DOI. No. 10.1109/MAES.2022.3166332

Abstracts of Previous Tutorials in This Series

TUTORIAL I

Published as *Part 2 of IEEE Aerospace & Electronic Systems Magazine*

Volume Nineteen-Number One-January 2004

MULTIPLE HYPOTHESIS TRACKING FOR MULTIPLE TARGET TRACKING

SAMUEL S. BLACKMAN
Raytheon Co., Segundo, CA

Multiple hypothesis tracking (MHT) is generally accepted as the preferred method for solving the data association problem in modern multiple target tracking (MTT) systems. This paper summarizes the motivations for MHT, the basic principles behind MHT and the alternative implementations in common use. It discusses the manner in which the multiple data association hypotheses formed by MHT can be combined with multiple filter models, such as used by the interacting multiple model (IMM) method. An overview of the studies that show the advantages of MHT over the conventional single hypothesis approach is given. Important current applications and areas of future research and development for MHT are discussed.

A STAP OVERVIEW

WILLIAM L. MELVIN, Senior Member, IEEE
GTRI, Smyrna, GA

This tutorial provides a brief overview of space-time adaptive processing (STAP) for radar applications. We discuss space-time signal diversity and various forms of the adaptive processor, including reduced-dimension and reduced-rank STAP approaches. Additionally, we describe the space-time properties of ground clutter and noise-jamming, as well as essential STAP performance metrics. We conclude this tutorial with an overview of some current STAP topics: space-based radar, bistatic STAP, knowledge-aided STAP, multi-channel synthetic aperture radar and non-sidelooking array configurations.

CLASS-SPECIFIC CLASSIFIER: AVOIDING THE CURSE OF DIMENSIONALITY

PAUL M. BAGGENSTOSS, Member, IEEE
Naval Undersea Warfare Center Newport, RI

This article describes a new probabilistic method called the "class-specific method" (CSM). CSM has the potential to avoid the "curse of dimensionality" which plagues most classifiers which attempt to determine the decision boundaries in a highdimensional featue space. In contrast, in CSM, it is possible to build classifiers without a common feature space. Separate lowdimensional features sets may be defined for each class, while the decision functions are projected back to the common raw data space. CSM effectively extends the classical classification theory to handle multiple feature spaces. It is completely general, and requires no simplifying assumption such as Gaussianity or that data lies in linear subspaces.

"STATISTICS 101" FOR MULTISENSOR, MULTITARGET DATA FUSION

RONALD P. S. MAHLER
Lockheed Martin, Eagan, MN

This tutorial summarizes the motivations, concepts, techniques, and applications of finite-set statistics (FISST), a system-level, "top-down" direct generalization of ordinary single-sensor, single-target engineering statistics to the multisensor, multitarget realm. FISST provides powerful new conceptual and computational methods for dealing with multisensor, multitarget, and multi-evidence data fusion problems. The paper begins with a broad-brush overview of the basic concepts of FISST. It describes how conventional single-sensor, single-target formal Bayesian modeling is carefully extended to general data fusion problems. We examine a simple example: joint detection and tracking of a possibly non-existent maneuvering target in heavy clutter. The tutorial concludes with a commentary on certain criticisms of FISST.

TUTORIAL II

Published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Twenty-Number Eight-August 2005

A REVIEW OF DISTRIBUTED POWER SYSTEMS PART I: DC DISTRIBUTED POWER SYSTEM

SHIGUO LUO
ISSA BATARSEH, Senior Member, IEEE
University of Central
Florida

The present development state in dc distributed power systems (DPS) is comprehensively reviewed in this tutorial.

Basic distributed structures and their characteristics are described. The system level design considerations are discussed. The profile of current technologies is drawn. Finally, the issues and challenges in this research area are identified. These issues include not only improving efficiency, but also increased concerns regarding the cost and complexity of power supplying systems.

FUNDAMENTALS OF ENERGY-CONSTRAINED SENSOR NETWORK SYSTEMS

BRIAN M. SADLER, Senior Member, IEEE
U.S. Army Research Laboratory

This article is an overview of energy-constrained sensor networks, focusing on energy-conserving communications and signal processing strategies. We assume battery-driven nodes, employing robust communications, with little or no fixed infrastructure. Our discussion includes architectures, communications connectivity, capacity and scalability, mobility, network localization and synchronization, distributed signal processing, and cross-layer issues. Because energy is a precious system resource, all aspects of the network must be designed with energy savings in mind. In particular, transmissions and idle listening must be minimized, which implies the use of duty cycling to the maximum extent possible. When external assets are available, for tasks such as network synchronization and node geolocation, these can greatly relieve the energy burden and significantly enhance network lifetime.

PROBABILISTIC DATA ASSOCIATION TECHNIQUES FOR TARGET TRACKING WITH APPLICATIONS TO SONAR, RADAR AND EO SENSORS

Y. BAR-SHALOM, Fellow, IEEE
University of Connecticut
T. KIRUBARAJAN, Member, IEEE
McMaster University
Canada
X. LIN
University of Connecticut

We present an overview of the probabilistic data association (PDA) technique and its application for different target tracking scenarios, in particular for low observable (LO) (low SNR) targets. A summary of the PDA technique is presented. The use of the PDA technique for tracking low observable targets with passive sonar measurements is presented. This "target motion analysis" is an application of the PDA technique, in conjunction with the maximum likelihood (ML) approach, for target motion parameter estimation via a batch procedure. The use of the PDA technique for tracking highly maneuvering targets combined radar resource management is described. This illustrates the application of the PDA technique for recursive state estimation using the interacting multiple model (IMM) estimator with probabilistic data association filter (PDAF) (IMMP- DAF). Then we present a flexible (expanding and contracting) sliding-window parameter estimator using the PDA approach for tracking the state of a maneuvering target using measurements from an electro-optical (EO) sensor. This, while still a batch procedure, has the flexibility of varying the batches depending on the estimation results in order to make the estimation robust to target maneuvers as well as target appearance or disappearance.

NONLINEAR FILTERS: BEYOND THE KALMAN FILTER

FRED DAUM, Member, IEEE
Raytheon

Nonlinear filters can provide estimation accuracy that is vastly superior to extended Kalman filters for some important practical applications. We compare several types of nonlinear filters, including: particle filters (PFs), unscented Kalman filters, extended Kalman filters, batch filters and exact recursive filters. The key practical issue in nonlinear filtering is computational complexity, which is often called "the curse of dimensionality." It has been asserted that PFs avoid the curse of dimensionality, designed PFs with good proposal densities sometimes avoid the curse of dimensionality, but not otherwise. Future research in nonlinear filtering will exploit recent progress in quasi-Monte Carlo algorithms (rather than boring old Monte Carlo methods), as well as ideas borrowed from physics (e.g., dimensional interpolation) and new mesh-free adjoint methods for solving PDEs. This tutorial was written for normal engineers, who do not have nonlinear filters for breakfast.

