSPER) datacube. [J38]

"Soil Surface Water Content Estimation by Full-Waveform GPR Signal Inversion in the Presence of Thin Layers"

We analyzed the effect of shallow thin layers on the estimation of soil surface water content using full-waveform inversion of off-ground ground penetrating radar (GPR) data. Strong dielectric contrasts are expected to occur under fast wetting or drying weather conditions, thereby leading to constructive and destructive interferences with respect to surface reflection. First, synthetic GPR data were generated and subsequently inverted considering different thin-layer model configurations. The resulting inversion errors when neglecting the thin layer were quantified, and then, the possibility to reconstruct these layers was investigated. Second, laboratory experiments

reproducing some of the numerical experiment configurations were conducted to assess the stability of the inverse solution with respect to actual measurement and modeling errors. Results showed that neglecting shallow thin layers may lead to significant errors on the estimation of soil surface water content(????>0.03 m3/m3), depending on the contrast. Accounting for these layers in the inversion process strongly improved the results, although some optimization issues were encountered. In the laboratory, the proposed full-waveform method permitted to reconstruct thin layers with a high resolution up to 2 cm and to retrieve the soil surface water content with an rmse less than 0.02 m3/m3, owing to the full-waveform inverse modeling. These results suggest that the proposed GPR approach is promising for field-scale mapping of soil surface water content of nondispersive soils with low electrical conductivity and for instances when soil layering is encountered. [J39]

"MIMO Radar Waveform Design via Alternating Projection"

Waveform design is essential to unleash the performance advantages promised by multiple-input multiple-output (MIMO) radar, and this topic has attracted a lot of attention in the recent years. Revisiting an earlier examined MIMO radar waveform design problem that optimizes both minimum mean-square error estimation (MMSE) and mutual information (MI), in this correspondence we formulate a new waveform design problem and provide some further results, which complement the previous study. More specifically, we present an iterative optimization algorithm based on the alternating projection method to determine waveform solutions that can simultaneously satisfy a structure constraint and optimize the design criteria. Numerical examples are provided, which illustrate the effectiveness of the proposed approach. In particular, we find that the waveform solutions obtained through our proposed algorithm can achieve very close and virtually indistinguishable performance from that predicted in the previous study. [J40]

"Clutter Rank of STAP in MIMO Radar With Waveform Diversity"

In recent years, multiple-input multiple-output (MIMO) radar systems with space-time adaptive processing (STAP) have been proposed to improve radar performance. For MIMO radars with STAP, one big concern is the clutter rank. Current studies employ the rule of time-bandwidth product to predict the clutter rank of MIMO radars using orthogonal waveforms. This paper investigates clutter rank estimation for MIMO radar systems with more flexible waveform diversity, where waveforms are not constrained to be orthogonal. Under general waveform assumption, we have derived the clutter covariance matrix as a function of waveform covariance matrix (WCM). The clutter rank is then found to be determined by the rank and structure of the WCM. For different waveform cases, the WCM may be either full rank or rank deficient. Rules for estimation of clutter rank in these cases are provided and demonstrated by numerical simulations. [J41]

"Communications-Inspired Sensing: A Case Study on Waveform Design"

Information theory, and particularly the mutual information (MI), has provided fundamental guidance for communications research. In Bell's 1993 paper, the MI was first applied to radar waveform design. Similar to its communications counterpart, the solution comes in a water-filling form. However, the practical meaning of MI in the sensing context remains unclear to date. Recently, Yang and Blum's 2007 paper shows that under the white noise assumption, the optimum water-filling scheme simultaneously maximizes the MI and minimizes the estimation minimum mean square error (MMSE). Such an equivalence, however, does not hold when the target parameter statistics are not perfectly known as shown in Yang and Blum's subsequent work. To further the understanding of the practical meaning of MI and to establish a connection between the MI and commonly adopted MSE measures for sensing, this paper takes a fresh look at the target estimation problem. We consider the general colored noise, incorporate the normalized MSE (NMSE), and develop joint robust designs for both the transmitter (waveforms) and the receiver (estimator) under various target and noise uncertainty models. Our results show that i) the optimum waveform designs resulted from the MI, MMSE and NMSE criteria are all different and ii) compared to MMSE, the NMSE-based designs share more similarities with the MI-based ones, especially when the target and noise statistics are not perfectly known. [J42]

"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. [J43]

"Adaptive Design of OFDM Radar Signal With Improved Wideband Ambiguity Function"

We propose an adaptive technique to design the spectrum of an orthogonal frequency division multiplexing (OFDM) waveform to improve the radar's wideband ambiguity function (WAF). The adaptive OFDM signal yields a better auto-correlation function (ACF) that results into an improved delay (range) resolution for the radar system. First, we develop a mutlicarrier OFDM signal model and the corresponding WAF at the output of the matched filter, emphasizing that the received signal depends on the scattering parameters of the target. Then, we devise an optimization procedure to select the OFDM waveform such that the volume of the corresponding WAF best approximates the volume of a desired ambiguity function. We demonstrate the improvement in the resulting ambiguity function, along with the associated ACF, through numerical examples. We find that the optimization algorithm puts more signal energy at subcarriers in which the target response is weaker. [J44]

"Polarimetric MIMO Radar With Distributed Antennas for Target Detection"

Multiple-input-multiple-output (MIMO) radar systems with widely separated antennas enable viewing the target from different angles, thereby providing spatial diversity gain. Polarimetric design of the transmit waveforms based on the properties of the target scattering matrix provides better performance than transmitting waveforms with only fixed horizontal or vertical polarizations. We propose a radar system that combines the advantages of both systems by transmitting polarized waveforms from multiple distributed antennas, in order to detect a point-like stationary target. The proposed system employs 2-D vector sensors at the receivers, each of which measures the horizontal and vertical components of the received electric field separately. We design the Neyman-Pearson detector for such systems. We derive approximate expressions for the probability of false alarm (PFA) and the probability of detection (PD). Using numerical simulations, we demonstrate that optimal design of the antenna polarizations provides improved performance over MIMO systems that transmit waveforms of fixed polarizations over all the antennas. We also demonstrate that having multiple widely separated antennas gives improved performance over single-input-single-output (SISO) polarimetric radar. We also demonstrate that processing the vector measurements at each receiver separately gives improved performance over systems that linearly combine both the received signals to give scalar measurements. [J45]

"Time Reversal in Multiple-Input Multiple-Output Radar"

Time reversal explores the rich scattering in a multipath environment to achieve high target detectability. Multiple-input multiple-output (MIMO) radar is an emerging active sensing technology that uses diverse waveforms transmitted from widely spaced antennas to achieve increased target sensitivity when compared to standard phased arrays. In this paper, we combine MIMO radar with time reversal to automatically match waveforms to a scattering channel and further improve the performance of radar detection. We establish a radar target model in multipath rich environments and develop likelihood ratio tests for the proposed time-reversal MIMO radar (TR-MIMO). Numerical simulations demonstrate improved target detectability compared with the commonly used statistical MIMO strategy. [J46]

"Multistatic Synthetic Aperture Radar Image Formation"

In this paper, we consider a multistatic synthetic aperture radar (SAR) imaging scenario where a swarm of airborne antennas, some of which are transmitting, receiving or both, are traversing arbitrary flight trajectories and transmitting arbitrary waveforms without any form of multiplexing. The received signal at each receiving antenna may be interfered by the scattered signal due to multiple transmitters and additive thermal noise at the receiver. In this scenario, standard bistatic SAR image reconstruction algorithms result in artifacts in reconstructed images due to these interferences. In this paper, we use microlocal analysis in a statistical setting to develop a filtered-backprojection (FBP) type analytic image formation method that suppresses artifacts due to interference while preserving the location and orientation of edges of the scene in the reconstructed image. Our FBP-type algorithm exploits the second-order statistics of the target and noise to suppress the artifacts due to interference in a mean-square sense. We present numerical simulations to demonstrate the performance of our multistatic SAR image formation algorithm with the FBP-type bistatic SAR image reconstruction algorithm. While we mainly focus on radar applications, our image formation method is also applicable to other problems arising in fields such as acoustic, geophysical and medical imaging. [J47]

"Noncausal Adaptive Spatial Clutter Mitigation in Monostatic MIMO Radar: Fundamental Limitations"

The problem of a point target detection masked by clutter distributed over range and Doppler, including the range and Doppler of the target, is considered for a multimode propagation scenario commonly encountered in quasimonostatic HF over-the-horizon radars (OTHR). Here, a clutter signal spread in Doppler frequency due to

propagation via a disturbed ionospheric layer competes with a target and narrowband clutter returns propagating via a stable ionospheric layer with the same group delay (radar range). Mitigation over all ranges of spread clutter propagating via a Г‚Вїmixed modeГ‚Вї path with indistinguishable direction-of-arrival (DoA) relative to the target requires (potentially adaptive) transmit beamforming to exploit the direction-of-departure (DoD) difference, which varies as a function of radar range. This range-dependent beamforming can be implemented only via the use of multiple-input multiple-output radar technology. In this paper, we explore the fundamental limitations that exist for the maximal dimension of the area in range-Doppler space occupied by spread clutter and the required properties (cardinality) of the orthogonal waveform set for efficient spread clutter mitigation. [J48]

"MIMO Radar Using Compressive Sampling"

A multiple-input multiple-output (MIMO) radar system is proposed for obtaining angle and Doppler information on potential targets. Transmitters and receivers are nodes of a small scale wireless network and are assumed to be randomly scattered on a disk. The transmit nodes transmit uncorrelated waveforms. Each receive node applies compressive sampling to the received signal to obtain a small number of samples, which the node subsequently forwards to a fusion center. Assuming that the targets are sparsely located in the angle-Doppler space, based on the samples forwarded by the receive nodes the fusion center formulates an l1-optimization problem, the solution of which yields target angle and Doppler information. The proposed approach achieves the superior resolution of MIMO radar with far fewer samples than required by other approaches. This implies power savings during the communication phase between the receive nodes and the fusion center. Performance in the presence of a jammer is analyzed for the case of slowly moving targets. Issues related to forming the basis matrix that spans the angle-Doppler space, and for selecting a grid for that space are discussed. Extensive simulation results are provided to demonstrate the performance of the proposed approach at difference jammer and noise levels. [J49]

"Hermite-Rodriguez UWB Circular Arrays"

Pulsed circular arrays are collecting growing interest in radar applications such as automotives and indoor navigations. This contribution presents the analytic derivation of the space-time and energy patterns of pulsed circular arrays in terms of geometrical and electrical parameters as well as of the signal distortion produced by the antennas' response. It is shown that the field emitted by circular arrays with many elements can be represented as a summation of a practically finite set of high-order Hermite-Rodriguez waveforms, while the energy pattern is a generalized hypergeometric function. The angular and temporal resolutions are finally related, through handy formulas, to the array size, the input signals and to the antenna types. [J50]

"Reconstruction of GPR Signals by Spectral Analysis of the SVD Components of the Data Matrix"

This letter considers the problem of reconstructing total-time responses from noisy data collected by ground-penetrating radar (GPR). The well-known singularity expansion method (SEM)-a theory-for late-time response representation is generalized to establish a matrix model (data matrix)representing total-time responses of radar scattering waveforms. Using singular value decomposition of the data matrix-an intermediate processing technique, we present an approach to model-order determination and successfully reconstruct the total-time responses. The model order is quantitativelyselected by spectral analysis of left singular vectors of the data matrix and of the emitted waveform. The most important discoveries in this letter are as follows: (1) the GPR upper frequency can be used as a criterion for the selection of left singular vectors of the data matrix, and (2) the left singular vectors of the data matrix, which should not be neglected, tend to be predominantly low-pass functions and also provide valuable information for model-order determination. [J51]

"Two-Dimensional Imaging via a Narrowband MIMO Radar System With Two Perpendicular Linear Arrays"

This paper presents a system model and method for the 2-D imaging application via a narrowband multiple-input multiple-output (MIMO) radar system with two perpendicular linear arrays. Furthermore, the imaging formulation for our method is developed through a Fourier integral processing, and the parameters of antenna array including the cross-range resolution, required size, and sampling interval are also examined. Different from the spatial sequential procedure sampling the scattered echoes during multiple snapshot illuminations in inverse synthetic aperture radar (ISAR) imaging, the proposed method utilizes a spatial parallel procedure to sample the scattered echoes during a single snapshot illumination. Consequently, the complex motion compensation in ISAR imaging can be avoided. Moreover, in our array configuration, multiple narrowband spectrum-shared waveforms coded with orthogonal polyphase sequences are employed. The mainlobes of the compressed echoes from the different filter band could be located in the same range bin, and thus, the range alignment in classical ISAR imaging is not necessary. Numerical simulations based on synthetic data are provided for testing our proposed

method. [J52]

"Contrast-Optimization-Based Range-Profile Autofocus for Polarimetric Stepped-Frequency Radar"

One of the main benefits brought by the use of fully polarimetric radars is the ability to identify scattering mechanisms, which are related to the target physical properties. One of the most critical problems in synthetic range-profile reconstruction is the distortion induced by the target motion. Radial target velocity and acceleration generate second- and third-order phase terms in the received signal, which produce range shift and point-spread-function smearing. The distortions induced by the target motion produce, as a consequence, a signal-to-noise ratio loss. Recently, a method based on contrast maximization has been proposed in order to compensate target radial motions using single-polarization data. In this paper, an extension of such an algorithm is proposed that exploits fully polarimetric data in order to improve the target radial motion compensation. [J53]

"Probing Waveform Synthesis and Receiver Filter Design"

Probing waveform synthesis and receive filter design play crucial roles in achievable performance for many active sensing applications, including radar, sonar, medical imaging, and communications (channel estimation and spread spectrum). A flexible receive filter design approach can be used to compensate for missing features of the probing waveforms, at the costs of lower signal-to-noise ratio (SNR) and higher computational complexity. A well-synthesized waveform, meaning one with good auto- and cross-correlation properties, can reduce computational burden at the receiver and improve performance. In this article, we will highlight the interplay between waveform synthesis and receiver design. We will provide a tutorial review of recent novel, cyclic approaches to single and multiple waveform designs. Both aperiodic and periodic correlations will be considered. We show that by making use of fast Fourier transforms (FFTs), we can now efficiently design sequences that were previously impossible to synthesize. Furthermore, we will provide an overview of some advanced techniques for receiver design, including data-independent instrumental variables (IV) filters and a data-adaptive iterative approach. We will show how these designs can significantly outperform conventional techniques in various active sensing applications. [J54]

"Adaptive Waveform Design for Separated Transmit/Receive ULA-MIMO Radar"

The colocated uniform linear array (ULA) multiple-input multiple-output (MIMO) radar has been demonstrated to provide enhanced performance in theory. Similar to a bistatic radar, performance of the separated transmit/receive (STR) ULA-MIMO radar is affected not only by the transmitted multiple orthogonal waveforms, but also by the position of the target. In this correspondence, the ambiguity function of the STR-ULA-MIMO radar is investigated and the corresponding range-velocity ambiguity function (RVAF) is deduced. The range and velocity resolution of RVAF for the STR-ULA-MIMO radar is discussed. Because the shape of RVAF for the STR-ULA-MIMO radar is related to the position of the target, a new algorithm for adaptively designing the orthogonal frequency-hopping waveforms according to the position of the target is proposed. This algorithm improves the range and velocity resolution and the integrated sidelobe level (ISL) of the matched filter output at the corresponding position. [J55]

"Focusing of high range resolution profiles of moving targets using stepped frequency waveforms"

A new approach is presented to remove the motion effect of a maneuvering target in a high range resolution (HRR) profile based on stepped frequency waveform (SFW). The effects of target's motion in the SFW HRR profile consists of dispersion and translation shift of HRR profiles. The proposed approach exploits a subarray averaging concept in conjunction with the entropy cost function in order to find the translational velocity and acceleration of the target. By making use of the inherent properties of the proposed entropy-based cost function, the authors devise an efficient scheme for the two-dimensional (2-D) optimisation problem in the velocity and acceleration space, thereby improving the computational efficiency as well as the estimation accuracy significantly. Once the kinematic motion parameters are known, the unwanted dispersion of HRR profiles caused by the target's motion can be easily removed, providing focused HRR profiles with no dispersion. The proposed algorithm is especially useful for SFWs having low pulse repetition frequencies (PRFs) rather than those with high PRFs. The effectiveness of the algorithm is illustrated and analysed with simulated targets comprised of point scatters and a real aircraft radar cross-section data with artificial motion effects. [J56]

"Passive Coherent Location as Cognitive Radar"

Cognitive Radar describes a generic radar system that is capable of adapting its transmission waveforms and cooperation with other sensors in order to achieve superior detection, recognition, and tracking of targets. For example, the sensors of a cognitive radar system might use the illumination signals to carry broadcast data, allowing the sharing of target information. Herein, we postulate that it would be possible to implement a cognitive

version of Passive Coherent Location (PCL) which has much in common with the broad cognitive radar concept, but adapts only to the waveforms it senses in the environment, and exploits those that are most useful to it for target detection. In addition, it would model the terrain to improve coverage and provide countermeasures against direct signal saturation. By its name, PCL does not transmit, but relies on emissions from other radiating systems, such as broadcast services, other radars, cellular radio, WiFi, and so on. It is clear that such a system, consisting of multiple, cooperating receivers, can achieve excellent performance in the presence of deliberate jamming, difficult terrain, and attempts at target stealth. In the civilian radar domain, the technology offers opportunities for bandwidth conservation. [J57]

"Measurement and comparative analysis of clutter for GSM and UMTS passive radars"

Passive radars have been known to the scientific community since their first application as a system to detect bombers by means of shortwaves radiated by radio broadcasting towers in 1935, although they lately raised a renewed interest among researchers for some specific features that make them more appealing than classic active radar systems. In fact, having the transmitter and receiver located at two different positions, and the adoption of signals carrying other kinds of information such as GSM (either classical or the 1800/1900 MHz DCS version) or UMTS waveforms, makes passive radar virtually undetectable and economically advantageous. A measurement system used to characterise the clutter from a GSM/DCS and UMTS-based passive radar is presented. The main objective is to study the statistical properties of the clutter signals, find theoretical models fitting the measured clutter data and analyse the differences between the modulated carriers of the two different standards. [J58]

"Time-orthogonal waveform diversity and joint domain localised algorithm for distributed aperture radars"

Distributed aperture radars represent an interesting solution for target detection in strong interference environments. Distributed apertures provide improved angular resolution or are able to view a target from multiple look-angles, thereby exploiting scintillation. However, because of the large distances between array elements, both target and interfering sources are in the near field of the antenna array. Furthermore, because of the relative motion between antenna elements and interference sources, the clutter Doppler frequency is not stationary. Recent works have demonstrated the benefits of combining frequency diversity and space-time adaptive processing (STAP) for distributed aperture radars. In this study a new waveform diversity system model is developed. Using orthogonal signalling, the receivers can treat the incoming signals independently, solving several bistatic problems instead of the initial multistatic problem. The authors also apply adaptive techniques to counteract the range dependency of the clutter Doppler frequency. In particular, the authors apply the joint domain localised algorithm, specifically chosen because of its need for only limited secondary data. [J59]

"A New Vector Waveform Inversion Algorithm for Simultaneous Updating of Conductivity and Permittivity Parameters From Combination Crosshole/Borehole-to-Surface GPR Data"

We have developed a new full-waveform groundpenetrating radar (GPR) multicomponent inversion scheme for imaging the shallow subsurface using arbitrary recording configurations. It yields significantly higher resolution images than conventional tomographic techniques based on first-arrival times and pulse amplitudes. The inversion is formulated as a nonlinear least squares problem in which the misfit between observed and modeled data is minimized. The full-waveform modeling is implemented by means of a finite-difference time-domain solution of Maxwell's equations. We derive here an iterative gradient method in which the steepest descent direction, used to update iteratively the permittivity and conductivity distributions in an optimal way, is found by cross-correlating the forward vector wavefield and the backward-propagated vectorial residual wavefield. The formulation of the solution is given in a very general, albeit compact and elegant, fashion. Each iteration step of our inversion scheme requires several calculations of propagating wavefields. Novel features of the scheme compared to previous full-waveform GPR inversions are as follows: 1) The permittivity and conductivity distributions are updated simultaneously (rather than consecutively) at each iterative step using improved gradient and step length formulations; 2) the scheme is able to exploit the full vector wavefield; and 3) various data sets/survey types (e.g., crosshole and borehole-to-surface) can be individually or jointly inverted. Several synthetic examples involving both homogeneous and layered stochastic background models with embedded anomalous inclusions demonstrate the superiority of the new scheme over previous approaches. [J60]

"Time-Delay Multiplexing of Two Beams in a Terahertz Imaging Radar"

We demonstrate a time-delay multiplexing technique that doubles the frame rate of a 660-690-GHz imaging radar with minimal additional instrument complexity. This is done by simultaneously projecting two offset, orthogonally polarized radar beams generated and detected by a common source and receiver. Beam splitting

and polarization rotation is accomplished with a custom designed waveguide hybrid coupler and twist. A relative time lag of approximately 2 ns between the beams' waveforms is introduced using a quasi-optical delay line, followed by spatial recombination using a selectively reflective wire grid. This delay is much longer than the approximately 20-ps time-of-flight resolution of the 30-GHz bandwidth radar, permitting the two beams' reflected signals from a compact target to be easily distinguished in digital post-processing of the single receiver channel. [J61]

"A Marked Point Process for Modeling Lidar Waveforms"

Lidar waveforms are 1-D signals representing a train of echoes caused by reflections at different targets. Modeling these echoes with the appropriate parametric function is useful to retrieve information about the physical characteristics of the targets. This paper presents a new probabilistic model based upon a marked point process which reconstructs the echoes from recorded discrete waveforms as a sequence ofparametric curves. Such an approach allows to fit each mode of a waveform with the most suitable function and to deal with both, symmetric and asymmetric, echoes. The model takes into account a data term, which measures the coherence between the models and the waveforms, and a regularization term, which introduces prior knowledge on the reconstructed signal. The exploration of the associated configuration space is performed by a reversible jump Markov chain Monte Carlo (RJMCMC) sampler coupled with simulated annealing. Experiments with different kinds of lidar signals, especially from urban scenes, show the high potential of the proposed approach. To further demonstrate the advantages of the suggested method, actual laser scans are classified and the results are reported. [J62]

"Space-Time Coding for MIMO Radar Detection and Ranging"

Space-time coding (STC) has been shown to play a key role in the design of MIMO radars with widely spaced antennas: In particular, rank-one coding amounts to using the multiple transmit antennas as power multiplexers, while full-rank coding maximizes the transmit diversity, compromises between the two being possible through rank-deficient coding. In detecting a target at known distance and Doppler frequency, no uniformly optimum transmit policy exists, and diversity maximization turns out to be the way to go only in a (still unspecified) large signal-to-noise ratio region. The aim of this paper is to shed some light on the optimum transmit policy as the radar is to detect a target at an unknown location: To this end, at first the Cramer-Rao bounds as a function of the STC matrix are computed, and then waveform design is stated as a constrained optimization problem, where now the constraint concerns also the accuracy in target ranging, encapsulated in the Fisher Information on the range estimate. Results indicate that such accuracy constraints may visibly modify the required transmit policy and lead to rank-deficient STC also in regions where pure detection would require pursuing full transmit diversity. [J63]

"ISAR imaging of multiple targets using particle imaging of multiple targets using particle swarm optimisation-adaptive joint time frequency approach"

When multiple radar targets are close to each other, the returned signals from these targets are overlapped in time. Therefore by applying conventional motion compensation algorithms designed for single target, the multiple targets cannot be resolved, and individual one cannot be clearly imaged. The authors conclude that whether the radar transmits linear frequency modulated (LFM) or stepped-frequency waveform, the chirp rate in the Doppler frequency shift induced by the translation motion is only concerned with the acceleration of the target. For different targets, the chirp rates are different from each other. Based on the different chirp rates, the signals from each target can be separated. Then a new algorithm based on the adaptive joint time frequency (AJTF) technique is proposed to separate the signals from different target in each cross-range cell. The use of the particle swarm optimisation (PSO) for multiple targets separation is a unique application of this evolutionary search. By the CLEAN technique, the number of targets need not be appointed. The simulation results confirm the efficiency of the proposed algorithm for multiple moving targets imaging. [J64]

"Correction to "A New Vector Waveform Inversion Algorithm for Simultaneous Updating of Conductivity and Permittivity Parameters From Combination Crosshole/Borehole-to-Surface GPR Data""

In the above titled paper (ibid., vol. 48, no. 9, pp. 3391-3407, Sep. 10), there is an error in equation (A-5). The correct form is presented here. [J65]

"Compensation of Range Migration for Cyclically Repetitive Doppler-Sensitive Waveform (OFDM)"

Range migration, which occurs for targets with high velocity when the radar range resolution is high, is solved

by exploiting the cyclically repetitive waveform-namely, orthogonal frequency division multiplexing. The proposed technique is based on a signal processing method that solves the Doppler ambiguity by exploiting the Doppler sensitivity of the multicarrier spread spectrum structure. The new method extends the availability of narrowband delay-Doppler processing to a wider range of waveform and target parameters. [J66]

"Optimisation of complete complementary codes in MIMO radar system"

