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Detection, Estimation, and Modulation Theory

Radar-Sonar Processing and

Gaussian Signals in Noise

HARRY L. VAN TREES George Mason University



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To Diane

and Stephen, Mark, Kathleen, Patricia, Eileen, Harry, and Julia

and the next generation— Brittany, Erin, Thomas, Elizabeth, Emily, Dillon, Bryan, Julia, Robert, Margaret, Peter, Emma, Sarah, Harry, Rebecca, and Molly

Preface for Paperback Edition

In 1968, Part I of *Detection, Estimation, and Modulation Theory* [VT68] was published. It turned out to be a reasonably successful book that has been widely used by several generations of engineers. There were thirty printings, but the last printing was in 1996. Volumes II and III ([VT71a], [VT71b]) were published in 1971 and focused on specific application areas such as analog modulation, Gaussian signals and noise, and the radar–sonar problem. Volume II had a short life span due to the shift from analog modulation to digital modulation. Volume III is still widely used as a reference and as a supplementary text. In a moment of youthful optimism, I indicated in the the Preface to Volume III and in Chapter III-14 that a short monograph on optimum array processing would be published in 1971. The bibliography lists it as a reference, *Optimum Array Processing*, Wiley, 1971, which has been subsequently cited by several authors. After a 30-year delay, *Optimum Array Processing*, Part IV of *Detection, Estimation, and Modulation Theory* will be published this year.

A few comments on my career may help explain the long delay. In 1972, MIT loaned me to the Defense Communication Agency in Washington, D.C. where I spent three years as the Chief Scientist and the Associate Director of Technology. At the end of the tour, I decided, for personal reasons, to stay in the Washington, D.C. area. I spent three years as an Assistant Vice-President at COMSAT where my group did the advanced planning for the INTELSAT satellites. In 1978, I became the Chief Scientist of the United States Air Force. In 1979, Dr. Gerald Dinneen, the former Director of Lincoln Laboratories, was serving as Assistant Secretary of Defense for C3I. He asked me to become his Principal Deputy and I spent two years in that position. In 1981, I joined M/A-COM Linkabit. Linkabit is the company that Irwin Jacobs and Andrew Viterbi had started in 1969 and sold to M/A-COM in 1979. I started an Eastern operation which grew to about 200 people in three years. After Irwin and Andy left M/A-COM and started Qualcomm, I was responsible for the government operations in San Diego as well as Washington, D.C. In 1988, M/A-COM sold the division. At that point I decided to return to the academic world.

I joined George Mason University in September of 1988. One of my priorities was to finish the book on optimum array processing. However, I found that I needed to build up a research center in order to attract young research-oriented faculty and

doctoral students. The process took about six years. The Center for Excellence in Command, Control, Communications, and Intelligence has been very successful and has generated over \$300 million in research funding during its existence. During this growth period, I spent some time on array processing but a concentrated effort was not possible. In 1995, I started a serious effort to write the Array Processing book.

Throughout the *Optimum Array Processing* text there are references to Parts I and III of *Detection, Estimation, and Modulation Theory.* The referenced material is available in several other books, but I am most familiar with my own work. Wiley agreed to publish Part I and III in paperback so the material will be readily available. In addition to providing background for Part IV, Part I is still useful as a text for a graduate course in Detection and Estimation Theory. Part III is suitable for a second level graduate course dealing with more specialized topics.

In the 30-year period, there has been a dramatic change in the signal processing area. Advances in computational capability have allowed the implementation of complex algorithms that were only of theoretical interest in the past. In many applications, algorithms can be implemented that reach the theoretical bounds.

The advances in computational capability have also changed how the material is taught. In Parts I and III, there is an emphasis on compact analytical solutions to problems. In Part IV, there is a much greater emphasis on efficient iterative solutions and simulations. All of the material in parts I and III is still relevant. The books use continuous time processes but the transition to discrete time processes is straightforward. Integrals that were difficult to do analytically can be done easily in Matlab[®]. The various detection and estimation algorithms can be simulated and their performance compared to the theoretical bounds. We still use most of the problems in the text but supplement them with problems that require Matlab[®] solutions.

We hope that a new generation of students and readers find these reprinted editions to be useful.

HARRY L. VAN TREES

Fairfax, Virginia June 2001

Preface

In this book I continue the study of detection, estimation, and modulation theory begun in Part I [1]. I assume that the reader is familiar with the background of the overall project that was discussed in the preface of Part I. In the preface to Part II [2] I outlined the revised organization of the material. As I pointed out there, Part III can be read directly after Part I. Thus, some persons will be reading this volume without having seen Part II. Many of the comments in the preface to Part II are also appropriate here, so I shall repeat the pertinent ones.