MULTIBASELINE CROSS-TRACK SAR INTERFEROMETRY: A SIGNAL PROCESSING PERSPECTIVE

FULVIO GINI, Senior Member, IEEE
FABRIZIO LOMBARDINI, Senior Member, IEEE
University of Pisa
Italy

Synthetic aperture radar interferometry (InSAR) is a powerful and increasingly expanding technique for measuringthe topography of a surface, its changes over both short- and long-time scale, and other changes in the detailed characteristicsof the surface. We provide a tutorial description of recent results of the research activity at the University of Pisa on multibaseline (MB) InSAR processing. The main focus is on the problem of retrieving both heights and radar reflectivities of natural layover areas by means of a cross-track InSAR (XTI-SAR) system with a uniform linear array (ULA). It is formulated as the problem of detecting and estimating a multi-component signal corrupted by multiplicative noise-the speckle in the radar imaging jargon-and by additive white Gaussian noise. Application to the InSAR problem of both nonparametric and parametric modern spectral estimation techniques is described. The problem of estimating the number of signal components in the presence of speckle is also addressed. Finally, a brief mention is given to recent research trends on robust methods for nonperfectly calibrated arrays, on processing for non-ULA configurations, and on MB SAR tomography, which is an extension of MB SAR interferometry for the full 3D mapping of semitransparent volume scattering layers. State of the art of other advanced multichannel interferometric techniques is also briefly recalled.

TUTORIAL III

Published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Twenty-One-Number Six-June 2006

A REVIEW OF DISTRIBUTED POWER SYSTEMS PART II: HIGH FREQUENCY AC DISTRIBUTED POWER SYSTEMS

SHIGUO LUO
ISSA BATARSEH, Fellow, IEEE
University of Central
Florida

The present development state in high frequency (HF) ac distributed power systems (DPS) is reviewed. First, background and motivations of developing HF AC-DPS are addressed. Two types of basic HF AC-DPSs based on sine wave and square/PWM (pulse- width modulated) wave bus are described, and the system level design considerations are discussed. Further, the issues and challenges in this research area are identified. These issues include high electromagnetic interference (EMI) level, difficulty to back up power, nonredundant system structure and limited post-regulation capability, etc. Finally, a viable HF AC-DPS is proposed, which is expected to yield effective EMI trade-off and system redundancy.

This is Part II of a two part review of Distributed Power Systems. *Part I: DC Distributed Power System* appeared in

Tutorial II, August 2005. See **Abstracts,** page 87, for more details.

BIOMETRIC SECURITY TECHNOLOGY

MARCOS FAUNDEZ-ZANUY
Escola Universitaria Politecnica de Mataró
Spain

This paper presents an overview of the main topics related to biometric security technology, with the central purpose to provide a primer on this subject.

Biometrics can offer greater security and convenience than traditional methods for people recognition. Even if we do not want to replace a classic method (password or handheld token) by a biometric one, for sure, we are potential users of these systems, which will even be mandatory for new passport models. For this reason, it is useful to be familiarized with the possibilities of biometric security technology.

OVERVIEW OF GENERALIZED MONOPULSE ESTIMATION

ULRICH NICKEL
FGAN-FHR
Germany

Monopulse is an established technique for radar angle estimation. One can show that monopulse estimation is based on a general approximation derived from maximum likelihood (ML) estimation. This tutorial provides a derivation of this relation and presents extensions of this monopulse principle to multi-dimensional array and parameter estimation problems, in particular to space-time adaptive processing (STAP) with reduced dimension, subarrays and generalized sidelobe canceller (GSLC) configurations. The performance of these monopulse applications can be predicted by exploiting the distribution of the monopulse ratio. It is demonstrated that this distribution is more realistic than the Cram'er-Rao bound (CRB). Several examples of performance of monopulse estimators are given for thinned and fully filled planar arrays, adaptive beamforming with and without low sid- elobes, GSLC, and STAP. Finally, conditions for estimates with low variance are discussed.

TUTORIAL IV

Published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Twenty-Two-Number Nine-September 2007

A BEGINNER'S GUIDE TO INTERFEROMETRIC SAR CONCEPTS AND SIGNAL PROCESSING

MARK A. RICHARDS, Senior Member, IEEE
Georgia Institute of Technology

Interferometric synthetic aperture radar (IFSAR, also abbreviated as InSAR) employs pairs of high resolution SAR images to generate high quality terrain elevation maps using phase interferometry methods. IFSAR provides an all-weather, day/night capability to generate measurements of terrain elevation on a dense grid of sample points with accuracies of ones of meters. Both spaceborne and airborne IFSAR systems are in use.

In this paper we present a tutorial introduction to the concepts, techniques, and applications of IFSAR. After a brief introduction to digital elevation models (DEMs) and digital terrain elevation data (DTED), the fundamental IFSAR equation relating interferometric phase measurements to terrain elevation is derived from simple geometric

considerations. The central section of the paper describes the major algorithmic steps required to form an IFSAR terrain map. Finally, variations of IFSAR for mapping terrain elevation or reflectivity changes are briefly described. A web site at users.ece.gatech.edu/»mrichard/AESS IFSAR.htm provides access to color versions of many of the IFSAR images included in this paper.

LORAN DATA MODULATION: A PRIMER

SHERMAN C. LO, Member, IEEE
Stanford University
BENJAMIN B. PETERSON, Senior Member, IEEE
Peterson Integrated Geopositioning
PER K. ENGE, Fellow, IEEE
Stanford University

Loran has provided navigation service since 1958. Though not originally designed with data broadcast capabilities, Loran's versatility has enabled data to be broadcast with great benefits.

Research in the last two decades has resulted in a tremendous increase in the data capacity of Loran thereby increasing its utility. Currently, a modernized Loran is being evaluated for its capability to backup GPS and data modulation is an integral part of this Loran design. An overview and analysis of Loran modulation techniques is provided.

TEMPLATE-BASED TARGET IDENTIFICATION AND CONFUSION MATRICES

KENT HASPERT, Member, IEEE
JAMES HEAGY
ROGER SULLIVAN, Member, IEEE
Institute for Defense Analyses

One-dimensional high-range-resolution (HRR) and two-dimensional range-Doppler-imaging (RDI) radar represent possible sensor technologies where template-based techniques can be applied to perform combat identification (CID). The majority of the research reported in these areas consists of empirical studies. This article provides a theoretical basis for understanding some of the fundamental trade-offs associated with these CID techniques, such as the following.

1) What are the relative advantages of RDI over HRR radar or of finer versus coarser resolution in the HRR process?
2) What is the relative advantage of coherent over noncoherent processing?
3) How do target correlations, signal-to-noise ratio (SNR), and target scintillation affect the ability to identify targets?