The novelty of multiple-input multiple-output (MIMO) radar is to improve the performance of radar utilising spatial diversity and waveform diversity. Proposed is the optimisation design of complete complementary sequence (CC-S) for MIMO radar based on channel capacity with the clutter statistical properties known. The method obtains the optimised CC-S through maximising the channel capacity of MIMO radar. The result shows that the optimised CC-S is a function of the clutter covariance matrix. Finally, the method from the information theoretical point of view is verified. [J67]

"AESA upgrade option for Eurofighter Captor Radar"

The Euroradar Consortium has successfully developed and demonstrated an Active Electronically Scanned Array (AESA) technology upgrade for the Eurofighter Typhoon Captor Radar. This technology demonstrator, designated Captor Active Electronically Scanned Array Radar (CAESAR), enables E-scan capability to be fully exploited by the existing Captor radar, while retaining all features and capabilities of the original system. Advanced waveforms, designed and optimized for electronically-scanned radar systems, have been evaluated in recent CAESAR flight trials. Production of the CAESAR system will address repackaging of the AESA and associated components to minimize mass and volume, reduce cost, and ensure ease of supportability. CAESAR has demonstrated that AESA benefits can be provided within the existing Captor framework, enhancing sensor capability while retaining existing Eurofighter Typhoon interfaces. [J68]

"MIMO Radar Moving Target Detection in Homogeneous Clutter"

A multiple-input multiple-output (MIMO) radar approach employing widely dispersed transmit and receive antennas is studied for the detection of moving targets. The MIMO radar transmits orthogonal waveforms from the different transmit antennas so these waveforms can be separated at each receive antenna. For a moving target in colored Gaussian noise-plus-clutter, we quantify the gains from having widely dispersed antennas that allow the overall system to "view" the target simultaneously from several different directions. The MIMO radar performance is contrasted with that of a traditional phased-array approach, which employs closely spaced antennas for this purpose. The MIMO radar approach is well suited to handle targets that have small radial velocities for scenarios in which colocated sensors cannot separate the target from the background clutter. Both a centralized processing and a simple distributed processing form of the MIMO radar approach are developed and studied, and the gains from the centralized version, which come at the price of additional complexity, are clearly demonstrated and explained intuitively. The constant false alarm rate (CFAR) property of an adaptive version of the MIMO moving target detector is also demonstrated for homogeneous clutter. [J69]

"SAR Imaging with Noise Radar"

Two ground-based coherent imaging systems designed on the basis of noise radar technology (NRT) using continuous waveform with a linear synthetic aperture and pulse coherent noise waveform with a circular synthetic aperture are presented. A short description of noise waveform synthetic aperture radar (SAR) theory and data processing algorithms are given. Experimental results obtained show that the quality of the imagery is comparable to that of frequency-modulation continuous-wave (FMCW) or stepped frequency radar systems. Experimental validation of the technique at different locations provides confidence in the ability of noise waveform SAR to achieve high-resolution imaging at low cost. The exploitation of the interferometric phase combining pairs of images spaced in time is shown to allow the detection of displacements in the scene with a submillimeter accuracy. [J70]

"Multistatic and MIMO Distributed ISAR for Enhanced Cross-Range Resolution of Rotating Targets"

In this paper, we present a new technique to exploit the data acquired simultaneously by multiple radar sensors carried by multiple air platforms to increase the cross-range resolution of inverse synthetic aperture radar (ISAR) images of rotating targets. This distributed ISAR technique is devised for two different cases: 1) multiple-input-multiple-output (MIMO) case with each platform carrying an active radar that transmits and receives RF waveforms and 2) multistatic case with a single platform carrying an active radar (transmitting and receiving) and the remaining platforms equipped with passive sensors (namely, receiving only). The processing chain proposed for the distributed ISAR is shown, together with the results obtained against simulated ISAR data for both the

MIMO and the multistatic cases. The performance analysis shows that the proposed technique is able to provide an increase of the cross-range resolution up to the number of platforms in the multistatic case and even higher in the MIMO case, if the platforms are properly located. This is of great benefit in applications where the target rotation angle is insufficient to guarantee the desired resolution. A typical case is the imaging of ship targets with rotation induced by the sea swell structure under low sea state conditions. To make the results appealing for practical application, the performance degradation is also analyzed arising from errors in the knowledge of both the target rotation motion and the acquisition geometry. Experimental data collected by a ground-based radar operating together with a rotating platform are processed by following the presented distributed ISAR technique to validate the proposed approach. [J71]

"OFDM MIMO Radar With Mutual-Information Waveform Design for Low-Grazing Angle Tracking"

We propose an information theoretic waveform design algorithm for target tracking in a low-grazing angle (LGA) scenario. We incorporate realistic physical and statistical effects, such as Earth's curvature, vertical refractivity gradient of lower atmosphere, and compound-Gaussian characteristics of sea-clutter, into our model. We employ a co-located multiple-input-multiple-output (MIMO) radar configuration using wideband orthogonal frequency division multiplexing (OFDM) signalling scheme. The frequency diversity of OFDM provides richer information about the target as different scattering centers resonate at different frequencies. Additionally, we use polarization-sensitive transceivers to resolve the multipath signals with small separation angles. Thus, we track the scattering coefficients of the target at different frequencies along with its position and velocity. We apply a sequential Monte Carlo method (particle filter) to track the target. Our tracker works in a closed-loop fashion with an integrated optimal waveform design technique based on mutual information (MI) criterion. We seek the optimal OFDM waveform at the current pulse duration to maximize the MI between the state and measurement vectors at the next pulse duration utilizing all the measurement history up to the current pulse. Our numerical examples demonstrate the importance of realistic physical modeling, effects of frequency diversity through OFDM MIMO configuration, and achieved performance improvements due to adaptive OFDM waveform design. [J72]

"Large Time-Bandwidth Product Microwave Arbitrary Waveform Generation Using a Spatially Discrete Chirped Fiber Bragg Grating"

We propose and experimentally demonstrate an approach to generating large time-bandwidth product (TBWP) microwave arbitrary waveforms based on optical pulse shaping using a single spatially discrete chirped fiber Bragg grating (SD-CFBG). The SD-CFBG functions to perform simultaneously spectral slicing, frequency-to-time mapping, and temporal shifting of the input optical pulse, which leads to the generation of an optical pulse burst with the individual pulses in the burst temporally spaced by the time delays determined by the SD-CFBG. With the help of a bandwidth-limited photodetector (PD), a smooth microwave waveform is obtained. The SD-CFBG is fabricated using a linearly chirped phase mask by axially shifting the photosensitive fiber to introduce a spatial spacing between two adjacent sub-gratings during the fabrication process. By properly designing the fiber shifting function, a large TBWP microwave arbitrary waveform with the desired frequency chirping or phase coding can be generated. An equation that relates the fiber shifting function and the microwave waveform frequency chirping is derived. The photonic generation of large TBWP microwave waveforms with a linear, nonlinear and stepped frequency chirping is experimentally demonstrated. [J73]

"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. [J74]

"A Novel Technique for Acquisition and Presentation of Complex Vibration Waveforms"

Oscilloscopes are traditionally used for the graphical presentation and analysis of electrical waveforms. In many experiments, waveform acquisition and live presentation forms the heart of the problem. In particular, data acquisition and presentation of repeating complex signals like sine sweep in vibration generation and testing and frequency-modulated signals in radar and sonar applications offers the challenge of live waveform presentation

and their basic measurements. In this paper, we present a new, robust, fast, and simple technique for waveform period estimation in the time domain and oscilloscope triggering for both complex and simple waveforms. The proposed technique, namely, the normalized degree of difference (DOD), has both these capabilities, and it has been verified by extensive software simulations and implementation on the National Instruments (NI) LabVIEW-PXI platform. Successful real-time results are obtained for the sine sweep vibration waveform. The proposed technique, simulation, and implementation results are presented in this paper. [J75]

"A CMOS Integrated Analog Pulse Compressor for MIMO Radar Applications"

Conventional radar pulse compressors use either surface acoustic wave devices or fast convolution processing, but both solutions have significant drawbacks. To overcome these drawbacks, an integrated analog pulse compressor for a multiple-input multiple-output (MIMO) radar has been developed with an 0.18-??m CMOS process using an arbitrary waveform generator, analog correlators, and analog-to-digital converters. The proposed scheme not only has advantages over conventional methods but also adds additional flexibility to the MIMO system. The die area is 5.67 mm2, and the power consumption is 62.6 mW from the 1.8-V supply. Arbitrary waveforms such as the wavelet and the chirp signal have been demonstrated, and the average signal-to-noise ratio for the pulse compression is 18.09 dB. The identification of overlapping multiple chirp signals is successfully demonstrated. [J76]

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

The wide variability of sea surface conditions is reflected in a corresponding variability in sea clutter characteristics; moreover, these characteristics manifest a strong dependence on radar parameters such as frequency, waveform and polarisation. Ideally, radar systems should adapt their parameters to the prevailing sea conditions and viewing geometry so as to optimise performance. In practice this is seldom done, in large part because most radar systems have very limited capability to adapt, but also because the rules that might guide the adaptation process are not yet clearly established. Where an appreciable change in radar parameters or viewing geometry would yield only a slight change in clutter severity and a commensurately modest improvement in radar performance, there is little incentive to adapt. On the other hand, if there are sharp transitions in clutter properties as some radar parameter is varied, then exploitation of the transition may be highly advantageous. This study presents the results of a search for transitions in polarimetric X-band sea clutter, focusing on the dependence on scattering geometry. Experiments were conducted to study clutter variation with elevation angle and azimuth with respect to wind direction. The results demonstrate that transitions exist, that they can be surprisingly sharp, and that the consequences for target detectability may be significant. [J77]

"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. [J78]

"From the editor-in-chief [JDr. Philip Woodward, recipient of the IEEE Picard Model]"

Congratulations to Dr. Philip Woodward, recipient of the IEEE Picard Model for his pioneering work in radar waveform design. This award is made by the IEEE Awards Board and was originally to be presented late Spring at the 2009 Radar Conference in California; as it could not be presented then, it was presented in October in Malvern, England, as depicted on our cover. Additional congratulations are extended to Dr. Woodward for receiving the Tompion Medal of the Worshipful Company of Clockmakers for his skills in horology. [J79]

"HFSW Radar Model: Simulation and Measurement"

High-frequency surface-wave (HFSW) radars are usually used to remotely measure oceanographic parameters. These systems can also potentially detect targets beyond the conventional microwave radar coverage. In this paper, the backscattered Doppler spectrum made up of the sea clutter, ship echoes, and the background noise has been modeled. Taking into account the propagation and the signal-processing effects, a range-Doppler image has been generated. This model can be used for different purposes like the (theoretical) evaluation of detection performance. This paper gives an overview of the theoretical elements for modeling the backscatter

signal. The processing effects on the range-Doppler image and the time-evolving target signature are also introduced. Some of the simulated elements and the obtained range-Doppler images are compared with real data. Finally, from this model, the detection capabilities of HFSW radars are evaluated. [J80]

"A Doppler Robust Max-Min Approach to Radar Code Design"

This correspondence considers the problem of robust waveform design in the presence of colored Gaussian disturbance under a similarity and an energy constraint. We resort to a max-min approach, where the worst case detection performance (over the possible Doppler shifts) is optimized with respect to the radar waveform under the previously mentioned constraints. The resulting optimization problem is a non-convex Quadratically Constrained Quadratic Program (QCQP) with an infinite number of constraints, which is NP-hard in general and typically difficult to solve. Hence, we propose an algorithm with a polynomial computational complexity to generate a good sub-optimal solution for the aforementioned QCQP. The analysis, conducted in comparison with some known radar waveforms, shows that the sub-optimal solutions by the algorithm lead to high-quality radar signals. [J81]

"Adaptive waveform design for range-spread target tracking"

Suboptimal waveform design based on the wide sense stationary-uncorrelated scattering target impulse response model is proposed, which reduces the minimum mean square error of estimation. Simulation results show that the waveform designed by the proposed method performs better than the traditional waveform. [J82]

"MIMO Radar Waveform Design in Colored Noise Based on Information Theory"

In this paper, we consider multiple input multiple output (MIMO) radar waveform design in colored noise. Two information theoretic measures are used as criterions for optimal waveform design under transmitted power constraint. The first one is by maximizing the mutual information between target impulse response and target echoes; the second one is by maximizing the relative entropy between two hypotheses: in the first hypothesis we assume the target is not present in the echoes while in the second hypothesis we assume the target exists in the echoes. We derive optimal solutions for both cases. Interestingly, both optimal solutions require that transmitted waveform should "match" with the target and noise. However, the optimal solutions of the two problems lead to different power allocation strategies. [J83]

"Signal level Simulator for netted text radar waveforms evaluation"

When evaluating the performances of radar waveforms, it is crucial to understand how the signal is affected by multiple interactions with the environment and the system hardware. Analysis of complex radar systems, such as multistatic and netted designs (see Figure 1) is often intractable without the application of a dedicated radar simulation system. Recent research into radar simulation has focused primarily on synthetic aperture radar (SAR) systems [1] and is not entirely applicable to traditional radar systems concerned with the location and tracking of remote targets. A complete simulator has been designed for the accurate simulation of raw returns in complex, multistatic, and netted radars, and is applicable to pulsed and continuous wave (CW) systems, and both active and passive radar systems. The Flexible Simulator for Multistatic Radars (FERS) can be used to simulate radar systems with arbitrary waveforms and arbitrary numbers of receivers, transmitters, and scatterers. Herein, algorithms for the simulation of raw radar return signals are presented, based on interpolation and modification of the transmitted signal and modeling of the radar hardware and environment. The algorithms are expected to be especially valuable for the simulation of emerging radar technologies, such as Passive Coherent Location (PCL) [2], netted radar and phased array radar. Preliminary results, presented herein, suggest that these algorithms can simulate physical systems with excellent accuracy. [J84]

"Compressive Stepped-Frequency Continuous-Wave Ground-Penetrating Radar"

Data acquisition speed is an inherent problem of stepped-frequency continuous-wave (SFCW) radars, which may discourage further usage and development of this technology. We propose an emerging paradigm called compressed sensing (CS) to overcome this problem. In CS, a signal can be reconstructed exactly based on only a few samples below the Nyquist rate. Accordingly, the data acquisition speed can be increased significantly. A novel design of an SFCW ground-penetrating radar (GPR) with high acquisition speed is proposed and evaluated. Simulation by a monocycle waveform and actual measurement by a vector network analyzer at a GPR test range indicate the applicability of the proposed system. [J85]

"CFAR detection of range-spread target in white Gaussian noise using waveform entropy"

A detection scheme for a range-spread target in white Gaussian noise is developed. The detector is based on

waveform entropy of the arithmetic average of multiple successive high-resolution range profiles, and has the precious property of a constant false-alarm rate (CFAR). The proposed detector is compared with the conventional detectors based on measured data, and good performance is reported. [J86]

"NEW: Network-Enabled Electronic Warfare for Target Recognition"

Network-enabled electronic warfare (NEW) is the development of modeling and simulation efforts that explore the advantages and limitations of NEW concepts. The advantages of linking multiple electronic support measures (ESM) and electronic attack (EA) assets to achieve improved capabilities across a networked battle force have yet to be quantified. In this paper, we utilize radar sensors as ESM and EA assets to demonstrate the advantages of NEW in collaborative automatic target recognition (CATR). Signal (waveform) design for radar sensor networks (RSN) in NEW is studied theoretically. The conditions for waveform coexistence and the interferences among waveforms in RSN are analyzed. We apply the NEW to CATR via waveform diversity combining and propose maximum-likelihood (ML)-ATR algorithms for nonfluctuating targets as well as fluctuating targets. Simulation results indicate that our NEW-CATR performs much better than the single sensor-based ATR algorithm for nonfluctuating and fluctuating targets. [J87]

"Waveform Diversity in Radar Signal Processing"

This article shows that suitably transmitted and processed, radar waveforms based on Golay sequences provide new primitives for adaptive transmission that enable better detection and finer resolution, while managing computational complexity at the receiver. The ability to exploit space-time adaptive processing is limited by the computational power available at the receiver, and increased flexibility on transmission only exacerbates this problem unless the waveforms are properly designed to simplify processing at the receiver. [J88]

"Target Estimation, Detection, and Tracking"

In this article, we explore the adaptive design of radar polarization waveforms for optimal performance, when the statistical properties of the target and clutter are unknown. We focus on a closed-loop system that sequentially estimates the target and clutter scattering parameters, and then uses these estimates to select the polarization of the subsequent waveforms. We demonstrate that the radar system performance is significantly improved when the polarization of the transmitted signal is optimally and adaptively selected to match the polarimetric aspects of the target and environment. In particular, we provide an overview of our recent results showing that the adaptive design of the radar signal polarization enables achieving optimal performance in several operating modes, including detection, estimation, and tracking. [J89]

"Waveform-agile sensing for tracking"

Waveform-agile sensing is fast becoming an important technique for improving sensor performance in applications such as radar, sonar, biomedicine, and communications. The paper provided an overview of research work on waveform-agile target tracking. From both control theoretic and information theoretic perspectives, waveforms can be selected to optimize a tracking performance criterion such as minimizing the tracking MSE or maximizing target information retrieval. The waveforms can be designed directly based on their estimation resolution properties, selected from a class of waveforms with varying parameter values over a feasible sampling grid in the time-frequency plane, or obtained from different waveform libraries. [J90]

"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. [J91]

"Cloud and Rain Effects on AltiKa/SARAL Ka-Band Radar Altimeter-Part II: Definition of a Rain/Cloud Flag"

The main instrument of the French-Indian AltiKa/SARAL mission scheduled for launch in 2010 is the Ka-band AltiKa altimeter. The high attenuation due to atmospheric water (liquid or vapor) at this frequency band is the major drawback of the use of Ka-band. In part I of this paper, the impact of rain/clouds on Ka-band data and on the accuracy of the estimates of the geophysical parameters has been analyzed and quantified using an analytical model of waveform. Waveform distortion and errors on the geophysical parameters can be significant particularly for small dense clouds and rain cells. It is thus necessary to flag the data potentially affected by rain and clouds. The use of a single channel for AltiKa prevents the use of the classical dual-frequency rain flag used for Topex or Jason altimeters, and requires the definition of a new flag based on the altimeter signal alone. Past studies showed that clouds and rain are characterized by sharp coherent along-track fluctuations of the off-nadir angle estimates. The new flagging algorithm is based on the analysis of the variations of this parameter by the Matching Pursuit (MP) algorithm. MP allows the decomposition of a signal into a few salient features or atoms chosen from a dictionary of elementary functions. The dictionary is here defined by the wavelet decomposition of the signal. The method has been tested on an ensemble of AltiKa passes simulated for cloudy, rainy, and cloud/rain-free situations. The false alarm rate is almost nil while the detection performances are better than 90% at a range error of 5 cm and significant wave height error of 20 cm. The flag can easily be adapted to other altimeters' data and has been used to flag several Jason-1 passes. The comparison to the operational dual-frequency flag shows that the MP flag performs better in detecting range errors and waveforms distortion, while its performances are inferior in detecting samples attenuated by rain. [J92]

"A Virtual Antenna Beamforming (VAB) Approach for Radar Systems by Using Orthogonal Coding Waveforms"

An innovative approach is introduced to form virtual transmitting and receiving radar antenna beams simultaneously by transmitting orthogonal coding waveforms from the antenna elements and digitally processing of their echoes at the receiver. Multiple virtual transmitting-receiving beams can be formed simultaneously by employing an equal number of beamforming filters without increasing transmitting power or antenna gain or resolution loss. The virtually formed antenna beams can provide equivalent antenna gains and spatial resolutions as the conventional phased arrays of the same size. Because the actual antenna radiation pattern can be made almost isotropic, the new system has low probability of intercept (LPI) property. With both transmitting and receiving beams virtually implemented through digital filtering, costly radiation phase shift used in phased arrays is not needed for beam scanning in the proposed system. [J93]

"Cloud and Rain Effects on AltiKa/SARAL Ka-Band Radar Altimeter-Part I: Modeling and Mean Annual Data Availability"

The AltiKa project, developed by the French Centre National d'Etudes Spatiales, is based on a wideband Ka-band altimeter (35.75 GHz). The technical characteristic of the instrument will offer higher performance both in terms of spatial and vertical resolutions that will lead to the improved observation of ice, coastal areas, inland waters, and wave height. An Indian Space Research Organization satellite, called Satellite with ARgos and AltiKa, will embark the AltiKa altimeter. The launch is scheduled at the end of 2010. The major drawback of Ka-band use is the attenuation of the radar signal by atmospheric liquid water. Clouds and rain effects will thus be a strong constraining factor, because the altimeter link budget imposes an attenuation of less than 3 dB. The impact of rain and clouds on Ka-band altimeter data is analyzed and quantified using an analytical model that computes AltiKa waveforms in the presence of rain or clouds. The results are then used to quantify the waveform attenuation and distortion, as well as the error induced on the altimeter geophysical parameter estimates. Because of the nonlinearity of attenuation relations, the impact of clouds/rain depends more on the cloud/rain variability within the altimeter footprint than on the mean characteristics, which makes correction using coincident rain or cloud data difficult. Small rain cell and small dense clouds can thus strongly distort the waveforms and lead to erroneous geophysical parameter estimates. The probability of 20 Hz and 1-s averaged data loss are computed from the model results and from cloud and rain climatologies. On a global scale, about 3.5% of the 20-Hz data will be lost because of rain and clouds and 2.5% of the 1-s averaged data. However, the probability strongly varies over the global ocean and can exceed 10% in the Tropics. [J94]

"Improved design of DFCW for MIMO radar"

The successful design of a discrete frequency-coding waveform for MIMO radar which can achieve a lower range autocorrelation sidelobe peak and range cross-correlation peak is presented. The numerical results are presented to verify the effectiveness of this method. [J95]

"Code-Division Multiple Transmission for High-Speed UWB Radar Imaging With an Antenna Array"

The ultrawideband (UWB) radar is a promising high-resolution 3-D imaging technique for near targets. We have developed a high-speed imaging algorithm, SEABED, for a UWB pulse radar, a key real-time imaging technology. When the algorithm is applied to UWB, antenna scanning for data acquisition takes significantly longer than calculating the SEABED algorithm itself. This presents a serious problem for the real-time application of UWB radar. In this paper, we use pseudonoise (PN) sequences as the transmitting waveforms, while the original work on the SEABED algorithm assumed impulsive short-wave pulses. Using PN sequences enables us to simultaneously transmit signals with multiple antennas, eliminating the need to scan antennas. We demonstrate that the proposed radar system works well using random sequences to suppress direct waves, which is critical in achieving high speeds for imaging. [J96]

"Phase-Coded Waveforms and Their Design"

The design of radar waveforms has received considerable attention since the 1950s. In 1953, P.M. Woodward (1953; 1953) defined the narrowband radar ambiguity function or, simply, ambiguity function. It is a device formulated to describe the effects of range and Doppler on matched filter receivers. Woodward acknowledged the influence that Shannon's communication theory from 1948 had on his ideas; and he explained the relevance of ambiguity in radar signal processing, perhaps best conceived in terms of a form of the uncertainty principle (see the sections "Motivation" and "Ambiguity Functions"). However, in the 50 or so years since Woodward's book was published, radar signal processing has used the ambiguity function as an intricate and flexible tool in the design of waveforms to solve diverse problems in radar. In the process, substantial connections were established in mathematics, physics, and other areas of signal processing. As such, we are introducing two new methods, discussed in sections "CAZAC Sequences" and "Aperiodic Simulations". [J97]

"Time-Reversal Detection Using Antenna Arrays"

The paper studies detection of a target buried in a rich scattering medium by time reversal. We use a multi-static configuration with receive and transmit arrays of antennas. In time reversal, the backscattered field is recorded, time reversed, and retransmitted (mathematically or physically) into the same scattering medium. We derive two array detectors: the time-reversal channel matched filter when the target channel response is known; and the time-reversal generalized-likelihood ratio test (TR-GLRT) when the target channel response is unknown. The noise added in the initial probing step to the time-reversal signal makes the analysis of the TR-GLRT detector non trivial. The paper derives closed form expressions for the signal-to-noise ratio gain provided by this detector over the corresponding conventional clutter subtraction energy detector in the two extreme conditions of weak and strong (electronic additive) noise and shows that time reversal provides, under weak noise, the optimal waveform shape to probe the environment. We analyze the impact of the array configuration on the detection performance. Finally, experiments with electromagnetic data collected in a multipath scattering laboratory environment confirm our analytical results. Under the realistic conditions tested, time reversal provides detection gains over conventional detection that range from 2 to 4.7 dB. [J98]

"Experimental results on ISAR imaging with stepped-frequency waveforms"

A simple and successful processing for the bandwidth synthetic of stepped-frequency waveforms (SFWs) is presented. The high range resolution is obtained by combining the sub-pulses of SFWs in the frequency domain. The overlapping bandwidth of the two adjacent sub-pulses is used to estimate phase errors. Also the usual motion compensation approach is avoided if the band coherent processing is used. Experimental results of the ship target are shown. [J99]

"Optimal Polarized Beampattern Synthesis Using a Vector Antenna Array"

