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

ТЕМАТИЧЕСКИЙ РЕФЕРАТИВНЫЙ СБОРНИК № 23-1

“Radar Clutter Suppression”
(«Подавление помеховых отражений в радиолокации»)

Журнальные публикации

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

Томск – 2011

ТЕМАТИЧЕСКИЙ РЕФЕРАТИВНЫЙ СБОРНИК № 23-1

"Radar Clutter Suppression"
(«Подавление помеховых отражений в радиолокации»)

Журнальные публикации

"Taylor series expansions for airborne radar space-time adaptive processing"

Space-time adaptive processing (STAP) for range-dependent clutter rejection in airborne radar is considered. Indeed, radar antenna architectures or configurations that are different from the conventional uniform linear antenna array (ULA) and side-looking (SL) configuration have consequences on the clutter properties. The authors here investigate the use of Taylor series expansions (TSEs) of the space-time covariance matrix in the classical sample matrix inversion (SMI) STAP method in order to mitigate the range non-stationarity of the clutter and they compare it to the derivative-based updating (DBU) already proposed in the literature. The authors also propose a new algorithm based on a TSE of the clutter plus noise subspace in conjunction with the eigencanceler-based (EC) STAP, which improves the performance in term of signal-to-interference plus noise ratio (SINR) loss, compared to the DBU method. In this study, the particular cases of a ULA and a uniform circularly curved antenna (UCCA) array in SL and non-SL monostatic configurations as well as a ULA in some bistatic configurations are considered for the test and the comparison of the presented algorithms. [J1]

"Adaptive HF interference cancellation for sky wave over-the-horizon radar"

A computationally efficient adaptive beamforming algorithm for high-frequency (HF) sky wave over-the-horizon radar to suppress the spatially nonstationary HF interference while preserving the temporal coherence of the clutter echoes is proposed. The proposed algorithm is based on the generalised sidelobe canceller structure with constraint on the time-varying weight vectors. Experimental data-processing results show the effectiveness of the algorithm. [J2]

"Target detection in high-resolution sea clutter via block-adaptive clutter suppression"

Attentions have been focused on the moving target detection in a high-resolution sea clutter. This study commences with a proposal of median-based estimator to estimate the power spectrum of high-resolution sea clutter by the time series observed in adjacent range cells and time intervals. The estimator provides a robust estimation when just a few aberrant time series happen in observation. Based on the estimator, a block-adaptive clutter suppression filter (BACSF) is designed to suppress the clutter prior to the pulse integration. Then, the residual clutter, the output of the BACSF, is modelled as spherically invariant random vector. Upon applying an adaptive normalised matched filter (ANMF) to the residual clutter, a residual clutter's ANMF detector is derived. Moreover, in high-resolution radar background, considering that the approximately stationary intervals of sea clutter and residual clutter are much shorter than the coherent processing interval, another heuristic block-ANMF detector is proposed. It can integrate more pulses and can achieve better performance than the ANMF detector does. This study concludes with the experiments of simulated target against the real sea clutter. The experimental results demonstrate that, when target's Doppler frequency is beyond strong clutter region, the ANMF detector and block-ANMF detector perform better in the residual clutter than in the clutter. [J3]

"Adaptive clutter suppression and resolving of velocity ambiguities for an experimental three-channel airborne synthetic aperture radar-ground moving target indication system"

This study investigates practical processing methods aiming at detecting ground moving targets and estimating their motion parameters for an experimental three-channel airborne synthetic aperture radar-ground moving target indication (SARGMTI) system. It focuses on two key points of GMTI processing: adaptive clutter suppression and resolving of velocity ambiguities. Different from the conventional clutter suppression based on SAR images or in range-Doppler domain of the entire-aperture pulses, the clutter cancellation is proposed to be performed in the Doppler domain of short-aperture pulses to avoid the superposition of clutter echoes from different ground patches in azimuth; meanwhile, the ground moving target signals are focused with the full aperture to maximise the signal-to-noise ratio. To resolve the velocity ambiguity, a joint strategy is proposed that combines the estimates of the along-track interferometric phases and the Doppler spectrum information of a ground moving target according to the Chinese remainder theorem. The implementations of the processing

operations are verified with real data from the experimental three-channel airborne SAR-GMTI system. [J4]

"On the Essence of Knowledge-Aided Clutter Covariance Estimate and Its Convergence"

Space-time adaptive processing (STAP) is a popularly used strategy for clutter suppression in moving-platform radar. In this context, the estimate of the clutter covariance matrix (CCM) is usually required to derive a near-optimum processing. The problem of estimation convergence then arises, especially in heterogeneous clutter environments, where, in the case of low convergence, the limited number of training samples will result in significantly degraded performance. Recently proposed knowledge-aided (KA) approaches show strong capability in improving convergence. Such capability is shown here to be essentially due to the reduction on the number of degrees of freedom (NDoF) of the sample space of the clutter process that bounds the convergence. In addition, the convergence measure of effectiveness (MOE) of two primary KA approaches, i.e., colored loading (CL) and fast maximum likelihood with assumed clutter covariance (FMLACC), is theoretically analyzed. The application of covariance matrix tapers (CMT) is proposed to enhance their robustness against knowledge mismatches. The simulation verifies the conclusions. [J5]

"Sandglass transformation for synthetic aperture radar detection and imaging of ship at low signal-to-clutter-plus-noise ratio"

Space/air-borne synthetic aperture radar (SAR) detection and imaging of moving ships at sea are important for ocean reconnaissance and fishery monitoring. A novel algorithm based on sandglass transformation to detect weak ships and form high-quality images under the conditions of low signal-to-clutter-plus-noise ratio is presented here. It requires no prior information about motion parameters of targets. The sandglass transformation can decouple the time and lag time in the instantaneous autocorrelation function of a linear frequency modulated (LFM) signal. Thus the cross-range signals of ship in the approximate form of LFM signals can be integrated coherently via the two-dimensional fast Fourier transformation. The proposed algorithm can not only achieve high-energy accumulation gain, but also suppress the interference of cross terms effectively without loss of resolution. Hence, it is effective to detect weak ships and generate high-resolution images. Numerical and experimental results confirm the effectiveness of the proposed algorithm. [J6]

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

The Technical University of Denmark has developed and tested a P-band ice sounding radar for European Space Agency (ESA). With the recent by the International Telecommunication Union (ITU) allocation of a radar band at 435 MHz, increased interest in space-based sounding of the Earth s ice caps has been encountered. ESA s POLarimetric Airborne Radar Ice Sounder (POLARIS) is intended to provide a better understanding of P-band scattering and propagation through ice sheets and to verify novel surface clutter suppression techniques in preparation for a potential space-based ice sounding mission. POLARIS is a nadir-looking, fully polarimetric radar featuring aperture synthesis, a multi-aperture antenna for surface clutter suppression and a large dynamic range based on a shallow/deep sounding approach. The system is installed in a De Haviland DHC-6 Twin Otter aircraft, and in May 2008, a proof-of-concept campaign was conducted in Greenland. This study outlines the design and implementation of the system, and based on first results it is concluded that in the central dry snow zone of Greenland, POLARIS can resolve shallow and deep internal ice layers, penetrate the thickest ice encountered and detect the bedrock. [J7]

"Resolution Enhancement for Inversed Synthetic Aperture Radar Imaging Under Low SNR via Improved Compressive Sensing"

The theory of compressed sampling (CS) indicates that exact recovery of an unknown sparse signal can be achieved from very limited samples. For inversed synthetic aperture radar (ISAR), the image of a target is usually constructed by strong scattering centers whose number is much smaller than that of pixels of an image plane. This sparsity of the ISAR signal intrinsically paves a way to apply CS to the reconstruction of high-resolution ISAR imagery. CS-based high-resolution ISAR imaging with limited pulses is developed, and it performs well in the case of high signal-to-noise ratios. However, strong noise and clutter are usually inevitable in radar imaging, which challenges current high-resolution imaging approaches based on parametric modeling, including the CS-based approach. In this paper, we present an improved version of CS-based high-resolution imaging to overcome strong noise and clutter by combining coherent projectors and weighting with the CS optimization for ISAR image generation. Real data are used to test the robustness of the improved CS imaging compared with other current techniques. Experimental results show that the approach is capable of precise estimation of scattering centers and effective suppression of noise. [J8]

"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. [J9]

"Signal Processing for Improved Detection of Trapped Victims Using UWB Radar"

Detection of trapped victims using ultrawideband radar is considered a highly challenging task due to multiple unknown parameters and generally very low signal-to-noise-and-clutter ratio (SNCR) conditions. In this paper, we propose a novel detection algorithm which is designed for detection of periodic motion caused by, e.g., respiratory motion of the victim for low SNCR conditions. The aim is to separate the respiratory-motion response of a trapped victim from nonstationary clutter originating from moving objects in the scene of interest. The algorithm performs stationary-clutter removal, high-level noise, and nonstationary-clutter suppression, indicates presence of the trapped victim, and estimates its range. The performance of the algorithm is investigated, both by means of simulation and experimental verification. The results show improved detection capabilities in low SNCR over an existing algorithm proposed by Zaikov et al. [J10]

"GMTI clutter cancellation using real non-ideal data"

The performance of displaced phase centre antenna (DPCA), adaptive DPCA (ADPCA) and joint domain localised space time adaptive processing (JDL-STAP) was examined when applied to data that were not gathered for ground moving target indication (GMTI) purposes, and using very few array elements. Three different methods to be applied at the pre-processing stage to match pulses from different spatial channels were compared. The ADPCA method was shown to be the most robust in the presence of signals leaked from other range cells while traditional DPCA proved to be the most effective at attenuating stationary targets in non-ideal conditions, providing that pre-processing, using a pulse shift and a ramp in phase, was applied to the data. Quantitative results are presented, which are drawn from real experiments using real airborne radar data and which provide a valuable insight into the tolerance of DPCA, ADPCA and STAP when put to use with few spatial channels on non-ideal data. The study shows that all three GMTI algorithms used with few antenna elements can successfully resolve moving targets from clutter in such data and discusses the limitations of each in suppressing unwanted stationary peaks. [J11]

"Direct-path suppression by spatial filtering in digital television terrestrial broadcasting-based passive radar"

The signal model of digital television terrestrial broadcasting (DTTB) is introduced and its ambiguity function is analysed here. In order to suppress the direct-path (and multipath) interference generated by single frequency network in DTTB-based passive radar, the corresponding spatial filtering methods are designed according to the feature of each channel. In the echo channel, the interference is suppressed by discarding the signal-subspace. The noise-subspace can be estimated from the power of the covariance matrix to avoid the eigen-decomposition and to eliminate the need to obtain the corresponding dimension. In the reference channel, the transmitting signal of a certain transmitter is regarded as the desired signal. The desired signal will be cancelled by conventional spatial filtering algorithms for the high signal-to-noise ratio case, which will also result in a distorted pattern and high side-lobes. To solve this problem, an improved general side-lobe canceller structure is proposed to realise the adaptive beamformer. To improve the robustness of the proposed methods and suppress the distributed clutter, the `broad null` algorithm is combined with the beamformer. The simulation results show that the proposed methods are effective to suppress the interference in DTTB-based passive radar. [J12]

"Multi-Channel SAR-GMTI Method Robust to Coregistration Error of SAR Images"

High accuracy in complex images coregistration is essential in ground moving target indication (GMTI) processing of synthetic aperture radar (SAR) data, normally termed SAR-GMTI. The clutter suppression performance is proportional to the coregistration accuracy. In this correspondence, we propose a new SAR-GMTI approach, which is robust to the SAR images coregistration error. The observed clutter-plus-noise vector is built using the neighboring pixels as the first step, thus the corresponding covariance matrix, termed as joint covariance matrix, can be estimated. The joint noise subspace is obtained by eigen-decomposing of the joint

covariance matrix. The clutter is suppressed successfully by a projecting operation, i.e., a projection of the joint observed vector into the resulting joint noise subspace. The information of neighboring pixels is substantially exploited in the clutter suppression, resulting in the robustness, even at the presence of large coregistration error. Both the simulated and real multi-channel airborne data are used to validate the proposed approach. [J13]