Because confusion matrices are often used to characterize the performance of CID systems, we provide analytical methods for calculating the entries in confusion matrices as a function of the issues cited above. These formulations provide analytical bases to guide system trade-off decisions. The organization of this paper is as follows. We begin with a short overview of HRR and RDI and then explore a number of ways to process the associated target templates that range from an ideal, theoretical approach to an approach that would be more feasible to implement within current-day radars. We first develop analytic template-based methodologies for constructing confusion matrix entries for nonscintillating targets for both coherent and noncoherent processing assumptions. The confusion matrix entries in these cases are conditional probabilities obtained from a simple rule: find the probability that among m (in general, correlated) random variables, each associated with a possible target, that any one is the largest. For the noncoherent case, the successful application of this rule requires the target template values to explicitly include the effects of thermal noise (noise-adjusted templates). We conclude by showing how to calculate theoretically optimum results (e.g., using maximum likelihood techniques) for noncoherent processing of targets that exhibit uncorrelated Swerling 1 scintillation in all resolution bins as a function of the SNR. This approach allows us to include overall target intensity (e.g., total radar cross section (RCS)) as a further factor in the target decision process.

TUTORIAL V

Published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Twenty-Five Number Seven-July 2010.

A TUTORIAL OVERVIEW OF ANOMALY DETECTION IN HYPERSPECTRAL IMAGES

STEFANIA MATTEOLI, Student Member, IEEE
MARCO DIANI, Member, IEEE
GIOVANNI CORSINI, Member, IEEE
University of Pisa

In this paper, a tutorial overview on anomaly detection for hyperspectral electro-optical systems is presented. This tutorial is focused on those techniques that aim to detect small man-made anomalies typically found in defense and surveillance applications. Since a variety of methods have been proposed for detecting such targets, this tutorial places emphasis on the techniques that are either mathematically more tractable or easier to interpret physically. These methods are not only more suitable for a tutorial publication, but also an essential to a study of anomaly detection. Previous surveys on this subject have focused mainly on anomaly detectors developed in a statistical framework and have been based on well-known background statistical models. However, the most recent research trends seem to move away from the statistical framework and to focus more on deterministic and geometric concepts. This work also takes into consideration these latest trends, providing a wide theoretical review without disregarding practical recommendations about algorithm implementation. The main open research topics are addressed as well, the foremost being algorithm optimization, which is required for embodying anomaly detectors in real-time systems.

ON BAYESIAN TRACKING AND DATA FUSION: A TUTORIAL INTRODUCTION WITH EXAMPLES

WOLFGANG KOCH, Senior Member, IEEE
Fraunhofer-FKIE
Germany

This tutorial paper provides a short introduction to selected aspects of sensor data fusion by discussing characteristic examples. We consider three cases when fusion of sensor data is important: when emphasis is placed on data produced at different instants of time (i.e., target tracking), when data being collected from different sensor sources are important, and when we have data with background information on the sensor performance as well as data with nonsensor context information. The feedback from data processing to the data acquisition process is illustrated by a sensor management example.

PARTICLE FILTER THEORY AND PRACTICE WITH POSITIONING APPLICATIONS

FREDRIK GUSTAFSSON, Senior Member, IEEE
Linköping University
Sweden

The particle filter (PF) was introduced in 1993 as a numerical approximation to the nonlinear Bayesian filtering problem, and there is today a rather mature theory as well as a number of successful applications described in literature. This tutorial serves two purposes: to survey the part of the theory that is most important for applications and to survey a number of illustrative positioning applications from which conclusions relevant for the theory can be drawn.

The theory part first surveys the nonlinear filtering problem and then describes the general PF algorithm in relation to classical solutions based on the extended Kalman filter (EKF) and the point mass filter (PMF). Tuning options, design alternatives, and user guidelines are described, and potential computational bottlenecks are identified and remedies suggested. Finally, the marginalized (or Rao-Blackwellized) PF is overviewed as a general framework for applying the PF to complex systems.

The application part is more or less a stand-alone tutorial without equations that does not require any background knowledge in statistics or nonlinear filtering. It describes a number of related positioning applications where geographical information systems provide a nonlinear measurement and where it should be obvious that classical approaches based on Kalman filters (KFs) would have poor performance. All applications are based on real data and several of them come from real-time implementations. This part also provides complete code examples.

TUTORIAL VI

REVIEW OF RANGE-BASED POSITIONING ALGORITHMS

JUNLIN YAN
Intel Mobile Communications GmbH
CHRISTIAN C. J. M TIBERIUS & GERARD J. M JANSSEN
Delft University of Technology
PETER J. G. TEUNISSEN
Curtin University of Technology
GIOVANNI BELLUSCI
Xsens

This tutorial reviews algorithms which turn measured ranges into position solutions. From their basic mathematical principles, we relate and compare relevant aspects of these algorithms. Special attention is given to the direct (non-iterative) algorithms, which are frequently applied in indoor positioning. Most of them are shown to be essentially the same, as they can be related through applying different weighting schemes. This tutorial is intended as a useful guide to help researchers and system designers evaluate and select appropriate range-based positioning algorithms for their applications at hand.

TUTORIAL VII

BASIC TRACKING USING NONLINEAR 3D MONOSTATIC AND BISTATIC MEASUREMENTS

DAVID CROUSE
Naval Research Laboratory
Washington, DC USA

Monostatic and bistatic position and Doppler measurements used in radar and sonar systems are nonlinear transformations of a Cartesian state. These nonlinearities pose a challenge for many target tracking algorithms, causing the so-called contact lens problem, which describes the nonlinear appearance of the measurement probability density function in Cartesian coordinates. This tutorial considers methods for measurement filtering (tracking without considering data association) using a singleGaussian approximation when monostatic and bistatic position and Doppler measurements are available. The connection between the cubature Kalman filter and numerous other filtering algorithms is shown, and the accuracy and consistency of different algorithms are compared through simulation. An effort is made to express the geometric relationships associated with multistatic tracking in a simple vectorial manner. This tutorial focuses on basic tracking, and the companion tutorials "Tracking Using 3D Monostatic and Bistatic Measurements in Refractive Environments" and "Basic Tracking Using Nonlinear Continuous-Time Dynamic Models" extend the results to more sophisticated physical models.