Using polarized waveforms increases the capacity of communication systems and improves the performance of active sensing systems such as radar. We consider the optimal synthesis of a directional beam with full polarization control using an array of electromagnetic vector antennas (EMVA). In such an array, each antenna consists of pges 2 orthogonal electric or magnetic dipole elements. The control of polarization and spatial power patterns is achieved through carefully designing the amplitudes and phases of the weights of these dipole antennas. We formulate the problem in a convex form, which is thus efficiently solvable by existing solvers such as the interior point method. Our results indicate that vector antenna arrays not only enable full polarization control of the beampattern, but also improve the power gain of the main beam (over the sidelobes), where the gain is shown numerically to be linearly proportional to vector antenna dimensionality p. This implies that EMVA not only offers the freedom to control the beampattern polarization, but also virtually increases the array size by exploiting the full electromagnetic (EM) field components. We also study the effect of polarization on the spatial power pattern. Our analysis shows that for arrays consisting of pairs of electrical and magnetic dipoles, the

spatial power pattern is independent of the mainbeam polarization constraint. [J100]

"Design of Phase Codes for Radar Performance Optimization With a Similarity Constraint"

This paper deals with the design of coded waveforms which optimize radar performances in the presence of colored Gaussian disturbance. We focus on the class of phase coded pulse trains and determine the radar code which approximately maximizes the detection performance under a similarity constraint with a prefixed radar code. This is tantamount to forcing a similarity between the ambiguity functions of the devised waveform and of the pulse train encoded with the prefixed sequence. We consider the cases of both continuous and finite phase alphabet, and formulate the code design in terms of a nonconvex, NP-hard quadratic optimization problem. In order to approximate the optimal solutions, we propose techniques (with polynomial computational complexity) based on the method of semidefinite program (SDP) relaxation and randomization. Moreover, we also derive approximation bounds yielding a ldquomeasure of goodnessrdquo of the devised algorithms. At the analysis stage, we assess the performance of the new encoding techniques both in terms of detection performance and ambiguity function, under different choices for the similarity parameter. We also show that the new algorithms achieve an accurate approximation of the optimal solution with a modest number of randomizations. [J101]

"New Algorithms for Designing Unimodular Sequences With Good Correlation Properties"

Unimodular (i.e., constant modulus) sequences with good autocorrelation properties are useful in several areas, including communications and radar. The integrated sidelobe level (ISL) of the correlation function is often used to express the goodness of the correlation properties of a given sequence. In this paper, we present several cyclic algorithms for the local minimization of ISL-related metrics. These cyclic algorithms can be initialized with a good existing sequence such as a Golomb sequence, a Frank sequence, or even a (pseudo)random sequence. To illustrate the performance of the proposed algorithms, we present a number of examples, including the design of sequences that have virtually zero autocorrelation sidelobes in a specified lag interval and of long sequences that could hardly be handled by means of other algorithms previously suggested in the literature. [J102]

"Waveform-Agile Sensing and Processing [JFrom the Guest Editors]"

The focus of this special issue is the development of signal processing techniques that are able to take full advantage of advances in radar systems. Phased array radars and space-time adaptive processing illuminate the value of waveform diversity with respect to time, space, frequency, and polarization. [J103]

"Waveform Libraries"

Our goal was to provide an overview of a circle of emerging ideas in the area of waveform scheduling for active radar. Principled scheduling of waveforms in radar and other active sensing modalities is motivated by the nonexistence of any single waveform that is ideal for all situations encountered in typical operational scenarios. This raises the possibility of achieving operationally significant performance gains through closed-loop waveform scheduling. In principle, the waveform transmitted in each epoch should be optimized with respect to a metric of desired performance using all information available from prior measurements in conjunction with models of scenario dynamics. In practice, the operational tempo of the system may preclude such on-the-fly waveform design, though further research into fast adaption of waveforms could possibly attenuate such obstacles in the future. The focus in this article has been on the use of predesigned libraries of waveforms from which the scheduler can select in lieu of undertaking a real-time design. Despite promising results, such as the performance gains shown in the tracking example presented here, many challenges remain to be addressed to bring the power of waveform scheduling to the level of maturity needed to manifest major impact as a standard component of civilian and military radar systems. [J104]

"Waveform-Diversity-Based Millimeter-Wave UAV SAR Remote Sensing"

To integrate a synthetic aperture radar (SAR) into an operational unmanned airborne vehicle (UAV), it should be as small as possible to meet stringent limitations of size, weight, and power consumption. It appears that the novel combination of millimeter-wave frequency-modulated continuous-wave (FMCW) technology and SAR techniques can provide an optimal solution. However, some efficient techniques should be applied to resolve range/Doppler ambiguities in FMCW UAV SAR systems. As such, a technique of waveform-diversity-based millimeter-wave UAV SAR imaging is presented in this paper. Along with the described system concept and signal model, the performance of the diversified waveforms evaluated by their cross correlations is detailed. As the conventional stop-and-go approximation is not valid for FMCW SAR, a modified wavenumber-domain algorithm with a consideration of continuous antenna motion during transmission and reception is derived. This imaging algorithm is validated with computer simulations. Furthermore, one parallel direct-digital-synthesizer-

driven phase-locked-loop synthesizer with adaptive nonlinearity compensation, which has been validated by the experimental results, is proposed to obtain a millimeter-wave FMCW signal with fine frequency linearity. [J105]

"Using Altimetry Waveform Data and Ancillary Information From SRTM, Landsat, and MODIS to Retrieve River Characteristics"

In this paper, spaceborne radar altimeters are shown to have the potential for monitoring the height of large rivers with accuracies of approximately 1 m. However, the need for a better height accuracy and the observations of smaller continental basins have led to studies on how to improve and extend the use of nadir-altimeter data. Conventional retracking techniques over land are limited to the examination of altimeter waveforms on a case-by-case basis. Due to the arbitrary geometry which may be present at altimeter river crossings, this approach may be limited to large rivers, which approximate ocean crossings. To overcome this limitation, we introduce a waveform-fitting method which uses the entire set of waveforms associated with a water crossing, rather than individual waveforms. By using ancillary data, such as digital elevation model (obtained from Shuttle Radar Topography Mission and Gtopo30) and classification maps (obtained from Landsat and MODIS), it is possible to recast the retracking problems as a maximum-likelihood-estimation problem. Theoretical power returns based on the a priori knowledge of the observed scenes are generated, resulting in a parametric library of waveform histories, which is then used to constrain the estimation. For demonstration, we concentrate on the river Meuse in northern western Europe and on the river Lena in Russia. The Meuse has important social impact, since it has flooded in the past and better real-time predictions of its changing stage may improve flood-forecasting skill. Furthermore, it presents a challenge to conventional nadir-altimeter waveform retracking. We will present both theoretical performance results and demonstrate the feasibility based on real altimeter data. [J106]

"Non-adaptive multiple-input, multiple-output radar techniques for reducing clutter"

Multiple-input, multiple-output (MIMO) radars enhance performance by transmitting and receiving coded waveforms from multiple locations. This paper describes MIMO techniques that can be used to improve radar performance, especially in airborne ground moving target indicator (GMTI) applications. The authors begin by showing how MIMO techniques can lower airborne radar clutter to noise ratios (CNRs). This results in smaller losses when observing stationary or low-velocity targets. Next, the authors consider the implementation of MIMO radar modes using electronically scanned arrays (ESAs). Specifically, the authors show how MIMO techniques, applied to subarray-based ESAs, can cause high grating lobes and/or reduced search rates. To address this problem, the authors describe new space/time waveform coding techniques that can be used to improve performance. Two space/time waveform encoding approaches are proposed: (i) an overlapped virtual transmit subarray approach, and (ii) a beamspace MIMO approach. A third approach, involving conventional MIMO waveforms and irregular subarrays, is also briefly considered. [J107]

"Waveform design in signal-dependent interference and application to target recognition with multiple transmissions"

The authors present illumination waveforms matched to stochastic targets in the presence of signal-dependent interference. The waveforms are formed by SNR and mutual information (MI) optimisation. We also use these waveforms in cognitive radar (CR) target identification application. In this application, the radar system attempts to identify a deterministic or random target using multiple transmissions. These transmissions are adaptively modified in response to previously received echoes. In addition, the authors present a new multi-band application of the CR platform. [J108]

"Limiting Case of a Lack of Rich Scattering Environment for MIMO Radar Diversity"

A radar system with Mtransmit and Nreceive antennas which are widely separated is employed to detect the presence of a target at a given point in space. This target is assumed to be composed of Qpoint scatterers which are closely spaced with respect to the waveforms transmitted by the radar system. The diversity gain for radar systems employing optimum processing (likelihood ratio tests) for detecting the presence of these targets is shown to be less than or equal to min(Q,MN). [J109]

"Multiple-input multiple-output over-thehorizon radar: experimental results"

Results from an experiment that applied one class of multiple-input multiple-output (MIMO) waveform techniques to over-the-horizon radar (OTHR) are reported. The experiment objective was to demonstrate that adaptive transmitter beamforming could be used in an appropriately design radar to reject spatially discrete Doppler-spread clutter. In the particular MIMO radar architecture that the authors call non-causal transmit beamforming,

conventional or adaptive transmitter beamforming occurs following waveform transmission, propagation, scatter from targets and clutter sources, return propagation and finally signal reception. In the case reported herein spatially discrete clutter was successfully rejected to the noise floor of the radar return with rejection in excess of 35 dB achieved using common adaptive algorithms and straightforward training data selection. As part of the rejection algorithm the transmitted waveform direction-of-departure (DOD) from the transmitter array to the target was estimated and used as the preserved steer direction in the adaptive beamformer. The DOD estimates agree well with the geometrically determined true values. The demonstration of non-causal transmit beamforming suggests that it will be possible to create multiple simultaneous adaptive range-dependent transmitter beams with an appropriately designed OTHR. This has several applications including for the mitigation of Doppler-spread clutter. [J110]

"Waveform Design for Multistatic Radar Detection"

We derive the optimal Neyman-Pearson (NP) detector and its performance, and then present a methodology for the design of the transmit signal for a multistatic radar receiver. The detector assumes a Swerling I extended target model as well as signal-dependent noise, i.e., clutter. It is shown that the NP detection performance does not immediately lead to an obvious signal design criterion so that as an alternative, a divergence criterion is proposed for signal design. A simple method for maximizing the divergence, termed the maximum marginal allocation algorithm, is presented and is guaranteed to find the global maximum. The overall approach is a generalization of previous work that determined the optimal detector and transmit signal for a monostatic radar. [J111]

"Adaptive radar phase-coded waveform design"

A simple and successful design for an adaptive radar phase-coded waveform is presented. The optimised phase-coded waveform is designed by the phase-only conjugate gradient method. The signal-to-interference-plus-noise ratio of the optimised phase-coded waveform is compared with an optimal waveform and good approximation is achieved. [J112]

"Models and performance evaluation for multiple-input multiple-output space-time adaptive processing radar"

Signal and clutter modelling and optimum performance evaluation for multiple-input multiple-output (MIMO)-based space-time adaptive processing radar is addressed. A signal model is developed to account for both code diverse MIMO (c-MIMO) and frequency diverse MIMO (f-MIMO), and a general framework on performance evaluation is presented to take into account various waveform configurations including phased array (PA), partially correlated MIMO and ideally orthogonal MIMO. The proposed framework evaluates the system performance through optimum processing (OP) gain and transmit array (TA) gain. The OP gain is in turn evaluated by the number of available space-time measurements (ASMs) that depends on the number of clutter degrees of freedom (clutter NDoF) relative to the system degrees of freedom (system NDoF). The waveform diversity introduced by MIMO, especially f-MIMO, could significantly enhance the OP gain by increasing the number of ASMs. Hence, in OP-gain-limited scenarios, where the overall performance significantly degrades despite the TA gains, the preferable configuration in terms of optimum performance would be ordered as f-MIMO, c-MIMO, and last, PA, that is, no MIMO. [J113]

"Orthogonal Block Coded ECCM Schemes Against Repeat Radar Jammers"

This paper develops radar signaling schemes to combat the impact of repeat jammers on radar systems. Robustness against jammers is achieved by employing the concept of pulse diversity where the radar, at each pulse repetition interval, emits either a modified version of the previous waveform or a new waveform following a specific orthogonal structure. Two pulse coding techniques are presented; both enable the radar to separate the signals being reflected off the true targets and the false reflectors being emulated by a jammer. Simulations are used to show the validity of the introduced concepts. [J114]

"New waveform design for magnetron-based marine radar"

At their long-range mode, conventional magnetron-based marine radar use low pulse repetition frequency (PRF) to extend the unambiguous range, and increase the pulse-width to regain the average power. The proposed new waveform maintains narrow pulses and high PRF even at the long-range mode. Range ambiguity is mitigated by periodic `yes`no` coding of the transmitted pulse train. Using narrow pulses improves the range resolution and reduces the radial dimension of the illuminated clutter. [J115]

"Estimating Moving Targets Behind Reinforced Walls Using Radar"

We consider the estimation of moving targets located behind concrete walls reinforced with metallic bars, using radar measurements. The periodic structure of the rebar severely attenuates and distorts transmitted waveforms, which produces defocused images with ghost target estimates. We apply beamforming to estimate permittivity and thickness of the wall and number and position of the targets. The proposed solution is based on accurate physical models calculated using the method of moments. We show that the estimation is significantly improved by modeling the waveform distortion due to the bars. The resulting images are focused and clearly represent the contours of the targets. The algorithm is robust to the ambiguities in bar parameter values. In addition, the minimal necessary SNR is lower compared with the case in which the influence of the bars on the signal shape is ignored. [J116]

"A Waveform Model for Near-Nadir Radar Altimetry Applied to the Cassini Mission to Titan"

The radar altimeter of the Cassini mission to Titan operates in a transition region between pulse- and beam-limited conditions. Due to the specific observation geometry, low values of mispointing angle have been found to significantly affect altimeter impulse response (IR). This involves a nonconventional formulation of the system response which is the main goal of this paper. An analytical model of the average return power waveform, valid for near-nadir altimetry measurements, has been developed in order to cope with the particular operating conditions of Cassini mission. The model used to approximate the altimeter waveform is based on the same general assumptions of the classical Brown's model (1977) but exploits a flat surface response approximation by Prony's methods. Both theoretical considerations and simulated data have been taken into account to support the accuracy of the proposed model. To infer the main geophysical parameters describing surface topography from altimetry data, a parametric estimation procedure has been used. The maximum likelihood estimator procedure has been chosen since, in principle, it can assure optimal performance as a consequence of the analytical model we used to describe the system IR. Performances of the implemented method have been numerically evaluated through simulation of data received by CASSINI in high-resolution altimeter mode. [J117]

"Performance analysis of interrupted sparse HFSWR waveform coded with successive fast Fourier transforms"

A successive Fourier transform technique is applied to efficiently generate an interrupted sparse waveform for a monostatic high-frequency surface wave radar. With few iterations a good stop to passband ratio is reached, and it is show that, when using an optimised envelope, a better average and a lower standard deviation are obtained in terms of minimal contrast ratio than in the case of a simple train of pulses. [J118]

"Target Detection in Clutter Using Adaptive OFDM Radar"

We address the problem of detecting a target moving in clutter environment using an orthogonal frequency division multiplexing (OFDM) radar. The broadband OFDM signal provides frequency diversity to improve the performance of the system. First, we develop a parametric model that accounts for the measurements at multiple frequencies including the Doppler shift. Then, we present a statistical detection test and evaluate its performance characteristics. Based on this, we propose an algorithm to adaptively design the parameters for the next transmitting waveform. Numerical examples illustrate our analytical results, demonstrating the achieved performance improvement due to the OFDM signaling method and adaptive waveform design. [J119]

"MIMO Radar Waveform Optimization With Prior Information of the Extended Target and Clutter"

The concept of multiple-input multiple-output (MIMO) radar allows each transmitting antenna element to transmit an arbitrary waveform. This provides extra degrees of freedom compared to the traditional transmit beamforming approach. It has been shown in the recent literature that MIMO radar systems have many advantages. In this paper, we consider the joint optimization of waveforms and receiving filters in the MIMO radar for the case of extended target in clutter. A novel iterative algorithm is proposed to optimize the waveforms and receiving filters such that the detection performance can be maximized. The corresponding iterative algorithms are also developed for the case where only the statistics or the uncertainty set of the target impulse response is available. These algorithms guarantee that the SINR performance improves in each iteration step. Numerical results show that the proposed methods have better SINR performance than existing design methods. [J120]

"Joint Transmitter and Receiver Polarization Optimization for Scattering Estimation in Clutter"

Controlling the polarization information in transmitted waveforms enables improving the performance of radar systems. We consider the design of optimal polarizations at both the radar transmitter and receiver for the estimation of target scattering embedded in clutter. The goal is to minimize the mean squared error of the

scattering estimation subject to an average radar pulse power constraint. Under the condition that the target and clutter scattering covariance matrices are known a priori, we show that such a problem is equivalent to the optimal design of a radar sensing matrix that contains the polarization information. We formulate the optimal design as a nonlinear optimization problem and then recast it in a convex form and is thus efficiently solvable by semi-definite programming (SDP). We compare the sensing performance of the optimally selected polarization over conventional approaches. Our numerical results demonstrate that a significant amount of power gain is achieved in the target scattering estimation through such an optimal design. [J121]

"Filter Design for Steady-State Tracking of Maneuvering Targets with LFM Waveforms"

Modern radars employ linear frequency modulated (LFM) waveforms for target tracking as the range-Doppler coupling enables better track accuracy in range. This paper derives expressions for the sensor-noise only (SNO) covariance matrix and the position and velocity lags during maneuvers for an alphabeta-filter processing measurements from LFM waveforms. These expressions were confirmed through computer simulations. An analysis of the maximum root-mean-square error (RMSE) in position and velocity estimates is performed, and the gains that minimize the maximum RMSE in either position or velocity are plotted versus the tracking index. For deterministic maneuvers, the paper introduces the concept of the deterministic tracking index and shows its relation to the typical tracking index generally used for random maneuvers. Using these relations, the paper also proposes a method to calculate the optimal process noise variance to be used in the tracking filter for a deterministic tracking index. [J122]

"A Multistage Processing Algorithm for Disturbance Removal and Target Detection in Passive Bistatic Radar"

The paper examines the problem of cancellation of direct signal, multipath and clutter echoes in passive bistatic radar (PBR). This problem is exacerbated as the transmitted waveform is not under control of the radar designer and the sidelobes of the ambiguity function can mask targets including those displaced in either (or both) range and Doppler from the disturbance. A novel multistage approach is developed for disturbance cancellation and target detection based on projections of the received signal in a subspace orthogonal to both the disturbance and previously detected targets. The resulting algorithm is shown to be effective against typical simulated scenarios with a limited number of stages, and a version with computational savings is also introduced. Finally its effectiveness is demonstrated with the application to real data acquired with an experimental VHF PBR system. [J123]

"Lake Level Variations Monitored With Satellite Altimetry Waveform Retracking"

Over lake shores, altimetric waveforms are generally contaminated by lands, rough lake surfaces, and lag effects of the altimeter's automatic gain control. To improve altimeter ranging accuracy and in turn to get better surface height measurement, contaminated waveforms should be retracked against geophysical corrections. In this paper, an improved threshold retracker (ITR) is developed to retrack waveforms over lakes. ITR considers not only the physical characteristics of the reflecting surface, but also the stochastic feature of waveform, and two new retrackers, the N-Beta function model, and the N-5-Beta function model, are also put forward to develop the waveform retracking program of this study. TOPEX/POSEIDON waveforms over Hulun Lake in the North China are retracked to monitor the temporal lake level variations. A comparison with the in situhydrological data indicates ITR is very efficient to monitor the lake level variations with the retracked altimetric data. The result of our study shows accurate seasonal level variations and the descending trend of Hulun Lake. [J124]

"Designing Unimodular Sequence Sets With Good Correlations-Including an Application to MIMO Radar"

A multiple-input multiple-output (MIMO) radar system that transmits orthogonal waveforms via its antennas can achieve a greatly increased virtual aperture compared with its phased-array counterpart. This increased virtual aperture enables many of the MIMO radar advantages, including enhanced parameter identifiability and improved resolution. Practical radar requirements such as unit peak-to-average power ratio and range compression dictate that we use MIMO radar waveforms that have constant modulus and good auto- and cross-correlation properties. We present in this paper new computationally efficient cyclic algorithms for MIMO radar waveform synthesis. These algorithms can be used for the design of unimodular MIMO sequences that have very low auto- and cross-correlation sidelobes in a specified lag interval, and of very long sequences that could hardly be handled by other algorithms previously suggested in the literature. A number of examples are provided to demonstrate the performances of the new waveform synthesis algorithms. [J125]

"Software-Defined Six-Port Radar Technique for Precision Range Measurements"

A software-defined radar measurement system on the basis of a six-port receiver technique is proposed and described in this paper. The system makes use of a hybrid scheme of two performance-complementary operating modes, namely, frequency-modulated continuous-wave (FMCW) and two-tone continuous-wave signals. Generally, the FMCW-based measurement technique is deployed to give an approximate range value of target while the two-tone continuous-wave (CW)-based measurement technique can accurately determine the range that may, however, be ambiguous. The six-port circuit is used for the receiver as a precision phase detector in two-tone CW function and at the same time as a mixer in FMCW function. Various waveforms are generated in direct digital synthesizers and processed by different algorithms in a digital signal processor. The switching between the frequency-modulated CW and two-tone CW functions is controlled by software to improve the resolution and ensure a reliable operation. A system prototype is designed and made for a C-band demonstration. The Schottky diodes used as power detectors in the six-port are calibrated so that they can be used beyond the square-law region, thus allowing a higher power level and a better dynamic range. Measured results validate the proposed software-defined platform and accurate range results are confirmed. [J126]

"A Contrast-Based Algorithm For Synthetic Range-Profile Motion Compensation"

In stepped-frequency radar, target motions produce range-profile distortions. Range shift, signal-to-noise ratio loss, and symmetric spreading are produced by target radial velocity, whereas target radial acceleration is mainly responsible for asymmetric smearing. Acceleration-distortion effects are usually negligible when a high Pulse Repetition Frequency (PRF) is used, although this is not the case for low-PRF radars. In this paper, a new motion-compensation technique based on contrast optimization is proposed. The innovative contributions of this paper are as follows: (1) A theoretical analysis of the distortions produced by target motions on the reconstruction of synthetic aperture radar is provided; (2) the proposed technique compensates both phase terms, which are due to target radial velocity and acceleration; therefore, synthetic range profiles can be focused by processing low-PRF radar returns; (3) a new cost function for the synthetic range profiles (namely, contrast) is defined and used for motion compensation; (4) the proposed technique can be applied to any kind of stepped-frequency waveforms; and (5) an estimation error analysis is performed, first theoretically and then by means of both simulations and real data. [J127]

"Adaptive pulse compression of MIMO radar based on GSC"

Adaptive pulse compression (APC) is an effective method for mitigating the mutual interference of the multiple waveforms transmitted in multiple-input multiple-output (MIMO) radar. But APC based on minimum mean-square error (MMSE) is computationally inefficient. Therefore, APC of MIMO radar based on a generalised sidelobe canceller (GSC) is proposed, which can effectively reduce the complexity. Numerical experiments show that the proposed method is superior to the matched filter (MF), and performs similarly as APC based on MMSE. [J128]

"Code Design to Optimize Radar Detection Performance Under Accuracy and Similarity Constraints"

This paper deals with the design of coded waveforms which optimize radar performances in the presence of colored Gaussian disturbance. We focus on the class of linearly coded pulse trains and determine the optimum radar code according to the following criterion: maximization of the detection performance under a control on the region of achievable Doppler estimation accuracies, and imposing a similarity constraint with a prefixed radar code. This last constraint is tantamount to requiring a similarity between the ambiguity functions of the devised waveform and of the pulse train encoded with the prefixed sequence. The resulting optimization problem is nonconvex and quadratic. In order to solve it, we propose a technique (with polynomial computational complexity) based on the relaxation of the original problem into a semidefinite program. Thus, the best code is determined through a rank-one decomposition of an optimal solution of the relaxed problem. At the analysis stage, we assess the performance of the new encoding technique in terms of detection performance, region of achievable Doppler estimation accuracies, and ambiguity function. [J129]

"Multi-range-resolution radar using inverse filters"

The resolution of a radar range is generally fixed regardless of the detection range. The proposed receiving system for radars is configured with multiple inverse filters so that it has different range resolutions depending on the detection range, and the signal is compressed to a narrow arbitrary pulse width of less than or equal to the reciprocal of the spectrum bandwidth of the transmitted signal. Then the proposed receiving system may be able to have no sidelobes. The frequency response function of each inverse filter used in the receiver is expressed as D(f)/S(f), where D(f) is the Fourier transform of the desired output waveform d(t) and S(f) is the Fourier transform of the transmitted waveform s(t). Specific signal examples are used to clarify what sort of D(f) and S(f) are suitable for preventing D(f)/S(f) from diverging. With regard to this proposed receiving system, a theoretical

improvement factor is indicated for the signal-to-noise ratio, and simulations and experiments are conducted to confirm the validity of the proposed receiving system. [J130]

"Two-dimensional ISAR model and image reconstruction with stepped frequency-modulated signal"