"Estimation of the ocean clutter rank for HF/ VHF radar space-time adaptive processing"

The rank of clutter covariance matrix is an important indicator of both the severity of the clutter scenario and the number of degrees-of-freedom required to produce effective clutter suppression. Thus, the estimation of clutter rank is an essential issue for space-time adaptive processing. The rank of ground clutter covariance matrix can be accurately predicted by the well-known Brennan's rule. Unfortunately, the similar rule for ocean clutter rank estimation has not been developed. In this paper, a formula to estimate the rank of ocean clutter covariance matrix is derived, with which the eigenspectrum structure of ocean clutter can be correctly predicted. The validity of this formula is verified by simulation results. [J14]

"Clutter suppression for airborne nonsidelooking radar using ERCB-STAP algorithm"

Clutter suppression for airborne non-sidelooking radar is a challenging problem due to the range-dependent clutter. In this study, an algorithm combining elevation robust Capon beamforming (ERCB) and two-dimensional azimuth-Doppler space-time adaptive processing (STAP) is presented to realise clutter suppression for airborne non-sidelooking radar. The presented algorithm can place range-dependent nulls to eliminate the range-dependent clutter and the residual range-independent clutter can be suppressed by two-dimensional azimuth-Doppler STAP methods. Numerical examples are given to demonstrate the effectiveness of the presented algorithm. [J15]

"Hybrid direct data domain sigma-delta space-time adaptive processing algorithm in non-homogeneous clutter"

The need to deal with non-homogeneous clutter has driven much of the recent research in space-time adaptive processing (STAP). An extension of the low-complexity, sigma-delta (ΣΔ) algorithm incorporating the direct data domain (D3) processing is presented. The new algorithm is practical and improves target detection in nonhomogeneous clutter environments. The algorithm employs a hybrid approach, combining D3processing with the more traditional statistical approach, thereby obtaining advantages of both. First, a modified D3algorithm, which maximises signal-to-interference-plus-noise ratio (SINR), is presented. Then this D3algorithm is used as an adaptive transformer to create sum (Σ) and difference (Δ) beams. The residual interference after the D3processing is further cancelled by ΣΔ STAP. The proposed hybrid algorithm using D3-ΣΔ STAP is tested in nonhomogeneous clutter modelled using spherically invariant random variables (SIRV) and artificially injected discrete interferers. Performance of the proposed methods is compared with those of traditional statistical approaches, illustrating significant benefits of hybrid processing in non-homogeneous scenarios. [J16]

"Partially Adaptive STAP using the FRACTA Algorithm"

A partially adaptive space-time adaptive processor (STAP) utilizing the recently developed FRACTA algorithm is presented which significantly reduces the high computational complexity and large sample support requirements of fully adaptive STAP. Multi-window post-Doppler dimensionality reduction techniques are employed to transform the data prior to application of the FRACTA algorithm. The FRACTA algorithm is a reiterative censoring (RC) and detection algorithm which has been shown to provide excellent detection performance in nonhomogeneous interference environments. Two multi-window post-Doppler dimensionality reduction techniques are considered: PRI-staggered and adjacent-bin. The partially adaptive FRACTA algorithm is applied to the KASSPER I (knowledge-aided sensor signal processing & expert reasoning) challenge datacube. The pulse repetition interval (PRI)-staggered approach with D=6 filters per Doppler bin is found to provide the best detection performance, outperforming the fully adaptive case while simultaneously reducing the runtime by a factor of ten. Using this implementation, partially adaptive FRACTA detects 197 out of 268 targets with one false alarm. The clairvoyant processor (the covariance matrix for each range cell is known) detects 198 targets with one false alarm. In addition, the partially adaptive FRACTA algorithm is shown to be resilient to jamming, and performs well for reduced sample support situations. When compared with partially adaptive STAP using traditional sliding window processing (SWP), the runtime of partially adaptive FRACTA is 14 times faster, and the detection performance is significantly increased (SWP detects 46 out of 268 targets with one false alarm). [J17]

"Two-dimensional pulse-to-pulse canceller of ground clutter in airborne radar"

It is well known that in the airborne radar, the location of the ground clutter spectrum in the angle-Doppler space is dependent mainly on the platform velocity and radar parameters. The authors propose a two-dimensional

pulse-to-pulse canceller (TDPC) that can make full use of such prior information. The more detailed formulations of the ground clutter model and the signal model are given in a matrix-vector form. The least-squares-typical cost function associated with the filter coefficient matrix of the TDPC is established on the basis of the ground clutter model and the signal model. Like the classical displaced phase centre antenna (DPCA) processing, the proposed TDPC is also a spatial-temporal suppressor of ground clutter and can decrease the ground clutter signals, even though the DPCA condition is not satisfied. The proposed TDPC can also be used as an efficient pre-filtering tool before the conventional moving target indication (MTI) processing and the classical adaptive processing. Moreover, if only the TDPC plus the conventional MTI is used, it takes less computational time than the adaptive canceller. Experimental results show that the proposed TDPC has the satisfactory ground clutter suppression capability by using both simulated data and measured data. [J18]

"Short-Range Clutter Suppression for Airborne Radar by Utilizing Prefiltering in Elevation"

Space-time adaptive processing (STAP) techniques have achieved good performance when applied to side-looking airborne radar (SLAR) where the ground clutter is relatively stationary, but due to severe range dependence, the performance is not so good in non-SLAR particularly when the pulse repetition frequency is high enough to induce range ambiguity. Because the short-range clutter Doppler for non-SLAR varies rapidly with range while the long-range clutter Doppler varies gently, at the presence of range ambiguity, the clutter in different ambiguous ranges does not coincide. The clutter range dependence mitigation for the case of range ambiguity is the major problem that this letter intends to solve. A subarray synthesis algorithm with prefiltering in elevation is presented. By this technique, the ambiguous short-range clutter is eliminated before STAP; therefore, the clutter range dependence is alleviated, and then, the STAP performance will be improved greatly. [J19]

"Efficient Methods of Clutter Suppression for Coexisting Land and Weather Clutter Systems"

The removal of coexisting land and weather clutter signals is a common problem in many radar applications. Although the optimal method for land-weather clutter suppression is known, it is usually not amenable to implementation due to computation and storage limitations of the processor. We propose an alternative method that employs low rank approximations on weather clutter correlation matrix to obtain detectors which are feasible to implement. The performance of the proposed method is compared with the optimal detector and some other detectors used for this task to illustrate the trade-off between the improvement factor gain and the computational, storage requirements. [J20]

"Adaptive ground clutter suppression for conformal array radar systems"

Conformal arrays (CFAs) possess certain desirable characteristics for deployment on unmanned aerial vehicles and other payload-limited platforms. However, the CFA non-planar geometry induces clutter non-stationarity, resulting in elevated signal-to-interference-plus-noise ratio (SINR) loss when applying conventional space-time adaptive processing (STAP) algorithms. Non-stationary clutter leads to covariance matrix estimation error and, consequently, an erroneous STAP frequency response. In this study, the authors examine two practical conformal antenna configurations: a belly-mounted canoe and a nose-mounted, chined shape. Using high-fidelity signal models, the authors show traditional STAP losses in excess of 10-dB because of the effects of clutter non-stationarity. The authors then investigate a number of ameliorating techniques compatible with standard STAP implementation, including localised processing, localised processing with time-varying weights, equivalent uniform linear array transformation, angle-Doppler warping and higher-order angle-Doppler warping. The authors demonstrate very good performance for the higher-order angle-Doppler warping method applied to the chined radome shape, with peak adaptive SINR losses reduced from nearly 16-dB for the uncompensated case to 3-dB of loss consistent with performance attainable in a homogeneous clutter environment. The authors also find good performance for three-dimensional angle-Doppler warping over azimuth, elevation and Doppler when applied to the tapered canoe shape, with uncompensated losses of roughly 14-dB reduced to 3-dB, again a level compatible with STAP applied in a homogeneous clutter environment. The authors thus show that CFA STAP can yield performance similar to that of a conventional planar array when using appropriate compensation methods. [J21]

"Through-Wall Imaging of Moving Targets Using UWB Random Noise Radar"

For a through-wall ultrawideband (UWB) random noise radar using array antennas, subtraction of successive frames of the cross-correlation signals between each received element signal and the transmitted signal is able to isolate moving targets in heavy clutter. Images of moving targets are subsequently obtained using the back projection (BP) algorithm. This technique is not constrained to noise radar, but can also be applied to other kinds of radar systems. Different models based on the finite-difference time-domain (FDTD) algorithm are set up to

simulate different through-wall scenarios of moving targets. Simulation results show that the heavy clutter is suppressed, and the signal-to-clutter ratio (SCR) is greatly enhanced using this approach. Multiple moving targets can be detected, localized, and tracked for any random movement. [J22]

"Spatial-temporal separable filter for adaptive clutter suppression in airborne radar"

A spatial-temporal separable filter (STSF) for adaptive clutter suppression in airborne radar is proposed. The STSF coefficients can be efficiently obtained by the proposed bi-iterative algorithm. The STSF performance is illustrated by experiment results on the simulated data and measured data. [J23]

"Ground Moving Target Indication Using an InSAR System With a Hybrid Baseline"

In this letter, a two-channel airborne experimental interferometric synthetic aperture radar (InSAR) designed for terrain height estimation is exploited to acquire the ability of ground moving target indication (GMTI). Due to the hybrid baseline of this system, the interferometric phase changes with the target motion as well as the terrain height. The fluctuation of the interferometric phase worsens the performance of the clutter suppression and the radial velocity estimation. In order to resolve this problem, a GMTI method with three steps is proposed. After two steps are used to eliminate the local flat-Earth phase and the cross-track interferometric phase of the scene, respectively, an adaptive filtering method is used to suppress the stationary clutter with the benefit of calibrating the sensor responses. A conventional constant false alarm rate detector is then used to indicate the moving targets. The validity of the proposed method is demonstrated with real data collected using an experimental airborne InSAR system. [J24]

"Post-adaptive processing time-delay beamforming for clutter suppression in airborne radar"

A novel beamforming architecture is presented in which time delay steering is applied after the application of space-time adaptive processing (STAP) in a phased array for airborne radar. Improved clutter suppression and slow moving target detection performance can be achieved over that associated with STAP and conventional time delay steering in wideband sideways looking applications. The architecture also provides a computationally efficient means of applying time-delay beamforming in conjunction with STAP in applications where multiple receive beams are required. [J25]

"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. [J26]

"Suppression of Clutter Residue in Weather Radar Reveals Birds' Corridors Over Urban Area"

An adaptive spectral technique for ground clutter and noise suppression in weather radar echoes is presented. This technique detects weak echoes that are masked by the residuals from ground clutter. The technique is demonstrated on two clear air cases observed with Doppler weather radar. After adaptive suppression of ground clutter and its residue, features appear over the Oklahoma City urban area where otherwise none could be seen. These are interpreted as birds' corridors between two lakes and along a river. [J27]

"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. [J28]

"Improved Space-Based Moving Target Indication via Alternate Transmission and Receiver Switching"

