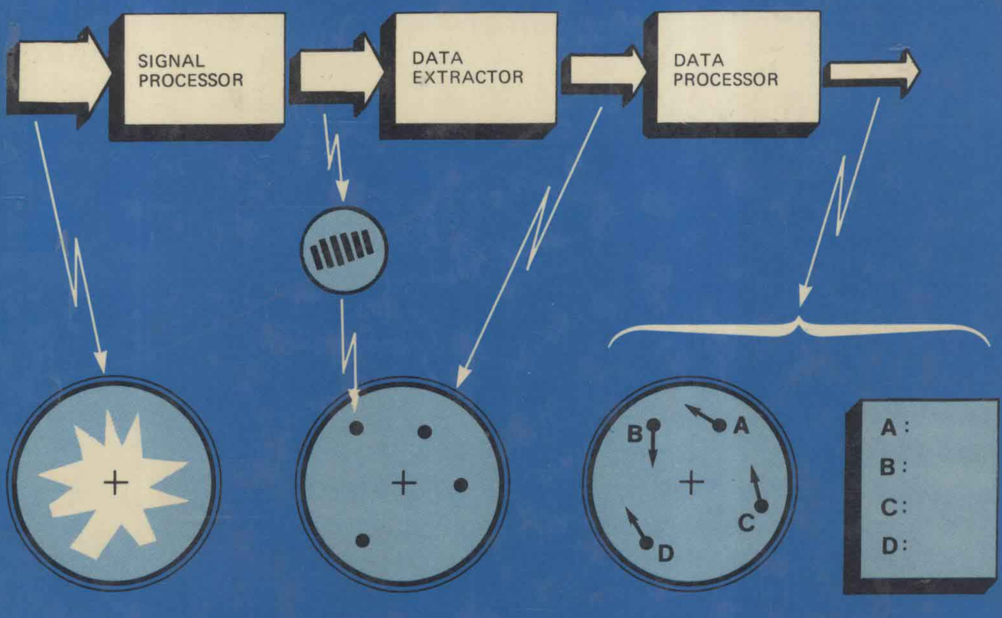
Radar Data Processing

VOLUME I—INTRODUCTION AND TRACKING

A. Farina *and*
F. A. Studer



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Radar
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VOLUME I—INTRODUCTION AND TRACKING

to our families

Editor's Foreword

In this second monograph in the RSP series on Electronic Circuits and Systems, the authors Alfonso Farina and Flavio A. Studer have maintained the high technical standard already established by Douglas Maclean. While the field is very different, covering another part of the editorial range of the series, the text shares some features with its predecessor. Both make reference to modern system theory and are based on a rigorous mathematical background. Again, both books have the practical flavour expected from authors employed in the electronics industry.

There has been an increasing need for a definitive text specifically on automatic radar data processing (RDP) in order to unify and consolidate the contributions reported in technical papers over recent years. The few existing treatments generally consist of collections of distinct papers whereas this is an integrated whole. The authors are particularly well qualified to provide such a work, having both been engaged in relevant research with Selenia S.p.A. over a long period. Many of their findings have already been presented at various international conferences and published in institutional journals, but they are now collected together with added background and perspective.

The monograph is divided into two convenient parts, for ease of handling as much as for production reasons. The structure is arranged so that Volume I first introduces RDP principles in the framework of radar system theory before providing convenient mathematical tools. Such propaedeutic concepts enable description of track-while-scan systems, leading up to detailed discussion of tracking algorithms. This sets the scene for Volume II which is concerned with netted radar systems together with performance evaluation by means of computer simulation, implementation techniques and application examples. In fact, an awareness of applications pervades the whole text while the research interest is heightened by the inclusion of advanced sensors, such as phased-array and bistatic systems. Designers of radar systems should particularly welcome discussion of computer requirements and the inclusion of some computer simulation algorithms.

Throughout the monograph, the preferred approach is first to appeal to intuition in order to explain the rationale of RDP techniques, and then to develop a rigorous mathematical treatment.

Finally, whenever the optimal solutions lead to impractical implementation, the authors discuss sub-optimal approaches of reduced complexity. Relevant literature is chronologically listed at the end of each chapter, thereby providing a valuable bibliography of current techniques.

The binational production has, it is hoped, resulted in a clear and readable English text which should do justice to a very useful and comprehensive treatment by authors known to be active in the field. These two volumes should prove indispensable to all radar engineers.

P. BOWRON

Preface

"Nessuna humana investigazione si pio dimandara vera scienzia s'essa non passa per le matematiche dimonstrazione."

(Leonardo da Vinci, 1452-1519)

In recent years, much interest has centred around the study and application of automatic data processing in radar systems. This has been so because, in traffic control and air defence applications, modern surveillance systems using radar as sensors require rapid and highly accurate data to be subsequently processed.