At the time Part I was published, in January 1968, I had completed the "final" draft for Part II. During the spring term of 1968, I used this draft as a text for an advanced graduate course at M.I.T. and in the summer of 1968, I started to revise the manuscript to incorporate student comments and include some new research results. In September 1968, I became involved in a television project in the Center for Advanced Engineering Study at M.I.T. During this project, I made fifty hours of videotaped lectures on applied probability and random processes for distribution to industry and universities as part of a self-study package. The net result of this involvement was that the revision of the manuscript was not resumed until April 1969. In the intervening period, my students and I had obtained more research results that I felt should be included. As I began the final revision, two observations were apparent. The first observation was that the manuscript has become so large that it was economically impractical to publish it as a single volume. The second observation was that since I was treating four major topics in detail, it was unlikely that many readers would actually use all of the book. Because several of the topics can be studied independently, with only Part I as background, I decided to divide the material into three sections: Part II, Part III, and a short monograph on Optimum Array Processing [3]. This division involved some further editing, but I felt it was warranted in view of increased flexibility it gives both readers and instructors.

x Preface

In Part II, I treated nonlinear modulation theory. In this part, I treat the random signal problem and radar/sonar. Finally, in the monograph, I discuss optimum array processing. The interdependence of the various parts is shown graphically in the following table. It can be seen that Part II is completely separate from Part III and *Optimum Array Processing*. The first half of *Optimum Array Processing* can be studied directly after Part I, but the second half requires some background from Part III. Although the division of the material has several advantages, it has one major disadvantage. One of my primary objectives is to present a unified treatment that enables the reader to solve problems from widely diverse physical situations. Unless the reader sees the widespread applicability of the basic ideas he may fail to appreciate their importance. Thus, I strongly encourage all serious students to read at least the more basic results in all three parts.

	Prerequisites
Part II	Chaps. I-5, I-6
Part III Chaps. III-1 to III-5 Chaps. III-6 to III-7 Chaps. III-8-end	Chaps. I-4, I-6 Chaps. I-4 Chaps. I-4, I-6, III-1 to III-7
Array Processing Chaps. IV-1, IV-2 Chaps. IV-3-end	Chaps. I-4 Chaps. III-1 to III-5, AP-1 to AP-2

The character of this book is appreciably different that that of Part I. It can perhaps be best described as a mixture of a research monograph and a graduate level text. It has the characteristics of a research monograph in that it studies particular questions in detail and develops a number of new research results in the course of this study. In many cases it explores topics which are still subjects of active research and is forced to leave some questions unanswered. It has the characteristics of a graduate level text in that it presents the material in an orderly fashion and develops almost all of the necessary results internally.

The book should appeal to three classes of readers. The first class consists of graduate students. The random signal problem, discussed in Chapters 2 to 7, is a logical extension of our earlier work with deterministic signals and completes the hierarchy of problems we set out to solve. The last half of the book studies the radar/sonar problem and some facets of the digital communication problem in detail. It is a thorough study of how one applies statistical theory to an important problem area. I feel that it provides a useful educational experience, even for students who have no ultimate interest in radar, sonar, or communications, because it demonstrates system design techniques which will be useful in other fields.

The second class consists of researchers in this field. Within the areas studied, the results are close to the current research frontiers. In many places, specific research problems are suggested that are suitable for thesis or industrial research.

The third class consists of practicing engineers. In the course of the development, a number of problems of system design and analysis are carried out. The techniques used and results obtained are directly applicable to many current problems. The material is in a form that is suitable for presentation in a short course or industrial course for practicing engineers. I have used preliminary versions in such courses for several years.

The problems deserve some mention. As in Part I, there are a large number of problems because I feel that problem solving is an essential part of the learning process. The problems cover a wide range of difficulty and arc designed to both augment and extend the discussion in the text. Some of the problems require outside reading, or require the use of engineering judgement to make approximations or ask for discussion of some issues. These problems are sometimes frustrating to the student but I feel that they serve a useful purpose. In a few of the problems I had to use numerical calculations to get the answer. I strongly urge instructors to work a particular problem before assigning it. Solutions to the problems will be available in the near future.

As in Part I, I have tried to make the notation mnemonic. All of the notation is summarized in the glossary at the end of the book. I have tried to make my list of references as complete as possible and acknowledge any ideas due to other people.

Several people have contributed to the development of this book. Professors Arthur Baggeroer, Estil Hoversten, and Donald Snyder of the M.I.T. faculty, and Lewis Collins of Lincoln Laboratory, carefully read and criticized the entire book. Their suggestions were invaluable. R. R. Kurth read several chapters and offered useful suggestions. A number of graduate students offered comments which improved the text. My secretary, Miss Camille Tortorici, typed the entire manuscript several times.

My research at M.I.T. was partly supported by the Joint Services and by the National Aeronautics and Space Administration under the auspices of the Research Laboratory of Electronics. I did the final editing xii Preface

while on Sabbatical Leave at Trinity College, Dublin. Professor Brendan Scaife of the Engineering School provided me office facilities during this period, and M.I.T. provided financial assistance. I am thankful for all of the above support.

