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Introduction to the Issue on Advanced Signal Processing Techniques for Radar Applications

IN THE last decade, the radar world is assisting to a sort of new revolution, comparable to that caused by the introduction of adaptivity in the 70s. Continuing advances in device technologies combined with adaptive processing present rich opportunities for new sensing methodologies and new challenges in signal processing. Complex and integrated systems, waveform diversity, multi-mission and multi-mode operation systems are the new paradigms in the radar field theory and technology.

In this context, emerging signal processing theories and methods play a very important role in boosting research and improving performance in radar detection, estimation and tracking, particularly in non-standard conditions, that is, in presence of non-Gaussian disturbance, outliers and interferences, or when only few data are available at the receiver, with applications to many radar systems, spanning from weather radar to scatterometers, from through-the-wall to automotive systems, from active to passive systems.

This special issue received more than 80 high-quality submissions and through an extensive peer-review process this final version collects 26 excellent papers touching on a wide variety of topics, including waveform optimization, radar cognition, robust detection and estimation, sparse signal recovery and compressive sensing techniques, being naturally interdisciplinary and involving contributions from experts in the areas of signal processing, array processing, radar systems.

The issue is opened by a group of papers focused on radar waveform design and optimization in different scenarios. Future radar systems are expected to employ signals with a higher instantaneous bandwidth and to synthesize on-the-fly transmit signals. These capabilities give new degrees of freedom, so the systems can be optimized for different environments, but complicate as well the receive/transmit design and the associated detection and estimation algorithms. The first paper "Wideband waveform and receiver filter bank design for clutter suppression," by M. Ström, M. Viberg, and K. Falk, proposes two algorithms to select transmit waveforms and receiver filters, based on the clutter suppression achieved by minimizing the correlation between receiver filters and interfering clutter echoes.

In the following paper, "Waveform design with unit modulus and spectral shape constraints via Lagrange programming neural network," by J. Liang, H. C. So, C. S. Leung, J. Li, and A. Farina, the design of the waveforms is formulated as a nonlinear constrained optimization problem and solved using the Lagrange programming neural network. In "Optimizing radar waveform and Doppler filter bank via generalized fractional programming," by A. De Maio, A. Aubry, and M. Naghsh, the authors focus on robust joint design of the transmit radar waveform and receive Doppler filter bank in the presence of signal-dependent interference.

In the paper "Waveform design for MIMO radars with matrix completion," by S. Sun and A. Petropulu, the problem of orthogonal waveform design in Multiple Input Multiple Output (MIMO) radars with sparse sensing is formulated as an optimization problem on the complex Stiefel manifold.

A special case of MIMO radar is considered in the paper "Adaptive receive processing of spatially-modulated physical radar emissions," by P. McCormick, T. Higgins, S. Blunt, and M. Rangaswamy, where the authors, inspired by the fixational movement of the human eye, develop a joint delay-angle adaptive filtering strategy that exploits the physical waveform-diverse emission structure to realize significant enhancement to target separability.

Strictly related to the optimum waveform design and selection is the possible feedback between the radar transmitter and the sensing of the environment. This feedback concept has been developed in 2006 by S. Haykin who introduced the "Cognitive Radar" idea in [1]. Since then, many conference and journal papers have been published but still many problems are open and worth of research.

In the paper "Cognitive radar framework for target detection and tracking," by K. L. Bell, C. Baker, G. Smith, J. T. Johnson, and M. Rangaswamy, the radar cognition concept is applied to a radar system engaged in target tracking, providing a flexible framework applicable to the general tracking problem. In the subsequent paper "Optimal cognitive beamforming for target tracking in MIMO Radar/Sonar," by N. Sharaga, J. Tabrikian, and H. Messer, the authors propose a cognitive beamforming method for target tracking by MIMO radar or sonar. With this method, at each step, the transmit beampattern is sequentially determined based on history observations and the conditional Bayesian Cramér-Rao bound for one-step prediction of the target state-vector is used as the optimization criterion for beampattern design.

In the optimum design of a radar waveform, quite often the ambiguity function plays a fundamental role. For narrowband signals, where the dilation due to mutual movement of signal sources and the sensor is usually represented as a Doppler frequency shift of the received signal, the use of the ambiguity function was introduced and explained by P. Woodward [2]. For wideband signal the dilation doesn't convert anymore in a simple frequency shift, so the Woodward ambiguity function is useless. The Mellin transform is a natural foundation in this case. In the paper "The Mellin matched filter," by A. Monakov, three interconnected problems where the Mellin transform plays a key role are considered: synthesis of a linear matched filter that is invariant to signal scale, estimation of the signal scale, and wideband ambiguity function and properties.

Another problem that is often related to the generation of optimum waveforms is the optimization of the radar antenna array. To this problem is dedicated the paper "Optimization of subarray partition for large planar phased array radar based on weighted K-means clustering method" where the authors, X. Yang, W. Xi, Y. Sun, T. Zeng, T. Long, and T. Sarkar, consider the optimization of subarray partition for large planar phased array radar in monopulse applications.