BASIC TRACKING USING NONLINEAR 3D MONOSTATIC AND BISTATIC MEASUREMENTS IN REFRACTIVE ENVIRONMENTS

DAVID CROUSE
Naval Research Laboratory
Washington, DC USA

The deleterious effects of atmospheric refraction are often overlooked in work on target tracking. This tutorial shows how the effects of refraction can be directly incorporated into tracking algorithms, improving the performance of tracking algorithms that make use of monostatic and bistatic measurements. Additionally, a technique for converting measurements from the radar's refraction-corrupted local coordinate system (typically bistatic r - u - v coordinates) into Cartesian coordinates is presented. The refraction-compensation algorithms can be used with arbitrary refraction models for which ray tracing techniques for solving boundary value problems and initial value problems are available, though extensions to more complicated propagation scenarios are possible. The algorithms are run on a simple exponential refraction model to demonstrate their effectiveness. This tutorial builds upon the tutorial entitled "Basic Tracking Using Nonlinear 3D Monostatic and Bistatic Measurements" and is complemented by the companion tutorial "Basic Tracking Using Nonlinear Continuous-Time Dynamic Models."

COHERENT MIMO RADAR: THE PHASED ARRAY AND ORTHOGONAL WAVEFORMS

MICHAEL S. DAVIS
Gregory A. Showman Georgia Tech Research Institute
Atlanta, Georgia, USA
AARON D. LANTERMAN
Georgia Institute of Technology
Atlanta, Georgia, USA

Coherent multiple-input multiple-output (MIMO) radar is a natural extension of the phased array antenna that has been used by radar systems for decades. This tutorial unifies concepts from the literature and provides a framework for the analysis of an arbitrary suite of MIMO radar waveforms. A number of gain patterns are introduced, which quantify the antenna performance of a MIMO radar, and the impact of the waveform characteristics (e.g., range sidelobes) is discussed.

TUTORIAL VIII

BASIC TRACKING USING NONLINEAR CONTINUOUS-TIME DYNAMIC MODELS

DAVID CROUSE, Member IEEE
Naval Research Laboratory
Washington, DC

Physicists generally express the motion of objects in continuous time using differential equations, whereas the majority of target tracking algorithms use discrete-time models. This tutorial considers the use of general, nonlinear, continuous time motion models for use in target tracking algorithms that perform measurements at specific, discrete times. The basics of solving/simulating deterministic/stochastic differential equations is reviewed. The difference between most direct-discrete and continuous-discrete tracking algorithms is the prediction step. Consequently, a number of continuous-time state prediction techniques are presented, focusing on derivative-free techniques. Consistent with common filtering techniques, such as the cubature Kalman filter, Gaussian approximations are used for the propagated state. Three dynamic models are considered for evaluating the performance of the algorithms: a highly nonlinear spiraling motion mode, a multidimensional geometric Brownian model, which has multiplicative noise, and an integrated Ornstein-Uhlenbeck process. Track initiation is also discussed.

NAVIGATION USING INERTIAL SENSORS

PAUL D. GROVES
University College London
London, United Kingdom

This tutorial provides an introduction to navigation using inertial sensors, explaining the underlying principles. Topics covered include accelerometer and gyroscope technology and their characteristics, strapdown inertial navigation, attitude determination, integration and alignment, zero updates, motion constraints, pedestrian dead reckoning using step detection, and fault detection.

TUTORIAL IX

DETECTION OVER SENSOR NETWORKS: A TUTORIAL

S. HAMED JAVADI
University of Bojnord
Bojnord, Iran

The applications of sensor networks (SNs) are increasing since they facilitate real-time remote information monitoring and processing. Detection of an event is one of the main tasks of SNs in many applications. Sensors may transmit either raw or processed data to a fusion center (FC), where a final decision is taken. The problems and challenges that exist in detection over SNs and the previously proposed methods to deal with them are reviewed and described in this tutorial.

A SURVEY OF CORRELATED WAVEFORM DESIGN FOR MULTIFUNCTION SOFTWARE RADAR

SAJID AHMED
MOHAMED ALOUINI
King Abdullah University of Science and Technology
Thuwal, Saudi Arabia

To change the transmit beam pattern, single antenna radar requires a change of antenna while multiple antenna array radar, such as phased-array, require amplitude/phase tapers, which are hardware components. Therefore, there is a genuine demand that the parameters of future radar systems be controlled through a software without changing any hardware or using amplitude/phase tapers. It is well known that the parameters of an antenna array radar can be controlled by transmitting suitable correlated waveforms. This approach provides more degree-of-freedom and if constant-envelope (CE) or low peak-to-average power ratio (PAPR) correlated waveforms are used, it allows us to control the parameters of the radar without changing any hardware. Therefore, this approach can be considered as a step towards a software radar. The aim of this article is to provide a survey of recent techniques used to design CE and low PAPR correlated waveforms and discuss the benefits and drawbacks of each.

GEOMETRY OF COMPLEX DATA

K. JAMES SANGSTON
Georgia Tech Research Institute
Atlanta, GA USA

Geometric algebra has been called a “unified language for mathematics and physics.” Sometimes known as Clifford algebra, it is based on the notion of an invertible product of vectors that captures the geometric relationship between two vectors, i.e., their relative magnitudes and the angle between them. This seemingly simple concept leads to a rich system of algebra and calculus that encompasses the diverse areas of complex numbers, quaternions, vectors, tensors, spinors, and differential forms. This tutorial provides a basic introduction to geometric algebra and presents formulations of known electrical engineering and signal processing concepts to illustrate some inherent advantages of geometric algebra for formulating and solving problems involving vectors. Being introductory, the goal of the tutorial is to introduce this emerging area that, although old as a mathematics discipline, has only recently started to garner significant attention in engineering communities. Geometric algebra should give another potentially powerful tool for pursuing research in any area that uses vectors.

RECURSIVE BAYESIAN FILTERING IN CIRCULAR STATE SPACES

GERHARD KURZ
Karlsruhe Institute of Technology
Karlsruhe, Germany
IGOR GILITSCHENSKI
Swiss Federal Institute of Technology
Zurich, Switzerland
UWE D. HANEBECK
Karlsruhe Institute of Technology
Karlsruhe, Germany

To facilitate recursive state estimation in the circular domain based on circular statistics, we introduce a general framework for estimation of a circular state based on different circular distributions. Specifically, we consider the wrapped normal (WN) distribution and the von Mises distribution. We propose an estimation method for circular systems with nonlinear system and measurement functions. This is achieved by relying on efficient deterministic sampling techniques. Furthermore, we show how the calculations can be simplified in a variety of important special cases, such as systems with additive noise, as well as identity system or measurement functions, which are illustrated using an example from aeronautics. We introduce several novel key components, particularly a distribution-free prediction algorithm, a new and superior formula for the multiplication of WN densities, and the ability to deal with nonadditive system noise. All proposed methods are thoroughly evaluated and compared with several state-of-the-art approaches.