A two-dimensional (2-D) inverse synthetic aperture radar (ISAR) return signal model that employs stepped frequency (SF) modulation is developed. The geometry of the examined ISAR scenario is described by analytical geometrical equations. The target to be imaged is represented by a rectangular grid of point scatterers, moving along a rectilinear trajectory at constant speed, without any rotational motion. Thus, the inverse synthetic aperture results from the translational motion of the target for a short period of time. The process of ISAR signal modelling through coherent summation of the SF-modulated signals reflected from different point scatterers of the target is thoroughly described. Moreover, an efficient ISAR image reconstruction approach, including cross-correlation-based range compression and fast-Fourier-transform-based azimuth compression, is presented through analytical mathematical expressions. Numerical simulations are carried out for various SF ISAR scenarios and high-resolution ISAR images are obtained by applying the proposed ISAR image reconstruction approach. Simulation results (ISAR images and corresponding entropy values) indicate the validity of the proposed 2-D SF ISAR return signal model and the efficiency of the proposed imaging algorithms. Finally, a numerical simulation result is illustrated, which shows the comparison of the performance of the proposed ISAR image reconstruction algorithms based on SF and linear frequency modulation waveforms. It is shown that the two waveforms attain almost the same ISAR image resolution. [J131]

"Detection of a manoeuvring air target in strong sea clutter via joint time-frequency representation"

Two new approaches for detecting a manoeuvring air target in strong sea clutter are proposed. Whereas one is based on the adaptive chirplet decomposition, the other is inspired by spectral subtraction. Unlike the other time-frequency transform-based methods, the approaches presented can both be used to compute a signal's time waveform with suppressed sea clutter. Experiments with real-world data samples show that both methods can effectively enhance the Doppler radar signals associated with a manoeuvring air target by more than 15-dB. [J132]

"Cramer-Rao bounds for target parameters in space-based radar applications"

The Cramer-Rao (CR) bounds for target Doppler and power are presented when detecting targets using a space-based radar (SBR) platform. The target in noise-only case is considered first and the results are compared with those obtained for a centro-symmetric uniform linear pulse array. When clutter is also present, the effect of the Earth's rotation and range foldover becomes significant; and they must be taken into consideration. The CR bounds are computed for target Doppler and power, and compared with their variance estimates obtained from simulation results corresponding to various airborne and SBR situations. From the simulation results, the Earth's rotation together with range foldover significantly increase the CR bounds for both target Doppler and power. This is in agreement with other results that show the Earth's rotation and range foldover together degrade the clutter suppression performance of adaptive processing algorithms. It is shown that when both the Earth's rotation effect and range foldover effect are present in the data, target detection is difficult, and it is necessary to introduce waveform diversity into the transmit design to minimize the effect of clutter and other interference. In this context, using waveform diversity on transmit, it is possible to compensate the degradation in terms of the CR bounds and achieve performance close to the ideal case. [J133]

"High-Resolution and Real-Time Three-Dimensional Imaging Algorithm With Envelopes of Spheres for UWB Radars"

Ultrawideband pulse radars have a great potential for high-range resolution in near field imaging and can be used for noncontact measuring in precision or specular products such as reflector antennas and aircraft fuselages. We have already proposed a high-speed 3-D imaging algorithm, SEABED, which is based on a reversible transform, which is the boundary scattering transform, between the received signals and the target shape. However, the estimated image with SEABED is unstable with random noise because it utilizes a derivative of the received data. In this paper, we propose a robust 3-D imaging algorithm with an envelope of spheres that completely resolves the instability due to derivative operations. Moreover, to enhance the resolution of estimated images, this method is combined with a direct waveform compensation method that does not sacrifice high-speed calculation. Numerical simulations and an experiment confirm that the proposed method can realize fast, robust, and high-resolution 3-D imaging for arbitrary targets. [J134]

"Simultaneous reduction of sidelobes and grating lobes by realising nonlinear synthetic wideband waveforms in SAR processing"

An alternative method of SAR signal processing which can be used to simultaneously reduce sidelobes and grating lobes of synthetic wideband waveforms (SWW) is proposed. The method applies the super spatially variant apodisation technique to each subpulse image of the SWW, and then cuts appropriate portions of the expanded spectra of the subpulses to effectively realise a nonlinear SWW with much better characteristics. [J135]

"Grating lobes suppression in stepped-frequency pulse train"

Frequency stepping is one of the known techniques employed by modern radars to achieve high range resolution. The main advantage of this approach is that the actual instantaneous bandwidth of a radar is quite small compared with the total processing bandwidth. This allows the transmission of waveforms with extremely wide overall bandwidth (and, as a consequence, the attainment of high range resolution) without the usage of the expensive hardware needed to support wide instantaneous bandwidth. Unfortunately, the autocorrelation function of uniform frequency stepped pulse trains can have undesirable peaks, known as "grating lobes." We address this issue, using an approach which allows us to suppress grating lobes below a desired threshold level in the case of appropriately chosen stepped frequency waveforms. We discuss in detail how to choose relevant parameters in order to produce such waveforms with small grating lobes, and give examples of waveforms with small overlap ratio. We also discuss the issue of high sidelobes in the vicinity of the mainlobe, which are inevitable in a stepped frequency train of linear frequency modulated (LFM) waveforms with small overlap ratio, and show that it is possible to suppress these, as well as the grating lobes, by means of nonlinear frequency modulation (NLFM). [J136]

"Calibration Method for Fully Polarimetric Microwave Radiometers Using the Correlated Noise Calibration Standard"

In this paper, a new and improved L-band version of the correlated noise calibration standard (CNCS) has been developed to aid in the characterization of polarimetric microwave radiometers. The CNCS generates a series of known polarimetric test signals using a two-channel commercial arbitrary waveform generator (AWG) and a pair of frequency-upconversion modules. When it is inserted in place of the antenna used by a radiometer-under-test (RUT), it can fully characterize the polarimetric response of the receiver portion of the RUT. Both hardware and software improvements have been made over a previous version of the CNCS. The frequency upconverters now include integral warm and cold calibration-reference targets to automatically compensate for small drifts in AWG output-signal strength. The procedure used to calibrate the RUT has been generalized to correct for nonideal characteristics of the CNCS itself. Moreover, the effects on the derived polarimetric gain matrix of impedance mismatches between the RUT, and either the CNCS or the antenna have been determined. Details of the CNCS improvements are presented. The results of an experimental demonstration of its use and of a series of validation tests of its performance are also presented. [J137]

"Array Modeling of Active Sonar Clutter"

Active sonar systems operating in shallow-water environments often deal with excessive false alarms, generically referred to as clutter, that are more numerous than expected for Rayleigh-distributed reverberation. The clutter probability density function, and therefore the probability of false alarm (Pfa), depends on the scattering sources, propagation conditions, sonar system, and signal processing. Clutter statistics are often approximated by the K-distribution where the shape parameter (alpha macr) provides an inverse relationship to Pfawith decreases in alpha macr representing an increase in Pfa. In this paper, the effect of sonar array processing on clutter statistics is evaluated by first modeling clutter at the hydrophone level and then analyzing the resulting K-distribution shape parameter after conventional beamforming. When the transmit-waveform bandwidth is narrowband with respect to the array processing and propagation consists primarily of low-angle paths, alpha macr was found to be separable into the product of a clutter-source scattering effect, an array processing effect, and a coupled transmit-waveform and propagation effect. The array effect was found to coarsely follow the array beamwidth, although precise evaluation is straightforward given the array beampattern. As might be expected, array design or processing that tends to increase the beamwidth was found to increase alpha macr. Uniform shading was seen to provide a practical, though not exact, lower bound on alpha macr for common array shading functions. For circular arrays with unaliased spatial sampling, an asymptotic beampattern was found to provide a very accurate approximation to alpha macr. These results should be useful in predicting the performance of sonar systems in clutter dominated areas, in the design of arrays and array processing, in the inversion of clutter data for clutter-source scattering parameters, or--to improve signal processing algorithms aiming to reduce or control clutter-related false alarms. [J138]

"Target detection and parameter estimation for MIMO radar systems"

We investigate several target detection and parameter estimation techniques for a multiple-input multiple-output (MIMO) radar system. By transmitting independent waveforms via different antennas, the echoes due to targets at different locations are linearly independent of each other, which allows the direct application of many data-dependent beamforming techniques to achieve high resolution and excellent interference rejection capability. In the absence of array steering vector errors, we discuss the application of several existing data-dependent beamforming algorithms including Capon, APES (amplitude and phase estimation) and CAPES (combined Capon and APES), and then propose an alternative estimation procedure, referred to as the combined Capon and approximate maximum likelihood (CAML) method. Via several numerical examples, we show that the proposed CAML method can provide excellent estimation accuracy of both target locations and target amplitudes. In the presence of array steering vector errors, we apply the robust Capon beamformer (RCB) and doubly constrained robust Capon beamformer (DCRCB) approaches to the MIMO radar system to achieve accurate parameter estimation and superior interference and jamming suppression performance. [J139]

"Design of frequency-coded waveforms for target detection"

The authors propose a novel approach to the design of frequency-coded waveforms using modified pushing sequences. The resulting waveforms show that there is considerable enhancement in delay-Doppler resolution in the ambiguity function. [J140]

"Lateral Current Confinement Determines Silicon Avalanche Transistor Operation in Short-Pulsing Mode"

The transient in a Si bipolar junction transistor was investigated in high-current short-pulsing (2 ns) mode both experimentally and numerically. A comparison of measured and simulated waveforms clearly showed that only a small fraction of the perimeter of the emitter-base interface (in the lateral direction) takes part in the switching transient when a capacitor of relatively small value (80 pF) is discharged across the transistor to obtain a current pulse of a few nanoseconds in duration. A good agreement was found between measurements and simulations in the 2-D numerical model when the effective operating perimeter was used as a parameter in the model. The results allowed reliable analyses of the thermal regime to be performed. Possible reasons for the significant current confinement in short-pulsing mode and relatively homogeneous transistor switching with longer current pulses are discussed, and a mechanism of fast lateral turn-on spread is assumed. One conclusion of practical importance is that a short-pulsing relatively high-current mode could not be realized without current confinement in the lateral direction. [J141]

"Mismatched Filtering of Aperiodic Quadriphase Codes"

Matched filtering of quadriphase coded radar signals creates unwanted sidelobes, which may mask important information. This correspondence presents a method of eliminating these sidelobes in aperiodic quadriphase codes. This is done by using a mismatched filter. The signal-to-noise ratio (SNR) at the output of the mismatched filter is less than the SNR at the output of the corresponding matched filter. A thorough computer search has been carried out to find quadriphase code-mismatched filter pairs with minimum possible SNR losses by considering a point target in the presence of white Gaussian noise. The phase patterns of the optimal codes, which were chosen from a total number of 1.466 times 1012investigated codes, are shown. It turned out that the mismatched filter of a quadriphase Barker code with 15 elements (1, 1, 1, j, j, 1,-j,-j, j, -1,-j, j, 1, -1, 1) has a loss in SNR of only 6.7% when compared with the corresponding matched filter. The mismatched filter of the well known 13-element Barker code, which has a loss in SNR of 4.8%, outperforms this filter. Finally, using numerical experiment it is shown that a randomly selected long code will most likely have very large SNR losses. [J142]

"Fast and accurate radar cross-section computation over a broad frequency band using the best uniform rational approximation"

The method of moments (MOM) in conjugation with the best uniform rational approximation is applied to predict the broad-band radar cross-section of arbitrarily shaped three-dimensional (3D) bodies. The surface integral equations are solved using MOM to obtain the equivalent surface currents at the frequency points corresponding to the Chebyshev nodes, and then the surface current within the given frequency band is represented by the Chebyshev series. To improve the accuracy, the Chebyshev series is matched via the Maehly approximation to a rational function, which can be as good as the best uniform rational approximation. Using the rational function, the surface current is obtained at any frequency point within the frequency band. Numerical results for 3D arbitrarily shaped perfectly electric conducting objects and homogenous dielectric bodies are considered. Compared with the asymptotic waveform evaluation technique and the model-based parameter estimation, the proposed technique is accurate in much broader frequency band with lower memory required. [J143]

"Quasi-continuous waveform design for dynamic range reduction"

A study of quasi-continuous waveform and its performance in detection is presented, taking into consideration eclipsing loss and free- space decay. A genetic algorithm is then used to optimise the waveform and lower the dynamic range of the matched filtering output. The resulting waveform with high duty cycle and minimal loss at maximal range maintains good detection performance along the whole operating range of the radar. [J144]

"Transmit beamforming for MIMO radar systems using signal cross-correlation"

Proposed next-generation radar systems will have multiple transmit apertures with complete flexibility in the choice of the signals transmitted at each aperture. Here we propose the use of multiple signals with arbitrary cross-correlation matrix R, and show that R can be chosen to achieve or approximate a desired spatial transmit beampattern. Two specific problems are addressed. The first is the constrained optimization problem of finding the value of R which causes the true transmit beampattern to be close in some sense to a desired beampattern. This is approached using convex optimization techniques. The second is the problem of designing multiple constant-modulus waveforms with given cross-correlation R. The use of coded binary phase shift keyed (BPSK) waveforms is considered. A method for finding the code sequences based on random signaling with a structured correlation matrix is proposed. It is also shown that by restricting the class of admissible waveforms one reduces the set of possible signal correlation matrices. [J145]

"Comments on "Discrete Frequency-Coding Waveform Design for Netted Radar Systems""

For original paper see H. Deng, ibid., vol.11, no.2, p.179-182, (2004). This comment points out some errors in the correlation calculations and conclusions in the literature. The ambiguity function and cross-ambiguity function for discrete frequency-coding waveform (DFCW) with arbitrary firing order are analyzed in that letter to corroborate the judgement. It shows that range autocorrelation sidelobe peak (ASP) for DFCW fluctuates around 0.21, the Doppler tolerance has sinc function form, while the range cross-correlation peak (CP) between two DFCWs is heavily varied with the different firing order. The correlation values are recalculated. [J146]

"Reply to "Comments on 'Discrete Frequency-Coding Waveform Design for Netted Radar Systems'""

For original paper see H. Deng, ibid., vol.11, no.2, p.179-182, (2004). This paper presents reply to "comments on 'discrete frequency-coding waveform design for netted radar systems'". [J147]

"MIMO Radar Space-Time Adaptive Processing Using Prolate Spheroidal Wave Functions"

In the traditional transmitting beamforming radar system, the transmitting antennas send coherent waveforms which form a highly focused beam. In the multiple-input multiple-output (MIMO) radar system, the transmitter sends noncoherent (possibly orthogonal) broad (possibly omnidirectional) waveforms. These waveforms can be extracted at the receiver by a matched filterbank. The extracted signals can be used to obtain more diversity or to improve the spatial resolution for clutter. This paper focuses on space-time adaptive processing (STAP) for MIMO radar systems which improves the spatial resolution for clutter. With a slight modification, STAP methods developed originally for the single-input multiple-output (SIMO) radar (conventional radar) can also be used in MIMO radar. However, in the MIMO radar, the rank of the jammer-and-clutter subspace becomes very large, especially the jammer subspace. It affects both the complexity and the convergence of the STAP algorithm. In this paper, the clutter space and its rank in the MIMO radar are explored. By using the geometry of the problem rather than data, the clutter subspace can be represented using prolate spheroidal wave functions (PSWF). A new STAP algorithm is also proposed. It computes the clutter space using the PSWF and utilizes the block-diagonal property of the jammer covariance matrix. Because of fully utilizing the geometry and the structure of the covariance matrix, the method has very good SINR performance and low computational complexity. [J148]

"Multidimensional Waveform Encoding: A New Digital Beamforming Technique for Synthetic Aperture Radar Remote Sensing"

This paper introduces the innovative concept of multidimensional waveform encoding for spaceborne synthetic aperture radar (SAR). The combination of this technique with digital beamforming on receive enables a new generation of SAR systems with improved performance and flexible imaging capabilities. Examples are high-resolution wide-swath radar imaging with compact antennas, enhanced sensitivity for applications like alongtrack interferometry and moving object indication, and the implementation of hybrid SAR imaging modes that are well suited to satisfy hitherto incompatible user requirements. Implementation-specific issues are discussed and performance examples demonstrate the potential of the new technique for different remote sensing applications.

[J149]

"Range Compression and Waveform Optimization for MIMO Radar: A CramЙr-Rao Bound Based Study"

A multi-input multi-output (MIMO) radar system, unlike standard phased-array radar, can transmit via its antennas multiple probing signals that may be correlated or uncorrelated with each other. This waveform diversity offered by MIMO radar enables superior capabilities compared with a standard phased-array radar. One of the common practices in radar has been range compression. We first address the question of ldquoto compress or not to compressrdquo by considering both the Cramer-Rao bound (CRB) and the sufficient statistic for parameter estimation. Next, we consider MIMO radar waveform optimization for parameter estimation for the general case of multiple targets in the presence of spatially colored interference and noise. We optimize the probing signal vector of a MIMO radar system by considering several design criteria, including minimizing the trace, determinant, and the largest eigenvalue of the CRB matrix. We also consider waveform optimization by minimizing the CRB of one of the target angles only or one of the target amplitudes only. Numerical examples are provided to demonstrate the effectiveness of the approaches we consider herein. [J150]

"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. [J151]

"Polarimetric Detection of Targets in Heavy Inhomogeneous Clutter"

Polarization diversity has proved to be a useful tool for radar detection, especially when discrimination by Doppler effect is not possible. In this paper, we address the problem of improving the performance of polarimetric detectors for targets in heavy inhomogeneous clutter. First, we introduce a new polarimetric radar model that includes the realistic dependence of the clutter reflections on the transmitted signal. Then, we develop a polarimetric detection test that is robust to inhomogeneous clutter. We run this polarimetric test against synthetic and real data to assess its performance in comparison with existing polarimetric detectors. Finally, we propose a polarimetric waveform-design algorithm to further improve the target-detection performance. A numerical analysis is presented to demonstrate the potential performance improvement that can be achieved with this algorithm. [J152]

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

In this paper, we develop an adaptive waveform design method for target tracking under a framework of sequential Bayesian inference. We employ polarization diversity to improve the tracking accuracy of a target in the presence of clutter. We use an array of electromagnetic (EM) vector sensors to fully exploit the polarization information of the reflected signal. We apply a sequential Monte Carlo method to track the target parameters, including target position, velocity, and scattering coefficients. This method has the advantage of being able to handle nonlinear and non-Gaussian state and measurement models. The measurements are the output of the sensor array; hence, the information about both the target and its environment is incorporated in the tracking process. We design a new criterion for selecting the optimal waveform one-step ahead based on a recursion of the posterior Cramer-Rao bound. We also derive an algorithm using Monte Carlo integration to compute this criterion and a suboptimal method that reduces the computation cost. Numerical examples demonstrate both the performance of the proposed tracking method and the advantage of the adaptive waveform design scheme. [J153]

"MIMO Radar with Widely Separated Antennas"

MIMO (multiple-input multiple-output) radar refers to an architecture that employs multiple, spatially distributed transmitters and receivers. While, in a general sense, MIMO radar can be viewed as a type of multistatic radar, the separate nomenclature suggests unique features that set MIMO radar apart from the multistatic radar literature and that have a close relation to MIMO communications. This article reviews some recent work on MIMO radar with widely separated antennas. Widely separated transmit/receive antennas capture the spatial diversity of the target's radar cross section (RCS). Unique features of MIMO radar are explained and illustrated

by examples. It is shown that with noncoherent processing, a target's RCS spatial variations can be exploited to obtain a diversity gain for target detection and for estimation of various parameters, such as angle of arrival and Doppler. For target location, it is shown that coherent processing can provide a resolution far exceeding that supported by the radar's waveform. [J154]

"Waveform Synthesis for Diversity-Based Transmit Beampattern Design"

Transmit beampattern design is a critically important task in many fields including defense and homeland security as well as biomedical applications. Flexible transmit beampattern designs can be achieved by exploiting the waveform diversity offered by an array of sensors that transmit probing signals chosen at will. Unlike a standard phased-array, which transmits scaled versions of a single waveform, a waveform diversity-based system offers the flexibility of choosing how the different probing signals are correlated with one another. Recently proposed techniques for waveform diversity-based transmit beampattern design have focused on the optimization of the covariance matrix of the waveforms, as optimizing a performance metric directly with respect to the waveform matrix is a more complicated operation. Given an, obtained in a previous optimization stage or simply pre-specified, the problem becomes that of determining a signal waveform matrix whose covariance matrix is equal or close to, and which also satisfies some practically motivated constraints (such as constant-modulus or low peak-to-average-power ratio constraints). We propose a cyclic optimization algorithm for the synthesis of such an, which (approximately) realizes a given optimal covariance matrix under various practical constraints. A numerical example is presented to demonstrate the effectiveness of the proposed algorithm. [J155]

"Quality enhancement of image generated with bistatic ground based noise waveform SAR"

A new method for quality enhancement in a noise synthetic aperture radar (SAR) image and the first results of its application to the SAR image generated with the use of a bistatic Ka-band ground-based noise waveform SAR (GB NW-SAR) are presented. A SAR image generated with a noise SAR suffers from the masking effect which is tied to residual random fluctuations in noise radar response from bright scatterers in the scene. This is similar to the masking effect present in the deterministic waveform SAR when the signal sidelobes of echoes from bright scatterers may mask the main response from a weaker target. The procedure presented is a variation of the CLEAN algorithm. Knowing precisely the emitted signal and finding positions of the strongest scatterers one may model the echo signal originated from a selected scatterer. Extraction of the modelled signal from the received one reduces the residual fluctuations and makes it possible to clean the image and increase its dynamic range. The final image is constructed from the cleaned signal and the previously removed strongest scatterers. A theoretical background is provided to the proposed procedure and its application to enhance the SAR image using simulated data as well as data generated by the Ka-band bistatic GB NW-SAR is demonstrated. The GB NW-SAR, recently developed and tested in LNDES IRE NASU, may operate in CW and pulse random signal regimes for short range applications. [J156]

"Ka-band bistatic ground-based noise waveform SAR for short-range applications"

The designing and testing of a new Ka-band ground-based noise waveform synthetic aperture radar (GB NW-SAR) are presented. Its design is based upon new synthetic aperture antennas and noise radar technology. The authors present preliminary results of its indoor trials. The GB NW-SAR designed may be reconfigured for operation in mono-, bi- and multistatic (or MIMO) modes in both CW and pulse regimes using single- and dual-frequency modes to enhance range resolution via expanding the frequency bandwidth of the signal. Potential resolution of the GB NW-SAR is 15 cm both in range and azimuth. Results of indoor trials are presented for both SAR imaging and differential interferometry measurements. Designed and tested Ka-band GB NW-SAR is applicable for precise remote monitoring of various manmade or natural objects, such as ceilings and roofs of big halls and hangars, dams, bridges, TV towers etc. [J157]

"Range-velocity estimation of multiple targets in randomised stepped-frequency radar"

A novel algorithm for estimating the ranges and velocities of multiple moving targets in randomised stepped-frequency pulse-train radar is presented. By using the iterative alternating projection technique, this algorithm can achieve high range-velocity resolution and estimation accuracy close to the Cramer-Rao bounds. The sidelobe pedestal problem of randomised stepped-frequency waveforms can also be mitigated. The effectiveness of the algorithm is illustrated with simulation results. [J158]

"Mutual interference and low probability of interception capabilities of noise radar"

Recently, there has been considerable interest in noise radar over a wide spectrum of applications, such as through-wall surveillance, tracking, Doppler estimation, polarimetry, interferometry, ground penetrating or subsurface profiling, detection, synthetic aperture radar (SAR) imaging, inverse SAR imaging, foliage penetration

imaging etc. Major advantages of using noise in the transmit signal are its inherent immunity from radio frequency and electromagnetic interference, improved spectrum efficiency, and hostile jamming as well as being very difficult to detect. The basic theory of digital signal processing in noise radar design is treated. The theory supports the use of noise waveforms for radar detection and imaging in such applications as covert military surveillance and reconnaissance. It is shown that by using wideband noise waveforms, one can achieve high resolution and reduced range estimation ambiguity. Mutual interference and low probability of interception capabilities of noise radar are also evaluated. The simulation results show the usefulness of the noise radar technology to improve on conventional radars. [J159]

"A range profiling technique for synthetic wideband radar"

A technique is proposed for reconstructing wide range profiles using stepped-frequency waveforms (SWFs). The technique is based on reconstructing range sub-profiles. With respect to previous methods, the proposed technique can be applied to any kind of SWFs. Moreover, for a given range resolution, long range profiles can be formed without increasing the number of transmitted frequencies. Theoretical results are also derived that provide a correct setting of waveform and processing parameter. Finally, as case studies, the proposed method is applied to three SFWs, namely short-pulse stepped-frequency, linear frequency modulated stepped frequency and phase-coded stepped-frequency waveforms. Simulations prove the effectiveness of the proposed range profile reconstruction. [J160]

"Hybrid interference suppression for multistatic radar"

The accurate estimation of a monostatic radar range profile is considered when in the presence of multistatic radar interference for which the illuminating waveforms are assumed known. In an effort to approach the ideal interference-free performance, the range-domain 'beamforming' properties of the recently developed multistatic adaptive pulse compression (MAPC) algorithm is herein combined with the well-known CLEAN algorithm which operates on an interference-subtraction basis. Two versions of this hybridised methodology are presented and compared. To ascertain relative sensitivity, both the mean-squared error and the probability of detection are examined as a function of SNR when in the presence of multistatic interference. It is demonstrated that the respective merits of MAPC and CLEAN can be used to offset the limitations of the other and thereby combine to provide significant additional sensitivity improvement. [J161]