Ground moving target indication (GMTI) by space-based radar systems requires special antenna and data acquisition concepts to overcome the problem of discriminating target signals from clutter returns. Owing to the high satellite speed, the clutter contains a broad mixture of radial velocities within the antenna beam, leading to a large Doppler spread. Effective clutter suppression can solely be achieved by multiple aperture or phase center antennas. For space-based systems, however, the number of receiver channels connected to subapertures is very limited due to their weight, volume, and high data rates (current systems such as TerraSAR-X and RADARSAT-2 possess only two). This classical along-track interferometry architecture, in which the antenna is split into two halves, achieves only suboptimum GMTI performance. This paper presents and statistically analyzes an innovative approach to create additional independent phase centers to improve the GMTI performance considerably. The extra degrees of freedom are created by cyclical phase and amplitude switchings of the transmit/receive modules for transmitter and receiver between pulses, hence trading Doppler bandwidth for extra spatial diversity. In the first part of this paper, different strategies of spatial-temporal diversity are introduced and analyzed for realistic system parameters with respect to ambiguities and detection performance. The second part is concerned with the elaborate theoretical analysis of the relocation improvement for the spatial diversity approach. [J29]

"Ground Moving Target Indication With Tandem Satellite Constellations"

Ground moving target indication (GMTI) from space by existing dual-channel radar systems such as TerraSAR-X and RADARSAT-2 has been shown to perform only insufficiently with respect to the relocation error of targets to their true ground position. Only two parallel receiver channels are too little to suppress the severe ground clutter and to estimate the target's parameters. Although this deficiency may partly be alleviated through antenna aperture switching, the resulting positioning accuracy is still not adequate for effective traffic monitoring purposes. Satisfactory results are only achievable with extended apertures, primarily with satellite constellations. This letter presents a statistical analysis of the performance of different concepts for cooperating back-to-back flying satellite systems. Particularly in anticipation of TanDEM-X, which will form the first operational GMTI-capable coherent synthetic aperture radar constellation after its launch in 2009. [J30]

"Interference Cancellation for High-Frequency Surface Wave Radar"

The performance of high-frequency surface wave radar (HFSWR) is known to suffer from external environmental interference and noise, such as cochannel radio-frequency interference from other radiating source, ionospheric clutter, lightning impulsive noise, etc. This paper experimentally evaluates the interference cancellation performance of various adaptive beamforming schemes with respect to the aforementioned three types of interferences in an attempt to find the most promising adaptive cancellation scheme in practical HFSWR environment. [J31]

"Phase-Based Clutter Identification in Spectra of Weather Radar Signals"

A novel method for suppression of ground clutter (GC) in weather radar is presented. The novel identification scheme is entirely phase based, unlike power-based schemes that are generally used. GC contributions to the Doppler spectrum are identified from the differential phase between complex spectral coefficients of two spectra estimated for odd- and even-indexed half-sequences of the original time series. Phase values near zero are used as indicators of clutter contributions for Doppler bins close to zero velocity. Indicated Doppler bins are notched from the original spectrum, and the moments are then obtained. The identification scheme is motivated by spectra of an electronically steered phased array of the National Weather Radar Testbed (NWRT) and requires a sufficient number of pulses/samples for spectral analyses. However, the method can be used with a mechanically steered antenna with an appropriate adjustment compensating smearing due to antenna rotation. The method was tested on several NWRT data sets obtained in clear air and in precipitation. One example of clutter-filtered power in precipitation is shown here. There is no baseline for comparison, as the NWRT does not have clutter filtering at the present time. Nonetheless, for a comparison of power- and phase-based identification schemes, a power-based clutter filter similar to the one used by the National Weather Service on the network of mechanically steerable Weather Surveillance Doppler radars WSR-88Ds is implemented on NWRT and used as a preliminary baseline for comparison. [J32]

"Knowledge-based recursive least squares techniques for heterogeneous clutter suppression"

The design of knowledge-based adaptive algorithms has been dealt with for the cancellation of heterogeneous

clutter. To this end, the application of the recursive least squares (RLS) technique has been revisited for the rejection of unwanted clutter, and modified RLS filtering procedures have been devised accounting for the spatial variation of the clutter power as well as of the disturbance covariance persymmetry property. Then the authors introduce the concept of knowledge-based RLS and explain how the a priori knowledge about the radar operating environment can be adopted for improving the system performance. Finally, the authors assess the benefits resulting from the use of knowledge-based processing both on simulated and on measured clutter data collected by the McMaster IPIX radar in November 1993 [J33]

"Suppression of Surface Clutter Interference With Precipitation Measurements by Spaceborne Precipitation Radar"

The sidelobe surface clutter along the nadir direction severely interferes with the rain echo in the off-nadir angle observations made using a spaceborne Precipitation Radar (PR). A new method to suppress this sidelobe clutter interference is introduced. A characteristic of the 1-D phased array antenna system is that high sidelobes arise along the beam scan plane. The proposed method tilts the antenna beam scan plane from the nadir such that these high sidelobes would not be directed along the nadir direction, along which a specular component of the backscattering radar cross section of the Earth's surface is dominant. The simulation results using the designed parameters of a Ka-band spaceborne PR indicate the validity of this method, which is also quantitatively confirmed using Tropical Rainfall Measuring Mission/PR observation data sets [J34]

"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 [J35]

"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. [J36]

"Adaptive cancellation method for geometry-induced nonstationary bistatic clutter environments"

This paper describes and characterizes a new bistatic space-time adaptive processing (STAP) clutter mitigation

method. The approach involves estimating and compensating aspects of the spatially varying bistatic clutter response in both angle and Doppler prior to adaptive clutter suppression. An important feature of the proposed method is its ability to extract requisite implementation information from the data itself, rather than rely on ancillary-and possibly erroneous or missing-system measurements. We justify the essence of the proposed method by showing its ability to align the dominant clutter subspaces of each range realization relative to a suitably chosen reference point as a means of homogenizing the space-time data set. Moreover, we numerically characterize performance using synthetic bistatic clutter data. For the examples considered herein, the proposed bistatic STAP method leads to maximum performance improvements between 17.25 dB and 20.75 dB relative to traditional STAP application, with average improvements of 6 dB to 10 dB. [J37]

"Experimental investigation of directional characteristics for ionospheric clutter in HF surface wave radar"

The unwanted radar echoes from the ionosphere are collectively called ionospheric clutter. It has proved to be the greatest impediment to achieve consistently good performance in long-range detection of surface vessels and sea-state monitoring for high-frequency surface wave radar (HFSWR). Field experimental data recorded by the HFSWR OSMAR2003 (Ocean State Monitor and Analysis Radar, manufactured in 2003) has been used in detailed investigations of the directional characteristics for this ionosphere clutter, leading to the development of effective mitigation techniques based on antenna design and adaptive signal processing. Particular attention is given to the amplitude and phase relationship among multiple spatial channels for two types of ionospheric clutter. Preliminary experimental results show that the random gain and phase variation of the antenna pattern overhead null destroyed the amplitude and phase consistency among channels. As a result, no significant measured directivity is observed in this type of specular clutter. For the incidence clutter from a lower elevation angle, it is observed that the spread clutter possesses high directivity. A nonlinear receiving array composed of multiple V-shaped antennas without deep and broad null at near-vertical incidence is proposed for adaptive ionospheric clutter suppression [J38]

"Outlier suppression in adaptive filtering through de-emphasis weighting"

A de-emphasis weighting approach is used to suppress the effect of outliers in background samples during the formation of a sample covariance matrix. The approach is relevant to a broad range of adaptive filtering techniques. Results from processing simulated and real coherent radar data using de-emphasis weighting are compared with results using no outlier suppression and censored sample matrix inversion pruning methods. De-emphasis techniques are shown to produce the most robust detection performance when outliers are present and are also shown to have minimal performance impact when clutter is homogeneous, that is no outliers present [J39]

"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 [J40]

"Prediction of inverse covariance matrix (PICM) sequences for STAP"

In this letter, we study issues associated with applying least-squares estimation to predict the inverse covariance matrix in bistatic airborne radar systems. For the bistatic ground moving target indication radar, the clutter Doppler frequency depends on the range for all array geometries. This range dependency leads to problems in clutter suppression through space-time adaptive processing (STAP) techniques. This paper proposes a new method of obtaining an estimate of the inverse covariance matrix using linear prediction techniques. Simulation results show a significant improvement in processor performance as compared to conventional STAP methods. [J41]

"Monitoring and surveillance potentialities obtained by splitting the antenna of the COSMO-SkyMed SAR into multiple sub-apertures"

The authors discuss the potentialities obtained by splitting the antenna of the COSMO-SkyMed synthetic aperture radar (SAR), developed by Alenia Spazio under contract to the Italian Space Agency and Italian Ministry of Defence, into multiple sub-apertures. The modified sensor has the capability to detect slowly moving ground targets that compete with the clutter Doppler spectrum. Special attention is devoted to a preliminary analysis of the signal processing techniques to be used. Moreover their capabilities for surveillance purposes are characterised based on theoretical and simulated results. Moreover the modified sensor is shown to allow sea current/wave monitoring by along-track SAR interferometry, relocation of moving targets in high resolution SAR images, and fully polarimetric imaging. Some practical implementation issues related to the possible modification are also briefly discussed. [J42]

"Experimental trials on ionospheric clutter suppression for high-frequency surface wave radar"

The unwanted radar echoes from the ionosphere are collectively called ionospheric clutter. This has proved to be the greatest impediment to achieving consistently good performance in long-range sea state monitoring for high-frequency surface wave radar (HFSWR). Ionospheric clutter can mask sea echoes having similar Doppler shifts. The potential for exploiting some fundamental characteristics of ionospheric clutter in directivity and frequency to suppress it is assessed. A post-Doppler spatial adaptive processing algorithm (PD-SAP) and the dual-frequency operation mode are introduced to suppress directional and non-directional ionospheric clutter, respectively. Experimental results confirm that both of these techniques can achieve effective ionospheric clutter suppression using the field experimental data recorded by the HFSWR OSMAR2003 (Ocean State Monitor and Analysis Radar, manufactured in 2003), located near Zhoushan in Zhejiang, China. [J43]

"Minimum norm property for the sum of the adaptive weights for a direct data domain least squares algorithm"

In most adaptive algorithms, it is generally assumed that one knows the direction of arrival (DOA) of the signal of interest (SOI) through the steering vector of the array and the goal is to estimate its complex amplitude in the presence of jammer, clutter and noise. In space-time adaptive processing (STAP) the goal is to seek for a target located along a certain look direction and at a particular Doppler frequency through a given steering vector. Therefore, the accuracy of the computed results in either case is based on the reliability of this a priori assumption of the steering vector. It is possible that due to mechanical vibrations, calibration errors or atmospheric refractions of the incident electromagnetic waves, the assumed DOA may not be very accurate or that the assumed value of the Doppler frequency is not appropriate. In either of these cases, the adaptive algorithm treats the SOI as an interferer and nulls it out. This perennial problem of signal cancellation is an open problem for adaptive algorithms. In this paper It is shown that the proper steering vector occurs at the minimum of the sum of the norm of the adaptive weights and can be used as an indicator to refine the estimate of the DOA of the SOI in adaptive algorithms or both the DOA or/and the Doppler frequency in STAP. Examples are presented to illustrate that the secondary processing outlined in this paper, may provide a refined estimate for the true DOA or/and Doppler frequency for the SOI in the presence of interference, clutter and noise [J44]

"Knowledge-aided signal processing: a new paradigm for radar and other advanced sensors"

Recently, significant progress has been made in the development of physics-based, knowledge-aided (KA) signal processing strategies supported by improvements in real-time embedded computing architectures. These developments provide designers of advanced sensor systems an unprecedented degree of flexibility when implementing next generation adaptive sensor systems. In the case of radar, this has been manifested in the first ever, real-time, KA space-time adaptive processing (KA-STAP) system for advanced clutter/interference suppression. This paper provides exemplars of real-world effects giving rise to the need for "intelligent" adaptation schemes and overviews the KA approach to sensor signal processing in some detail. Moreover, we survey a collection of papers describing recent KA sensor research that follow in this issue [J45]