TUTORIAL X

OVERVIEW OF RADAR WAVEFORM DIVERSITY

SHANNON D. BLUNT
University of Kansa
Lawrence, KS, USA
ERIC L. MOKOLE
Private Consultant
Burke, VA, USA

Waveform Diversity (WD) is an exciting technology that has sparked intense interest from the research community in recent years because of advances in high-fidelity electronic components and high-performance computing. WD is expected to have a profound impact on radar spectrum management, particularly in light of increasing competition for spectrum usage, as well as to facilitate enhanced radar sensitivity and discrimination and perhaps even to enable new sensing modes. The definition of WD is clearly broad, but such is to be expected for a topic that continues to evolve. The purpose of this tutorial is to provide the reader with the context in which WD has arisen, a sense of the tremendous breadth of the subject, and a sufficient starting point from which to explore WD further.

COHERENT RADAR DETECTION IN COMPOUND-GAUSSIAN CLUTTER: CLAIRVOYANT DETECTORS

K. JAMES SANGSTON
Sensors and Electromagnetic Applications Laboratory
Georgia Tech Research Institute
Smyrna, GA, USA
ALFONSO FARINA
Independent Consultant
Rome, Italy

This paper provides a historical and tutorial overview of coherent radar target detection in compound-Gaussian clutter and offers some new perspectives and avenues of research in this challenging area. It begins with a brief introduction that motivates the need to develop statistical models of non-Gaussian clutter and then reviews some of the physical ideas that led to modeling multivariate radar clutter statistics by the compound-Gaussian model. With this starting point, the paper then reviews a series of ideas that have been developed to describe clairvoyant detectors in such clutter. The term "clairvoyant" refers to the assumption that the properties of the clutter are assumed to be known. In a practical scenario, this assumption does not hold and adaptive techniques are needed to estimate clutter properties and implement the detector. Such techniques are guided however by the appropriate clairvoyant detector structures and hence it is proper to start by studying these detectors. As part of this review, the paper offers new ways of looking at this problem that suggest new research topics. This review is limited to the problem of clairvoyant detection in which the relevant properties of the clutter are assumed to be known. Adaptive detection in compound-Gaussian clutter will be the topic of a subsequent tutorial that the authors are preparing.

A SURVEY OF RADAR SYSTEMS FOR MEDICAL APPLICATIONS

STEFANO PISA
ERIKA PITTELLA
EMANUELE PIUZZI
Sapienza University of Rome
Rome, Italy

A survey of radar systems used in the medical field is presented. First, medical applications of radars are described, and some emerging research fields are highlighted. Then, medical radars are analyzed in terms of block diagrams and behavioral equations and some implementations are shown as examples. A section is dedicated to the radiating structures used in these radars. Finally, human safety and environmental impact issues are addressed. The most investigated medical applications of radars are breast tumor diagnostics and remote monitoring of cardiorespiratory activity. New fields of interest are physiological liquid detection, and the monitoring of artery walls and vocal cord movements. Among the various topologies, continuous wave (CW) radars have been proven to yield the highest range resolution that is limited only by the system noise while the resolution of ultra wideband (UWB) and frequency modulated continuous wave (FMCW) radars is also related to the used frequency bandwidth. Concerning the maximum range, UWB radars have the best performance due to their ability to operate in the presence of environmental clutter. As for the radiating structures, planar antennas are preferred for diagnostic applications, due to their small dimensions and good matching when placed in contact with the human body. Radar systems for remote monitoring, instead, are designed by using high gain antennas and taking into account the complex radar cross section (RCS) of the body.

SENSE AND AVOID FOR UNMANNED AIRCRAFT SYSTEMS

GIANCARMINE FASANO
DOMENICO ACCARDO
ANTONIO MOCCIA
University of Naples "Federico II
Naples, Italy
DAVID MARONEY
The MITRE Corporation
McLean, VA, USA

Sense and avoid (SAA) represents one of the main roadblocks to the integration of unmanned aircraft systems (UAS) operations by aviation authorities around the world. This tutorial outlines and reviews the substantial breadth of SAA architectures, technologies, and algorithms. Starting from a discussion about what constitutes a UAS and how it is different than manned aircraft, basic SAA definitions and taxonomies are discussed. The SAA process is dissected into three fundamental tasks, defined as sensing, detecting, and avoiding, which are discussed in detail. The tutorial concludes with a summary of the regulatory and technical issues that continue to challenge the progress on SAA, as a key component of reliable UAS operation in civil aviation authorities (CAAs) around the world.

TUTORIAL XI

INTRODUCTORY VIEW OF ANOMALOUS CHANGE DETECTION IN HYPERSPECTRAL IMAGES WITHIN A THEORETICAL GAUSSIAN FRAMEWORK

NICOLA ACITO
MARCO DIANI
Accademia Navale
Livorno, Italy
GIOVANNI CORSINI
Università di Pisa
Pisa, Italy
SALVATORE RESTA
Italian Navy

Exploitation of temporal series of hyperspectral images is a relatively new discipline that has gained a lot of

attention from the image processing scientific community. In this paper, we consider the specific problem of anomalous change detection (ACD) in hyperspectral images and discuss how images taken at two different times can be processed to detect changes caused by insertion, deletion, or displacement of small objects in the monitored scene. We introduce the ACD problem using an approach based on the statistical decision theory and we derive a common framework including different ACD approaches. Far from being inclusive of all the methods proposed in the literature, this tutorial overview places emphasis on techniques based on the multivariate Gaussian model that allows a formal presentation of the ACD problem and the rigorous derivation of the possible solutions in a way that is both mathematically more tractable and easier to interpret. The unification of different approaches under a single rigorous statistical scheme provides both a tutorial overview of ACD techniques, and a useful instrument for researchers already familiar with the ACD problem. Dedicated preprocessing methods aimed at improving the robustness of the ACD process are also discussed. Real data are exploited to test and compare the presented methods, highlighting advantages and drawbacks of each approach.

The tutorial aspect of the paper has suggested the use of a freely available data set. This should hopefully motivate the interested reader to experiment with the processing methods and performance evaluation chain presented herein.

ARE PLLS DEAD? A TUTORIAL ON KALMAN FILTER-BASED TECHNIQUES FOR DIGITAL CARRIER SYNCHRONIZATION

JORDI VILÀ-VALLS
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/ CERCA)
Barcelona, Spain
PAU CLOSAS
Northeastern University
Boston, MA, USA
MONICA NAVARRO
CARLES FERNÁNDEZ-PRADES
Centre Tecnològic de Telecomunicacions de Catalunya (CTTC/ CERCA)
Barcelona, Spain

Carrier synchronization is a fundamental stage in the receiver side of any communication or positioning system. Traditional carrier phase tracking techniques are based on well-known phase-locked loop (PLL) closed-loop architectures, which are still the methods of choice in modern receivers. Those techniques are well understood, easy to tune, and perform well under benign propagation conditions, but their applicability is seriously compromised in harsh propagation environments, where the signal may be affected by high dynamics, shadowing, strong fadings, multipath effects, or ionospheric scintillation. From an optimal filtering standpoint, the Kalman filter (KF) is clearly a powerful alternative, but the synchronization community seems still reluctant to exploit all the potential it has to offer. The purpose of this article is twofold: i) to review the basics and state of the art on both PLL and KF-based tracking techniques and ii) to present and justify the reasoning behind the systematic use of KF-based tracking approaches instead of the well established PLL-based architectures from both theoretical and practical points of view. To support the discussion, two specific scenarios of interest to the aerospace community are numerically evaluated: robust carrier tracking of global navigation satellite systems' signals and synchronization in a deep space communications system.