The implementation of fully adaptive radar systems, in order to cope with as many and diverse backgrounds as possible, gen-

erally requires a big amount of data in multiple domains, frequency, space and time. With the current technologies, even though largely improved over the last 50 years, it is seldom possible to realize all the adaptive signal processing algorithms in real time. Not to consider that sometimes, the processes that model targets and clutter are not stationary on large spaces/long intervals or, for some technical reason, the necessary data are not available. To mitigate partially the problem, new knowledge-based algorithms [3], which assume the availability of some a-priori knowledge about the environment, have first been introduced and developed. Then, over the last decade, the radar and signal processing communities witnessed a growth of the sparsity-based and compressive sensing (CS) techniques that exploit low dimensional signal structure, sparseness for vectors, low-rankness for matrices etc.

In the paper "Compressive sensing based multipath exploitation for stationary and moving indoor target localization," the authors M. Leigsnering, F. Ahmad, M. Amin, and A. Zoubir, apply compressive sensing (CS) techniques, based on multipath exploitation, to both stationary and moving targets in through-the-wall radar (TWR). Compressive sensing is again applied in a completely different scenario in the paper "High-resolution passive SAR imaging exploiting structured Bayesian compressive sensing" by Q. Wu, Y. D. Zhang, M. Amin, and B. Himed. In this work the sensor is not a TWR but an ultra-narrowband passive synthetic aperture radar (SAR) system. The proposed technique enables high-resolution SAR imaging in wide-angle as well as multi-angle observation systems, and the imaging performance is improved by exploiting the underlying structure of the target scene. The SAR sensor is again the focus of the paper "Joint sparsity in SAR tomography for urban mapping" by X. Zhu, N. Ge, and M. Shahzad. In this paper the authors propose a novel workflow for SAR tomography that marries the freely available 2D building footprint GIS data and the group sparsity concept for TomoSAR inversion in order to reduce the required number of images necessary for the processing.

In "Low-rank matrix decomposition and spatio-temporal sparse recovery for STAP Radar" the author S. Sen, applies the idea of sparse signal processing for estimating the interference covariance matrix in a space-time adaptive processing (STAP) radar. The sparsity concept is applied as well in the paper "Moving target detection in distributed MIMO radar on moving platforms" by H. Li, Z. Wang, J.Liu, and B. Himed. Two new detectors are proposed and compared: the first exploits a sparse representation of the clutter in the Doppler domain, the second employs a parametric autoregressive clutter model.

The lack of observation data is considered under the radar tracking framework in the paper "Multiple imputations particle filters: convergence and performance analyses for nonlinear state estimation with missing data" where the authors X.-P. Zhang, A. S. Khwaja, J.-A. Luo, A. Housfater, and A. Anpalagan present a multiple imputations particle filter (MIPF) to deal with non-linear state estimation when part of the observations are missing.

In "A superresolution wide null beamformer for undersampled signal reconstruction in SIMO SAR" by K. Mak, A. Manikas, a superresolution beamformer is proposed. The new beamformer allows the suppression of ambiguities in multiple sets of received undersampled SAR data in the cross-range direction and reconstruction of the Doppler spectrum to form a single unambiguous set of SAR data.

The persimmetry property, that allows the reduction by a factor of two of the number of secondary vectors necessary for the disturbance covariance matrix estimation, is exploited in the paper "Design and analysis of invariant receivers for Gaussian targets under covariance persymmetry," by A. De Maio, D. Orlando, A. Farina, and G. Foglia.

Another set of papers is dedicated to robust techniques of detection and estimation. The paper "Passive SAR Imaging using low-rank matrix recovery methods" by E. Mason, I.-Y. Son, and B. Yazici, presents a novel image formation method for passive SAR imaging based on a gradient-descent iterative reconstruction algorithm, particularly robust to phase errors. A robust azimuth signal reconstruction approach is proposed in "A robust imaging algorithm for squint mode multi-channel high-resolution and wide-swath SAR with hybrid baseline and fluctuant terrain" by S. Zhang, M.-D. Xing, X.-G. Xia, J. Li, R. Guo, Z. Bao. The paper "Plane localization for MIMO radar" by T. Kilpatrick, and V. Clarkson, considers the problem of localizing a ground plane with respect to a MIMO radar. The authors propose an extension to the common tangent algorithm, developing four methods for solving the related Non-Convex Quadratically Constrained Quadratic Program optimization problem. Last paper focused on parameter estimation is "Low computational enhancement of STFT-based parameter estimation" by B. Kim, S.-H. Kong, and S. Kim. In this paper, more than the robustness of the estimators, the major interest is the computational complexity. In particular, the authors propose here a low computational parameter estimation techniques for Short-Time Fourier Transform (STFT) output of radar signals with enhanced frequency or temporal resolution.