"Training strategies for joint domain localised-space-time adaptive processing in a bistatic environment"

Optimum space-time adaptive processing (STAP) requires knowledge of the true interference covariance matrix. In practice, this matrix is not known and must be estimated from training data, which must be target free and statistically homogeneous with respect to the range gate under test. These conditions are often not satisfied, which degrades the detection performance. Particularly for bistatic ground moving target indication radar, the clutter Doppler frequency depends on range for all array geometries. This range dependency leads to problems

in clutter suppression through STAP techniques. The main aim in this paper is to access the relative merits of several strategies associated with STAP weight training for bistatic airborne radar applications. In particular, the issues associated with applying reduced-dimension conventional STAP and in-the-gate processing are studied. Simulation results show that, for a bistatic radar environment, in-the-gate processing approach performs better than conventional STAP approaches [J46]

"X-band experimental airborne radar-Phase II: synthetic aperture radar and ground moving target indication"

Defence Research and Development Canada, Ottawa, has completed Phase II of a multifunction X-band wideband experimental airborne radar. The system consists of a high average power transmitter, a digital waveform generator, two wideband 8-bit channels for synthetic aperture radar (SAR)/inverse synthetic aperture radar and two narrowband 14-bit channels for ground moving target indication (GMTI). The reflector antenna uses a novel multimode feedhorn to derive two phase centres displaced in azimuth. The radar was designed to support research into SAR imaging of fixed and moving targets (ocean and land), time-frequency analysis of moving targets, clutter suppression for GMTI radar and ocean surveillance for small and large target detection. Highlights of the data collection capabilities, include a swath width 16 K points wide in the single-channel SAR modes, 8 K points wide in the two-channel integrated SAR-GMTI modes and 4 K points wide in the GMTI surveillance modes. The architecture of the radar, its modes of operation with respect to the SAR and GMTI data collection capabilities, the MATLAB-based GMTI processor, and the real-time kernel developed for the SAR processor are discussed; and results from its high resolution stripmap, landspot, seaspot and GMTI modes are presented from trials in July 2003. [J47]

"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 [J48]

"Adaptive ionospheric clutter suppressio based o subarrays i monostatic HF surface ave radar"

Coherent sidelobe cancellatio (CSLC) based o subarrays has emerged as a key technology for improving the performance of radar systems required to operate i the presence of severe interference hich generally includes clutter as ell as jamming. hile the theory of CSLC is ell kno n, practical issues such as ho to set up the subarrays and ho to avoid diminishing the desired signal he the clutter is rejected need to be addressed he it comes to implementing CSLC in operational radar systems. A ne adaptive ionospheric clutter suppressio algorithm based o subarrays for monostatic HF surface ave radar (HFS R) is introduced and analysed. Detailed comparisons bet ee the proposed algorithm and conventional CSLC are performed. Simulatio and real data results confirm that the general and robust algorithm can achieve effective ionospheric clutter suppression, hile not decreasing the strength of the first-order sea echo using the data recorded by the OSMAR2003 (Ocea State Monitor and Analysis Radar, manufactured i 2003), located near Zhousha i Zhejiang, China. [J49]

"The adaptive coherence estimator: a uniformly most-powerful-invariant adaptive detection statistic"

We show that the Adaptive Coherence Estimator (ACE) is a uniformly most powerful (UMP) invariant detection statistic. This statistic is relevant to a scenario appearing in adaptive array processing, in which there are auxiliary, signal-free, training-data vectors that can be used to form a sample covariance estimate for clutter and interference suppression. The result is based on earlier work by Bose and Steinhardt, who found a two-dimensional (2-D) maximal invariant when test and training data share the same noise covariance. Their 2-D maximal invariant is given by Kelly's Generalized Likelihood Ratio Test (GLRT) statistic and the Adaptive Matched Filter (AMF). We extend the maximal-invariant framework to the problem for which the ACE is a GLRT: The test data shares the same covariance structure as the training data, but the relative power level is not constrained. In this case, the maximal invariant statistic collapses to a one-dimensional (1-D) scalar, which is also the ACE statistic. Furthermore, we show that the probability density function for the ACE possesses the

property of "total positivity," which establishes that it has monotone likelihood ratio. Thus, a threshold test on the ACE is UMP-invariant. This means that it has a claim to optimality, having the largest detection probability out of the class of detectors that are also invariant to affine transformations on the data matrix that leave the hypotheses unchanged. This requires an additional invariance not imposed by Bose and Steinhardt: invariance to relative scaling of test and training data. The ACE is invariant and has a Constant False Alarm Rate (CFAR) with respect to such scaling, whereas Kelly's GLRT and the AMF are invariant, and CFAR, only with respect to common scaling. [J50]

"Daytime interference ing of OSMAR"

In order to cancel the daytime interference of Ocean State Monitoring and Analyzing Radar, which appears in some consecutive days, we analyze the interference characteristic. Based on the characteristic the sidelobe cancellation technique and the orthogonal expansion method are proposed to cancel the interference. Both methods increase the sea-echo-to-interference ratio, but the latter achieves better effect in the far distance, which confirms the orthogonal expansion is the best method to remove the interference. [J51]

"Performance analysis of the sidelobe blanking system for two fluctuating jammer models"

Sidelobe blanking (SLB) devices are used in connection with the radar system to reduce the number of false alarms due to impulsive interference. This paper presents analytical expressions for the probability of blanking a sidelobe jammer interference via an SLB device for two statistical models of interference amplitude, namely, the Swerling Chi and shadowed Rice models. Performance curves are presented and the role of the different jammer parameters thoroughly investigated. [J52]

"Ionospheric decontamination and sea clutter suppression for HF skywave Radars"

In this paper, a cascaded correction and suppression method of reducing ionospheric phase path contamination and sea clutter to enable detection of targets travelling at speeds near the Bragg Doppler is addressed. The Hankel rank reduction (HRR) technique based on singular value decomposition (SVD) has been used to estimate the ionospheric phase distortion and suppress the sea clutter. Simulation results show that such a technique is helpful for the worse conditions when the target masking effect happens even after ionospheric phase decontamination. Finally, an attempt to combine another phase decontamination algorithm based on the piecewise polynomial phase modeling with the clutter cancellation stage for faster phase fluctuation is discussed briefly and some results are given. [J53]

"A novel chaos-based high-resolution imaging technique and its application to through-the-wall imaging"

In this letter, we present a novel chaos-based imaging technique. The proposed technique has good range-Doppler resolution and excellent side lobe suppression characteristics that promise immense potential for high-resolution imaging applications. We derive the range and Doppler resolution functions of the proposed technique and compare it with that of conventional time modulation-based imaging. Additionally, the noise performance of the proposed scheme is derived to show the improvement compared to the conventional amplitude and time modulation schemes. The proposed imaging technique is applied to through-the-wall radar imaging. Numerical electromagnetic simulations are performed to illustrate the effectiveness of the proposed technique. [J54]

"Robust adaptive beamforming for HF surface wave over-the-horizon radar"

Adaptive beamforming is used to enhance the detection of target echoes received by high frequency (HF) surface wave (HFSW) over-the-horizon (OTH) radars in the presence of spatially structured interference. External interference from natural and man-made sources typically masks the entire range-Doppler search space and is characterized by a spatial covariance matrix that is time-varying or nonstationary over the coherent processing interval (CPI). Adaptive beamformers that update the spatial filtering weight vector within the CPI are likely to suppress such interference most effectively, but the intra-CPI antenna pattern fluctuations result in temporal decorrelation of the clutter which severely degrades subclutter visibility after Doppler processing. A robust adaptive beamformer that effectively suppresses spatially nonstationary interference without degrading subclutter visibility is proposed here. The proposed algorithm is computationally efficient and suitable for practical implementation. Its operational performance is evaluated using experimental data recorded by the Iluka HFSW OTH radar, located near Darwin in far north Australia. [J55]

"Novel multiple phase centre reflector antenna for GMTI radar"

Adaptive cancellation of stationary clutter for a ground moving target indicator (GMTI) radar requires antenna

sensing using multiple apertures. In essence, simultaneous independent observations of the target plus clutter are required. Conventionally, multiple antenna apertures can be achieved through the use of physically separated antennas, or antennas which can be controlled so that subsections are used to receive. Herein, the use of reflector antennas to effect multiple phase centres is described. Multiple feedhorns pointed laterally from the focal point of the reflector are first reviewed, with capabilities and limitations discussed. A new technique for achieving multiple phase centres with a reflector antenna is then introduced. This technique is based on the excitation and combination of TE and/or TM modes from a single antenna feedhorn. It is shown that, by proper combination of multiple TE modes from a single feedhorn, radiation patterns with separate phase centres can be produced from the same reflector. TE and TM modes can also be combined to effect the same, but this is omitted for brevity. The characteristics of the resulting radiation patterns are analysed with a view towards maximising the separation of the antenna phase centres while maintaining symmetry between the patterns and minimising the reduction in gain and constant phase beamwidth with respect to the reflector's conventional radiation pattern. [J56]

"Detection, location, and imaging of fast moving targets using multifrequency antenna array SAR"

In this correspondence, we generalize the linear antenna array synthetic aperture radar (SAR) from transmitting single-wavelength signals to transmitting multiple-wavelength signals (called multifrequency antenna array SAR). We show that, using multifrequency antenna array SAR, not only the clutters can be suppressed but also the locations of both slow and fast moving targets can be accurately estimated: A robust Chinese remainder theorem (CRT) is developed and used for the location estimation of fast and slowly moving targets. Simulations of SAR imaging of ground moving targets are presented to show the effectiveness of the multifrequency antenna array SAR imaging algorithm. [J57]

"A high precision Doppler radar based on optical fiber delay loops"

The proposed theory shows that, by using optical fiber delay lines or loops, it is no longer necessary to compress pulses with matched filters for optimum detection and it is possible to suppress interference from undesirable zones. The suppression leads to lessening of Doppler and range ambiguity. The theory further shows that it is feasible to measure Doppler beating with high precision based on a single pulse. Thus, with a single pulse, there is no Doppler and range ambiguity; interference from undesirable range zones due to Doppler range fold-over will no longer present; and the troublesome ground clutter problem would be greatly suppressed. The high precision Doppler beating provides a mechanism to reveal intrinsic characteristics of a target without time average blurring or masking. New information can be acquired on targets of interest for purpose of passive identification. [J58]

"Small-target detection in sea clutter"

Sea clutter in marine surveillance radar makes the task of detecting small targets a very challenging problem. In this paper, a set of three signal processing techniques designed to suppress unwanted sea clutter radar echo and achieve target detection with no prior knowledge of the ocean and environmental conditions is presented. These include signal averaging, time-frequency representation, and morphological filtering. Datasets from real marine radar operating in staring mode are used to illustrate the performance of the new approaches. [J59]

"Statistical normalization of spherically invariant non-Gaussian clutter"

Conventional detection in active sonar involves comparing the normalized matched filter output power to a fixed preset threshold. Threshold crossings from contacts of interest are labeled as detections and those from undesired clutter echoes as false alarms. To maintain a constant false-alarm rate (CFAR) in the presence of strong transient clutter, the system can either increase the threshold or apply some function that suppresses this background down to an acceptable level. The latter approach leads to a more consistent background on the display, which enables operator-assisted detection. Background clutter suppression should not come at the expense of contact detection; to maximize the probability of detection (PD) for a given probability of false alarm (PFA), the likelihood ratio test (LRT) is used. However, the LRT does not address display issues, since the threshold that achieves a desired PFA varies with the input distribution. Ideally, the LRT output is monotonically transformed using a "statistical normalizer" (SN) that returns a consistent CFAR background without degrading the optimized PD. Within the radar community, clutter suppression is proposed using a LRT tuned to a K-distributed spherically invariant random vector (SIRV) model. However, this model does not lend itself to SN, as a closed-form expression for the LRT output density does not exist. In contrast, the proposed SIRV clutter model, with Pareto distributed power, leads to a closed-form density from which the SN function is readily derived. This combined Pareto-LRT/SN detector nearly matches the optimized PD performance of the K-distributed LRT and maintains a consistent CFAR background for display purposes. [J60]