WEATHER RADAR: OPERATION AND PHENOMENOLOGY

JENNY L. REED
AARON D. LANTERMAN
JOHN M. TROSTEL
Georgia Tech Research Institute
Smyrna, GA, USA

Radar is an indispensable technology in areas of defense, air traffic control (ATC), and weather surveillance. The usual goal of defense and air traffic control radars is to detect and track individual

targets; in contrast, the "target" of weather radars may stretch hundreds of kilometers. The meteorology, defense, and ATC communities typically publish research in different venues, and each community has a vernacular and characteristic ways of approaching problems. The goals of this article are twofold. Its primary goal is to summarize typical weather radar systems and define associated jargon in terms more familiar to other radar communities. The second goal is to provide a detailed discussion

of the physical scattering phenomenology exploited specifically in radar meteorology. Furthermore, while there are a number of operational weather radars, we focus throughout much of this article on the most common weather radar, Weather Surveillance Radar 1988 Doppler (WSR-88D), as a canonical example, because much of the current research and phenomenological analysis are based on its operational parameters.

TUTORIAL XII

PASSIVE RADAR TUTORIAL

HEINER KUSCHEL
DIEGO CRISTALLINI
Fraunhofer, Germany
KARL ERIK OLSEN
Norwegian Defence Research Establishment
Norway

Passive Radar signifying the localization of a target by radar measurements without using own controlled emissions has been discussed, tried, reinvented, and matured within the last 80 years. Its advantage, like covert operation and saving the costs of a transmitter, are obvious. Military as well as civilian interests combined with the advance in technological developments have recently boosted research on passive radar and passive radar systems are currently approaching the market. This tutorial shall give an overview of the history, development, and processing in passive radar and enable the interested reader to further investigate the subject exploiting the presented material together with the cited references.

GPS RECEIVER ARCHITECTURES, FRONT-END AND BASEBAND SIGNAL PROCESSING

MICHAEL BRAASCH
Ohio University
Athens, OH, USA
ANDREW DEMPSTER
University of New South Wales
Sydney, Australia

This tutorial provides an overview of the hardware architectures and signal processing that form the core of satellite-based navigation receivers such as GPS. The concepts of spread spectrum and code division multiple access are introduced along with their roles in signal acquisition and tracking. The super-heterodyne front-end architecture will be described as well as the baseband architecture that utilizes in-phase and quadrature processing. Tracking loops are discussed along with measurement generation. The tutorial concludes with a brief look at so-called “modernized” satellite- based navigation signals.

DEALING WITH ROTATION MATRICES AND TRANSLATION VECTORS IN IMAGE-BASED APPLICATIONS: A TUTORIAL

ANDREA ZINGONI
MARCO DIANI
GIOVANNI CORSINI
University of Pisa
Italy

Rotation matrices are a convenient and intuitive way to describe algebraically the relative orientation of multiple cameras or of the same camera shooting from different points of view. However, the definition of a rotation matrix is prone to intrinsic ambiguity, which often leads to a mismatch with the physical rotation one wants to describe, even if the definition is mathematically correct. This is a common source of errors whenever it is required to compute a rotation matrix from camera orientation data, or vice versa, to recover such data from a given rotation matrix. This tutorial aims to describe and solve the main factors that generate the ambiguity in using rotation matrices and to permit dealing with them properly both in theory and in practice. Through a detailed analysis of these factors, which ranges from basic mathematical aspects to the notation used to refer to them, it is shown how to avoid errors in the algebraic description of the relative orientation of different cameras by means of rotation matrices. This work is followed by another contribution, in which the interaction between rotation matrices and translation vectors (used to describe the shifts between pairs of cameras) is also analyzed, and a recommendation on how to define a common reference system coherent with a camera (a crucial aspect to model the camera acquisition geometry) is given. The two contributions jointly embrace the entire description of the relative acquisition geometry of images taken from different points of view and provide a complete and error-free methodology to recover it or extract useful data from it. This topic is particularly important in a wide variety of aerospace applications, which often rely on multiple imaging sensors whose information should be merged, or on imaging devices carried by manned or unmanned vehicles. Such applications range from flying object detection to tridimensional reconstruction by using aerial or satellite images to drone automatic navigation, to change detection for area monitoring to georegistration by ground-to-aerial image matching.

DEALING WITH ROTATION MATRICES AND TRANSLATION VECTORS IN IMAGE-BASED APPLICATIONS: A COMMON REFERENCE SYSTEM FOR CAMERAS

ANDREA ZINGONI
MARCO DIANI
GIOVANNI CORSINI
University of Pisa
Italy

This tutorial follows and completes a previous work concerning how to solve the factors of ambiguity intrinsic in the definition of rotation matrices, to describe the relative orientation of one or more cameras acquiring images from different points of view. The two works, jointly, aim to provide an error-avoiding methodology to describe the whole relative acquisition geometry (pose). This is a crucial task for those aerospace applications based on the use of imaging devices, like flying objects detection and tracking, automatic guidance, tridimensional reconstruction, images georegistration, and change detection. To describe the pose, not only the orientation but also the relative shift should be taken into account. This can be conveniently modeled through a translation vector. Using it together with a rotation matrix it is possible to achieve the goal, but it is also prone to ambiguity. In this contribution, the main factors that result in such ambiguity are addressed. Through a detailed analysis, it is shown how to solve them, in order to manage the interaction between translation vectors and rotation matrices properly. This avoids the errors that frequently occur in practical applications, whenever it is required to find the transformation that makes the reference system of a camera coincident with the reference system of another, or to switch from the expression of the coordinates of a point of the scene in the reference system of a camera to its expression in the reference system of another. One of the reasons why errors are likely to be made in describing the pose is the lack of a commonly adopted choice for the camera reference system. To obviate this lack, the manuscript also presents a recommended definition for it. For the sake of completeness, the definition includes a second reference system for identifying points on a camera sensor plane, in order to permit describing also the projective transformation operated by the camera during the image formation process.

