

# Abstracts of Previous Tutorials in This Series

## TUTORIAL I

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### MULTIPLE HYPOTHESIS TRACKING FOR MULTIPLE TARGET TRACKING

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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

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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**  
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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 feature 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

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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

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

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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

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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

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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

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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

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Italy

Synthetic aperture radar interferometry (InSAR) is a powerful and increasingly expanding technique for measuring the topography of a surface, its changes over both short- and long-time scale, and other changes in the detailed characteristics of 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

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

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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

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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

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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 side lobes, GSLC, and STAP. Finally, conditions for estimates with low variance are discussed.

## TUTORIAL IV

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

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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](http://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

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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

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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

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### A TUTORIAL OVERVIEW OF ANOMALY DETECTION IN HYPERSPECTRAL IMAGES

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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

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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

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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

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**CHRISTIAN C. J. M TIBERIUS & GERARD**

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Delft University of Technology

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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

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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 single Gaussian 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

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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

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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

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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

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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

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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

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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

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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

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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

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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

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**ALFONSO FARINA**

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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**

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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**

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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 pre-processing 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

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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 fading, 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

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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

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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

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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

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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

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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

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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

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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 medium-term 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

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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

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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

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

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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

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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

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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

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

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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 SELÉNIA 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

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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

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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.

**TUTORIAL XVI**

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**A REVIEW ON RECENT DEVELOPMENT OF MULTIROTOR UAV FAULT-TOLERANT CONTROL SYSTEMS****MAJD SAIED**

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The past decades have witnessed an increase in the use of multirotor unmanned aerial vehicles (UAVs). This has led the way to the development of fault-tolerant control (FTC) algorithms to service the different applications provided by these UAVs in different situations and circumstances. This tutorial is concerned with theoretical approaches and real practices for fault detection and diagnosis (FDD) and FTC of multirotor UAVs, namely, quadrotors, hexarotors, and octorotors. The topic is addressed by identifying the most significant faults and failures on these vehicles, the different FDD and FTC architectures, as well as the experimental real-time validations available in the published literature. A review of some challenges in the general area of multirotor UAV FTC design is further concluded.

**MACHINE LEARNING IN GNSS MULTIPATH/NLOS MITIGATION: REVIEW AND BENCHMARK****PENGHUI XU, GUOHAO ZHANG, BO YANG, AND LI-TA HSU**

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Global navigation satellite system (GNSS) positioning accuracy is degraded in urban canyons due to signal blockages and reflections, which is still a major challenge. Recently, using machine learning to improve the accuracy of GNSS positioning in urban areas has become a new trend. This article summarizes the works focused on GNSS multipath/non-light-of-sight (NLOS) mitigation using machine learning. The review of the studies is categorized based on the input features, algorithms, and outputs. The categorization shows that the received signal strength, elevation angle, and receiver correlator outputs from a single channel of satellite signal are the most popular input features. For the algorithm selection, the support vector machine and fully connected neural network are the algorithms most widely used. In terms of the outputs, most of the works made improvements in measurement status prediction, namely, LOS, multipath, and NLOS. Besides, this article also provides an open-source dataset with four scenarios for machine learning algorithms for the GNSS multipath/NLOS mitigation. Finally, the benchmarks are established based on the proposed dataset and the FCNN and least-squares estimation to enable performance evaluation in *Kaggle*.

**AD ASTRA: SIMULTANEOUS TRACKING AND NAVIGATION WITH MEGACONSTELLATION LEO SATELLITES****ZAHER M. KASSAS**

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We are witnessing a space renaissance. Tens of thousands of broadband low Earth orbit (LEO) satellites are expected to be launched by the end of this decade. These planned megacostellations of LEO satellites along with existing constellations will shower the Earth with a plethora of signals of opportunity, diverse in frequency and direction. These signals could be exploited for navigation in the inevitable event that global navigation satellite system (GNSS) signals become unavailable (e.g., in deep urban canyons, under dense foliage, during unintentional interference, and intentional jamming) or untrustworthy (e.g., under malicious spoofing attacks). Nevertheless, to exploit “uncooperative” LEO satellites opportunistically for navigation, a number of incumbent challenges must be addressed, namely, the unknown nature of their signals, ephemerides, and clock errors. Recent advances in cognitive receiver design have shown the ability to extract navigation observables (pseudorange, Doppler, and/or carrier phase) from unknown LEO signals. This tutorial focuses on addressing the latter challenges via a framework termed STAN: simultaneous tracking and navigation. STAN estimates the navigating vehicle’s states simultaneously with the states of orbiting