"Results of flight tests of a two-channel radar system with real-time MTI processing"

Space-time adaptive processing (STAP) in real-time is discussed for two applications: first, STAP can be used for suppressing clutter and jammers; moreover, clutter filter coefficients gained by STAP can be used for the purpose of the correct positioning of moving targets within SAR images. Results of this real-time STAP technique as well as the results of the moving-target repositioning technique are presented: the clutter-suppression quality and the moving target repositioning accuracy are demonstrated with real SAR data and moving targets recorded during a measurement campaign. [J61]

"Effects of bistatic clutter dispersion on STAP systems"

The performance of several space-time adaptive processing (STAP) approaches in bistatic applications is analysed. Specific consideration is given to the effects of bistatic clutter spectral dispersion on covariance estimation and the algorithm's resulting clutter-rejection capability. The role of adaptive processing methods capable of high performance with efficient utilisation of the required training data is emphasised. A deterministic two-dimensional (angle-Doppler) compensation technique is used as a pre-processor and is compared to the Doppler warping approach. The algorithm performance is assessed using the output signal to interference plus noise ratio (SINR) compared to that of the matched filter with a known covariance. [J62]

"Comparison of Doppler clutter cancellation techniques for naval multi-function radars"

The authors describe a comparison of fixed and adaptive clutter cancellation processes applied to measured multi-function radar (MFR) data in a littoral environment. The adaptive filters require estimates of the clutter covariance, and comparisons of different strategies for obtaining this are made. The results for the adaptive filters generally show substantially improved target detectabilities over non-adaptive filters. [J63]

"Comparison between LS and TLS in adaptive processing for radar systems"

Adaptive signal processing strategies have to be developed for cancellation of electromagnetic noise-like interference in modern radar systems. The authors compare two signal processing methods, the least squares (LS) and the total least squares (TLS) algorithms, for adaptive phased-array radar systems. Results are presented which show that the TLS algorithm has a slight advantage over the LS algorithm at a cost of more computation. The LS algorithm therefore remains the preferred processing method. [J64]

"Benefits of space-time adaptive processing (STAP) in bistatic airborne radar"

The paper investigates the merits of using STAP for clutter suppression in bistatic airborne radar. Particular emphasis is placed on the clutter angle-Doppler inter-relationships in bistatic geometries, and it is demonstrated that there can be ground regions where small changes in arrival angle imply large changes in the Doppler shift. STAP clutter rejection methods are not ideally suited to these cases. It is also shown that the angle-Doppler inter-relationships vary with the ground topography, but the effects of this are usually small. Finally, it is shown that the clutter-suppression performance is dependent on the transmit and receive beam mainlobe/sidelobe interactions. [J65]

"Localised three-dimensional adaptive spatial-temporal processing for airborne radar"

Radar space-time adaptive processing (STAP) techniques have classically focused on azimuth-Doppler adaptivity while placing minimal emphasis on elevation. Elevation adaptivity offers significant clutter suppression improvement, allowing further suppression of interference sources having identical Doppler and azimuth as the expected target. Work is presented which incorporates elevation adaptivity using two approaches: a factored approach and a joint domain approach, both greatly improving clutter suppression performance. The proposed concepts are validated using results based on simulated range ambiguous airborne radar data. Target detection improvements on the order of 8 dB and 10 dB (as compared to standard 2D-JDL processing) are demonstrated for the factored and joint domain approaches, respectively, using an 8 Ч 8 nonuniform rectangular array. [J66]

"ISAR imaging in strong ground clutter using a new stepped-frequency signal format"

In this paper, a new easy-to-implement variant of the stepped-frequency signal format is presented for ground clutter cancellation application. A sequence of pulse-groups, where each pulse-group consists of two pulses of the same carrier frequency, is transmitted. The carrier frequency of each subsequent burst is stepped at Δf. Simple first-order cancellation of ground clutter can be carried out by comparing the returns of the two adjacent pulses, as the clutter movement (due to wind, etc.) can be assumed negligible within this interval (typically [J67]

"Manoeuvring target detection in over-the-horizon radar using adaptive clutter rejection and adaptive chirplet transform"

In over-the-horizon radar (OTHR) systems, the signal-to-clutter ratio (SCR) used for moving target detection is very low. For slowly moving targets such as ships, the SCR is typically from -50 dB to -60 dB and their Doppler frequencies are close to that of the clutter. For manoeuvring targets, such as aircraft and missiles, the Doppler frequencies are time-varying when a long integration time is considered. When a target does not move uniformly, the Fourier transform based target detection techniques, including super-resolution spectrum techniques, may fail to work appropriately. In such situations, the Doppler signatures are time-varying and, therefore, time-frequency analysis techniques can be used for manoeuvring target detection. In addition, clutter rejection is also required for target detection due to the low SCR. The existing adaptive clutter rejection algorithms combine clutter rejection with spectrum analysis methods, which usually assume uniformly moving target (i.e. sinusoidal Doppler signature) models. An adaptive clutter reject algorithm is proposed together with the adaptive chirplet transform technique for manoeuvring target detection in a multipath environment. Simulation results using a simulated manoeuvring target signal with received raw OTHR clutter data show that targets with SCR below -50 dB can be detected by using the proposed algorithm [J68]

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

A novel high-resolution time-frequency representation method is proposed for source detection and classification in over-the-horizon radar (OTHR) systems. A data-dependent kernel is applied in the ambiguity domain to capture the target signal components, which are then resolved using root-MUSIC based coherent spectrum estimation. This two-step procedure is particularly effective for analysing a multicomponent signal with time-varying complex time-Doppler signatures. By using the different time-Doppler signatures, important target manoeuvring information, which is difficult to extract using other linear and bilinear time-frequency representation methods, can be easily revealed using the proposed method [J69]

"Techniques for improving STAP performance in high PRF applications"

A novel beamforming architecture is presented in which space-time adaptive processing (STAP) for clutter suppression in airborne radar is implemented with tap delays of multiple PRIs. The resulting output is combined with the unadapted output. This can result in improved detection performance for targets obscured by clutter that covers only a small proportion of the unambiguous Doppler extent, as often occurs in high PRF modes [J70]

"A multiple-model prediction approach for sea clutter modeling"

Accurate modeling of sea clutter is an important problem in remote sensing and radar signal processing applications. Due to a recent discovery that sea clutter, the electromagnetic wave backscatter from a sea surface, is chaotic rather than purely random, computational intelligence techniques such as neural networks have been applied to develop new models for sea clutter. In this paper, we propose using the multiple neural network model approach to construct a predictive model for sea clutter. The motivation comes from the observation that the sea usually has some unpredictable motions that result in impulsive events such as sea spikes. Although a single nonlinear model could describe the Bragg scattering reasonably as shown in the literature, it is usually incapable of capturing sea spikes motions. Therefore, target detection performance might be degraded when such a clutter model is employed. Using a multiple radial basis function (RBF) net predictor, we found that a sea clutter signal with different underlying dynamics from sea spikes to normal motions can be modeled accurately. The multiple model (MM) approach automatically assigns different RBF predictors to model sea spikes and other mechanisms like Bragg scattering. The proposed multiple RBF neural network uses the expectation-maximization algorithm and multistep prediction for training, and hence it is suitable for real-time signal processing. Using real-life radar clutter data collected at the east coast of Canada, the proposed MM approach is shown to be effective in isolating and characterizing various components of sea clutter and, therefore, provides a promising model for clutter suppression in radar detection. [J71]

"Interference mitigation in STAP using the two-dimensional Wold decomposition model"

We propose a novel parametric approach for modeling, estimation, and detection in space-time adaptive processing (STAP) radar systems. The proposed parametric interference mitigation procedures can be applied even when information in only a single range gate is available, thus achieving high performance gain when the data in the different range gates cannot be assumed stationary. The model is based on the Wold-like decomposition of two-dimensional (2D) random fields. It is first shown that the same parametric model that results from the 2D Wold-like orthogonal decomposition naturally arises as the physical model in the problem of

space-time processing of airborne radar data. We exploit this correspondence to derive computationally efficient fully adaptive and partially adaptive detection algorithms. Having estimated the models of the noise and interference components of the field, the estimated parameters are substituted into the parametric expression of the interference-plus-noise covariance matrix. Hence, an estimate of the fully adaptive weight vector is obtained, and a corresponding test is derived. Moreover, we prove that it is sufficient to estimate only the spectral support parameters of each interference component in order to obtain a projection matrix onto the subspace orthogonal to the interference subspace. The resulting partially adaptive detector is simple to implement, as only a very small number of unknown parameters need to be estimated, rather than the field covariance matrix. The performance of the proposed methods is illustrated using numerical examples. [J72]

"Pattern synthesis for TechSat21-a distributed space-based radar system"

The TechSat21 space-based radar employs a cluster of free-floating satellites, each of which transmits its own orthogonal signal and receives all reflected signals. The satellites operate coherently at the X band. The cluster forms essentially a multielement interferometer, with a concomitantly large number of grating lobes and significant ground clutter. A novel technique for pattern synthesis in angle-frequency space is proposed, which exploits the double periodicities of the grating lobes in the angular domain and of the radar pulses in the frequency domain, and allows substantial gains in clutter suppression. Gains from 7 to 17 dB relative to the normal random, sparse array appear feasible. [J73]

"Suppression of sea clutter with orthogonal weighting for target detection in shipborne HFSWR"

It is difficult to detect a target submerged in the spread spectrum of the first-order sea clutter in shipborne HFSWR (high frequency surface wave radar). Based on the space-time distribution of the first-order sea clutter, a technique for the detection of a ship in the spread-clutter spectrum is presented, which can completely suppress interference coming from a known incident direction. The influence of orthogonal weighting on the mainbeam directed at the target is slight when interference is outside the mainbeam. Angle measurement can then be accomplished as for an onshore HFSWR. However, suppression of interference coming from within the main target beam would result in this mainbeam splitting into two beams. It is shown that amplitude comparison of the two split beams can be used to determine the azimuth of the target. Processing the results from the experimental data demonstrate reliable ship detection and estimation on the Yellow Sea of China [J74]

"Improved target classification using optimum polarimetric SAR signatures"

We present a new method for automatic target/object classification by using the optimum polarimetric radar signatures of the targets/objects of interest. The state-of-the-art in radar target recognition is based mostly either on the use of single polarimetric pairs or on the four preset pairs of orthogonal polarimetric signatures. Due to these limitations, polarimetric radar processing has been fruitful only in the area of noise suppression and target detection. The use of target separability criteria for the optimal selection of radar signal state of polarizations is addressed here. The polarization scattering matrix is used for the derivation of target signatures at arbitrary transmit and receive polarization states (arbitrary polarization inclination angles and ellipticity angles). Then, an optimization criterion that minimizes the within-class distance and maximizes the between-class metrics is used for the derivation of optimum sets of polarimetric states. The results of the application of this approach on real synthetic aperture radar (SAR) data of military vehicles are obtained. The results show that noticeable improvements in target separability and consequently target classification can be achieved by the use of the optimum over nonoptimum signatures [J75]

"A new method to separate ground clutter and atmospheric reflections in the case of similar Doppler velocities"