TUTORIAL XIII

ON COMPUTATIONAL COMPLEXITY REDUCTION METHODS FOR KALMAN FILTER EXTENSIONS

MATTI RAITOHARJU
Tampere University
Tampere, Finland
Aalto University
Helsinki, Finland
ROBERT PICHÉ
Tampere University
Tampere, Finland

The Kalman filter and its extensions are used in a vast number of aerospace and navigation applications for nonlinear state estimation of time series. In the literature, different approaches have been proposed to exploit the structure of the state and measurement models to reduce the computational demand of the algorithms. In this tutorial, we survey existing code optimization methods and present them using unified notation that allows them to be used with various Kalman filter extensions. We develop the optimization methods to cover a wider range of models, show how different structural optimizations can be combined, and present new applications for the existing optimizations. Furthermore, we present an example that shows that the exploitation of the structure of the problem can lead to improved estimation accuracy while reducing the computational load. This tutorial is intended for persons who are familiar with Kalman filtering and want to get insights for reducing the computational demand of different Kalman filter extensions.

CONFLICT DETECTION AND RESOLUTION FOR CIVIL AVIATION: A LITERATURE SURVEY

JUN TANG
College of Systems Engineering
National University of Defense Technology
Changsha, China

It is evident from the study of literatures that there are a great many of approaches to the conflict detection and resolution (CDR) research for civil aviation. However, there has been little comparative discussion of them. This survey contributes to the summarization of the CDR methods, mainly consisting of the long-term CDR, the mediumterm CDR, and the short-term CDR at three different categories, classified on account of the acting period. Furthermore, several typical characterizations of the taxonomy have been utilized to articulate their basic functions: Detection, Resolution, Cooperation, Maneuvers, Domino effects, Multiple Conflicts, Uncertainties, State variables, Equipped locations and methods status. It offers an intuitive and comprehensive general CDR process, as well as summarizes the various approaches for collision risk prediction and the different strategies for conflict resolution at a strategic/tactical/operational level, thus offering a comprehensive perspective of the research progresses and directions to promote the development.

AN OVERVIEW OF RADOMES FOR LARGE GROUND-BASED ANTENNAS

MICHAEL E. MACDONALD
MIT Lincoln Laboratory
Lexington, USA

This tutorial provides an overview of RF-transparent protective enclosures or “radomes” for ground-based antennas. In addition to electromagnetic behavior, structural and environmental considerations are highlighted which are important in large antenna installations such as those for satellite communication and deep space radar applications. Different radome types such as metal space frame, inflatable, and sandwich are contrasted with emphasis on the tradeoffs they entail for the antenna system.

MODELING THE STATISTICS OF MICROWAVE RADAR SEA CLUTTER

LUKE ROSENBERG
Defence Science and Technology Group
Edinburgh, Australia
SIMON WATTS
University College London
London, United Kingdom
MARIA SABRINA GRECO
University of Pisa
Pisa, Italy

One of the key requirements of a radar system is to detect targets against the background interference. This can be a challenging problem in the maritime domain when the sea moves in a complex manner and the characteristics are time-varying or nonstationary. Understanding the characteristics of sea clutter is therefore essential in developing effective and robust detection schemes.

The first part of this tutorial provides details of the relevant statistical models from the literature which are typically used to characterize the sea clutter. Using these models enables us to represent clutter in different environments that may be difficult to observe in trials and to predict the performance of radars over a range of different conditions with more confidence. Future radar systems may well comprise transmitters and receivers which are separated by some distance. Analysis of bistatic sea clutter is therefore covered in the second part of this paper with a focus on how the statistics vary with different bistatic angles. The final part then looks at the application of radar models for clutter simulation and performance prediction for both coherent and non-coherent detection schemes.

TUTORIAL XIV

Published as *Part 2 of IEEE Aerospace & Electronic Systems Magazine*

Volume Thirty Six-Number Three-March 2016

COUNTER-UNMANNED AIRCRAFT SYSTEM(S) (C-UAS): STATE OF THE ART, CHALLENGES, AND FUTURE TRENDS

JIAN WANG, **YONGXIN LIU**, **HOUBING SONG**
Embry-Riddle Aeronautical University, Daytona Beach, FL, 32114, USA

Unmanned aircraft systems (UAS), or unmanned aerial vehicles, often referred to as drones, have been experiencing healthy growth in the United States and around the world. The positive uses of UAS have the potential to save lives, increase safety and efficiency, and enable more effective science and engineering research. However, UAS are subject to threats stemming from increasing reliance on computer and communication technologies, which place public safety, national security, and individual privacy at risk. To promote safe, secure, and privacy-respecting UAS operations, there is an urgent need for innovative technologies for detecting, tracking, identifying, and mitigating UAS. A Counter-UAS (C-UAS) system is defined as a system or device capable of lawfully and safely disabling, disrupting, or seizing control of an unmanned aircraft or UAS. Over the past five years, significant research efforts have been made to detect, and mitigate UAS: detection technologies are based on acoustic, vision, passive radio frequency, radar, and data fusion; and mitigation technologies include physical capture or jamming. In this tutorial, we provide a comprehensive survey of existing literature in the area of C-UAS, identify the challenges in countering unauthorized or unsafe UAS, and evaluate the trends of detection and mitigation for protecting against UAS-based threats. The objective of this tutorial is to present a systematic introduction of C-UAS technologies, thus, fostering a research community committed to the safe integration of UAS into the airspace system.

AUTOMATIC TARGET RECOGNITION ON SYNTHETIC APERTURE RADAR IMAGERY: A SURVEY

ODYSSEAS KECHAGIAS-STAMATIS
NABIL AOUF
City University of London, London, EC1V 0HB, U.K.

Automatic target recognition (ATR) for military applications is one of the core processes toward enhancing intelligence and autonomously operating military platforms. Spurred by this and given that the synthetic aperture radar (SAR) presents several advantages over its counterpart data domains, this article surveys and assesses current SAR ATR algorithms that employ the most popular dataset for the SAR domain, namely the moving and stationary target acquisition and recognition (MSTAR) dataset. Specifically, we perform a direct comparison between current SAR ATR methods and highlight the strengths and weaknesses of each technique under both standard and extended operational conditions. Additionally, despite MSTAR being the standard SAR ATR benchmarking dataset, we also highlight its weaknesses and suggest future research directions.