LEO satellites. STAN employs a cognitive receiver that exploits LEO satellite downlink signals to produce navigation observables, which are fused through an extended-Kalman filter (EKF) to aid the vehicle's inertial navigation system (INS) in a tightly coupled fashion. First, this tutorial presents the models governing the vehicle's INS kinematics, LEO satellite dynamics, clock error dynamics, and LEO measurements (pseudorange, Doppler, and/or carrier phase). Next, the tutorial formulates the EKF's state vector and details the EKF's time and measurement updates. To demonstrate the efficacy of STAN, the tutorial presents simulation results showcasing an aerial vehicle navigating with unknown LEO satellites. The aerial vehicle is assumed to be equipped with an altimeter and a tactical-grade inertial measurement unit (IMU), navigating for 15.43 km in 300 s, in which GNSS signals were only available for the first 60 s. It is demonstrated that the final three-dimensional (3-D) position error and position root mean squared error (RMSE) of a typical tightly coupled GNSS-aided INS grows to 1,536 and 897 m, respectively. In contrast, the STAN framework with 77 LEO satellites (resembling Orbcomm, Iridium NEXT, and Starlink constellations) achieved a final 3-D position error and 3-D position RMSE of 15.2 and 7.3 m, respectively, with pseudorange measurements, and 37.1 and 10.6 m, respectively, with Doppler measurements. To demonstrate the efficacy of STAN in the real world, the tutorial presents experimental results of a ground vehicle navigating with multiconstellation LEO satellites. The vehicle traversed 4.15 km in 150 s, in which GNSS signals were only available for the first 80 s. It is shown that the final 3-D position error and 3-D position RMSE of the vehicle's GNSS-aided INS with an industrial-grade IMU and an altimeter grew to 472.7 and 118.5 m, respectively. In contrast, the final 3-D position error and position RMSE of the STAN framework with signals from 2 Orbcomm, 1 IridiumNEXT, and 3 Starlink LEOsatellites were 27.1 and 18.4m, respectively.

## DEVELOPMENT OF RELATIVE DEGREE-BASED AEROSPACE SLIDING MODE CONTROL MATLAB TOOLBOX WITH CASE STUDIES

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Sliding mode control and observation techniques are widely used in aerospace applications, including aircraft, UAVs, launch vehicles (LVs), missile interceptors, and hypersonic missiles. This work is dedicated to creating an MATLAB-based sliding mode controller design and simulation software toolbox that aims to support aerospace vehicle applications. An architecture of the aerospace sliding mode control toolbox (*SMC Aero*) using the relative degree approach is proposed. The *SMC Aero* libraries include first-order sliding mode control, second-order sliding mode control, and higher order sliding mode control (either fixed gain or adaptive), as well as higher order sliding mode differentiators. The efficacy of the *SMC Aero* toolbox is confirmed in two case studies: 1) controlling and 2) simulating resource prospector lander soft landing on the Moon and LV attitude control in ascent mode.

## AN END-TO-END MODULAR FRAMEWORK FOR RADAR SIGNAL PROCESSING: A SIMULATION-BASED TUTORIAL

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This tutorial presents an end-to-end modular framework for signal processing techniques used in radar systems. The taxonomy of radar has been reviewed, as well as the subsystems of radar. The radar range equation is discussed, and its terms are explained. The radar operating principle and radar signal processing techniques to implement those operations have been highlighted. The simulation of a complete radar has been performed, and the results have been shown after each stage/module of a radar, enabling the reader to appreciate the impact of the specific process on the radar signal. The transmitter, antenna, and receiver subsystems have been simulated in MATLAB with a detailed discussion on waveform generation and transmission, receiver side operations such as matched filtering, Doppler processing, moving target indication filtering, and constant false alarm rate detection. Each step of the receiver chain's signal processing has been discussed, along with its influence on the signal. The implementation is carried out by simulating a generic 2D pulse-Doppler radar. A comprehensive analysis of the waveform generation and its effect on the target detection performance, varying radar cross section effect on the reflected wave, and path loss during propagation has been demonstrated. The sensitivity of the received signal to changing pulse types, number of fast Fourier transform points, window types, and CFAR algorithms have been presented. We have also discussed a radar system's conflicting range and Doppler ambiguities.

## FLIGHT DATA RECORDERS: PAST, PRESENT, AND FUTURE

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Devices that record data generated by an aircraft and its crew during operation are known as flight data recorders (FDRs) and cockpit voice recorders (CVRs). Data recorded by these devices enable the analysis of aircraft state and behavior from takeoff to landing. The information provided by these devices is used to conduct inspections, investigations, training, and other measures by aviation experts following hazardous events or accidents. As of today, multiple instruction manuals covering the specifications of FDRs and CVRs have been presented by various organizations, experts, and scientists within the aviation industry. However, no consolidated research document that brings all this information together for regulatory and technical purposes has been published yet. Our objective is to carry out an in-depth study of FDRs for both manned and unmanned systems. We aim to examine the requirements used in the past, current technological advancements, and future intelligent FDR approaches, intending to advance FDR technology. Starting with manned aviation systems, we provide a comprehensive overview of general FDRs and then look at new challenges and the resulting requirements for unmanned aerial vehicles (UAVs). After reviewing all relevant resources, we present a roadmap for the next generation of FDRs.