"Doppler Resilient Golay Complementary Waveforms"

We describe a method of constructing a sequence (pulse train) of phase-coded waveforms, for which the ambiguity function is free of range sidelobes along modest Doppler shifts. The constituent waveforms are Golay complementary waveforms which have ideal ambiguity along the zero Doppler axis but are sensitive to nonzero Doppler shifts. We extend this construction to multiple dimensions, in particular to radar polarimetry, where the two dimensions are realized by orthogonal polarizations. Here we determine a sequence of two-by-two Alamouti matrices where the entries involve Golay pairs and for which the range sidelobes associated with a matrix-valued ambiguity function vanish at modest Doppler shifts. The Prouhet-Thue-Morse sequence plays a key role in the construction of Doppler resilient sequences of Golay complementary waveforms. [J162]

"A Low-Power High-Sensitivity X-Band Rail SAR Imaging System [JMeasurement's Corner]"

Wideband radar imaging with range gating and high sensitivity can be achieved with the use of low-cost commercially available narrowband IF filters. Such filters reduce the effective receiver noise bandwidth of the radar system. This allows for high sensitivity, comparable to that of single-sideband radio receivers, while at the same time acquiring de-chirped wide-band received waveforms. A carefully developed radar architecture, based on the use of these IF filters, is shown in this paper. This radar architecture is then implemented in an X-band linear rail synthetic-aperture-radar (SAR) imaging system. The X- band rail SAR is a linear FM-chirped radar, which chirps from approximately 7.5 GHz to 12.5 GHz. The radar front end is mounted onto an eight-foot-long linear rail. The transmitted power is adjustable to 10dBm or less. It will be shown that objects as small as groups of pushpins in free space can be imaged using transmitted power as low as 10 nW. These results are compared to previous direct-conversion X-band FMCW rail SAR work. A high-sensitivity X-band rail SAR such as this could be useful for measuring low-radar-cross-section (RCS) targets. This radar could be used in high clutter environments that require a range gate. This low-power X-band rail SAR could be useful for operation in restricted transmission areas, where maximum radiated power is severely limited. Other applications include any that require low transmitter power, such as automotive radar. [J163]

"ISRO's programmable digital waveform generator"

One of the major and common requirements for all active microware sensors is generation of the transmit

modulation signal-like chirp/LFM signal, MSK, etc., which can be generated by analog or digital means. With the increasing demands of side bandwidth, longer duration chirp signals in radar systems, digital signal generation, and processing has emerged as a preferred alternative. Design and development of programmable and generic digital waveform generator (DWG) system based on Xilinx Virtex XCV600 FPGA and high-speed DAC is carried out at the Space Applications Center. ISRO is to generate required transmit chirp signal of high time-bandwidth product (~ 1000) for ISO's microwave radar sensor missions. This gives a detailed description of the design requirements, implementation details, salient performance features, and test results of this programmable and generic digital waveform generator (DWG). [J164]

"Bounds on the Volume and Height Distributions for the MIMO Radar Ambiguity Function"

The multiple-input multiple-output (MIMO) radar delay-Doppler ambiguity function is introduced as the sum of all auto- and cross-ambiguity functions of the set of K spatially diverse waveforms. The integral of this function over the range-Doppler frequency region occupied by spread clutter relates to the clutter's power at the output of the matched MIMO receiver, and it serves as a measure of orthogonality of the waveforms in this region. We derive the upper bound on the attainable "clear area" for the ambiguity function, and we show that, with respect to the conventional single-waveform ambiguity function, the maximum clear area is K times smaller for the MIMO system. [J165]

"Signal Synthesis and Receiver Design for MIMO Radar Imaging"

Multiple-input-multiple-output (MIMO) radar is an emerging technology that has significant potential for advancing the state-of-the-art of modern radar. When orthogonal waveforms are transmitted, with M+N(Ntransmit and Mreceive) antennas, an MN-element filled virtual array can be obtained. To successfully utilize such an array for high-resolution MIMO radar imaging, constant-modulus transmit signal synthesis and optimal receive filter design play critical roles. We present in this paper a computationally attractive cyclic optimization algorithm for the synthesis of constant-modulus transmit signals with good auto- and cross-correlation properties. Then we go on to discuss the use of an instrumental variables approach to design receive filters that can be used to minimize the impact of scatterers in nearby range bins on the received signals from the range bin of interest (the so-called range compression problem). Finally, we present a number of numerical examples to demonstrate the effectiveness of the proposed approaches. [J166]

"MIMO Radar Ambiguity Properties and Optimization Using Frequency-Hopping Waveforms"

The concept of multiple-input multiple-output (MIMO) radars has drawn considerable attention recently. Unlike the traditional single-input multiple-output (SIMO) radar which emits coherent waveforms to form a focused beam, the MIMO radar can transmit orthogonal (or incoherent) waveforms. These waveforms can be used to increase the system spatial resolution. The waveforms also affect the range and Doppler resolution. In traditional (SIMO) radars, the ambiguity function of the transmitted pulse characterizes the compromise between range and Doppler resolutions. It is a major tool for studying and analyzing radar signals. Recently, the idea of ambiguity function has been extended to the case of MIMO radar. In this paper, some mathematical properties of the MIMO radar ambiguity function are first derived. These properties provide some insights into the MIMO radar waveform design. Then a new algorithm for designing the orthogonal frequency-hopping waveforms is proposed. This algorithm reduces the sidelobes in the corresponding MIMO radar ambiguity function and makes the energy of the ambiguity function spread evenly in the range and angular dimensions. [J167]

"Mapping the Shallow Water Seabed Habitat With the SHOALS"

The scanning hydrographic operational airborne light detection and ranging (LiDAR) Survey (SHOALS) consists of a bathymetric LiDAR system that provides high-precision measurements of water depth. Although the acquisition is focused on depth accuracy, the return signal, i.e., waveform, contains other relevant information because of integration signatures from the water surface, the water column, and the seabed. This paper highlights the benthic characterization in extracting statistical parameters derived from the bottom backscatter and classifying them. In implementing a specific unsupervised classification, it is significantly proven that the signals derived from habitat, described as statistically homogeneous throughout ground-truth analysis, are similar within an intrahabitat view, whereas they are different between themselves. [J168]

"Diversity-Integration Tradeoffs in MIMO Detection"

In this paper, a multiple-input multiple-output (MIMO) detection problem is considered. At first, we derive the generalized likelihood ratio test (GLRT) for arbitrary transmitted signals and arbitrary time-correlation of the disturbance. Then, we investigate design criteria for the transmitted waveforms in both power-unlimited and power-limited systems and we derive closed-form formulas for the probability of false alarm and the detection

probability. Finally, we study the interplay among the rank of the optimized space-time code (i.e., the number of linearly independent transmitted waveforms), the number of transmit diversity paths generated in the signal space, and the amount of energy integrated along each path. The results confirm that there is an inherent tradeoff between diversity and integration, and that no uniformly optimum waveform design strategy exists. [J169]

"Combined Multistatic Adaptive Pulse Compression and Adaptive Beamforming for Shared-Spectrum Radar"

The recently proposed Multistatic Adaptive Pulse Compression (MAPC) algorithm has been shown to successfully suppress both range sidelobes and interference from multiple radars operating in the same spectrum, thus enabling shared-spectrum multistatic radar. In this paper, we present a method to increase the overall information capacity of the MAPC algorithm by performing joint adaptive pulse compression in conjunction with adaptive beamforming. The addition of an adaptive beamforming stage to the MAPC algorithm enables further mutual interference suppression and thus better estimation performance such that the number of multistatic radars simultaneously operating in the same spectrum may be increased for the same mean-square estimation error. Analysis of the performance of the adaptive beamforming MAPC algorithm in a variety of scenarios is presented. In addition, Monte Carlo analyses on the number of shared-spectrum radars are also presented [J170]

"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. [J171]

"Phase-coded waveforms for radar"

This correspondence focuses on the use of phase-coded (PC) waveforms for radar. The authors present tradeoffs between the use of matched versus mismatched filters, loss in signal-to-noise ratio (SNR), time sidelobe levels, and Doppler intolerance for random and cyclic codes. A multiple hypothesis approach is introduced for countering intrapulse Doppler intolerance [J172]

"Ambiguity Function and Frame-Theoretic Properties of Periodic Zero-Autocorrelation Waveforms"

Periodic constant-amplitude zero-autocorrelation (CAZAC) waveforms u are analyzed in terms of the discrete periodic ambiguity function A u. Elementary number-theoretic considerations illustrate that peaks in Auare not stable under small perturbations in its domain. Further, it is proved that the analysis of vector-valued CAZAC waveforms depends on methods from the theory of frames. Finally, techniques are introduced to characterize the structure of Au, to compute u in terms of Au, and to evaluate MSE for CAZAC waveforms [J173]

"Adaptive Waveform Design and Sequential Hypothesis Testing for Target Recognition With Active Sensors"

Cognitive radar is a recently proposed approach in which a radar system may adaptively and intelligently interrogate a propagation channel using all available knowledge including previous measurements, task priorities, and external databases. A distinguishing characteristic of cognitive radar is that it operates in a closed loop, which enables constant optimization in response to its changing understanding of the channel. In this paper, we compare two different waveform design techniques for use with active sensors operating in a target recognition application. We also propose the integration of waveform design with a sequential-hypothesis-testing framework that controls when hard decisions may be made with adequate confidence. The result is a system that updates multiple target hypotheses/classes based on measured data, customizes waveforms as the class probabilities change, and draws conclusions when sufficient understanding of the propagation channel is achieved [J174]

"MIMO Radar Ambiguity Functions"

Multiple-Input Multiple-Output (MIMO) radar has been shown to provide enhanced performance in theory and in practice. MIMO radars are equipped with the ability to choose freely their transmitted waveforms at each aperture. In conventional radar systems Woodward's ambiguity function is used to characterize waveform resolution performance. In this paper we extend the idea of waveform ambiguity functions to MIMO radars. MIMO ambiguity functions are developed that simultaneously characterize the effects of array geometry and transmitted waveforms on resolution performance. Overall resolution performance is shown to be governed by a space-time covariance function that can be controlled by the system on transmit using waveform diversity. Visual examples are provided to illustrate the resolution enhancement possible using MIMO technology [J175]

"Adaptive Waveform Design for Improved Detection of Low-RCS Targets in Heavy Sea Clutter"

The dynamic adaptation of waveforms for transmission by active radar has been facilitated by the availability of waveform-agile sensors. In this paper, we propose a method to employ waveform agility to improve the detection of low radar-cross section (RCS) targets on the ocean surface that present low signal-to-clutter ratios due to high sea states and low grazing angles. Employing the expectation-maximization algorithm to estimate the time-varying parameters for compound-Gaussian sea clutter, we develop a generalized likelihood ratio test (GLRT) detector and identify a range bin of interest. The clutter estimates are then used to dynamically design a phase-modulated waveform that minimizes the out-of-bin clutter contributions to this range bin. A simulation based on parameters derived from real sea clutter data demonstrates that our approach provides around 10 dB improvement in detection performance over a nonadaptive system [J176]

"Automatic Radar Waveform Recognition"

In this paper, a system for automatically recognizing radar waveforms is introduced. This type of techniques are needed in various spectrum management, surveillance and cognitive radio or radar applications. The intercepted radar signal is classified to eight classes based on the pulse compression waveform: linear frequency modulation (LFM), discrete frequency codes (Costas codes), binary phase, and Frank, P1, P2, P3, and P4 polyphase codes. The classification system is a supervised classification system that is based on features extracted from the intercepted radar signal. A large set of potential features are presented. New features based on Wigner and Choi-Williams time-frequency distributions are proposed. The feature set is pruned by discarding redundant features using an information theoretic feature selection algorithm. The performance of the classification system is analyzed using extensive simulations. Simulation results show that the classification system achieves overall correct classification rate of 98% at signal-to-noise ratio (SNR) of 6 dB on data similar to the training data [J177]

"Optimal Signal Design for Detection of Gaussian Point Targets in Stationary Gaussian Clutter/Reverberation"

In this paper, we address the design of an optimal transmit signal and its corresponding optimal detector for a radar or active sonar system. The focus is on the temporal aspects of the waveform with the spatial aspects to be described in a future paper. The assumptions involved in modeling the clutter/reverberation return are crucial to the development of the optimal detector and its consequent optimal signal design. In particular, the target is assumed to be a Gaussian point target and the clutter/reverberation a stationary Gaussian random process. In practice, therefore, the modeling will need to be assessed and possibly extended, and additionally a means of measuring the "in-situ" clutter/reverberation spectrum will be required. The advantages of our approach are that a simple analytical result is obtained which is guaranteed to be optimal, and also the extension to spatial-temporal signal design is immediate using ideas of frequency-wavenumber representations. Some examples are given to illustrate the signal design procedure as well as the calculation of the increase in processing gain. Finally, the results are shown to be an extension of the usual procedure which places the signal energy in the noise band having minimum power [J178]

"Information Theoretic Adaptive Radar Waveform Design for Multiple Extended Targets"

In this paper, we use an information theoretic approach to design radar waveforms suitable for simultaneously estimating and tracking parameters of multiple extended targets. Our approach generalizes the information theoretic water-filling approach of Bell to allow optimization for multiple targets simultaneously. Our paper has three main contributions. First, we present a new information theoretic design criterion for a single transmit waveform using a weighted linear sum of the mutual informations between target radar signatures and the corresponding received beams (given the transmitted waveforms). We provide a family of design criteria that weight the various targets according to priorities. Then, we generalize the information theoretic design criterion for designing multiple waveforms under a joint power constraint when beamforming is used both at the transmitter and the receiver. Finally, we provide a highly efficient algorithm for optimizing the transmitted waveforms in the cases of single waveform and multiple waveforms. We also provide simulated experiments of both algorithms based on real targets and comment on the generalization of the proposed technique for other design criteria, e.g., the linearly weighted noncausal MMSE design criterion [J179]

"Bistatic Linear Antenna Array SAR for Moving Target Detection, Location, and Imaging With Two Passive Airborne Radars"

In this paper, we propose a bistatic linear array synthetic aperture radar (BLA-SAR) system for moving target detection, location, and imaging. In the BLA-SAR system, a geostationary satellite is used as a transmitter, and

two airborne linear array radars are used as passive receivers, where the transmitted waveforms from the geostationary satellite may have two different carrier frequencies, two linear array antennas on two different airplanes may be equipped with different spacings, or two airplanes may fly with two different velocities. It is shown that, using the BLA-SAR, not only the stationary clutter can be suppressed but also locations of both slow and fast moving targets can be accurately estimated. Furthermore, an effective BLA-SAR algorithm of moving target imaging is also proposed. Lastly, some numerical experiments are given to demonstrate the effectiveness of the BLA-SAR [J180]

"Reconstruction From Antenna-Transformed Radar Data Using a Time-Domain Reconstruction Method"

This paper discusses the reconstruction of the subsurface from radar data using a time-domain reconstruction method. Before the reconstruction is conducted, data preprocessing is carried out. The preprocessing transforms measured data transmitted and received by 3-D dipole antennas into equivalent data excited and received by 3-D ideal electric dipoles and, then, into equivalent data excited and received by 2-D ideal electric dipoles. Distributions of permittivity, conductivity, and permeability are reconstructed from the preprocessed data by a 2-D forward-backward time-stepping waveform inverse scattering technique. Two 2-D examples of permittivity and conductivity reconstruction from synthetic noisy and field borehole radar data are demonstrated to show the effectiveness of the proposed method [J181]

"Pulse Design for Time Reversal Method as Applied to Ultrawideband Microwave Breast Cancer Detection: A Two-Dimensional Analysis"

We conduct a two-dimensional study of pulse design for electromagnetic time-reversal (TR) imaging as applied to ultrawideband (UWB) breast cancer detection. We consider the situation when a tumor located in the human breast is surrounded by a large number of small tissue inhomogeneities that create strong signal clutter. When applying the TR algorithm, the excitation pulse should be properly designed such that there are distinguishable differences between the tumor and clutter responses. In this paper, we propose four pulse design criteria for the TR-based tumor detection. The modulated and modified Hermite polynomials (MMHPs) that fit well into the real pulse shapes are used as a general waveform template for the design process. Finally, numerical examples are used to demonstrate the usefulness of the proposed analytical framework. This paper can be a guide in the selection of suitable waveforms for which the tumor response can be enhanced and/or the clutter interference can be suppressed. The investigation is also well suited for applications to surface-penetrating radar using UWB signals [J182]

"A GPS-Reflections Receiver That Computes Doppler/Delay Maps in Real Time"

This paper describes a new instrument that was specially designed and developed to gather Global Positioning System (GPS) signals after they have been reflected from suitable surfaces (sea, ice, and ground), for Earth remote sensing. The device has been called the GPS open-loop differential real-time receiver (GOLD-RTR). Its main and most innovative feature is its computation and storage, in real time, of complex-valued (I and Q) cross correlations (waveforms) between GPS L1-C/A signals-received directly and after reflection-and the corresponding models of these signals. Particularly, the GOLD-RTR schedules consecutive coherent integration time slots of 1 ms over which ten parallel correlation channels, with 64 lags each, work simultaneously and continuously with the input raw data sampled at 40 MHz. The total throughput is 10 000 waveforms per second, each waveform being 64 lags long. These real-time correlation resources can be flexibly distributed in several configurations according to the observational requirements, for instance: Doppler/delay maps or up to ten simultaneous reflected waveforms for ten different GPS satellites are examples of what can be done. The further processing of the real-time computed 1-ms waveforms in a flight campaign over the ocean, ice, or ground can be used to obtain geophysical parameters such as sea level and tides, sea surface mean-square slopes, ice roughness and thickness, soil moisture and biomass, or future applications. This paper covers the GOLD-RTR architecture and hardware, signal processing and data storage issues, machine-user interface, laboratory readiness tests, and waveform data samples from the first two jet aircraft campaigns at 9300 m over the sea [J183]

"A Sharpened Dynamic Range of a Generalized Chinese Remainder Theorem for Multiple Integers"

A generalized Chinese remainder theorem (CRT) for multiple integers from residue sets has been studied recently, where the remainders in a residue set are not ordered. In this correspondence, we first propose a majority method and then based on the proposed majority method we present a sharpened dynamic range of multiple integers that can be uniquely determined from their residue sets [J184]

"Mathematics of Synthesizing Range Profile"

The mathematics of synthesizing a high-range resolution profile (HRRP) is discussed. With a generalized model of synthetic wideband signal and its echo signal, stretch processing technique is extended and refined. Then, an investigation on the mathematic principle of synthesizing a range profile demonstrates that quadratic phase error criterion does not exactly represent the effect of motion on a synthetic range profile (SRP). Therefore, a least-mean-square error criterion is proposed, and several conclusions about the new criterion are derived. In addition, specific conclusions about the distortion for a stepped-frequency waveform (SFW) are investigated with some simulations [J185]

"Hexagonal Multicarrier Modulation: A Robust Transmission Scheme for Time-Frequency Dispersive Channels"

By regarding signal transmission as tiling of the time-frequency plane, we propose a multicarrier transmission scheme on hexagonal lattice, coined the term hexagonal multicarrier modulation. To optimally combat the impact of the propagation channels, the underlying lattice parameters and the pulse shape of modulation waveform are jointly optimized to adapt to the channel scattering function from a minimum energy perturbation point of view. It comes out that there exist two equivalent pulse and lattice matching criteria for each channel scattering function to achieve minimal interpulse interference (IPI). Robustness of the proposed system against the wireless channels is analyzed in terms of robustness factor. Numerical analysis and simulation results show that the hexagonal multicarrier transmission system outperforms conventional orthogonal-frequency-division multiplexing (OFDM) and lattice-OFDM (LOFDM) systems with regard to robustness against channel dispersion [J186]

"Increasing the Existence of Very Shallow-Water LIDAR Measurements Using the Red-Channel Waveforms"

Mapping shallow-water bathymetry with acoustic techniques is complicated and expensive. The environmental parameters in shallow-water (<2 m) areas become more variable and greatly impact the depth extraction from the survey measurements. Current airborne light detection and ranging (LIDAR) bathymetry surveying in shallow-water depths uses green-channel waveforms to measure the water depth. Unfortunately, due to difficulties in distinguishing between the surface and bottom return of the water column, the timing of the bottom return is often ambiguous. Furthermore, the water often becomes optically "dirty" due to turbulence at these shallow depths. Therefore, it is common to find coastal areas that lack any measured depths. This paper presents a novel approach for measuring water depths in these shallow coastal waters with airborne LIDAR. Observations of the red-channel waveforms show that the waveforms are divided into two groups, namely: (1) waveforms in deep waters (>2 m) whose shape is invariant with respect to the water depth and (2) waveforms in shallow-water depths that show a change in shape as a function of the depth in the water column. The data for this study are from the US Geological Survey LIDAR surveys of Lake Tahoe, CA, and Lake Michigan, using a SHOALS-400 LIDAR system [J187]

"A Simple Signal Processing Architecture for Instantaneous Radar Polarimetry"

This paper describes a new radar primitive that enables instantaneous radar polarimetry at essentially no increase in signal processing complexity. This primitive coordinates transmission of distinct waveforms on orthogonal polarizations and applies a unitary matched filter bank on receive. This avoids the information loss inherent in single-channel matched filters. A further advantage of this scheme is the elimination of range sidelobes [J188]

"Random Noise Radar/Sodar With Ultrawideband Waveforms"

Random noise waveforms with ultrawide bandwidth improve the range resolution and reduces the probability of intercept in radar/sodar. As a result of the nonperiodic waveform, the range ambiguity is removed as well. By transmitting a sine signal that is phase or frequency modulated by random noise, autocorrelation functions with improved side lobe suppression in range can be formed. There are great similarities in the signal-processing algorithms applied in noise radar and sodar. The much slower propagation velocity of sound compared to light reduces the signal bandwidth but increases the time of measurement, however. In both sodar and radar, the range resolution is determined by the wavelength band occupied by the transmitted waveform, while the velocity resolution is controlled by the ratio of wavelength and time of measurement. The slower sound velocity also enhances the range/Doppler ambiguity problem in sodar when periodic waveforms are applied. This ambiguity could be suppressed if nonperiodic waveforms are introduced, such as random noise. In this paper, fundamental similarities and differences on system level between sodar and radar are first discussed, and signal-processing algorithms applied in random noise radar/sodar are reviewed. In particular, the noise floor of the ambiguity

function and its relationship to spectrum width and time of measurement are analyzed, including improved side lobe suppression using mismatched filtering. The signal-processing algorithms were tested on raw data from sodar measurements on moving targets, buildings, vegetation, and water surfaces. An adaptive filter algorithm for suppression of the increased noise floor from dominant reflectors was derived and successfully applied to both sodar and stepped frequency radar data [J189]

"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 [J190]

"A Novel Clutter Suppression Algorithm for Landmine Detection With GPR"

In this paper, we propose a new algorithm for the enhancement of plastic-cased antipersonnel mine detection using a video-impulse ground-penetrating radar (GPR). The algorithm is implemented as a nonlinear signal processor, which searches for the presence of a reference waveform in a 1D GPR echo return. The reference waveform represents a class of targets within a certain environment. The processor marks the presence of all responses similar to the reference waveform with a sharp mono-cycle. Simultaneously, responses with different waveforms, which presumably correspond to clutter, are suppressed. The reference waveform and other algorithm parameters are determined from training data sets acquired in a controlled environment. After training, the algorithm can be successfully applied at sites where soil, targets, and measurement scenarios are similar but not identical to those of the training site. The processor is integrated into an automated data processing and mine detection scheme as an additional clutter suppression step. The scheme consists of clutter suppression, synthetic aperture radar focusing, construction of a confidence map, and automated detection in it. The suggested algorithm is tested on experimental data, and its performance is compared against schemes where clutter suppression is organized by means of background removal and the cross correlation with a reference wavelet. The performance comparison is done in terms of receiver operating characteristic curves. It has been found that the suggested algorithm reduces the false alarm rate in about two and a half times in comparison to the cross-correlation-based clutter suppression. [J191]

"Petaloid antenna for passive UWB-RFID tags"

An ultra-wideband (UWB) antenna designed with a petal-shaped structure is presented. Its measured impedance bandwidth of 10 dB return loss is from 6.6 to 17.5 GHz whereas the size is just 18times16 mm. The radar cross-section and scattered waveforms of the proposed petaloid antenna are theoretically studied using the finite-difference time-domain (FDTD) method. Its backscattering of antenna mode is comparable to that of structural mode, and the scattering pattern is almost omnidirectional. This antenna is suitable for passive ultra-wideband radio-frequency identification (UWB-RFID) tag applications. [J192]

"On Parameter Identifiability of MIMO Radar"

A multi-input multi-output (MIMO) radar system, unlike a standard phased-array radar, can transmit multiple linearly independent probing signals via its antennas. We show herein that this waveform diversity enables the MIMO radar to significantly improve its parameter identifiability. Specifically, we show that the maximum number of targets that can be uniquely identified by the MIMO radar is up to Mttimes that of its phased-array counterpart, where Mtis the number of transmit antennas. [J193]

"High-bandwidth 220 GHz experimental radar"