This paper introduces a new ground clutter suppression technique which preserves weather echoes. This clutter suppression method uses both statistical and polarimetric properties of the target and clutter. This technique is intended for use in atmospheric studies for weather echoes the spectral properties of which do not differ much from those of ground clutter. This technique can be applied both to the total signal or to its separate Doppler frequency components [J76]

"Performance characterisation of hybrid STAP architecture incorporating elevation interferometry"

Radar space-time adaptive processing (STAP) techniques have classically focused on azimuth-Doppler adaptivity while placing minimal emphasis on elevation. Elevation beamforming offers significant clutter suppression improvement, allowing further suppression of interference sources having identical Doppler and azimuth. This work incorporates elevation adaptivity through an interferometric approach, greatly improving clutter suppression while providing an often overlooked target height discrimination capability. A mathematical

construct encapsulating the multistage processing framework is developed for the proposed technique. This framework allows extension of the traditional factored time-space (FTS) technique into the azimuth-Doppler-elevation hypercube and represents a subclass of more generalised hybrid methods. The proposed concept is validated through results based on simulated airborne radar data. Target detection improvement of the order of 25 dB, when compared to standard two-dimensional FTS processing, is demonstrated for an 8 Ч 8 nonuniform rectangular array. Elevation pattern data are provided to illustrate achievable null width/depth capabilities. These data also indicate target height discrimination is inherently provided and further development is warranted [J77]

"Low-cost digital adaptive antenna architecture combined with low-sidelobe beam synthesis"

The explosion of growth seen in the mobile telephony market has meant that the electronic components used in the manufacture of mobile terminals are now mass produced, with a commensurate fall in unit cost. By exploiting the functionality of such components in phased array antenna design a truly low-cost phased array antenna can be realised. An array antenna architecture is presented that exploits low-cost component technologies. A low-cost architecture for enabling an adaptive, or smart, capability is developed. By separation of the beamforming function and spatial adaptive processing function into two separate signal paths an undersampling technique can be used to provide low-cost spatial processing. The performance of an adaptive processing algorithm is investigated for a radar application. Simulations applied to array element patterns measured on a 16-element linear array demonstrate the performance of the antenna in sidelobe suppression and interference cancellation/spatial filtering. A penalty function approach for sidelobe suppression is applied and is shown to enable flexibility between adaptive cancellation of interference and overall sidelobe level. [J78]

"Minimal sample support space-time adaptive processing with fast subspace techniques"

The authors investigate finite data support for subspace or projection methods for STAP which are robust against strong clutter returns. A theoretical analysis of the eigenvector projection technique is presented that provides insight into the problem of determining the optimum choice of the projected clutter subspace and matched filter adjustments (with respect to target Doppler frequency). An estimator of the optimum subspace dimension, which is significantly smaller than clutter rank, as a function of the number of samples is presented. This result, combined with a previously proposed near-optimal eigenvector-free projection techniques with minimal sample support, reduce the computational burden so drastically that even fully adaptive optimum STAP with large degrees of freedom may become practical for real-time applications. [J79]

"A new high resolution color flow system using an eigendecomposition-based adaptive filter for clutter rejection"

We present a new signal processing strategy for high frequency color flow mapping in moving tissue environments. A new application of an eigendecomposition-based clutter rejection filter is presented with modifications to deal with high blood-to-clutter ratios (BCR). Additionally, a new method for correcting blood velocity estimates with an estimated tissue motion profile is detailed. The performance of the clutter filter and velocity estimation strategies is quantified using a new swept-scan signal model. In vivo color flow images are presented to illustrate the potential of the system for mapping blood flow in the microcirculation with external tissue motion. [J80]

"High-resolution autofocus techniques for SAR imaging based on fractional lower-order statistics"

The authors address the autofocusing problem in synthetic aperture radar imagery by introducing techniques that achieve robust image formation in the presence of severe heavy-tailed clutter and noise. Current state-of-the-art methods are extended, which are based on second-order moment theory, by employing fractional lower-order statistics (FLOS) of the phase-history data. The introduced FLOS-based methods perform a nonlinear transformation of the radar measurements, can mitigate the effects of impulsive additive clutter, and include the conventional algorithms as special cases. The benefits of the proposed approach are quantified by means of simulations, and the new FLOS-based methods are compared to current state-of-the-art processing with real synthetic aperture radar imagery data [J81]

"Multiple moving target feature extraction for airborne HRR radar"

This study considers the clutter suppression and feature extraction of multiple moving targets for airborne high range resolution (HRR) phased array radar. To avoid the range migration problems that occur in the HRR radar data, we divide each HRR profile into nonoverlapping low range resolution segments. No information is lost due to the division and hence no loss of resolution occurs. We show how to use a vector auto-regressive filtering technique to suppress the clutter. Then a relaxation-based parameter estimation algorithm is presented for

multiple moving target feature extraction. Numerical results are given to demonstrate the effectiveness of the algorithm [J82]

"Joint striping noise removal and background clutter cancellation in IR naval surveillance systems"

The clutter removal procedure for infrared (IR) naval surveillance systems presented is designed to manage a typical maritime scenario and is insensitive to the sharp transition between sea and sky across the horizon line. It is also effective for the removal of striping noise which arises as a consequence of the nonuniform calibration of the detector array. The low computational cost of this technique makes it well suited for real-time implementation. The effectiveness of the clutter removal procedure is illustrated on a set of experimental IR data [J83]

"Time-averaged subspace methods for radar clutter texture retrieval"

Subspace approaches have become popular in the last two decades for retrieving constant amplitude harmonics observed in white additive noise because they may exhibit superior resolution over the FFT-based methods, especially with short data records and closely spaced harmonics. We demonstrate that MUSIC and ESPRIT methods can also be applied when the harmonics are corrupted by white or wideband multiplicative noise. The application context is the retrieval of texture information from high resolution and low grazing angle radar clutter data affected by wideband colored speckle that is modeled as complex multiplicative noise. Texture information is fundamental for clutter cancellation and constant false alarm rate (CFAR) radar detection. A thorough numerical analysis compares the two subspace methods and validates the theoretical findings [J84]

"Extraction of moving ground targets by a bistatic ultra-wideband SAR"

The use of a bistatic antenna configuration for ground moving target indication in an ultra-wideband and widebeam synthetic aperture radar system is discussed. To suppress the strong clutter signal the radar channels have a strict requirement on equality. In a bistatic system they are not equal, and the author investigates how to compensate for the bistatic configuration. Bistatic effects on clutter scattering cannot be compensated, and an attempt is therefore made to estimate the bistatic scattering influence of the ground moving target indication. The bistatic to monostatic synthetic aperture inversion in a wide antenna beam is derived in both the time and the frequency domain. The mismatch between the radar channels will cause clutter leakage. The pulse compressed impulse response leakage is determined both for the time and frequency domains [J85]

"Moving target feature extraction for airborne high-range resolution phased-array radar"

We study the feature extraction of moving targets in the presence of temporally and spatially correlated ground clutter for airborne high-range resolution (HRR) phased-array radar. To avoid the range migration problems that occur in HRR radar data, we first divide the HRR range profiles into low-range resolution (LRR) segments. Since each LRR segment contains a sequence of HRR range bins, no information is lost due to the division, and hence, no loss of resolution occurs. We show how to use a vector auto-regressive (VAR) filtering technique to suppress the ground clutter, Then, a parameter estimation algorithm is proposed for target feature extraction. From the VAR-filtered data, the target Doppler frequency and the spatial signature vectors are first estimated by using a maximum likelihood (ML) method. The target phase history and direction-of-arrival (DOA) (or the array steering vector for an unknown array manifold) are then estimated from the spatial signature vectors by minimizing a weighted least squares (WLS) cost function. The target radar cross section (RCS)-related complex amplitude and range-related frequency of each target scatterer are then extracted from the estimated target phase history by using RELAX, which is a relaxation-based high-resolution feature extraction algorithm. Numerical results are provided to demonstrate the performance of the proposed algorithm [J86]

"STAP covariance matrix structure and its impact on clutter plus jamming suppression solutions"

The structure of the jamming plus clutter covariance matrix is analysed in the context of space-time adaptive processing (STAP) for sideways-looking airborne radar. A bound on the rank of the matrix is derived under the assumption of idealised conditions. It is shown how the rank deficiency of the matrix can be exploited to derive simple, computationally efficient, processing solutions [J87]

"Clutter suppression using elevation interferometry fused with space-time adaptive processing"

Radar space-time adaptive processing (STAP) techniques characteristically offer adaptivity in Doppler and azimuth. This research extends STAP concepts by incorporating elevation adaptivity using a two channel vertical interferometer. Using multi-stage processing and measured airborne radar data, clutter suppression improvement of 15 dB is achieved [J88]

"Optimal adaptive processing for domain factorised element-digitised array radar"

For large phased array radar, digitisation and adaptive beamforming are usually performed at the subarray level. The number of subarrays is usually much smaller than the number of array elements thus reducing the number of available adaptive degrees of freedom (DOF). For an element digitised array radar (EDAR), a subarray technique can also be employed to reduce the number of adaptive channels in order to reduce the adaptive processing load. However, EDAR allows greater flexibility in the choice of adaptive channels from the array elements, thus allowing alternative DOF reduction techniques to be investigated. An adaptive technique using a convolution approach, namely `range-dependent gain adaptation using domain factorisation' (RDGA-DF), has been shown to give significant advantages over subarray level adaptive beamforming when cancelling strong sidelobe clutter in the airborne environment. A new implementation of the RDGA-DF algorithm is developed to perform adaptive processing on a domain factorised array. This algorithm, called the `full aperture convolution technique' (FACT), is derived directly from the optimal Wiener filter solution. The performance advantages of FACT over RDGA-DF are demonstrated by simulation [J89]

"Experimental analysis of sea clutter in shipborne HFSWR"

The spreading of the dominant first order Bragg lines in shipborne HFSWR (high-frequency surface wave radar) severely obscures targets with Doppler frequencies within the spreading domain. STAP (space-time adaptive processing) is one of the effective methods for solving the problem. The experimental one-dimensional spreading spectrum and two dimensional space-time spectrum of sea clutter in shipborne HFSWR are given. The eigenvalue distribution of the space-time covariance matrix is also obtained. All experimental results show good agreement with the spreading model of sea clutter and theoretical analysis of the eigenspectrum for a random process, which is of advantage for sea clutter suppression and target detection in shipborne HFSWR with STAP [J90]

СПИСОК ЛИТЕРАТУРЫ

J1. Beau S. Taylor series expansions for airborne radar space-time adaptive processing. / Beau S., Marcos S. // IET Radar, Sonar & Navigation. - 2011. - Vol. 5, No. 3. - P. 266-278.

J2. Su H.-T. Adaptive HF interference cancellation for sky wave over-the-horizon radar. / Su H.-T., Liu H., Shui P., Bao Z. // Electronics Letters. - 2011. - Vol. 47, No. 1. - P. 50-52.

J3. Shi Y.-L. Target detection in high-resolution sea clutter via block-adaptive clutter suppression. / Shi Y.-L., Shui P.-L. // IET Radar, Sonar & Navigation. - 2011. - Vol. 5, No. 1. - P. 48-57.

J4. Guo J. Adaptive clutter suppression and resolving of velocity ambiguities for an experimental three-channel airborne synthetic aperture radar-ground moving target indication system. / Guo J., Li Z.F., Bao Z. // IET Radar, Sonar & Navigation. - 2011. - Vol. 5, No. 4. - P. 426-435.

J5. Yong Wu. On the Essence of Knowledge-Aided Clutter Covariance Estimate and Its Convergence. / Yong Wu, Jun Tang, Yingning Peng. // IEEE Transactions on Aerospace and Electronic Systems. - 2011. - Vol. 47, No. 1. - P. 569-585.