## A REVIEW OF RADAR DETECTION FUNDAMENTALS

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This article presents a review of the radar detection literature, which permits engineers to size radar systems considering various fundamental parameters. The monostatic radar equation is reviewed in detail and its different terms are explained. Its essential parameters are highlighted with evaluation means allowing us to choose their values.

Thus, the theoretical Swerling models are recalled for modeling the radar cross-section (RCS) of targets. The fluctuations of the RCS and their probability densities are presented according to the models. In addition, some practical examples are outlined to give ideas on when to use the Swerling models. Signal-to-noise ratio (SNR) is discussed in relation to the reliability performance of radar systems, i.e., detection and false alarm probabilities, but also through the fixed threshold and constant false alarm rate (CFAR) detection techniques. Equations and radar operating curves (ROCs) to estimate the SNR required to satisfy a given system performance are presented for the different target models. Radar signal integration techniques, such as coherent integration, noncoherent integration, binary integration, and cumulative detection, are also discussed in the context of multiple-observation detection to improve performance. The principle of operation of each of these integration techniques is explained and the equations and ROCs are presented for the different Swerling targets. The various system losses that contribute to the reduction of radar echo energy and signal processing losses that increase the required SNR are also exposed. These losses are included in the radar equation to complete the sizing and allow a more realistic estimate of the detection range.

## CYBERSECURITY OF UNMANNED AERIAL VEHICLES: A SURVEY

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Unmanned aerial vehicles (UAVs) are unmanned aircrafts operated by radio remote control and programmed control equipment. Due to their small size, low cost, and high flexibility, UAVs are widely used in military and civilian fields, such as geological detection, film shooting, traffic control, homeland security, and reconnaissance in battlefield. With the rapid increase of UAVs and the success of their related technologies, they also face many security problems, such as jamming, man-in-the-middle, and false message injection attacks. The security of UAVs has become a hot research topic. However, most UAV-related surveys are analyzed and summarized from a single perspective, there are few surveys about UAV cybersecurity. Hence, we believe that a categorized and comprehensive survey of UAV cybersecurity is urgently needed. In this tutorial, we present a comprehensive survey on UAV

cybersecurity, from three aspects of the physical domain, cyber domain, and cyber-physical domain. Specifically, in the physical domain, we review attacks that directly affect UAVs' fuselages or their significant components and discuss the solutions to these attacks. We survey the cyber threats against UAVs and the corresponding defense or detection methods in the cyber domain. One highlight is the security threat for UAV intelligent systems and the corresponding defense methods. Finally, in the cyber-physical domain, we summarize cyber-physical attacks such as GPS spoofing, these attacks are easy to destroy the chips and sensors of UAVs. In conclusion, understanding these attacks and their associated defense mechanisms will help pave a path towards the cybersecurity of UAVs. In addition, future research directions and problems to be solved are discussed at the end of this survey. With this comprehensive 45 literature review, we set out to provide a novel insight into the current state of cybersecurity of UAVs.

## COMMUNICATIONS FOR THE PLANET MARS: PAST, PRESENT, AND FUTURE

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Space exploration has been on the rise since the 1960s and Mars plays a significant role in the history of space exploration. As the amount of data collected from science instruments around and on Mars increased, the need for fast and reliable communication between Earth and space probes has emerged. However, communicating over deep space has always been a big challenge due to the propagation characteristics of radio waves. Nowadays, the collaboration of private companies like SpaceX with space agencies to make Mars colonization a reality, introduces even more challenges, such as providing high data rate, low-latency, energy-efficient, and mobility-resistant communication infrastructures in the Martian environment. Propagation medium and wireless channel characteristics of Mars should be extensively studied to achieve these goals. This survey article presents a comprehensive overview of the Mars missions and channel modeling studies of the near-Earth, interstellar, and near-planet links. Studies featuring three-dimensional (3D) channel modeling simulations on the Martian surface are reviewed. Novel computer simulations considering various scenarios based on realistic 3D Martian terrains using the Wireless Insite software are presented. Path loss exponent, power delay profile, and root-mean-square delay spread for these scenarios are calculated and tabularized in this study.

## OBTAINING PREVIOUS TUTORIALS

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

Volume Nineteen-Number One-January 2004.

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

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