The special issue next proceeds with the last set of 5 papers, dedicated to the clutter/interference cancellation in many applications. The first paper of this group "Range ambiguous clutters suppression for airborne FDA-STAP Radar," by J. Xu, S. Zhu,, and G. Liao, presents a new algorithm to cancel the range ambiguous, range dependent clutter in airborne radars. In the subsequent paper "Main-lobe cancellation of the space spread clutter for target detection in HFSWR," by X. Zhang, Q. Yang, D. Yao, and W. Deng, the problem of clutter cancellation is approached in a high frequency surface wave radar (HFSWR). A spread clutter estimated canceller based on single notch space filter is developed to cancel the clutter in the main-lobe. In "Low RCS target tracking in estimated rapidly-varying sea clutter," by S. Ebenezer, and A. Papandreou-Suppappola, it is the turn of rapidly-varying sea clutter in a tracking radar. In particular, the authors propose a method for estimating the space-time covariance matrix of the clutter following a dynamic state space matrix model. In "Short-range leakage cancellation in FMCW radar transceivers using an artificial on-chip target," by A. Melzer, A. Onic, F. Starzer, and M. Huemer, the problem of the so-called short-range (SR) leakage in frequency modulated continuous-wave (FMCW) automotive radar is addressed. An artificial on-chip target, essentially consisting of a delay line, is introduced to mitigate the SR leakage which models a disturbing reflections from an object in front of the antennas. The problem of target ghosts in tracking radars is addressed in "MIMO passive radar tracking under a single frequency network," by J. Yi, X. Wan, H. Leung, and F. Cheng. It is a non-standard multisensor tracking problem due to the unknown measurement-to-transmitter association that causes the new kind of ghosts.

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Maria S. Greco (S'96–M'98–SM'04–F'11) joined the Dept. of Information Engineering of the University of Pisa, in 1993, where she has been an Associate Professor since Dec. 2011. She has been an IEEE fellow since Jan. 2011 and she was co-recipient of the 2001 IEEE Aerospace and Electronic Systems Society's Barry Carlton Award for Best Paper and recipient of the 2008 Fred Nathanson Young Engineer of the Year award for contributions to signal processing, estimation, and detection theory.

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Yuri Abramovich (M'96–SM'06–F'08) was with the Odessa State Polytechnic University, Odessa, Ukraine, from 1968 to 1994, as a Research Fellow, Professor, and ultimately as Vice-Chancellor of Science and Research. From 1994 to 2006, he was at the Cooperative Research Centre for Sensor Signal and Information Processing (CSSIP), Adelaide, Australia. Since 2000, he has been with the Australian Defence Science and Technology Organisation (DSTO), Adelaide, as Principal Research Scientist, seconded to CSSIP until its closure. He is currently with WR Systems Ltd., Fairfax, Virginia, USA. His research interests are in signal processing (particularly spatio-temporal adaptive processing, beamforming, signal detection and estimation), its application to radar (particularly over-the-horizon radar), electronic warfare, and communication. Dr. Abramovich is currently an Associate Editor of the IEEE TRANSACTIONS ON AEROSPACE AND ELECTRONIC SYSTEMS and previously served as Associate Editor of IEEE Transactions on Signal Processing from 2002 to 2005.

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Dr. Li received the IEEE Jack Neubauer Memorial Award in 2013 from the IEEE Vehicular Technology Society, the Outstanding Paper Award from the IEEE AFICON Conference in 2011, the Harvey N. Davis Teaching Award in 2003 and the Jess H. Davis Memorial Award for excellence in research in 2001 from Stevens Institute of Technology, and the Sigma Xi Graduate Research Award from the University of Florida in 1999. He has been a member of the Signal Processing Theory and Methods (SPTM) Technical Committees (since 2011) and the Sensor Array and Multichannel (SAM) Technical Committee (2007–2012) of the IEEE Signal Processing Society. He is an Associate Editor for *EURASIP Signal Processing*, and served on the editorial boards for IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS, IEEE SIGNAL PROCESSING LETTERS, and IEEE TRANSACTIONS ON SIGNAL PROCESSING. He was a Guest Editor for *EURASIP Journal on Applied Signal Processing* and a General Co-Chair for the 7th IEEE Sensor Array and Multichannel Signal Processing Workshop, Hoboken, NJ, June 17–20, 2012. Dr. Li is a member of Tau Beta Pi and Phi Kappa Phi.

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Dr. Yang is the Technical program chair of IET international radar conference 2013 (IET Radar 2013), Technical program committee member of IEEE International Conference on Computer and Information Technology 2014 (IEEE CIT 2014), Technical program co-chair of IET international radar conference 2015(IET Radar 2015), Committee member of radar society of Beijing Institute of Electronics (BIE), Expert committee member of China Youth Science and Technology Innovation Contest, Evaluation expert of National Natural Science Foundation of China, and Advisory committee member of IEEE Macau AP/MTT Joint Chapter. He is deputy director of BIT-SIE 111Project of China. Dr. Yang received the excellent young scholar awards of BIT in 2010 and 2012, respectively, the best paper award of 2012 National Radar Conference of China, and the excellent supervisor award of Master thesis of BIT in 2013. He is also a member of IET, IEICE and BIE, and a senior member of CIE.