AN INTRODUCTION TO PRACTICAL QUANTUM KEY DISTRIBUTION

OMAR AMER
University of Connecticut, Storrs, CT, 06269, USA
VAIBHAV GARG
Comcast Cable, Philadelphia, PA, 19103, USA
WALTER O. KRAWEC
University of Connecticut, Storrs, CT, 06269, USA

Quantum technology, and especially quantum computing, is advancing rapidly. Our every-day secure communication infrastructure relies heavily on public key cryptography; unfortunately, many public key schemes are in fact insecure against quantum algorithms. Furthermore, adversaries who, today, capture information encrypted using classical key distribution systems, can wait and, as soon as quantum computers of sufficient power become available, they may decipher all previously captured information. While some new "postquantum" public key systems are assumed to be secure against quantum computers, this is only an assumption and, even if the assumption remains valid, still results in systems that are less efficient for end-users than the more commonly used public key systems employed today. While the advent of quantum technology may seem detrimental to security, in fact, one may harness the power of quantum through quantum key distribution (QKD) for stronger security guarantees. Such QKD protocols allow two (or more) parties to establish a shared secret key, secure against an all-powerful adversary. Perhaps surprising is that QKD technology is already here both experimentally and commercially. This tutorial serves as an introduction to basic QKD along with QKD technology from a practical perspective. Quantum communication is a highly interdisciplinary field of research, and one of the goals of this article is to introduce a larger set of researchers and practitioners to its study in the hopes of furthering its progress and eventual wide-scale adoption.

TUTORIAL XV

Published as *Part 2 of IEEE Aerospace & Electronic Systems Magazine*

Volume Thirty Seven–Number Five–May 2022

MONOCULAR VISUAL AUTONOMOUS LANDING SYSTEM FOR QUADCOPTER DRONES USING SOFTWARE IN THE LOOP

MIGUEL SAAVEDRA-RUIZ, ANA MARIA PINTO-VARGAS, AND VICTOR ROMERO-CANO

Universidad Autonoma de Occidente, Santiago de Cali, Colombia Autonomous landing is a capability that is essential to achieve the full potential of multirotor drones in many social and industrial applications. The implementation and testing of this capability on physical platforms is risky and resource-intensive; hence, in order to ensure both a sound design process and a safe deployment, simulations are required before implementing a physical prototype. This article presents the development of a monocular visual system, using a software-in-the-loop methodology that autonomously and efficiently lands a quadcopter drone on a predefined landing pad, thus reducing the risks of the physical testing stage. In addition to ensuring that the autonomous landing system as a whole fulfils the design requirements using a Gazebo-based simulation, our approach provides a tool for safe parameter tuning and design testing prior to physical implementation. Finally, the proposed monocular vision-only approach to landing pad tracking made it possible to effectively implement the system in an F450 quadcopter drone with the standard computational capabilities of an Odroid XU4 embedded processor.

A SURVEY ON THE APPLICATIONS OF CONVOLUTIONAL NEURAL NETWORKS FOR SYNTHETIC APERTURE RADAR: RECENT ADVANCES

AMIR HOSEIN OVEIS, ELISA GIUSTI, AND SELENIA GHIO, AND MARCO MARTORELLA

National Inter-University Consortium for Telecommunications, 56127 Pisa, Italy In recent years, convolutional neural networks (CNNs) have drawn considerable attention for the analysis of synthetic aperture radar (SAR) data. In this study, major subareas of SAR data analysis that have been tackled by CNNs are systematically reviewed, such as automatic target recognition, land use, and land cover classification, segmentation, change detection, object detection, and image denoising. Special emphasis has been given to practical techniques such as data augmentation and transfer learning. Complex-valued CNNs, which have been introduced to exploit phase information embedded in SAR complex images, have also been extensively reviewed. To conclude this review paper, open challenges and future research directions are highlighted.

A RATIONALE FOR BACKPROJECTION IN SPOTLIGHT SYNTHETIC APERTURE RADAR IMAGE FORMATION

JERALD L. BAUCK
Tempe, AZ 85283 USA

This note on backprojection for spotlight synthetic aperture radar image formation is mainly pedagogic in purpose and is intended to be accessible. The presentation from first principles is elementary and detailed, beginning with the wave equation and melding wave notions with signal processing notions using a compact and consistent notation throughout. A reflection model is developed including a general expression for the receiver signal, which does not depend on a particular transmitted waveform. Then, the signal is specialized to monochromatic waves to show how waves and the Fourier transform fit together. In the end, the signal is once again generalized so that the theory works for any signal type. Backprojection is shown to reconstruct the wave field that was lost by sampling it at only one point, the receiving antenna. After specializing some details to the synthetic aperture radar geometry, the Projection Slice Theorem is introduced late, after an understanding of the underlying principles is obtained. Computational aspects are considered and it is seen that backprojection and direct Fourier inversion, also known as the polar format algorithm, are fundamentally the same, differing only in some implementation details, albeit significant ones, thus overturning the notion that backprojection is not a Fourier process. Those who might benefit from this article include people who have worked in this field and who seek a somewhat different point of view from the usual presentation, people in other fields who are unfamiliar with some of the engineering concepts involved, and signal processing engineers who appreciate a bit of wave theory.

DETECTING A TARGET WITH QUANTUM ENTANGLEMENT

GIACOMO SORELLI
Sorbonne Universite, 75005 Paris, France, and also
Universite Paris Saclay, Palaiseau F-91123, Franc

NICOLAS TREPS AND FREDERIC GROSSHANS
Sorbonne Universite, Paris F-75005, France
FABRICE BOUST
Universite Paris Saclay, Palaiseau F-91123, France

Over the last decade, research activity has focused on the use of quantum entanglement as a resource for remote target detection, i.e., on the design of a quantum radar. The literature on this subject uses tools of quantum optics and quantum information theory, and therefore, results are often obscure to radar engineers. This tutorial has been written with the purpose of removing this obscurity. As such, it contains a review of the main advances in quantum radar literature accompanied by a thorough introduction of the quantum optics background necessary for its understanding.

OBTAINING PREVIOUS TUTORIALS

Tutorial I was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Nineteen-Number One-January 2004.

Tutorial II was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Twenty-Number Eight-August 2005.

Tutorial III was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Twenty-One-Number Six-June 2006.

Tutorial IV was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Twenty-Two-Number Nine-September 2007.

Tutorial V was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Twenty-Five Number Seven-July 2010.

Tutorial VI was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Twenty-Eight Number Seven - July 2013

Tutorial VII was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Twenty-Nine Number Eight - August 2014

Tutorial VIII was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Thirty Number Two - February 2015

Tutorial IX was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Thirty-One Number Three - March 2016

Tutorial X was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Thirty-One Number Eleven - November 2016

Tutorial XI was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Thirty-Two Number Seven - July 2017.

Tutorial XII was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Thirty-Four Number Two - February 2019.

Tutorials XIII was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Thirty-Four Number Ten - October 2019.

Tutorials XIV was published as Part 2 of IEEE Aerospace & Electronic Systems Magazine

Volume Thirty-Six Number 3 - March 2021.

Copies of tutorials are available for use by any AESS function, as long as stocks last. Requests must indicate Tutorial Number and quantity (minimum 25), be in writing, provide a complete street shipping address including telephone number, give adequate lead time for fulfillment, and indicate the date desired at the destination. Direct your requests to Amanda Osborn by e-mail at aosborn@conferencecatalysts.com.