An experimental radar at 220 GHz has been developed which is capable of delivering an instantaneous bandwidth of 8000 MHz. The solid-state radar uses an FM-CW waveform. The development is based on experience with a 94 GHz broadband measurement radar. The data undergo an ISAR imaging process to derive high-resolution scattering centre distributions for targets measured in tower/turntable configuration. High-resolution processing algorithms have been developed which result in scattering centre distributions with a resolution better than 2 cm at ranges of and exceeding 200 m. The radar will be used for investigations on target signatures of small objects for stand-off detection of concealed weapons and other threat material. [J194]

"MIMO Radar with Colocated Antennas"

We have provided a review of some recent results on the emerging technology of MIMO radar with colocated antennas. We have shown that the waveform diversity offered by such a MIMO radar system enables significant superiority over its phased-array counterpart, including much improved parameter identifiability, direct applicability of adaptive techniques for parameter estimation, as well as superior flexibility of transmit beampattern designs. We hope that this overview of our recent results on the MIMO radar, along with the related results obtained by our colleagues, will stimulate the interest deserved by this topic in both academia and government agencies as well as industry. [J195]

"Pulse Compression Sidelobe Reduction by Minimization of Lp -Norms"

Most modern radar systems make extensive use of pulse compression techniques. This paper presents a technique for the design of mismatched receive finite impulse response (FIR) filters based on the minimization of Lp-norms of the sidelobes. The goal of the minimization process is to reduce the range sidelobe levels of the convolution of the transmit pulse and the receive filter. A closed-form solution is derived for the least-squares case (which is equivalent to the L2-norm) and an expression for the optimization of the higher order norms is developed. The solutions for the higher order norms have to be obtained by means of iterative numerical methods. The effect of using receive filters which are longer than the transmit pulses is also investigated. Results are presented for linear FM transmit waveforms having time-bandwidth products ranging from 10 to 100 in combination with selected values of the norm order ranging from 2 to 200. Receive filter lengths up to three times the transmit pulse lengths are investigated. Results are presented which highlight the tradeoffs between sidelobe level, mismatch loss and mainlobe width. The effect of Doppler shift on the sidelobe response of these receive filters is also investigated. [J196]

"Real-time sparse frequency waveform design for HFSWR system"

High frequency surface wave radar (HFSWR) systems operate in heavily congested high frequency (HF) band. It is very difficult to find continuous clear channels for the wideband HFSWR systems. Presented is a real-time sparse frequency waveform design approach. [J197]

"Waveform Design for MIMO Radars"

We consider the problem of waveform design for multiple input/multiple output (MIMO) radars, where the transmit waveforms are adjusted based on target and clutter statistics. A model for the radar returns which incorporates the transmit waveforms is developed. The target detection problem is formulated for that model. Optimal and suboptimal algorithms are derived for designing the transmit waveforms under different assumptions regarding the statistical information available to the detector. The performance of these algorithms is illustrated by computer simulation. [J198]

"Focused 70-cm Wavelength Radar Mapping of the Moon"

We describe new 70-cm wavelength radar images of the lunar near-side and limb regions obtained via a synthetic-aperture-radar patch-focusing reduction technique. The data are obtained by transmitting a circularly polarized pulsed waveform from the Arecibo telescope in Puerto Rico and receiving the echo in both senses of circular polarization with the Robert C. Byrd Green Bank Telescope in West Virginia. The resultant images in both polarizations have a spatial resolution as fine as 320 m 450 m near the lunar limb. The patch-focusing technique is a computationally efficient method for compensating for range migration and Doppler (azimuth) smearing over long coherence times, i.e., 983 s, which is needed to achieve the required Doppler resolution. Three to nine looks are averaged for speckle reduction and to improve the signal-to-noise ratio. At this long wavelength, the radar signal penetrates up to several tens of meters into the dry lunar surface materials, thus revealing details of the bulk loss properties and decimeter-scale rock abundance not evident in multispectral and other remote-sensing data. Application of the new radar images to the analysis of basalt flow complexes in Mare Serenitatis shows that the long-wavelength radar data are sensitive to differences in both flow age and composition, and may be particularly useful for studies of smaller deposits that do not have robust crater statistics. The new 70-cm lunar radar data are archived at the National Aeronautics and Space Administration Planetary Data System. [J199]

"Radar Pulse Compression Repair"

This correspondence presents an adaptive approach for range sidelobe mitigation for use by future radar systems as well as in-service radar systems in which the precompressed received signal may not be readily

available or it may not be feasible to replace the current pulse compression system. The approach, denoted as pulse compression repair (PCR), utilizes a previously developed adaptive technique to operate on the match filtered output treating the resulting waveform autocorrelation as if it were the transmitted waveform thus "repairing" the effects of range-sidelobe masking that are induced by matched filtering. Illustrative results are presented comparing PCR with the matched filter and the CLEAN algorithm which demonstrate significant performance advantages for PCR as well as robustness to Doppler mismatch and system errors. [J200]

"Algebraic Algorithms to Separate Overlapping Secondary Surveillance Radar Replies"

The secondary surveillance radar (SSR) is a transponder system used in air-traffic control (ATC). Due to growing traffic densities, it is increasingly likely that a ground station receives a mixture of responses of various aircraft, partly overlapping in frequency and time. Currently such "collisions" are disregarded, at a loss of system performance and reliability. In this paper, we propose to equip the ground station with an antenna array, and investigate techniques to blindly separate such a mixture based on source waveform properties. At baseband, a received SSR signal consists of a binary sequence with alphabet {0,1}, modulated by a complex exponential due to the residual carrier frequency. We present three algebraic algorithms to compute the separating beamformers by taking into account the particular modulation format of the received signal. The Cramer-Rao bound (CRB) is derived, extensive simulations are presented, and an experimental platform has been built to collect measurement data and demonstrate the algorithms. [J201]

"Dynamic Configuration of Time-Varying Waveforms for Agile Sensing and Tracking in Clutter"

The advent of waveform-agile sensors has enabled the design of tracking systems where the transmitted waveform is changed on-the-fly in response to the tracker's requirements. This approach can provide performance improvements over individual optimization of the sensor waveform or the tracking algorithm. In this paper, we consider joint sensor configuration and tracking for the problem of tracking a single target in the presence of clutter using range and range-rate measurements obtained by waveform-agile, active sensors in a narrowband environment. We propose an algorithm to select and configure linear and nonlinear frequency-modulated waveforms to minimize the predicted mean square error (MSE) in the target state estimate; the MSE is predicted using the Cramer-Rao lower bound on the measurement error in conjunction with the unscented transform. We further extend our algorithm to match wideband environments, and we demonstrate the algorithm performance through a Monte Carlo simulation of a radar tracking example. [J202]

"Concurrent Extraction of Target Range and Doppler Information by Using Orthogonal Coding Waveforms"

In this paper, a novel approach for concurrent extraction of target range and Doppler information in radar systems is introduced. A pair of orthogonal waveforms with different pulse repetition frequencies (PRF) are bundled and transmitted as a single hybrid radar waveform for target measurement. At the receiver, two orthogonal signal processing channels consisting of a low PRF (LPRF) channel and a high PRF (HPRF) one, perform the extraction of target range and Doppler information, respectively. The CLEAN algorithm is innovatively used to suppress the interference from the cross-correlation residues and the autocorrelation sidelobe in the LPRF channel. The processing results, based on the proposed signal processing approach, demonstrate the technical feasibility of implementing such a signal processing scheme in radar systems. [J203]

"Concurrent Operation of Two Over-the-Horizon Radars"

By exploiting the reflective and refractive nature of high-frequency (HF) radiowave propagation through the ionosphere or the conducting sea surface, over-the-horizon radar (OTHR) systems perform wide-area surveillance at long range well beyond the limit of the horizon of conventional line-of-sight (LOS) radars. Improved characterizations of the targets can be achieved by using multiple OTHRs operating simultaneously as compared to a single OTHR operating alone. In this paper, we consider concurrent operations of two OTHR systems that occupy the same frequency band with different chirp waveforms. The objective is to respond to the advanced wide-area surveillance needs without reducing the wave repetitive frequency. For this purpose, a new cross-radar interference cancellation technique is developed and its effectiveness is verified through both analytical and simulation results [J204]

"COMMENT-COMMENT ON 'MULTI-RANGERESOLUTION RADAR USING SIDEBAND SPECTRUM ENERGY'"

The prevailing pulse compression technique utilises a matched filter receiver in order to achieve the highest attainable output signal-to-noise ratio (SNR), and relies on a judicious choice of transmitted waveform to achieve

range response with narrow mainlobe and low sidelobes. As is well known, the magnitude of the frequency response of the matched filter is identical to the magnitude of the spectrum of the transmitted waveform. The logic is to amplify those frequencies where the signal's power spectral density is high and attenuate frequencies dominated by noise. A recently published paper [M. Shinriki et al., 2006] suggests a new pulse compression approach that is the antithesis of the matched filter. Rather than utilising the power in the spectral mainlobe of the transmitted waveform, the suggested mismatched filter attenuates the frequencies occupied by the waveform's spectral mainlobe and enhances the sidelobe frequencies. In this way, the suggested approach squeezes a 1 ms delay resolution out of an unmodulated 5 ms pulse. [J205]

"Full-Waveform Inversion of Crosshole Radar Data Based on 2-D Finite-Difference Time-Domain Solutions of Maxwell's Equations"

Crosshole radar techniques are important tools for a wide range of geoscientific and engineering investigations. Unfortunately, the resolution of crosshole radar images may be limited by inadequacies of the ray tomographic methods that are commonly used in inverting the data. Since ray methods are based on high-frequency approximations and only account for a small fraction of the information contained in the radar traces, they are restricted to resolving relatively large-scale features. As a consequence, the true potential of crosshole radar techniques has yet to be realized. To address this issue, we introduce a full-waveform inversion scheme that is based on a finite-difference time-domain solution of Maxwell's equations. We benchmark our new scheme on synthetic crosshole data generated from suites of increasingly complex models. The full-waveform tomographic images accurately reconstruct the following: (1) the locations, sizes, and electrical properties of isolated subwavelength objects embedded in homogeneous media; (2) the locations and sizes of adjacent subwavelength objects embedded in homogeneous media; (3) abrupt media boundaries and average and stochastic electrical property variations of heterogeneous layered models; and (4) the locations, sizes, and electrical conductivities of water-filled tunnels and closely spaced subwavelength pipes embedded in heterogeneous layered models. The new scheme is shown to be remarkably robust to the presence of uncorrelated noise in the radar data. Several limitations of the full-waveform tomographic inversion are also identified. For typical crosshole acquisition geometries and parameters, small resistive bodies and small closely spaced dielectric objects may be difficult to resolve. Furthermore, electrical property contrasts may be underestimated. Nevertheless, the full-waveform inversions usually provide substantially better results than those supplied by traditional ray methods. [J206]

"Ultrawideband Radar Measurements of Thickness of Snow Over Sea Ice"

An accurate knowledge of snow thickness and its variability over sea ice is crucial in determining the overall polar heat and freshwater budget, which influences the global climate. Recently, algorithms have been developed to extract snow thicknesses from satellite passive microwave data. However, validation of these data over the large footprint of the passive microwave sensor has been a challenge. The only method used thus far has been with meter sticks during ship cruises. To address this problem, we developed an ultrawideband frequency-modulated continuous-wave radar to measure the snow thickness over sea ice. We synthesized a very linear chirp signal by using a phase-locked loop with a digitally generated chirp signal as a reference to obtain a fine-range resolution. The radar operates over the frequency range from 2-8 GHz. We made snow-thickness measurements over the Antarctic sea ice by operating the radar from a sled in September and October 2003. We performed radar measurements over 11 stations with varying snow thicknesses between 4 and 85 cm. We observed an excellent agreement between radar estimates of snow thickness with physical measurements, achieving a correlation coefficient of 0.95 and a vertical resolution of about 3 cm. Comparison of simulated radar waveforms using a simple transmission line model with the measurements confirms our expectations that echoes from snow-covered sea ice are dominated by reflections from air-snow and snow-ice interfaces. [J207]

"Bipolar waveform generator for time limited response when driving RC loads"

A method is presented whereby a compact circuit generates bipolar VHF waveforms of which the relative duration and amplitude of the positive and negative half cycles are adjustable. This facilitates fine timing of the waveform for a time limited response when driving resistor-capacitor loads. Performance is verified by measurements on a system functioning as a ground penetrating radar system where the antenna presents such an equivalent load. [J208]

"22–29 GHz Ultra-Wideband CMOS Pulse Generator for Short-Range Radar Applications"

The pseudo-millimeter-wave ultra-wideband (UWB) is attractive for applications in short-range automotive radar systems using 22 to 29 GHz in order to realize road safety and intelligent transportation. Although the CMOS is suitable for short- range radar since processing units can be implemented in the same chip as the UWB front-end building block, it is difficult to operate CMOS pulse generators at such a high frequency. To realize the

pseudo-millimeter-wave band using CMOS, we have proposed a new pulse generator consisting of a series of delay cells and edge combiners with waveform shaping for short-range radar. As a result of measurement using 90-nm CMOS technology, 1 Gb/s/bit pulses with 71 mV peak-to-peak, 39.2 ps monopulse width and 552 ps envelope width are successfully generated with a power consumption of 1.4 mW at a supply voltage of 0.91 V. This result can be the basis for developing the key technology for one-chip short-range radar sensors. [J209]

"Wavelet Based Deconvolution Algorithm for Time-Domain Near-Field ISAR Imaging"

Based on correlation receiver in communication theory, the measured backscattering waveform of a calibration conducting sphere is adopted as the system impulse response. This antenna-target system response is then approximated by the derivatives of a Gaussian function (DGF) as well as the Coiflets to restore the impulse response of the target and to reconstruct the ISAR images. Both the DGF and Coiflets are applied to the deconvolution and their results are compared. The Gaussian and Coiflet function parameters are derived by a best-fit to the measured time-domain system response. Employing the parametric fits, a lowpass filter has been automatically embedded which performs regularization of the conjugate gradient (CG) optimization and speeds up the CG convergence. Numerical results show that the image quality from the Coiflet system is similar to or better than from the DGF system. Owing to the continuity, smoothness, orthogonality and compact support of the Coiflets, the size of the system matrix has been reduced from 1024 times 1024 for DGF to 261 times 261, and the deconvolution process is accelerated more than 22 fold without sacrificing image characters. [J210]

"Spatial diversity in radars-models and detection performance"

Inspired by recent advances in multiple-input multiple-output (MIMO) communications, this proposal introduces the statistical MIMO radar concept. To the authors' knowledge, this is the first time that the statistical MIMO is being proposed for radar. The fundamental difference between statistical MIMO and other radar array systems is that the latter seek to maximize the coherent processing gain, while statistical MIMO radar capitalizes on the diversity of target scattering to improve radar performance. Coherent processing is made possible by highly correlated signals at the receiver array, whereas in statistical MIMO radar, the signals received by the array elements are uncorrelated. Radar targets generally consist of many small elemental scatterers that are fused by the radar waveform and the processing at the receiver, to result in echoes with fluctuating amplitude and phase. It is well known that in conventional radar, slow fluctuations of the target radar cross section (RCS) result in target fades that degrade radar performance. By spacing the antenna elements at the transmitter and at the receiver such that the target angular spread is manifested, the MIMO radar can exploit the spatial diversity of target scatterers opening the way to a variety of new techniques that can improve radar performance. This paper focuses on the application of the target spatial diversity to improve detection performance. The optimal detector in the Neyman-Pearson sense is developed and analyzed for the statistical MIMO radar. It is shown that the optimal detector consists of noncoherent processing of the receiver sensors' outputs and that for cases of practical interest, detection performance is superior to that obtained through coherent processing. An optimal detector invariant to the signal and noise levels is also developed and analyzed. In this case as well, statistical MIMO radar provides great improvements over other types of array radars. [J211]

"Exploiting nonacoustic sensors for speech encoding"

The intelligibility of speech transmitted through low-rate coders is severely degraded when high levels of acoustic noise are present in the acoustic environment. Recent advances in nonacoustic sensors, including microwave radar, skin vibration, and bone conduction sensors, provide the exciting possibility of both glottal excitation and, more generally, vocal tract measurements that are relatively immune to acoustic disturbances and can supplement the acoustic speech waveform. We are currently investigating methods of combining the output of these sensors for use in low-rate encoding according to their capability in representing specific speech characteristics in different frequency bands. Nonacoustic sensors have the ability to reveal certain speech attributes lost in the noisy acoustic signal; for example, low-energy consonant voice bars, nasality, and glottalized excitation. By fusing nonacoustic low-frequency and pitch content with acoustic-microphone content, we have achieved significant intelligibility performance gains using the DRT across a variety of environments over the government standard 2400-bps MELPe coder. By fusing quantized high-band 4-to-8-kHz speech, requiring only an additional 116 bps, we obtain further DRT performance gains by exploiting the ear's insensitivity to fine spectral detail in this frequency region. [J212]

"Monopulse radar based on spatiotemporal correlation of stochastic signals"

The theory and technique of angle-of-arrival (AOA) estimation using random-noise or other stochastic transmit waveforms is addressed. The additional uncertainties induced by signal itself and the statistical complexity of the received signals result in major challenges. The statistical properties of the random-noise interferometer and

monopulse radar system are studied and compared theoretically using an approximation method. Furthermore, a random-noise coherent correlation receiver (CCR) architecture is proposed. The concept of mean monopulse characteristic curve (MMCC) is introduced. Experimental results using an X-band random-noise monopulse radar system validate the theoretical predictions of random-noise monopulse characteristics and suggest potential applications such as surveillance, imaging, and maneuvering target tracking. [J213]

"Impact of diverse polarisations on clutter statistics"

The author addresses the impact of diverse polarisations on clutter statistics in the context of waveform diversity for multi-functional operation from a specific platform as well as for multiple sensing from multiple platforms. A key issue in this context is that of clutter mitigation via the use of diverse waveforms. Classical space-time adaptive processing (STAP) methods for radar target detection can be viewed in the context of a whiten and match filter. To this end, efficient waveforms that lend themselves for such processing are sought. The author specifically considers a statistical analysis of experimental data collected at low grazing angles to validate the fact that vertical transmit-vertical receive (VV) polarised data conform to Rayleigh scatter, whereas horizontal transmit-horizontal receive data do not. Consequently, VV data are suitable for whiten and match processing adopted in conventional radar STAP. [J214]

"Knowledge-based radar signal and data processing: a tutorial review"

Radar systems are an important component in military operations. In response to increasingly severe threats from military targets with reduced radar cross sections (RCSs), slow-moving and low-flying aircraft hidden in foliage, and in environments with large numbers of targets, knowledge-based (KB) signal and data processing techniques offer the promise of significantly improved performance of all radar systems. Radars under KB control can be deployed to utilize valuable resources such as airspace or runways more effectively and to aid human operators in carrying out their missions. As battlefield scenarios become more complex with increasing numbers of sensors and weapon systems, the challenge will be to use already available information effectively to enhance radar performance, including positioning, waveform selection, and modes of operation. KB processing fills this need and helps meet the challenge. [J215]

"Inversion of a lidar waveform model for forest biophysical parameter estimation"

Due to its measurement principle, light detection and ranging (lidar) is particularly suited to estimate the horizontal as well as vertical distribution of forest structure. Quantification and characterization of forest structure is important for the understanding of the forest ecosystem functioning and, moreover, will help to assess carbon sequestration within forests. The relationship between the signal recorded by a lidar system and the canopy structure of a forest can be accurately characterized by physically based radiative transfer models (RTMs). A three-dimensional RTM is capable of representing the complex forest canopy structure as well as the involved physical processes of the lidar pulse interactions with the vegetation. Consequently, the inversion of such an RTM presents a novel concept to retrieve biophysical forest parameters that exploits the full lidar signal and underlying physical processes. A synthetic dataset and data acquired in the Swiss National Park (SNP) successfully demonstrated the feasibility and the potential of RTM inversion to retrieve forest structure from large-footprint lidar waveform data. The SNP lidar data consist of waveforms generated from the aggregation of small-footprint lidar returns. Derived forest biophysical parameters, such as fractional cover, leaf area index, maximum tree height, and the vertical crown extension, were able to describe the horizontal and vertical forest canopy structure. [J216]

"Transform domain approach for sequence design and its applications"

Many communication and radar systems necessitate the use of sequences with desired autocorrelation (AC) and cross-correlation (CC) properties. This paper presents a systematic method based on the transform domain characterization of the AC and CC constraints to generate new families of sequences that meet the requirements. We demonstrate that some existing families can easily be generated by our approach. Our approach, however, renders new families of sequences with less constraints. The proposed approach is elementary and can easily be extended to synthesize two-dimensional arrays or even higher dimensional waveforms that possess the desired multidimensional correlation properties. A preamble structure based on our new sequence family is suggested and performance of frequency offset and channel estimation algorithms for a multiantenna orthogonal frequency-division multiplexing (OFDM) system that uses such a preamble is given. [J217]

"Optical signal processing in Radar systems"

Opto-electronic components and their performances are well suited to be integrated in radar systems. In this

paper, two optical architectures illustrate functions that are specific to optical processing of microwave signals, i.e., time-delay-based processing and arbitrary waveform generation of large frequency bandwidth signals. [J218]

"The autocorrelation of waveforms generated from ocean-scattered GPS signals"

A "waveform" is generated by cross-correlating local copies of a global positioning system (GPS) signal with an ocean-reflected GPS signal, over a range of carrier frequencies and code delays. The shape of this waveform can be inverted to obtain estimates of the ocean surface roughness. To assess the accuracy of these retrievals, a stochastic model for the waveform time series measurements was developed in a previous publication. In this letter, this model is validated by comparing the predicted autocorrelation function of the waveform against the autocorrelation computed from experimental waveforms collected from an airborne receiver. A 1-ms coherent integration time was used at first. Then, blocks of these measurements were concatenated to produce equivalent integration times of up to 5 ms to compare the dependence of model predictions on integration time. Correlation time was estimated by fitting a model Gaussian function to the magnitude or the real part of the autocorrelation function. The magnitude and phase of the complex autocorrelation function from the model were also studied to show the location of the first, and better explain cases in which the Gaussian function did not fit well. The autocorrelation is found to be weakly dependent upon the surface roughness, over a range of moderate wind speeds. [J219]

"Two-valued frequency-coded waveforms with favorable periodic autocorrelation"

There are known phase-coded (two-valued or polyphase) CW radar signals that exhibit perfect periodic autocorrelation function (PACF). A PACF is perfect when all its out-of-phase autocorrelation values are identically equal to zero. This paper investigates periodic, two-valued, frequency-coded signals. While none could be found with perfect PACF, we present examples with nearly perfect PACF. Their relationship to binary phase-coded signals is also considered. These signals should be attractive for CW radars because of their simple implementation, clean spectrum, and the favorable range response of their matched receiver. [J220]

"HFSWR based on synthetic impulse and aperture processing"

A novel high-frequency surface wave radar (HFSWR) has been proposed, which is based on the principles of synthetic impulse and aperture processing. It uses multiple omnidirectional transmit antennae to simultaneously transmit a set of orthogonal waveforms, and the echoed signals are received and processed by one or multiple reception arrays. Although the transmit beam pattern is omnidirectional, by proper processing, the received signal multiple equivalent directional transmit beam patterns can be simultaneously formed. The signal processing scheme to obtain equivalent directional transmit beam pattern is investigated in detail. Considerations for system parameter selection to achieve an overall best system performance are proposed and discussed. In particular, for the novel HFSWR, target range and angle estimates are coupled together due to the orthogonality of the transmitted waveforms. A necessary and sufficient condition on the transmit antenna array geometry and transmit frequencies, which ensures that target range and angle estimates are uncoupled, is presented [J221]

"Wideband Extended Range-Doppler Imaging and Waveform Design in the Presence of Clutter and Noise"

This paper presents a group-theoretic approach to address the wideband extended range-Doppler target imaging and design of clutter rejecting waveforms. An exact imaging method based on the inverse Fourier transform of the affine group is presented. A Wiener filter is designed in the affine group Fourier transform domain to minimize wideband clutter range-Doppler reflectivity. The Wiener filter is then used to form an operator to precondition transmitted waveforms to reject clutter. Alternatively, the imaging and clutter rejection methods are equivalently re-expressed to perform clutter suppression upon reception. These methods are coupled with noise suppression upon reception. Numerical simulations are performed to demonstrate the performance of the proposed approach. Our study shows that the framework introduced in this paper can address the joint design of receive and transmit processing, design of clutter rejecting waveforms, suppression of noise, and reduction of computational complexity in receive processing [J222]

"Radar target identification using a likelihood ratio test and matching pursuit technique"

On the basis of likelihood ratio test (LRT) theory, a new method for radar target identification with matching pursuits, including the estimation method for target scattering response and the extraction technique for the reference atom dictionary to characterise the target scattering, is introduced. When compared with the generalised LRT (GLRT) target identification method, there is a very important contribution in our method that the whole scattering waveform, not only a few main poles, is used to identify targets without any prior parameterisation model hypothesis. Furthermore, the identification to candidate targets can be performed in an

almost aspect-independent manner over a full aspect angle in white Gaussian noise through a finite size reference atom dictionary. Simulation results using scattered responses synthesised from weighted sums of some exponentially damped sinusoids and calculated scattering signatures of three thin wires through a time-domain electric field integral equation are presented to contrast the performance of our method to the GLRT and the best LRT target identification method as a function of signal-to-noise ratio [J223]