Location, velocity, manoeuvre and possible identification of each target of interest can be provided by radar data processing (RDP) with an accuracy and reliability greater than that available from a single-look radar report. Furthermore, RDP can enhance the signal-processing function by removing false detections caused, for example, by residual clutter.

Radar data processing applies to both monostatic and bistatic sensors with antenna beams mechanically or electronically scanned. A relevant example of the second type of sensor is the phased-array radar. In this case, the data processor takes part in the scheduling of the radar actions by requiring, for example, more looks in the direction of a sharply manoeuvring target. Today, it is also of practical interest to net several radar systems, sometimes having complementary characteristics, in order to achieve superior performance.

In a single-radar system, the data processing is performed on a digital computer inserted between the plot extractor and immediately before the display. RDP performs its action over a time span of several radar scans while the manipulations involved in the signal processing are carried out over some adjacent radar looks in the same scan. In netted radar, the data-processing function can be concentrated in a main centre or distributed among the different radar sites.

The radar data processor can be defined as the set of algorithms which, when applied to the radar detections acquired during successive scans, allows

- recognition of a pattern of successive detections as pertaining to the same target,
- estimation of the kinematic parameters (position, velocity and acceleration) of a target, thus establishing a so-called 'target track',
- extrapolation of the track parameters,
- distinguishing of different targets and thus establishing a different track for each target,
- distinguishing of false detections (caused by intentional or natural interference) from true targets,
- adaptive refinement of the threshold setting of the signal processor in order to make the radar more or less sensitive in the different spatial directions, depending on the content of a map of false detections refreshed on a scan-to-scan base,
- scheduling of the track dwells of a phased-array radar in order to follow a manoeuvring target with constant accuracy and to interleave in an optimum manner the tracking phases with search looks and other radar functions,
- efficient managing of the detections or the tracks provided by the different radar sets of a netted system looking at the same portion of the controlled space, in order to provide a better picture of the latter.

The aim of this text is to provide a reasonably comprehensive treatment of RDP theory at a level which can be useful to practising radar engineers for analysis and design purposes. The theory developed is corroborated with applications. A whole chapter is dedicated to digital computer simulation of the tracking filters, which are the main components of RDP. Another chapter is devoted to the application of RDP to cases of practical interest in both civilian and military systems.

The relevance and modernity of the topics described ensure that the book can also be used with benefit for specialised undergraduate and graduate courses in Communications and Electronic Engineering at universities and colleges as well as in the so-called "continuing education courses" for graduate employees in industry. It is assumed that the reader is familiar with basic concepts of radar techniques, dynamic system theory, probability and stochastic processes as well as computer programming.

While an abundance of papers has been written on the subject of tracking in the last twenty years, a unified and systematic treatment of the topic is not available in the open literature as far as the authors are aware. It is hoped that this text will help to fill a gap in the literature.

For convenience of handling, the work is divided into two volumes. Volume I introduces radar data processing and reviews the necessary mathematical techniques, leading up to a detailed treatment of tracking. On the other hand, Volume II is more specialised. It concerns netted radar followed by RDP performance evaluation using computer simulation and, finally, examples of application. The first volume thus comprises essential background while the second volume is indispensable to practising radar engineers.

Structurally, the text of Vol. I is divided as follows. The introduction is concerned with the scope of data processing in radar systems. The general structure of RDP and the connections with other subsystems are described in both the mechanically scanned and phased-array radar cases. The benefits of netting several radar systems and the related problems are then presented in a preliminary manner. Consideration is next turned to the tracking filter, which is the heart of radar data processing. There are many forms of possible tracking filters, and the selection of the proper algorithm is usually a compromise between computational resources and operational requirements. Finally, typical applications of radar data processing in Air-Traffic-Control (ATC) and surveillance systems are described.

Because the mathematical tools needed in radar data processing are more familiar to control systems engineers than to radar engineers, the whole of Chapter 2 is devoted to an outline of estimation and filtering theory which represents the best framework in which the tracking algorithms can be derived.

Chapter 3 is devoted to the so-called Track-While-Scan (TWS) system, which is the data processing performed in mechanically scanning radar. The functions performed by a TWS system (track initiation, track formation, correlation logic) are presented and analysed in detail. The α-β algorithm is also described as the first employed to track targets. In addition, the computer organisation of the radar reports and of the processed data is detailed.

The fourth chapter is one of the major parts of the book. Several filtering algorithms can be developed and applied to the different operational conditions which can arise. A flexible algorithm based on the Kalman filtering theory is presented first. This is the foundation for deriving adaptive filters to follow manoeuvring targets and to distinguish a particular target from others in a formation or from false detections. The suite of tracking algorithms is completed with those relevant to active tracking by means of phased-array radar and the employment of radial-velocity measurements. One section is devoted to tracking by means of bistatic radar.