J6. Liu Y. Sandglass transformation for synthetic aperture radar detection and imaging of ship at low signal-to-clutter-plus-noise ratio. / Liu Y., Xing M., Guo R., Zhang L., Bai X., Bao Z. // IET Radar, Sonar & Navigation. - 2011. - Vol. 5, No. 3. - P. 361-373.

J7. Dall J. ESA'S POLarimetric Airborne Radar Ice Sounder (POLARIS): design and first results. / Dall J., Kristensen S.S., Krozer V., Hernandez C.C., Vidkjr J., Kusk A., Balling J., Skou N., Sbjrg S.S., Christensen E.L. // IET Radar, Sonar & Navigation. - 2010. - Vol. 4, No. 3. - P. 488-496.

J8. Lei Zhang. Resolution Enhancement for Inversed Synthetic Aperture Radar Imaging Under Low SNR via Improved Compressive Sensing. / Lei Zhang, Mengdao Xing, Cheng-Wei Qiu, Jun Li, Jialian Sheng, Yachao Li, Zheng Bao. // IEEE Transactions on Geoscience and Remote Sensing. - 2010. - Vol. 48, No. 10. - P. 3824-3838.

J9. Xiufeng Song. Reducing the Waveform Cross Correlation of MIMO Radar With Space-Time Coding. / Xiufeng Song, Shengli Zhou, Willett P. // IEEE Transactions on Signal Processing. - 2010. - Vol. 58, No. 8. - P. 4213-4224.

J10. Nezirovic A. Signal Processing for Improved Detection of Trapped Victims Using UWB Radar. / Nezirovic A., Yarovoy A.G., Ligthart L.P. // IEEE Transactions on Geoscience and Remote Sensing. - 2010. - Vol. 48, No. 4. - P. 2005-2014.

J11. Banahan C.P. GMTI clutter cancellation using real non-ideal data. / Banahan C.P., Perks D., Baker C., Woodbridge K. // IET Radar, Sonar & Navigation. - 2010. - Vol. 4, No. 2. - P. 302-314.

J12. Tao R. Direct-path suppression by spatial filtering in digital television terrestrial broadcasting-based passive radar. / Tao R., Wu H.Z., Shan T. // IET Radar, Sonar & Navigation. - 2010. - Vol. 4, No. 6. - P. 791-805.

J13. Zhiyong Suo. Multi-Channel SAR-GMTI Method Robust to Coregistration Error of SAR Images. / Zhiyong Suo, Zhenfang Li, Zheng Bao. // IEEE Transactions on Aerospace and Electronic Systems. - 2010. - Vol. 46, No. 4. - P. 2035-2043.

J14. Sun H. Estimation of the ocean clutter rank for HF/ VHF radar space-time adaptive processing. / Sun H., Guo X., Lu Y., Lesturgie M. // IET Radar, Sonar & Navigation. - 2010. - Vol. 4, No. 6. - P. 755-763.

J15. Wu J. Clutter suppression for airborne nonsidelooking radar using ERCB-STAP algorithm. / Wu J., Wang T., Meng X., Bao Z. // IET Radar, Sonar & Navigation. - 2010. - Vol. 4, No. 4. - P. 497-506.

J16. Yang E. Hybrid direct data domain sigma-delta space-time adaptive processing algorithm in non-homogeneous clutter. / Yang E., Adve R., Chun J. // IET Radar, Sonar & Navigation. - 2010. - Vol. 4, No. 4. - P. 611-625.

J17. Shackelford A.K. Partially Adaptive STAP using the FRACTA Algorithm. / Shackelford A.K., Gerlach K., Blunt S.D. // IEEE Transactions on Aerospace and Electronic Systems. - 2009. - Vol. 45, No. 1. - P. 58-69.

J18. Li X.-M. Two-dimensional pulse-to-pulse canceller of ground clutter in airborne radar. / Li X.-M., Feng D.-Z., Liu H.-W., Xing M.-D., Luo D. // IET Radar, Sonar & Navigation. - 2009. - Vol. 3, No. 2. - P. 133-143.

J19. Xiangdong Meng. Short-Range Clutter Suppression for Airborne Radar by Utilizing Prefiltering in Elevation. / Xiangdong Meng, Tong Wang, Jianxin Wu, Zheng Bao. // IEEE Geoscience and Remote Sensing Letters. - 2009. - Vol. 6, No. 2. - P. 268-272.

J20. Candan C. Efficient Methods of Clutter Suppression for Coexisting Land and Weather Clutter Systems. / Candan C., Yilmaz A.O. // IEEE Transactions on Aerospace and Electronic Systems. - 2009. - Vol. 45, No. 4. - P. 1641-1650.

J21. Hersey R.K. Adaptive ground clutter suppression for conformal array radar systems. / Hersey R.K., Melvin W.L., McClellan J.H., Culpepper E. // IET Radar, Sonar & Navigation. - 2009. - Vol. 3, No. 4. - P. 357-372.

J22. Hong Wang. Through-Wall Imaging of Moving Targets Using UWB Random Noise Radar. / Hong Wang, Narayanan R.M., Zheng Ou Zhou. // IEEE Antennas and Wireless Propagation Letters. - 2009. - Vol. 8, {no data available}. - P. 802-805.

J23. Li X.-M. Spatial-temporal separable filter for adaptive clutter suppression in airborne radar. / Li X.-M., Feng D.-Z., Liu H.-W., Bao Z. // Electronics Letters. - 2008. - Vol. 44, No. 5. - P. 380-381.

J24. Lei Yang. Ground Moving Target Indication Using an InSAR System With a Hybrid Baseline. / Lei Yang, Tong Wang, Zheng Bao. // IEEE Geoscience and Remote Sensing Letters. - 2008. - Vol. 5, No. 3. - P. 373-377.

J25. Herbert G.M. Post-adaptive processing time-delay beamforming for clutter suppression in airborne radar. / Herbert G.M., Richardson P.G. // Electronics Letters. - 2008. - Vol. 44, No. 5. - P. 378-379.

J26. Moura J.M.F. Time Reversal Imaging by Adaptive Interference Canceling. / Moura J.M.F., Yuanwei Jin. // IEEE Transactions on Signal Processing. - 2008. - Vol. 56, No. 1. - P. 233-247.

J27. Bachmann S.M. Suppression of Clutter Residue in Weather Radar Reveals Birds' Corridors Over Urban Area. / Bachmann S.M., Zrnic D.S. // IEEE Geoscience and Remote Sensing Letters. - 2008. - Vol. 5, No. 2. - P. 128-132.

J28. Pillai U.S. Cramer-Rao bounds for target parameters in space-based radar applications. / Pillai U.S., Ke Yong Li, Himed B. // IEEE Transactions on Aerospace and Electronic Systems. - 2008. - Vol. 44, No. 4. - P. 1356-1370.

J29. Ender J.H.G. Improved Space-Based Moving Target Indication via Alternate Transmission and Receiver Switching. / Ender J.H.G., Gierull C.H., Cerutti-Maori D. // IEEE Transactions on Geoscience and Remote Sensing. - 2008. - Vol. 46, No. 12. - P. 3960-3974.

J30. Gierull C.H. Ground Moving Target Indication With Tandem Satellite Constellations. / Gierull C.H., Cerutti-Maori D., Ender J. // IEEE Geoscience and Remote Sensing Letters. - 2008. - Vol. 5, No. 4. - P. 710-714.

J31. Xin Guo. Interference Cancellation for High-Frequency Surface Wave Radar. / Xin Guo, Hongbo Sun, Tat Soon Yeo. // IEEE Transactions on Geoscience and Remote Sensing. - 2008. - Vol. 46, No. 7. - P. 1879-1891.

J32. Bachmann S.M. Phase-Based Clutter Identification in Spectra of Weather Radar Signals. IEEE Geoscience and Remote Sensing Letters. - 2008. - Vol. 5, No. 3. - P. 487-491.

J33. Maio A.D. Knowledge-based recursive least squares techniques for heterogeneous clutter suppression. / Maio A.D., Farina A., Foglia G. // IET Radar, Sonar & Navigation. - 2007. - Vol. 1, No. 2. - P. 106-115.

J34. Tagawa T. Suppression of Surface Clutter Interference With Precipitation Measurements by Spaceborne Precipitation Radar. / Tagawa T., Hanado H., Okamoto K., Kozu T. // IEEE Transactions on Geoscience and Remote Sensing. - 2007. - Vol. 45, No. 5. - P. 1324-1331.

J35. Axelsson S.R.J. Random Noise Radar/Sodar With Ultrawideband Waveforms. IEEE Transactions on Geoscience and Remote Sensing. - 2007. - Vol. 45, No. 5. - P. 1099-1114.

J36. Kovalenko V. A Novel Clutter Suppression Algorithm for Landmine Detection With GPR. / Kovalenko V., Yarovoy A.G., Ligthart L.P. // IEEE Transactions on Geoscience and Remote Sensing. - 2007. - Vol. 45, No. 11. - P. 3740-3751.

J37. Melvin W.L. Adaptive cancellation method for geometry-induced nonstationary bistatic clutter environments. / Melvin W.L., Davis M.E. // IEEE Transactions on Aerospace and Electronic Systems. - 2007. - Vol. 43, No. 2. - P. 651-672.

J38. Wan X. Experimental investigation of directional characteristics for ionospheric clutter in HF surface wave radar. / Wan X., Xiong X., Cheng F., Ke H. // IET Radar, Sonar & Navigation. - 2007. - Vol. 1, No. 2. - P. 124-130.

J39. Mcdonald M. Outlier suppression in adaptive filtering through de-emphasis weighting. / Mcdonald M., Bhashyam B. // IET Radar, Sonar & Navigation. - 2007. - Vol. 1, No. 1. - P. 38-49.

J40. Chen Y. Pulse Design for Time Reversal Method as Applied to Ultrawideband Microwave Breast Cancer Detection: A Two-Dimensional Analysis. / Chen Y., Gunawan E., Low K. S., Wang S., Kim Y., Soh C. B. // IEEE Transactions on Antennas and Propagation. - 2007. - Vol. 55, No. 1. - P. 194-204.

J41. Chin Heng Lim. Prediction of inverse covariance matrix (PICM) sequences for STAP. / Chin Heng Lim, Mulgrew B. // IEEE Signal Processing Letters. - 2006. - Vol. 13, No. 4. - P. 236-239.

J42. P. Lombardo. Monitoring and surveillance potentialities obtained by splitting the antenna of the COSMO-SkyMed SAR into multiple sub-apertures. / P. Lombardo, F. Colone, D. Pastina. // IEE Proceedings - Radar, Sonar and Navigation. - 2006. - Vol. 153, No. 2. - P. 104-116.

J43. Xianrong W. Experimental trials on ionospheric clutter suppression for high-frequency surface wave radar. / Xianrong W., Feng C., Hengyu K. // IEE Proceedings - Radar, Sonar and Navigation. - 2006. - Vol. 153, No. 1. - P. 23-29.

J44. Choi W. Minimum norm property for the sum of the adaptive weights for a direct data domain least

squares algorithm. / Choi W., Sarkar T.K. // IEEE Transactions on Antennas and Propagation. - 2006. - Vol. 54, No. 3. - P. 1045-1050.

J45. Melvin W.L. Knowledge-aided signal processing: a new paradigm for radar and other advanced sensors. / Melvin W.L., Guerci J.R. // IEEE Transactions on Aerospace and Electronic Systems. - 2006. - Vol. 42, No. 3. - P. 983-996.

J46. Lim C.H. Training strategies for joint domain localised-space-time adaptive processing in a bistatic environment. / Lim C.H., Aboutanios E., Mulgrew B. // IEE Proceedings Radar, Sonar and Navigation. - 2006. - Vol. 153, No. 6. - P. 516-524.