"Range/Doppler ambiguity elimination in high-frequency chirp radars"

Range/Doppler ambiguity is an important problem in chirp radar operations with all the existing schemes for ambiguity elimination relying on multiple waveform switching. Now, a new method for ambiguity elimination is proposed. It is based on a single waveform and only involves a series of software computations associated with the instantaneous amplitudes of the target under consideration at adjacent range bins. Besides the ambiguity factor, the instantaneous range of the target is also estimated. The method can greatly improve the target detection and tracking capability of high-frequency chirp radars. Both simulation and real data processing results are demonstrated to validate of the method [J224]

"Signal Waveform's Optimal-under-Restriction Design for Active Sensing"

We consider Signal Waveform's Optimal-under-Restriction Design (SWORD) for active sensing. In the presence of colored interference and noise with known statistical properties, waveform optimization for active sensors such as radar can significantly increase the signal-to-interference-plus-noise ratio needed for much improved target detection. However, the so-obtained optimal waveforms can result in significant modulus variation, poor range resolution, and/or high peak sidelobe levels. To mitigate these problems, we can constrain the waveform optimization problem by restricting the sought-after waveform to be similar to a desired waveform, which is known to have, for example, constant modulus as well as reasonable range resolution and peak sidelobe level. One example of the desired waveform is the widely used linear frequency modulated waveform or chirp. We will provide a detailed solution to the constrained optimization problem and explain how it is related with the existing waveform optimization methods [J225]

"A new approach for synthesizing the range profile of moving targets via stepped-frequency waveforms"

In radar target imaging, motion induces a range-Doppler coupling effect, which results in distortion in synthesizing a range profile for a moving target. To eliminate or suppress the distortion of the synthetic range profile, conventional technology such as motion compensation requires velocity estimation. Unfortunately, for a high-speed moving target, it is difficult to achieve real-time accurate estimation of the velocity of the target. Based on phase cancellation, a new technology is proposed to achieve a motion target range profile via stepped-frequency waveform. The new technology does not need the estimation of the velocity. Hence, its computational cost can be minimized. It is also easier to use. The simulation result confirms the effect of the new technology [J226]

"A unified framework for the Sussman, Moyal, and Janssen formulas"

This paper derives three fundamental identities in the radar and sonar literature, namely, Sussman' identity for ambiguity functions, Moyal's formula which establishes the value of the inner product between two scattering functions, and Janseen's formula which establishes identities for mixed inner products between waveforms and Gabor wavelets. Starting from the fundamental convolution identity, we derive Sussman's identity. Following from an initial value theorem of Fourier analysis, we obtained Moyal's formula. Following from Poisson's sum formula and an initial value theorem, we also obtained Janssen's equality. The relationship between these three identities is as follows: Janssen's formula is a sampled-data version of Moyal's formula, and both follow from Sussman's identity. In turn, Sussman's identity is a consequence of the fundamental convolution identity. [J227]

"Waveform diversity & design"

First Page of the Article [J228]

"Effective bandwidth SF-CW SAR increase using frequency agility"

The use of a frequency-agile waveform is proposed as a way of providing significantly increased bandwidth for a stepped frequency continuous wave (SF-CW) SAR, than is provided by traditional imaging schemes. The range resolution is set by the bandwidth of the transmitted waveform, and is built up as a set of monotonically increasing stepped frequencies. As these frequencies are sampled sequentially, a constraint with SF-CW waveforms is the time restriction available to build up the bandwidth, imposed by the spatial sampling

requirements along the aperture to avoid grating-lobe effects. To address this problem, an approach is outlined which allows the frequency spectrum to be greatly undersampled to provide a greater effective bandwidth. It was found that randomizing the set of frequencies omitted from sweep to sweep allowed significant thinning before the appearance of significant unwanted image artifacts due to the under-sampling. This scheme allows great flexibility in the choice of bandwidths that can be realized for a particular imaging scenario. Their application is considered from the point of view of operation from UAV SAR platforms [J229]

"Implementation of fully polarimetric random noise radar"

A heterodyne correlation receiver technique has been developed for coherent processing of backscatter data acquired by a radar system transmitting ultrawideband (UWB) random noise waveforms. In such a receiver, the reflected signal is correlated with a time-delayed and frequency-shifted version of the transmitted waveform, which is able to provide the phase of the reflected waveform. We describe the implementation of fully polarimetric capability in a coherent random noise radar system operating in the ultrahigh frequency (UHF) range designed for foliage penetration (FOPEN) applications. Using this implementation, the polarimetric response of various foliage targets has been characterized. [J230]

"Detection and Processing of bistatically reflected GPS signals from low Earth orbit for the purpose of ocean remote sensing"

We will show that ocean-reflected signals from the global positioning system (GPS) navigation satellite constellation can be detected from a low-earth orbiting satellite and that these signals show rough correlation with independent measurements of the sea winds. We will present waveforms of ocean-reflected GPS signals that have been detected using the experiment onboard the United Kingdom's Disaster Monitoring Constellation satellite and describe the processing methods used to obtain their delay and Doppler power distributions. The GPS bistatic radar experiment has made several raw data collections, and reflected GPS signals have been found on all attempts. The down linked data from an experiment has undergone extensive processing, and ocean-scattered signals have been mapped across a wide range of delay and Doppler space revealing characteristics which are known to be related to geophysical parameters such as surface roughness and wind speed. Here we will discuss the effects of integration time, reflection incidence angle and examine several delay-Doppler signal maps. The signals detected have been found to be in general agreement with an existing model (based on geometric optics) and with limited independent measurements of sea winds; a brief comparison is presented here. These results demonstrate that the concept of using bistatically reflected global navigation satellite systems signals from low earth orbit is a viable means of ocean remote sensing. [J231]

"Optically generated arbitrary waveforms for radar applications"

A fibred optoelectronic arbitrary waveform generator for radar calibration purposes is proposed. The ability to generate radar arbitrary waveforms composed of 700 Doppler frequency components from 12 to 14 GHz with 20 dB spurious free dynamic range is demonstrated. [J232]

"Use of modulated excitation signals in medical ultrasound. Part I: basic concepts and expected benefits"

This paper, the first from a series of three papers on the application of coded excitation signals in medical ultrasound, discusses the basic principles and ultrasound-related problems of pulse compression. The concepts of signal modulation and matched filtering are given, and a simple model of attenuation relates the matched filter response with the ambiguity function, known from radar. Based on this analysis and the properties of the ambiguity function, the selection of coded waveforms suitable for ultrasound imaging is discussed. It is shown that linear frequency modulation (FM) signals have the best and most robust features for ultrasound imaging. Other coded signals such as nonlinear FM and binary complementary Golay codes also have been considered and characterized in terms of signal-to-noise ratio (SNR) and sensitivity to frequency shifts. Using the simulation program Field II, it is found that in the case of linear FM signals, a SNR improvement of 12 to 18 dB can be expected for large imaging depths in attenuating media, without any depth-dependent filter compensation. In contrast, nonlinear FM modulation and binary codes are shown to give a SNR improvement of only 4 to 9 dB when processed with a matched filter. Other issues, such as depth-dependent matched filtering and use of filters other than the matched filter (inverse and Wiener filters) also are addressed. [J233]

"Common Waveform Analysis-A New and Practical Generalization of Fourier Analysis [JBook Review]"

{no data available} [J234]

"Multiple scale correlation of signals by shift-invariant discrete wavelet transform"

Correlation of signals at multiple scales of observation is useful for multiresolution interpretation of image, data and target signature analysis. Multiresolution analysis is inherent in the discrete wavelet transform (DWT), but shift-variance of the coefficients of the transform in dyadic orthogonal and biorthogonal basis spaces is the problem associated with it. Shift-variance of the transform and absence of a direct transform domain relationship make correlation of signals by the DWT inconvenient at multiple scales. The circulant shift property of the DWT coefficients is used in a novel way to produce correlation of signals at multiple scales with the critically sampled DWT only. The algorithm is derived in both discrete time and z-domain for signal vectors of finite duration. The algorithm is independent of signal waveform and wavelet kernel and is applied particularly for multiple scale correlation of radar signals, namely linear frequency modulated (LFM) chirp signals. [J235]

"Very high bandwidth millimetre-wave radar"

An experimental radar at 94 GHz has been developed, which is capable of delivering an instantaneous bandwidth of 4 GHz. The radar uses an FM-CW waveform and is fully solid state. The data undergo an ISAR imaging process to derive high resolution scattering centre distributions for targets measured in tower/turntable configuration. The high resolution processing has to rely on an appropriate polar reformatting procedure, which is not necessary for ISAR imaging at millimetre waves with resolutions worse than 10 cm. [J236]

"Suppressing coherent noise in radar applications with long dwell times"

A method for suppressing internally produced coherent noise in radar applications is presented and experimentally demonstrated. The technique enhances conventional coherent averaging and involves interpulse phase modulation that is introduced digitally in the transmit waveform and removed digitally following digitization in the receiver. Experimental demonstration of this concept resulted in an additional noise floor reduction of 15 to 20 dB (compared to the conventional coherent averaging alone) when the number of coherent averages was between 1000 to 100 000, beyond which no significant suppression was observed. [J237]

"Closed-form correlation functions of generalized Hermite wavelets"

A closed-form expression is given for the correlation functions of generalized Hermite wavelets, constructed from an also-generalized definition of Hermite polynomials. Due to their Gaussianity, these wavelets can be used as a tool in the analysis or design of systems involving nonsinusoidal wavelets as well as to model impulsive waveforms found in real-world applications and signal processing problems. As such, the formula is potentially applicable to various areas of science. [J238]

"Passive radar using Global System for Mobile communication signal: theory, implementation and measurements"

Passive radars using illuminators of opportunity have attracted much attention in the international radar community. One existing radio transmission system that may be utilised for this purpose is the Global System for Mobile communication (GSM). This paper presents a study showing the feasibility of using a GSM signal for passive radar. The analysis of the GSM waveform, and any significance or influence it has with respect to the passive radar design considerations are investigated in detail. The paper describes fully the design and implementation of a low-cost GSM-based passive radar prototype in addition to the associated signal processing scheme. Numerous measurements for various ground-moving targets were investigated extensively. The preliminary processing results demonstrate the feasibility of using GSM signals as a radar waveform and have the potential capability to detect and track different types of ground-moving targets. [J239]

"Direct position determination of narrowband radio frequency transmitters"

The most common methods for location of communications or radar transmitters are based on measuring a specified parameter such as signal angle of arrival (AOA) or time of arrival (TOA). The measured parameters are then used to estimate the transmitter location. Since the AOA/TOA measurements are done at each base station separately, without using the constraint that all measurements must correspond to the same transmitter, they are suboptimal. We propose a technique that uses exactly the same data as the common methods, except that the estimation of location is based on exact maximum likelihood, and the location determination is direct. Although there are many stray parameters, including the attenuation coefficients and the signal waveform, the method requires only a two-dimensional search. Monte Carlo simulations indicate that the accuracy is equivalent to AOA, TOA, and their combination for high SNR, while for low SNR, the accuracy of the proposed method is superior. [J240]

"Toward a high-speed arbitrary waveform generation by a novel photonic processing structure"

A new photonics-based method for high-speed arbitrary waveform generation is presented. It is based on generating high-speed short optical pulse samples and a grating and delay structure for amplitude weighting and time delaying the optical samples. In order to increase the number of samples, a novel delay-attenuation-coupling processing method is presented for realizing high resolution in waveform generation. Results are given for sawtooth waveform generation with fast fall time of 10% of period and waveform linearity deviation of 1%, demonstrating the high resolution and wide-band capabilities of this technique. [J241]

"Programmable ultrawideband signal generator for electromagnetic susceptibility testing"

Under Phase I of the Defense Advanced Research Projects Agency (DARPA) Networking in Extreme Environments (NETEX) initiative, Multispectral Solutions, Inc. (MSSI) was tasked with the development of a general-purpose, ultrawideband hardware simulator capable of reproducing a wide variety of ultrawideband (UWB) waveforms. The simulator, with UWB outputs from baseband through millimeter wave, was to be used for the purpose of electromagnetic susceptibility testing of legacy military radio, radar, and positioning systems. The ultimate goal of this portion of the Phase I program was the quantitative determination of those UWB parameters (e.g., frequency, power, pulse rate, pulse shape, dithering, etc.) which had the least impact on the operational performance of legacy designs. This describes the development of the MSSI NETEX UWB simulator (BFP1000). [J242]

"A DSP-based mixed-signal waveform generator"

As it currently stands, waveform generators are being employed in many diverse areas, such as radar applications, communication systems, simulation, and testing. There is considerable interest in exploring the beacon of opportunity posed by using digital signal processor (DSP)-based systems to replace costly and inadequate conventional waveform generators. The availability of high performance DSPs allows for the design of highly flexible equipment capable of real-time processing. The arbitrary waveform generator introduced in this paper consists of a DSP, a FIFO memory, a video palette, and a PC interface. A program running on the PC creates a digital representation of a waveform according to user parameters and sends it to the DSP's RAM. The DSP algorithmically converts the digital representation to a point-by-point representation of the desired analog signal. The data points are sent to the FIFO buffer, which latches the data to a video palette that serves a three-channel digital-to-analog converter. The system employs a high-speed serial port interface to communicate with a PC, to allow for readily programmed signals. In addition to the production of traditional signals, such as sinusoids and squarewaves, a mathematical tool known as splines is employed to aid in the development of customized arbitrary waveforms. Finally, a picture of our new device is presented in the paper. [J243]

"Eight-channel 77-GHz front-end module with high-performance synthesized signal generator for FM-CW sensor applications"

This paper presents a new frequency-modulated continuous-wave front-end module intended to serve next-generation automotive radar sensors. Providing one transmit and eight receive channels, the module is designed to operate between a multibeam antenna and an advanced signal-processing unit. All receive channels are equipped with low-noise amplifiers, mixers for downconversion, and IF amplifiers. Cascaded buffer amplifiers for the local-oscillator signal enable parallel operation of all receive channels. A high-performance synthesizer provides generation and transmission of arbitrarily programmable frequency ramped waveforms with high stability and linearity. Slope and frequency deviation of the waveforms can be adjusted for the respective radar application. Short settling times of the synthesizer allow very fast slopes and, thus, short distance measurements. An overview of the overall front-end module design and realization approach is given, including a more detailed description of the synthesizer concept. All active millimeter-wave functions are realized with GaAs monolithic microwave integrated circuits assembled in a hermetically sealed multichip module (MCM). The MCM itself is incorporated into a three-layer printed-circuit-board stack onto which IF amplification, frequency control, waveform generation as well as dc and bias control is realized. A summary of the measured performance data obtained from correspondingly built-up prototypes is given. [J244]

"Discrete frequency-coding waveform design for netted radar systems"

A novel method is proposed to design discrete frequency-coding waveforms (DFCWs) for the netted radar systems. Some of the designed results are presented and they indicate that the proposed algorithm is effective for the DFCW design. [J245]

"Effective CLEAN algorithms for performance-enhanced detection of binary coding radar signals"

With binary coding waveform as radar pulse compression signal, the sidelobe of the matched processing result of the received signals is a serious interference to the effective detection of multiple targets. In this paper, the CLEAN algorithms are introduced to eliminate such sidelobes and significantly improve the target detection performance of binary coding radar signals. A novel modified CLEAN algorithm is proposed to remove the sidelobe interferences in formulating target range profile when wideband binary coding signals are used. The effectiveness of the CLEAN algorithms is demonstrated through the processing results. [J246]

"Time-frequency radar processing for meteor detection"

In this paper, we present signal processing techniques to detect meteor returns from Arecibo Observatory 430-MHz UHF radar data. We exploit the characteristics of the transmit waveform in the frequency domain as well as in the time domain. Two detection methods are investigated. First, when a meteor is present in the radar return over several interpulse periods, there will be a periodic structure in frequency spectrum. By detecting this structure, we detect the presence of a meteor. Second, we construct a matched filter bank to detect the energy of different Doppler frequency components. When the energy exceeds a certain threshold, we declare meteor detection. We also find the altitude of a meteor by finding the peak of the matched filter output. Analytical and experimental results show that we can efficiently and reliably detect meteors using these methods. [J247]

"High range resolution (HRR) improvement using synthetic HRR processing and stepped-frequency polyphase coding"

The authors exploit radar waveform coding techniques to improve high range resolution (HRR) performance. Phase-coded, stepped-frequency (PCSF) waveforms are presented and performance characterised relative to a common 13-element biphase-coded PCSF waveform. Analysis includes PCSF waveforms using biphase coding derived from Gold and minimum peak sidelobe level codes. Synthetic HRR results for PCSF waveforms using Frank and P4 polyphase codes are also presented and achieve HRR performance rivalling their biphase counterparts. Individual code performance is analysed and characterised using a single-point target and realistic target scene comprised of 320 closely spaced complex scattering centres, representing a fighter-sized aircraft. The P4 polyphase coded waveforms achieved best overall HRR performance and were least sensitive to Doppler variation for relative velocities up to 250 m/s. The P4 polyphase coded synthetic HRR profiles exhibit 7.0dB and 10.0 dB improvement (peak sidelobe level reduction) relative to Frank and biphase coding, respectively. [J248]

"Improved ultra-low range sidelobe pulse compression waveform design"

A continuous nonlinear FM waveform design capable of achieving range sidelobe levels of better than -70 dB, suitable for use with a satellite-borne precipitation radar, is presented. The waveform shows good Doppler tolerance. It is shown that slowly-varying phase and amplitude errors in the transmitter and receiver have relatively little effect, but rapidly-varying errors result in paired echo sidelobes, the level of which can be significant. A closed-loop calibration system will undoubtedly be required to remove such errors. [J249]

"Doppler aliasing artifact filtering in SAR imagery using randomised stepped-frequency waveforms"

A new technique for mitigating Doppler aliasing artifacts in synthetic aperture radar (SAR) imagery is demonstrated. The technique uses continuous-wave (CW) transmission of randomised stepped-frequency waveforms. Subsequent processing places Doppler aliasing artifacts in Doppler filter s, effectively removing them from the imagery. Simulated 2-D SAR images illustrate the effectiveness of the technique. [J250]

"Super-fast scanning technique for phased array weather radar applications"

The authors present a super-fast scanning (SFS) technique for phased array weather radar applications. The fast scanning feature of the SFS technique is described and its drawbacks identified. Techniques which combat these drawbacks are also presented. A concept design phased array radar system (CDPAR) is used as a benchmark to compare the performance of a conventional scanning phased array radar system with the SFS technique. It is shown that the SFS technique, in association with suitable waveform processing, can realise four times the scanning speed and achieve similar accuracy compared to the conventional phased array benchmark. [J251]

"Noise radar using random phase and frequency modulation"

Pulse compression radar is used in a great number of applications. Excellent range resolution and high electronic counter-countermeasures performance is achieved by wideband long pulses, which spread out the transmitted energy in frequency and time. By using a random noise waveform, the range ambiguity is

suppressed as well. In most applications, the random signal is transmitted directly from a noise-generating microwave source. A sine wave, which is phase or frequency modulated by random noise, is an alternative, and in this paper, the ambiguity function and the statistical characteristics of the correlation output for the latter configuration are further analyzed. Range resolution is then improved because the noise bandwidth of the modulated carrier is wider than that of the modulating signal, and the range sidelobes are also further suppressed. Random biphase modulation gives a 4-dB (pi2/4) improvement, but much higher sidelobe suppression could be achieved using continuous phase/frequency modulation. Due to the randomness of the waveform, the output correlation integral is accompanied by a noise floor, which limits the possible sidelobe suppression as determined by the time-bandwidth product. In synthetic aperture radar (SAR) applications with distributed targets, this product should be large compared with the number of resolution elements inside the antenna main beam. The advantages of low range sidelobes and enhanced range resolution make frequency/phase-modulated noise radar attractive for many applications, including SAR mapping, surveillance, altimetry, and scatterometry. Computer algorithms for reference signal delay and compression are discussed as replacements for the classical delay line implementation. [J252]

"Possible ultra-wideband radar terminology"

This is a supplement to the terms proposed by Malek G.M. Hussain and James D. Taylor (see ibid., vol.19, no.7, p.39, July 2004). [J253]

"Acoustooptic correlation processing in random noise radar"

A new technique has been developed that permits coherent processing of backscatter data acquired by a radar system transmitting ultrawideband (UWB) random noise waveforms and processing the received signals using a heterodyne correlation receiver. This technique has been used in various applications, such as Doppler estimation, polarimetry, interferometry, buried-object detection, synthetic aperture radar (SAR) imaging, inverse SAR (ISAR) imaging, foliage penetration imaging, etc. One of the major advantages of the noise radar system is its inherent immunity to external interference. In such a radar system, the correlation receiver consists of a programmable variable-delay line, a mixer followed by a lowpass filter. One drawback of this type of receiver is that it sequentially processes the target returns, thus limiting the system response time and the dynamic detection range. We have recently integrated a novel heterodyning acoustooptic (AO) time-integrating correlation receiver that uses a traveling-wave AO deflector for wideband signal processing. The transmit waveform modulates the intensity of a laser diode that is multiplied by the traveling-wave modulation produced by the AO deflector, and the correlation is time-integrated on a charge-coupled device photodetector array. The principal advantages of this AO correlation receiver are its ability to generate a large range of variable delays, as well as to perform the signal correlation operation in parallel. Compared to the conventional sequential correlation receiver using a variable stepped delay line and correlator, implementation of the AO variable-delay line and heterodyning correlator can 1) reduce the processing time and greatly increase the processing gain due to the parallel correlation mechanism and 2) greatly increase the number of range cells depending on the number of resolvable spots of the AO deflector. This results in rapid data acquisition, longer integration time on parallel detector pixels (3000 pixels), and improved SNR. It is also shown that this radar has more range gates (up to 1000), which ultimately improves the detectable range resolution. Furthermore, several field experiments performed with different target arrangements demonstrate that the acoustooptic variable-delay line and c-orrelator is able to profile various targets instantaneously and with very high SNR. [J254]

"Waveform fusion in sonar signal processing"

In active sonar systems, proper selection of the transmitted waveform is critical for target detection and parameter estimation, especially with the existence of clutter (reverberation). Two commonly used waveforms (constant frequency (CF) and linear frequency modulated (LFM)) are studied. Their characteristics are complementary both with respect to their accuracies and their sensitivity to the blind zero-Doppler ridge. Several fusion schemes of the two kinds of waveforms are explored and fusion results are studied both analytically and from simulation. It is concluded that fusion of the information of different waveforms can be not only more robust, but in some cases outright preferable, in term of detection probability and estimation accuracy. [J255]

"Time-domain measurements of radiated and conducted UWB emissions"

This paper summarizes results obtained from time-domain full-bandwidth emissions measurements of selected ultra wideband (UWB) transmitting devices. Brief descriptions of two NIST-developed measurement systems are provided. High-fidelity time-domain waveforms are shown, along with associated amplitude spectra for several devices. Results are shown for both conducted and radiated emissions from UWB devices. [J256]

"Sparse frequency transmit-and-receive waveform design"

A computationally efficient algorithm derives complex digital transmit and receive ultra-wideband radar and communication waveforms with excellent arbitrary frequency band suppression and range sidelobe minimization. The transmit waveform minimizes a scalar function penalizing weighted spectral energy in arbitrary frequency bands. Near constant power results from another penalty function for deviations from constant power, or constant power is enforced by a phase-only formulation. Next, a least squares solution for the receive waveform minimizes a weighted sum of suppressed band spectral energy and range sidelobes (for pulse and continuous wave operation), with a mainlobe response constraint. Both waveforms are calculated by iterative algorithms whose updates require only linear order in memory and computation, permitting quick calculation of long pulses with thousands of samples. [J257]

"Measurement and analysis of ambiguity functions of off-air signals for passive coherent location"

Passive coherent location (PCL) radar systems make use of broadcast or communications 'illuminators of opportunity'. To understand the performance limitations of this type of radar it is necessary to know the ambiguity properties of these waveforms, and how they vary with the form of modulation, and as a function of time. A set of off-air measurements of signals that might be used for PCL systems are presented and analysed. [J258]

"Time-domain array factor for UWB antenna array"

A cross-correlation formulation for the computation of time-domain array factor for ultra-wideband (UWB) antenna arrays is presented. In addition, a dual band UWB waveform is proposed for high directivity and high-resolution radar imaging. The dual band UWB waveform is based on a frequency truncated, Gaussian modulated, higher-order sinusoidal UWB pulse. [J259]

"High range resolution by means of synthetic bandwidth generated by frequency-stepped chirps"

A method is presented to achieve large bandwidths with a synthetic chirp waveform adequate for short transmit pulses, which are typical for all millimetre-wave-radar applications using solid state transmitter stages. The usual 'stretch' processing for the deramping of individual chirps of concatenated waveforms is avoided in order to be able to use measured instead of synthetic reference chirps to compensate all kinds of hardware-induced amplitude and phase errors. Due to 'spatial concatenation' the method is applicable to scenarios with a range extent much larger than the chirp length. [J260]

"Direct-path filtering of DAB waveform from PCL receiver target channel"