Additional relevant topics, such as netted radar systems, simulation tools and applications are discussed in Volume II. Throughout, further details on any particular topic can be pursued in the references listed, in chronological order, at the end of each chapter.

Alfonso Farina

Flavio A. Studer

December, 1984

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Glossary of Notation

LIST OF ABBREVIATIONS

ARM	Anti-Radiation Missile
ATC	Air Traffic Control
ATCAS	Air Traffic Control Automated System
BITE	Built-In Test Equipment
CFAR	Constant False-Alarm Rate
DBM	Detection of Beginning Manoeuvre
DE	Data Extractor
DEM	Detection of Ending Manoeuvre
FIR	Flight Information Region
IFF	Identification Friend Foe
LMSE	Linear Mean-Square Estimate
LSE	Least-Square Estimate
MLE	Maximum-Likelihood Estimate
MSE	Mean-Square Estimate
MTBF	Mean Time Between Failures
MTD	Moving Target Detector
MTI	Moving Target Indicator
PC	Pulse Compression
PDAF	Probabilistic Data Association Filter
PDP	Pulse Doppler Processing
PPI	Plane Position Indicator
PR	Primary Radar
PRT	Pulse Repetition Time
R	Receiver
RCS	Radar Cross Section
RDP	Radar Data Processing
RF	Radio Frequency
ROC	Receiver Operating Characteristics
SNR	Signal-to-Noise Ratio
SP	Signal Processing
SSC	Scan-to-Scan Correlator

SSR	Secondary Surveillance Radar
STF	Stationary Track Filter
SW	Switch
T	Transmitter
TF	Tracking Filter
TOC	Track Operating Characteristics
TWS	Track-While-Scan
UHF	Ultra High Frequency
VHF	Very High Frequency
WLSE	Weighted Least-Square Estimate

LIST OF THE MAIN SYMBOLS

Chapter 1

$a(t)$	time-varying acceleration value (scalar)
$\underline{\mathbf{F}}$	n×n transition matrix of target model
$\underline{\mathbf{G}}$	n×p matrix of target model
k	discrete time instant
P_D	detection probability
$\underline{\mathbf{s}}$	state vector of target model
T	radar scan period
$\underline{\mathbf{u}}$	forcing vector of target model
$\underline{\mathbf{v}}$	random vector of target model
$\underline{\mathbf{w}}$	random vector of measurement model
x^m, y^m	measured target Cartesian co-ordinates
x^p, y^p	predicted target Cartesian co-ordinates
x^s, y^s	smoothed target Cartesian co-ordinates
$\dot{x}^p$, $\dot{y}^p$	predicted Cartesian components of target speed
$\hat{x}$	estimated x co-ordinate
x_e	error in the estimated x co-ordinate
$\underline{\mathbf{z}}$	vector of measurements
α, β	parameters of tracking filter
ρ	target range
θ	target azimuth angle
ϕ	target elevation angle
ρ_T	target range from the transmitter
ρ_R	target range from the receiver
$\dot{\rho}$	target range rate (Doppler velocity)
σ	standard deviation
$\sigma_{\hat{x}}$	standard deviation of $\hat{x}$
σ_{x_e}	standard deviation of x_e

Chapter 2

$\underline{\mathbf{B}}, \underline{\mathbf{G}}, \underline{\mathbf{H}}, \underline{\mathbf{L}}, \underline{\mathbf{\Phi}}$	matrices in dynamic system models
$E\{.\}$	expectation operator
$E\{\underline{\mathbf{x}}/\underline{\mathbf{z}}\}$	conditional expectation of $\underline{\mathbf{x}}$ given $\underline{\mathbf{z}}$

$\underline{K}_k$	Kalman gain matrix at time k
$\mathbf{P}$	covariance matrix
$\hat{\mathbf{P}}$	estimation covariance matrix
$\hat{\mathbf{P}}_{k/k}, \hat{\mathbf{P}}_{k/k-1}$	covariance matrix of filtered and predicted estimates
$\underline{P}_{xx}$	covariance matrix of $\underline{\mathbf{x}}$
$\underline{\mathbf{P}}_{xz}$	mutual covariance matrix between $\underline{\mathbf{x}}$ and $\underline{\mathbf{z}}$
$\underline{\mathbf{Q}}, \underline{\mathbf{R}}$	covariance matrices of random processes
$\underline{\mathbf{s}}_k$	system state at k-th time instant
$\hat{\underline{\mathbf{s}}}_{k/k}$	filtered estimate of $\underline{\mathbf{s}}_k$
$\hat{\underline{s}}_{k/k-1}$	predicted estimate of $\underline{s}_k$
$\underline{\mathbf{u}}_k, \underline{\mathbf{v}}_k$	samples of noise processes
$\underline{\mathbf{x}}$	unknown vector
$\hat{\underline{\mathbf{x}}}$	estimate of $\underline{\mathbf{x}}$
$\underline{\mathbf{z}}$	vector of measurements
$\underline{\mathbf{Z}}^{(k)}$	collection of measurements up to time k
$\underline{\boldsymbol{\nu}}_k$	innovation process at time k
$\underline{\boldsymbol{\Theta}}_k$	covariance matrix of the innovation
$\Delta_i(\ell, p)$	scalar second derivatives of nonlinear measurement
$\underline{\mathbf{A}}_k$	additional covariance matrix for second-order filter
$\underline{\boldsymbol{\delta}}^2$	second-order term in nonlinear filter approximation