J47. A. Damini. X-band experimental airborne radar-Phase II: synthetic aperture radar and ground moving target indication. / A. Damini, B. Balaji, G. Haslam, M. Goulding. // IEE Proceedings - Radar, Sonar and Navigation. - 2006. - Vol. 153, No. 2. - P. 144-151.

J48. Yazici B. Wideband Extended Range-Doppler Imaging and Waveform Design in the Presence of Clutter and Noise. / Yazici B., Gang Xie. // IEEE Transactions on Information Theory. - 2006. - Vol. 52, No. 10. - P. 4563-4580.

J49. Xianrong W. Adaptive ionospheric clutter suppressio based o subarrays i monostatic HF surface ave radar. / Xianrong W., Hengyu K., Biyang W. // IEE Proceedings - Radar, Sonar and Navigation. - 2005. - Vol. 152, No. 2. - P. 89-96.

J50. Kraut S. The adaptive coherence estimator: a uniformly most-powerful-invariant adaptive detection statistic. / Kraut S., Scharf L.L., Butler R.W. // IEEE Transactions on Signal Processing. - 2005. - Vol. 53, No. 2. - P. 427-438.

J51. Yang Jun. Daytime interference ing of OSMAR. / Yang Jun, Wen Biyang, Shicai W. // IEEE Signal Processing Letters. - 2005. - Vol. 12, No. 1. - P. 71-74.

J52. De Maio A. Performance analysis of the sidelobe blanking system for two fluctuating jammer models. / De Maio A., Farina A., Gini F. // IEEE Transactions on Aerospace and Electronic Systems. - 2005. - Vol. 41, No. 3. - P. 1082-1091.

J53. Kun Lu. Ionospheric decontamination and sea clutter suppression for HF skywave Radars. / Kun Lu, Xingzhao Liu, Yongtan Liu. // IEEE Journal of Oceanic Engineering. - 2005. - Vol. 30, No. 2. - P. 455-462.

J54. Venkatasubramanian V. A novel chaos-based high-resolution imaging technique and its application to through-the-wall imaging. / Venkatasubramanian V., Leung H. // IEEE Signal Processing Letters. - 2005. - Vol. 12, No. 7. - P. 528-531.

J55. Fabrizio G.A. Robust adaptive beamforming for HF surface wave over-the-horizon radar. / Fabrizio G.A., Gershman A.B., Turley M.D. // IEEE Transactions on Aerospace and Electronic Systems. - 2004. - Vol. 40, No. 2. - P. 510-525.

J56. Damini A. Novel multiple phase centre reflector antenna for GMTI radar. / Damini A., Balaji B., Shafai L., Haslam G. // IEE Proceedings - Microwaves, Antennas and Propagation. - 2004. - Vol. 151, No. 3. - P. 199-204.

J57. Genyuan Wang. Detection, location, and imaging of fast moving targets using multifrequency antenna array SAR. / Genyuan Wang, Xiang-Gen Xia, Chen V.C., Fielder R.L. // IEEE Transactions on Aerospace and Electronic Systems. - 2004. - Vol. 40, No. 1. - P. 345-355.

J58. Ming-Chiang Li. A high precision Doppler radar based on optical fiber delay loops. IEEE Transactions on Antennas and Propagation. - 2004. - Vol. 52, No. 12. - P. 3319-3328.

J59. Panagopoulos S. Small-target detection in sea clutter. / Panagopoulos S., Soraghan J.J. // IEEE Transactions on Geoscience and Remote Sensing. - 2004. - Vol. 42, No. 7. - P. 1355-1361.

J60. Barnard T.J. Statistical normalization of spherically invariant non-Gaussian clutter. / Barnard T.J., Khan F. // IEEE Journal of Oceanic Engineering. - 2004. - Vol. 29, No. 2. - P. 303-309.

J61. Meyer-Hilberg J. Results of flight tests of a two-channel radar system with real-time MTI processing. /

Meyer-Hilberg J., Bickert B., Schmitt K.-P. // IEE Proceedings - Radar, Sonar and Navigation. - 2003. - Vol. 150, No. 1. - P. 23-27.

J62. Himed B. Effects of bistatic clutter dispersion on STAP systems. IEE Proceedings - Radar, Sonar and Navigation. - 2003. - Vol. 150, No. 1. - P. 28-32.

J63. Dawber W.N. Comparison of Doppler clutter cancellation techniques for naval multi-function radars. / Dawber W.N., Harwood N.M. // IEE Proceedings - Radar, Sonar and Navigation. - 2003. - Vol. 150, No. 1. - P. 37-40.

J64. Farina A. Comparison between LS and TLS in adaptive processing for radar systems. / Farina A., Golino G., Timmoneri L. // IEE Proceedings - Radar, Sonar and Navigation. - 2003. - Vol. 150, No. 1. - P. 2-6.

J65. Herbert G.M. Benefits of space-time adaptive processing (STAP) in bistatic airborne radar. / Herbert G.M., Richardson P.G. // IEE Proceedings - Radar, Sonar and Navigation. - 2003. - Vol. 150, No. 1. - P. 13-17.

J66. Hale T.B. Localised three-dimensional adaptive spatial-temporal processing for airborne radar. / Hale T.B., Temple M.A., Raquet J.F., Oxley M.E., Wicks M.C. // IEE Proceedings - Radar, Sonar and Navigation. - 2003. - Vol. 150, No. 1. - P. 18-22.

J67. Qun Zhang. ISAR imaging in strong ground clutter using a new stepped-frequency signal format. / Qun Zhang, Tat Soon Yeo, Du G. // IEEE Transactions on Geoscience and Remote Sensing. - 2003. - Vol. 41, No. 5. - P. 948-952.

J68. Wang G. Manoeuvring target detection in over-the-horizon radar using adaptive clutter rejection and adaptive chirplet transform. / Wang G., Xia X.-G., Root B.T., Chen V.C., Zhang Y., Amin M. // IEE Proceedings - Radar, Sonar and Navigation. - 2003. - Vol. 150, No. 4. - P. 292-8.

J69. Zhang Y. High-resolution time-frequency distributions for manoeuvring target detection in over-the-horizon radars. / Zhang Y., Amin M.G., Frazer G.J. // IEE Proceedings - Radar, Sonar and Navigation. - 2003. - Vol. 150, No. 4. - P. 299-304.

J70. Herbert G.M. Techniques for improving STAP performance in high PRF applications. Electronics Letters. - 2003. - Vol. 39, No. 23. - P. 1674-6.

J71. Nan Xie. A multiple-model prediction approach for sea clutter modeling. / Nan Xie, Henry Leung, Hing Chan. // IEEE Transactions on Geoscience and Remote Sensing. - 2003. - Vol. 41, No. 6. - P. 1491-1502.

J72. Francos J.M. Interference mitigation in STAP using the two-dimensional Wold decomposition model. / Francos J.M., Nehorai A. // IEEE Transactions on Signal Processing. - 2003. - Vol. 51, No. 10. - P. 2461-2470.

J73. Steyskal H. Pattern synthesis for TechSat21-a distributed space-based radar system. / Steyskal H., Schindler J.K., Franchi P., Mailloux R.J. // IEEE Antennas and Propagation Magazine. - 2003. - Vol. 45, No. 4. - P. 19-25.

J74. Xie J. Suppression of sea clutter with orthogonal weighting for target detection in shipborne HFSWR. / Xie J., Yuan Y., Liu Y. // IEE Proceedings - Radar, Sonar and Navigation. - 2002. - Vol. 149, No. 1. - P. 39-44.

J75. Sadjadi F. Improved target classification using optimum polarimetric SAR signatures. IEEE Transactions on Aerospace and Electronic Systems. - 2002. - Vol. 38, No. 1. - P. 38-49.

J76. Moisseev D. A new method to separate ground clutter and atmospheric reflections in the case of similar Doppler velocities. / Moisseev D., Unal C., Russchenberg H., Ligthart L. // IEEE Transactions on Geoscience and Remote Sensing. - 2002. - Vol. 40, No. 2. - P. 239-246.

J77. Hale T.B. Performance characterisation of hybrid STAP architecture incorporating elevation interferometry. / Hale T.B., Temple M.A., Wicks M.C., Raquet J.F., Oxley M.E. // IEE Proceedings - Radar, Sonar and Navigation. - 2002. - Vol. 149, No. 2. - P. 77-82.

J78. Fletcher P.N. Low-cost digital adaptive antenna architecture combined with low-sidelobe beam synthesis. / Fletcher P.N., Dean M. // IEE Proceedings - Radar, Sonar and Navigation. - 2002. - Vol. 149, No. 6. - P. 265-270.

J79. Gierull C.H. Minimal sample support space-time adaptive processing with fast subspace techniques. / Gierull C.H., Balaji B. // IEE Proceedings - Radar, Sonar and Navigation. - 2002. - Vol. 149, No. 5. - P. 209-220.

J80. Kruse D.E. A new high resolution color flow system using an eigendecomposition-based adaptive filter for clutter rejection. / Kruse D.E., Ferrara K.W. // IEEE Transactions on Ultrasonics, Ferroelectrics and Frequency Control. - 2002. - Vol. 49, No. 10. - P. 1384-1399.

J81. Tsakalides P. High-resolution autofocus techniques for SAR imaging based on fractional lower-order statistics. / Tsakalides P., Nikias C.L. // IEE Proceedings - Radar, Sonar and Navigation. - 2001. - Vol. 148, No. 5. - P. 267-276.

J82. Nanzhi Jiang. Multiple moving target feature extraction for airborne HRR radar. / Nanzhi Jiang, Jian Li. // IEEE Transactions on Aerospace and Electronic Systems. - 2001. - Vol. 37, No. 4. - P. 1254-1266.

J83. Diani M. Joint striping noise removal and background clutter cancellation in IR naval surveillance systems. / Diani M., Baldacci A., Corsini G. // IEE Proceedings - Vision, Image and Signal Processing. - 2001. - Vol. 148, No. 6. - P. 407-412.

J84. Gini F. Time-averaged subspace methods for radar clutter texture retrieval. / Gini F., Giannakis G.B., Greco M., G. Tong Zhou. // IEEE Transactions on Signal Processing. - 2001. - Vol. 49, No. 9. - P. 1886-1898.

J85. Pettersson M.I. Extraction of moving ground targets by a bistatic ultra-wideband SAR. IEE Proceedings - Radar, Sonar and Navigation. - 2001. - Vol. 148, No. 1. - P. 35-40.

J86. Jian Li. Moving target feature extraction for airborne high-range resolution phased-array radar. / Jian Li, Guoqing Liu, Nanzhi Jiang, Stoica P. // IEEE Transactions on Signal Processing. - 2001. - Vol. 49, No. 2. - P. 277-289.

J87. Richardson P.G. STAP covariance matrix structure and its impact on clutter plus jamming suppression solutions. Electronics Letters. - 2001. - Vol. 37, No. 2. - P. 118-119.

J88. Hale T.B. Clutter suppression using elevation interferometry fused with space-time adaptive processing. / Hale T.B., Temple M.A., Wicks M.C. // Electronics Letters. - 2001. - Vol. 37, No. 12. - P. 793-794.

J89. Paine A.S. Optimal adaptive processing for domain factorised element-digitised array radar. IEE Proceedings - Radar, Sonar and Navigation. - 2001. - Vol. 148, No. 2. - P. 81-88.

J90. Xie J. Experimental analysis of sea clutter in shipborne HFSWR. / Xie J., Yuan Y., Liu Y. // IEE Proceedings - Radar, Sonar and Navigation. - 2001. - Vol. 148, No. 2. - P. 67-71.