Signal space projection techniques are introduced to filter the direct-path signal component from the passive coherent location (PCL) receiver target channel. Filter performance is characterised using ambiguity function analysis of the digital audio broadcast (DAB) waveform, considered here as a PCL waveform of opportunity. For ideal DAB phase reference synchronisation, the direct-path component is perfectly eliminated. For non-ideal phase synchronisation, the direct-path component is sufficiently attenuated to permit target detection; approximately 22 dB of direct-path signal attenuation is demonstrated. [J261]

"Detection of polyphase pulse compression waveforms using the radon-ambiguity transform"

The recently developed Radon-ambiguity transform (RAT) detects unknown linear frequency modulated (LFM) signals by computing line integrals through the origin of the signal's ambiguity function (AF) magnitude. It is shown that this method also detects the step LFM and frequency-derived polyphase pulse compression waveforms with varying performance degradation. Simulations are provided to estimate the detection loss relative to the LFM. [J262]

"Synthetic aperture inversion for arbitrary flight paths and nonflat topography"

The paper considers synthetic aperture radar (SAR) and other synthetic aperture imaging systems in which a backscattered wave is measured from positions along an arbitrary (known) flight path. The received backscattered signals are used to produce an image of the terrain. We assume a single-scattering model for the radar data, and we assume that the ground topography is known but not necessarily flat. We focus on cases in which the antenna footprint is so large that the standard narrow-beam algorithms are not useful. We show that certain artifacts can be avoided if the antenna and antenna footprint avoid particular relationships with the ground topography. We give an explicit backprojection imaging algorithm that corrects for the ground topography, flight path, antenna beam pattern, source waveform, and other geometrical factors. For the case of a non-directional antenna, the image produced by the above algorithm contains artifacts. For this case, we analyze the strength of the artifacts relative to the strength of the true image. The analysis shows that the artifacts can be somewhat

suppressed by increasing the frequency, integration time, and the curvature of the flight path. [J263]

"Frequency-coded waveforms for enhanced delay-Doppler resolution"

In this paper, we propose techniques for the construction of frequency-coding sequences that give rise to frequency-coded waveforms having ambiguity functions with a clear area-containing no sidelobes-in a connected region surrounding the main lobe. These constructed sequences are called pushing sequences. First, two important properties of pushing sequences are investigated: the group D4dihedral symmetry property and the frequency omission property. Using the group D4dihedral symmetry property, we show how to construct additional pushing sequences from a given pushing sequence. Using the frequency omission property, we show how to construct pushing sequences of any length N and design proper frequency-coded waveforms that meet specific constraints in the frequency domain. Next, we use the Lempel T4construction of Costas sequences to construct pushing sequences with power 1. Finally, we show how to construct pushing sequences with any desired power using Lee codewords. Because these arbitrary-power pushing sequences constructed using Lee codewords do not have the Costas property, we derive expressions for the pattern of hits in the geometric array. Based on this, the general form of the positions and levels of all the sidelobe peaks are derived. [J264]

"Ultra-wideband technology and random signal radar: an ideal combination"

Ultra-wideband radar and random signal radar are two types of newly-developed radar systems. This paper introduces the special advantages of the combination of ultra-wideband technology and random signal radar to the international radar community. It shows that these two radar systems have a very close relationship in nature and can gain significant benefits from each other. It can be anticipated that the random signal modulated waveform will open many potential possibilities for the applications of ultra-wideband radar systems to civilian operating environments. [J265]

"Noise Radar for range/Doppler processing and digital beamforming using low-bit ADC"

Pulse compression radar is used in a great number of radar applications. Excellent range resolution and high resistance to electronic countermeasures (ECM) can be achieved by long wideband modulated pulses, which spread out the transmitted energy in frequency and time. By using random noise as the waveform, the range ambiguity can be suppressed as well. In this paper, noise radar for Doppler/range indication and digital beamforming is described. Main factors influencing the resolution and sidelobe level in range and Doppler are surveyed. In particular, the possible use of binary or low-bit analog-to-digital converters (ADCs) in noise radar is analyzed, which highly improves the signal-processing rate and reduces the costs. The very significant improvement of sidelobe suppression, when an extra noise signal is added before ADC, is explained theoretically and confirmed by simulation results. Mostly, the random signal is transmitted directly from a noise generating high-frequency source. A sine wave, which is phase or frequency modulated by random noise, is an alternative, giving lower range sidelobes, and higher transmitted mean power when peak-limited transmitters are applied. The dynamic requirements and the bandwidth of the modulating signal can be reduced as well. [J266]

"The application of matched filters to PD detection and localization"

In practice, partial discharge (PD) signals are corrupted mainly by narrowband noise caused by radio communications. Matched filters are very well suited for PD detection in the presence of such noise, since they exploit spectral regions with high SNR to maximize the SNR of a measured PD signal. In addition to its noise suppressing capabilities, a matched filter provides a means to estimate accurately PD pulse magnitude and arrival time. Consequently, PD detection can benefit greatly from the application of matched filters. However, good knowledge of the signal waveform is required. In many cases, such information can be obtained by measurement or modeling of the PD pulse propagation. [J267]

"Effect of nonuniform target motion on radar backscattered waveforms"

The effect of nonuniform motion on radar waveforms is discussed. By considering the physical model of a perfectly reflecting mirror with an arbitrary law of motion r(t), it is possible to determine the functional form of the scattered wave at the receiver for any waveform in general. The particular example of an interrupted continuous wave waveform is used to analyse the effect of nonuniform motion on the return spectrum. These models provide a theoretical foundation for the observations of micro-Doppler that have been discussed by a number of authors. Finally, some of the implications, both physical and mathematical, of nonuniform motion for time-frequency methods are addressed [J268]

"X-band wideband experimental airborne radar for SAR, GMTI and maritime surveillance"

Defence Research and Development Canada-Ottawa has completed Phase I in the development of a new multimode X-band wideband experimental airborne radar (XWEAR) to support studies in synthetic aperture radar (SAR) imaging, inverse SAR (ISAR), ground moving target indication (GMTI) radar and maritime surveillance radar with particular focus on small target detection and long-range surface surveillance. Specific areas of interest include research into SAR imaging techniques for fixed and moving targets, time-frequency analysis of ocean and land moving targets, space-time adaptive processing for application to GMTI, investigation into the electromagnetic backscatter properties of the ocean surface, generation of signatures for automatic target recognition and feature extraction, and analysis on the immunity of wide bandwidth systems against electronic countermeasures. Phase I culminated with the flight trialling of the SAR and maritime surveillance modes. Phase II will see the trialling of the wide area surveillance GMTI (WAS GMTI) and integrated SAR-GMTI modes. A description of the experimental radar is given along with an overview of its data collection capability. Distinguishing features include operation at X-band, single-channel operation for SAR and maritime surveillance, and two-channel operation for WAS-GMTI and integrated SAR-GMTI. The new radar maximises the use of an existing digital scan converter as a controller, and commercially available components including the transmitter, A/D converters and computer boards. The timing circuitry, waveform generator, single- and dual-channel receivers are custom built [J269]

"Principles of space-time array processing for ultrawide-band impulse radar and radio communications"

The emerging ultrawide-band (UWB) impulse technology has found numerous applications in the commercial as well as the military sector. The rapid technological advances have made it possible to implement (cost-effective, short-range) impulse radar and impulse-radio communication and localization systems. Array beamforming and space-time processing techniques promise further advancement in the operational capabilities of impulse radar and impulse-radio communications to achieve long-range coverage, high capacity and interference-free quality of reception. We introduce a realistic signal model for UWB impulse waveforms and develop the principles of space-time array processing based on the signal model. A space-time resolution function (STRF), a space-frequency distribution function (SFDF) and a monopulse-tracking signal are derived for impulse waveforms received by a self-steering array beamforming system. The directivity peak-power pattern and energy pattern of the beamformer are also derived. Computer plots of the STRF, SFDF and the beam patterns are obtained. The directivity beam patterns of impulse waveforms are sidelobe-free and, therefore, there is no need for sidelobe suppression via amplitude weighting of the array elements. Also, the resolution angle for the beam patterns is derived as a decreasing function of array size and frequency bandwidth. Electronic beamsteering based on slope processing of monopulse waveforms is described [J270]

"A single-chip false target radar image generator for countering wideband imaging radars"

This paper describes the theory, design, implementation, simulation, and testing of an ASIC capable of generating false target radar images for countering wideband synthetic aperture and inverse synthetic aperture imaging radars. The 5.5 Ч 6.1 mm IC has 81632 transistors, 132 I/O pins, and consumes 0.132 W at 70 MHz from a 3.3-V supply. An introduction to the application and operation of the ASIC in an electronic attack system is also presented. The false target image is fully programmable and the chip is capable of generating images of both small and large targets, even up to the size of an aircraft carrier. This is the first reported use of all-digital technology to generate false target radar images of large targets [J271]

"Tracking considerations in selection of radar waveform for range and range-rate measurements"

The conventional approach for tracking system design is to treat the detection and tracking subsystems as completely independent units. However, the two subsystems can be designed jointly to improve system (tracking) performance. It is known that different radar signal waveforms result in very different resolution cell shapes (for example, a rectangle versus an eccentric parallelogram) in the range/range-rate space, and that there are corresponding differences in overall tracking performance. We develop a framework for the analysis of this performance. An imperfect detection process, false alarms, target dynamics, and the matched filter sampling grid are all accounted for, using the Markov chain approach of Li and Bar-Shalom. The role of the grid is stressed, and it is seen that the measurement-extraction process from contiguous radar "hits" is very important. A number of conclusions are given, perhaps the most interesting of which is the corroboration in the new measurement space of Fitzgerald's result for delay-only (i.e., range) measurements, that a linear FM upsweep offers very good tracking performance [J272]

"Blind adaptive multiuser detection based on Kalman filtering"

Although several Kalman filtering algorithms have been presented for adaptive multiuser detection, none is

"blind" due to requiring training data sequences and/or more knowledge than the spreading waveform and delay of the desired user. This paper proposes a novel blind adaptive multiuser detector based on Kalman filtering and compares it with previously published LMS and RLS algorithms for blind adaptive multiuser detection. It is shown that the steady-state excess output energy of the Kalman filtering algorithm is identically zero for a stationary environment. Simulation results show the effectiveness of the new Kalman filtering algorithm [J273]

"New approach to target identification by use of a robust algorithm for optimal matching of wideband radar signal to target"

Using an array of coupled oscillators, a novel broadband radar signalling scheme is introduced. It is shown that the collective output of the oscillator array is a flexible signal that can be matched to a target at a specific aspect. Also, a new robust algorithm based on eigenvectors of the correlation matrix is introduced, by which the generated signal can be matched to the target over a limited range of aspects. This capability is important, because radars are unable to estimate the aspect of a real target precisely. In this new approach to radar target identification, after estimation of the approximate aspect of an unknown target, a variety of waveforms matched to different potential targets are synthesised and transmitted to the target in turn. The maximum peak power of the backscattered signals will then specify the identity of the target. Computer simulations have shown that this technique is robust to both additive noise and aspect angle uncertainty [J274]

"Wind speed measurement using forward scattered GPS signals"

Instrumentation and retrieval algorithms are described which use the forward scattered range-coded signals from the global positioning system (GPS) radio navigation system for the measurement of sea surface roughness. This roughness has long been known to be dependent upon the surface wind speed. Experiments were conducted from aircraft along the TOPEX ground track and over experimental surface truth buoys. These flights used a receiver capable of recording the cross-correlation power in the reflected signal. The shape of this power distribution was then compared against analytical models, which employ a geometric optics approach. Two techniques for matching these functions were studied. The first recognized the most significant information content in the reflected signal is contained in the trailing edge slope of the waveform. The second attempted to match the complete shape of the waveform by approximating it as a series expansion and obtaining the nonlinear least squares estimate. Discussion is also presented on anomalies in the receiver operation and their identification and correction [J275]

"High range resolution profiling using phase-coded, stepped-frequency waveforms"

A phase-coded stepped-frequency (PCSF) waveform with high range resolution (HRR) processing is presented as an improvement to stepped-frequency (SF) processing. By combining intrapulse phase and interpulse frequency modulations, the PCSF technique enables larger frequency step sizes than SF processing-system effective bandwidth is traversed more quickly, allowing shorter burst times while decreasing Doppler sensitivity. The PCSF framework presented and corresponding HRR simulation results for complex targets are shown consistent with the ideal SF response and demonstrate Doppler sensitivity reduction [J276]

"ECCM capabilities of an ultrawideband bandlimited random noise imaging radar"

Investigated here is high-resolution imaging of targets in noisy or unfriendly radar environments through a simulation analysis of the ultrawideband (UWB) continuous-wave (CW) bandlimited random noise waveform. The linear FM chirp signal was selected as a benchmark radar waveform for comparison purposes. Simulation of the recovery of various types of target reflectivity functions (TRFs) for these waveforms were performed and analyzed. In addition, electronic counter-countermeasure (ECCM) capabilities for both types of systems were investigated. The results are compared using the error between the interference (jamming)-free recovered TRF and the recovered TRF under noisy conditions as a function of the signal-to-interference/jamming ratio (SIR/SJR). Our analysis shows that noise waveforms possess better jamming immunity (of the order of 5-10 dB improvement over the linear FM chirp) due to the unique radar correlation processing in the receiver. [J277]

"Noniterative techniques for GPR imaging through a nonplanar air-ground interface"

It is often advantageous to acquire pulse-echo ground-penetrating radar (GPR) measurements from antennas that are offset from the air-ground interface by a nonnegligible distance, either because the ground's surface is rough, or because measurements must be collected remotely. This paper describes the effects of incorrectly estimating the location of the air-ground interface on GPR images created with the plane-to-plane backpropagation (PPB) method. To compensate for a nonplanar air-ground interface, the wideband time-domain synthetic aperture method is reviewed and reformulated, using Snell's law of refraction, to account for measurements taken some distance above an undulating interface. A modification of the PPB algorithm that

accounts for a nonplanar interface is also formulated, and examples of imaging with both methods are given to validate, the algorithms' performance for surface variations that are relatively smooth with respect to the radar waveform wavelengths. Additionally, a method for inferring the surface topography from the radar returns is described. Finally, the modified PPB is demonstrated by imaging buried targets sensed in field-acquired data. [J278]

"Stochastic versus deterministic models in the analysis of communication systems"

When trying to analyze a complex communication system, scientists often apply concepts from stochastic modeling and analysis to obtain a description of the system, frequently assuming that this will supplement our knowledge and improve our understanding. The philosophy is to obtain a result that would occur on the average, when this system is working under normal conditions. However, we must consider the fact that the introduction of probability in communication-system analysis often involves invoking certain assumptions and additional information about the system, which may not be valid. Hence, under these circumstances one may obtain a result that may not be commensurate with the conceived communication system. The objective of this paper is to highlight the basic assumptions that are invariably associated with the signal analysis in a system using stochastic analysis, and the introduction of probabilistic methods. Surprisingly, in many cases, analysis using stochastic methods may provide results equivalent to those obtained using deterministic methods. Examples are presented to illustrate our approach, and to explain the basic assumptions and formulate the mathematical framework associated with a stochastic analysis. We also demonstrate the equivalence between a random and a deterministic process, and under what conditions they approach the Cramer-Rao bound. Analysis using stochastic models to describe a system may be superior to a deterministic description. However, such a characterization comes with a large cost: namely, one must have more definitive knowledge about the system, knowledge that is often unavailable. For convenience, with the application of a random model, the concepts of stationarity and ergodicity are used to simplify the mathematical analysis of measured data. It is shown that the introduction of ergodicity in probability is similar to a deterministic analysis of a single waveform, and, in both cases, characterizes the entire underlying mathematical agenda. An example is presented to illustrate the salient features of an ergodic process as opposed to a deterministic process. It is seen that for practical problems, it might be easier and more relevant to introduce a deterministic model and to then carry out a stochastic analysis. However,- this may not be practical, since the underlying ensemble is not available nor are its probability density functions. Moreover a deterministic solution may present the best solution for a given data set, whereas the stochastic approach yields an "average" solution for all the waveforms in the ensemble. Hence, the stochastic solution may not be the desired solution for the given data set. However, when accurate statistics are available, a better solution may be obtained using probabilistic methods. [J279]

"Ultra-wideband continuous-wave random noise arc-SAR"

A coherent ultra-wideband random noise radar system operating in the 1-2-GHz frequency range has been developed at the University of Nebraska. A unique signal processing procedure based on heterodyne correlation techniques preserves phase coherence within the system, thereby enabling it to be used for synthetic aperture radar (SAR) imaging. Data acquisition is performed using a rotating boom with antennas installed atop a van containing radar equipment. This setup facilitates a simple and low-cost mobile SAR implementation, best suited for short-range quasi-stripmap Arc-SAR imaging. The use of ultra-wideband signals provides reasonable resolution of the obtained imagery. The amplitude and the phase response of the system are used to form the frequency-domain target scattering profile matrix, which are then transformed into a SAR image. The paper discusses the theory of SAR imaging using random noise signals and presents a detailed description of the radar and experimental imagery obtained using this system. [J280]

"A delay/Doppler-mapping receiver system for GPS-reflection remote sensing"

A delay/Doppler-mapping receiver system, developed specifically for global positioning system (GPS)-reflection remote sensing, is described, and example delay/Doppler waveforms are presented. The high-quality data obtained with this system provide a more accurate and detailed examination of ground-based and aircraft GPS-reflection phenomenology than has been available to date. As an example, systematic effects in the reflected signal delay waveform, due to nonideal behavior of the C/A-code auto-correlation function, are presented for the first time. Both a single-channel open-loop recording system and a recently developed 16-channel recorder are presented. The open-loop data from either recorder are postprocessed with a software GPS receiver that performs the following functions: signal detection; phase and delay tracking; delay, Doppler, and delay/Doppler waveform mapping; dual-frequency (L1 and L2) processing; C/A-code and Y-code waveform extraction; coherent integrations as short as 125 μs; navigation message decoding; and precise observable time tagging. The software can perform these functions on all detectable satellite signals without dead time, and custom signal-processing features can easily be included into the system [J281]

"Implicit averaging and delay determination of random binary waveforms"

It is shown that for a broad class of random binary processes, the mean of a binary process, conditioned on its zero crossings, is proportional to the derivative of the correlation function of that process. This specific mean, referred to as the implicit mean, can be used both to characterize a random binary waveform and to determine its delay. The proposed empirical estimator of the implicit mean is unbiased, and its variance depends on the number of selected trajectories of the waveform being processed and the correlation between those trajectories. [J282]

"Doppler compensation for binary phase-coded waveforms"

Codes used in phase-coded pulse compression waveforms suffer from Doppler mismatch. Based on an analysis of the effects of Doppler mismatch on binary phase-coded waveforms, a class of codes is proposed (hereafter referred to as the component codes), its derivation and processing is described, and the performance results are analyzed. This technique solves the problem of the Doppler mismatch of binary phase-coded waveforms at the expense of about 3 dB loss in signal-to-noise ratio (SNR). This technique may be used in tracking applications, such as accurately and rapidly measuring and tracking targets of unknown speeds. Simulation results demonstrate the validity of this technique. [J283]

"Modeling lidar waveforms in heterogeneous and discrete canopies"

This study explores the relationship between laser waveforms and canopy structure parameters and the effects of the spatial arrangement of canopy structure on this relationship through a geometric optical model. Studying laser waveforms for such plant canopies is needed for the advanced retrieval of three-dimensional (3D) canopy structure parameters from the vegetation canopy lidar (VCL) mission. For discontinuous plant canopies, a hybrid geometric optical and radiative transfer (GORT) model describing the effects of 3D canopy structure parameters of discrete canopies on the radiation environment has been modified for use with lidar. The GORT model is first used to describe the canopy lidar waveforms as a function of canopy structure parameters and then validated using scanning lidar imager of canopies by echo recovery (SLICER) data collected in conifer forests in central Canada during the boreal ecosystem-atmosphere study (BOREAS). Model simulations show that the clumping in natural vegetation, such as leaves clustering into tree crowns causes larger gap probability and smaller waveforms for discontinuous plant canopies than for horizontally homogeneous plant canopies. Ignoring the clumping effect can result in significantly lower values for the estimated foliage amount in the profile and in turn lower estimated biomass. Because of clumping, only the gap probability and apparent vertical projected foliage profile can be directly retrieved from the canopy lidar data. The retrieval is sensitive to the ratio of the volume backscattering coefficients of the vegetation and background, and this ratio depends on canopy architecture as well as foliage spectral characteristics [J284]

"Negative correlation and optimal tracking with Doppler measurements"

In target tracking systems that utilize Doppler radar (or sonar), the measurements consist of range, range rate, and one or two angles, When multiple sensors are used in the proper geometry, the final accuracy is determined primarily by each sensor's range estimation accuracy. In this case it is particularly important to extract the most accurate state estimate in the range direction by processing optimally the range and range rate measurements. The usual assumption in the design of tracking filters is that the measurement errors in range and range rate are uncorrelated. However, in the case of the commonly used upsweep chirp (linear FM) waveforms, there can be a significant negative correlation between the range and range rate measurement noises. The purpose of this note is to quantify the performance improvement one can obtain when this correlation is present, as it is in certain waveforms, and accounted for [J285]

"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 [J286]

"Simple estimation of equivalent magnetic dipole moment to characterize ELF magnetic fields generated by electric appliances incorporating harmonics"

A simple method of quantifying the ELF (extremely low frequency) magnetic field distribution around electric appliances, which takes the harmonics into account, is newly proposed. The proposed method involves: (1) a simple estimation of the position of an equivalent magnetic dipole moment inside an appliance, using two magnetic field meters; (2) identification of the amplitude of the dipole moment magnetic-field measurements at certain points; and (3) calculation of the magnetic field distribution around the appliance using the estimated dipole moment. In this method, the dipole moment vector is assumed to be a similar value by allowing an uncertainty of 6 dB in the estimated magnetic field, which enables easy estimation of the dipole moment. In addition, the frequency characteristics of the magnetic field are taken into account by considering the harmonic components in the magnetic field waveform. The proposed method was applied to 13 types of appliances, and their equivalent magnetic dipole moments and harmonic components were determined. The results revealed that the proposed method is applicable to many electric appliances. The conditions required for the adoption of the method were also clarified [J287]

"On-board selection of relevant images: an application to linear feature recognition"

We propose an on-board selection scheme for aerial and space images, based on linear feature detection in a feature hyperspace. The detection task is performed by means of the Radon transform (RT) and the wavelet transform; a fast algorithm for the RT computation is described, and counteractions against the discretization errors are proposed. A new, wavelet-based algorithm is introduced, which performs a fine analysis of the waveforms of the RT peaks, yielding a possibly error-free detection in images corrupted by a high level of noise. A technique, based on the feature hyperspace, is proposed, able to significantly exploit all the available pieces of information on these peaks. Results of the tests on synthetic and real images are reported, which show that this method achieves satisfactory results, making the detection task highly reliable in the presence of both noise and clutter [J288]

"Theoretical aspects of radar imaging using stochastic waveforms"

In this work, we develop the theory of radar imaging using stochastic waveforms, such as random noise or chaotic signals. Specifically, we consider one-dimensional (1-D) (range profiles) and two-dimensional (2-D) (range-Doppler) radar imaging performed with a random signal radar, in which the transmit signals are assumed to be stationary random processes. We calculate the 1-D and 2-D point-spread functions as the expected value of the radar return. We show that the 2-D point-spread function is spatially invariant; however, the reduction in height and broadening of the mainlobe is small in the case of bandlimited noise. We also derive a formula that is useful in calculating the variance of the radar return under the assumption that the transmit signal is real valued and Gaussian [J289]

"Receiver operating characteristics for the coherent UWB random noise radar"

An ultrawideband (UWB) random-noise radar operating in the 1-2 GHz frequency band has been developed and held-tested at a 200 m range at the University of Nebraska. A unique heterodyne correlation technique based on a delayed transmitted waveform using a photonic delay line has been used to inject coherence within this system. The performance of this radar, assuming a point target, has been investigated from a statistical point of view by developing the theoretical basis for the system's receiver operating characteristics (ROC). Explicit analytical expressions for the joint probability density function (pdf) of the in-phase (I) and quadrature (Q) components of the receiver output have been derived under the assumption that the input signals are partially correlated Gaussian processes. The pdf and the complementary cumulative distribution function (cdf) for the envelope of the receiver output are also derived. These expressions are used to relate the probability of detection (Pd) to the probability of false alarm (Pf) for different numbers of integrated samples, and the results are analyzed [J290]

"SAR imaging of buried objects from MoM modelled scattered field"

Synthetic aperture radar (SAR) images of resonant buried objects are modelled in the presence of ground surface clutter. The method of moments (MoM) is used to model scattered fields from a resonant buried conductor and clutter is modelled as a bivariant Gaussian distribution. A diffraction stack SAR imaging technique is applied to the ultra-wideband waveforms to give a bipolar signal image. A number of examples have been computed to illustrate the combined effects of SAR processing with resonant targets and clutter. SAR images of different targets show differences which may facilitate target identification. To maximise the peak signal-to-clutter

ratio, an image correlation technique is applied and the results are shown [J291]

"Enhanced target detection and identification via optimised radar transmission pulse shape"

The optimisation of the transmission radar pulse shape to maximise either target detection or identity discrimination between the T-72 and M1 main battle tanks is investigated. Significant performance improvements in target detection and identification are obtained using such matched illumination transmission waveforms over that of standard chirped pulses [J292]

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