Chapter 3

a_x, a_y, a_ξ, a_η	components of acceleration
$\underline{\mathbf{G}}, \underline{\boldsymbol{\Phi}}$	matrices of the target model
$\underline{\mathbf{H}}$	matrix of the measurement model
k	discrete-time instant
$\underline{K}_k$	Kalman gain matrix
$K_x, K_{\dot{x}}$	components of the Kalman gain for position and speed
K_ρ, K_θ	size of the correlation gate in polar co-ordinates
$\hat{\underline{\mathbf{P}}}_{k/k}, \hat{\underline{\mathbf{P}}}_{k/k-1}$	covariance matrices of the state estimates
$\underline{\mathbf{Q}}, \underline{\mathbf{R}}, \underline{\boldsymbol{\Sigma}}$	noise covariance matrices
r	ratio of measurement noise to acceleration noise
$\hat{\underline{s}}_{k/k}, \hat{\underline{s}}_{k/k-1}$	filtered and predicted state estimates
T	radar scan period
x, y, z	Cartesian co-ordinates
$\underline{\mathbf{w}}$	measurement noise
$\underline{\mathbf{z}}$	vector of measurements
α, β	tracking filter coefficients
$\alpha_{xx}, \alpha_{xy}, \ldots, \beta_{yy}$	two-dimensional filter coefficients
$\underline{\boldsymbol{\nu}}$	plot-to-track displacement
ρ, θ	polar co-ordinates
$\sigma_\rho, \sigma_\theta, \sigma_x, \sigma_y, \sigma_w$	standard deviations of measurements

Chapter 4

a(t)	target acceleration at time t
d	transmitter duty cycle
$\underline{\mathbf{F}}, \underline{\mathbf{G}}$	matrices in dynamic target model
$\underline{\mathbf{H}}$	matrix in the measurement equation
$\underline{\mathbf{K}}_k$	Kalman gain matrix at time k

$\underline{\mathbf{K}}_k$	Kalman gain matrix at time k
$\hat{\underline{\mathbf{P}}}_{k/k}$, $\hat{\underline{\mathbf{P}}}_{k/k-1}$	covariance matrix of filtered and predicted estimates
$\underline{\mathbf{Q}}$, $\underline{\mathbf{R}}$	covariance matrices of random processes
$\hat{\underline{\mathbf{s}}}_{k/k}$	filtered estimate of target state
$\hat{\underline{\mathbf{s}}}_{k/k}^{\ell}$	filtered estimate of target state for the ℓth track history
T	radar scan period
$\underline{\mathbf{u}}_k$	forcing process for the target model
$\underline{\mathbf{w}}_k$	measurement noise
$\underline{\mathbf{z}}_k$	measurement at kth scan
$\underline{\mathbf{Z}}_k$	set of plots at kth scan
$\underline{\mathbf{Z}}^k$	set of all plots up to kth scan
$N(\underline{\mathbf{m}},\underline{\mathbf{\Sigma}})$	Gaussian probability density function, with mean value $\underline{\mathbf{m}}$ and covariance matrix $\underline{\mathbf{\Sigma}}$
α^{-1}	expected time duration of a manoeuvre
γ_k	binary random variable
$\underline{\boldsymbol{\nu}}_k$	vector of statistical innovation at time k
ρ, θ, ϕ	target polar co-ordinates
ρ_B, ρ_T, ρ_R	range measurements in a bistatic system
θ_R	bearing of receiving bistatic beam
τ	pulse duration
$\sigma_\rho, \sigma_\theta, \sigma_{\dot{\rho}}$	standard deviations
$\Omega^{k,\ell}$	ℓth track history up to time k
$\underline{\mathbf{\Theta}}_k$	covariance matrix of statistical innovation
x, y	target Cartesian co-ordinates
$\dot{x}, \dot{y}$	Cartesian components of target velocity
σ_a^2	variance of target acceleration
$\underline{\mathbf{\Phi}}_k$	state transition matrix for target model

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