Dublin, Ireland,

Harry L. Van Trees

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- [3] Harry L. Van Trees, Optimum Array Processing, Wiley, New York, 1971.

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Contents

1	Intr	oducti	on	1		
	1.1	Review	w of Parts I and II	1		
	1.2	Rando	om Signals in Noise	3		
	1.3	Signal Processing in Radar-Sonar Systems				
	Refe	erences		7		
2	Dei	ection	n of Gaussian Signals in White Gaussian Noise	8		
	2.1	Optim	num Receivers	9		
		2.1.1	Canonical Realization No. 1: Estimator-Correlator	15		
		2.1.2	Canonical Realization No. 2: Filter-Correlator			
			Receiver	16		
		2.1.3	Canonical Realization No. 3: Filter-Squarer-Inte-			
			grator (FSI) Receiver	17		
		2.1.4				
			Filter Receiver	19		
		2.1.5				
			ization	23		
		2.1.6	Summary: Receiver Structures	31		
	2.2	Perfor	rmance	32		
		2.2.1	Closed-form Expression for $\mu(s)$	35		
			Approximate Error Expressions	38		
		2.2.3	An Alternative Expression for $\mu_R(s)$	42		
		2.2.4	51 5	44		
	2.3		nary: Simple Binary Detection	46		
	2.4	Probl	ems	48		
	Ref	erences		54		

xiii

Gen	neral Binary Detection: Gaussian Processes	56
3.1	Model and Problem Classification	56
3.2	Receiver Structures	59
	3.2.1 Whitening Approach	59
	3.2.2 Various Implementations of the Likelihood Ra	tio
	Test	61
	3.2.3 Summary: Receiver Structures	65
3.3	Performance	66
3.4	Four Special Situations	68
	3.4.1 Binary Symmetric Case	69
	3.4.2 Non-zero Means	72
	3.4.3 Stationary "Carrier-symmetric" Bandpass Proble	ms 74
	3.4.4 Error Probability for the Binary Symmetric Bar	
	pass Problem	77
3.5	General Binary Case: White Noise Not Necessarily Pr	·es-
	ent: Singular Tests	79
	3.5.1 Receiver Derivation	80
	3.5.2 Performance: General Binary Case	82
	3.5.3 Singularity	83
3.6	Summary: General Binary Problem	88
3.7	Problems	90
Ref	erences	97

4.1	Stationary Processes: Long Observation Time	99
	4.1.1 Simple Binary Problem	100
	4.1.2 General Binary Problem	110
	4.1.3 Summary: SPLOT Problem	119
4.2	Separable Kernels	119
	4.2.1 Separable Kernel Model	120
	4.2.2 Time Diversity	122
	4.2.3 Frequency Diversity	126
	4.2.4 Summary: Separable Kernels	130
4.3	Low-Energy-Coherence (LEC) Case	131
4.4	Summary	137
4.5	Problems	137
Ref	erences	145

Disc	cussio	n: Detection of Gaussian Signals	147
5.1	Relate	ed Topics	147
	5.1.1	M-ary Detection: Gaussian Signals in Noise	147
	5.1.2	Suboptimum Receivers	151
	5.1.3	Adaptive Receivers	155
	5.1.4	Non-Gaussian Processes	156
	5.1.5	Vector Gaussian Processes	157
5.2	Summ	nary of Detection Theory	157
5.3	Probl	ems	159
Refe	erences		164

6.1	Parameter Estimation Model	168
6.2	Estimator Structure	170
	6.2.1 Derivation of the Likelihood Function	170
	6.2.2 Maximum Likelihood and Maximum A-Pos	steriori
	Probability Equations	175
6.3	Performance Analysis	177
	6.3.1 A Lower Bound on the Variance	177
	6.3.2 Calculation of $J^{(2)}(A)$	179
	6.3.3 Lower Bound on the Mean-Square Error	183
	6.3.4 Improved Performance Bounds	183
6.4	Summary	184
6.5	Problems	185
Refe	erences	186
2		
Spe	ecial Categories of Estimation Problems	188
i		

1.1	Statio	hary rocesses. Long Observation rime	100
	7.1.1	General Results	189
	7.1.2	Performance of Truncated Estimates	194
	7.1.3	Suboptimum Receivers	205
	7.1.4	Summary	208
7.2	Finite	e-State Processes	209
7.3	3 Separable Kernels		211
7.4	Low-	Energy-Coherence Case	213

xvi Contents

7.5	Related Topics		217
	7.5.1	Multiple-Parameter Estimation	217
	7.5.2	Composite-Hypothesis Tests	219
7.6	Sumn	nary of Estimation Theory	220
7.7	Probl	ems	221
Refe	erences		232

8 The Radar-sonar Problem

Rej	ferences

234 237

9	De	tectio	n of Slowly Fluctuating Point Targets	238
	9.1	Mode	l of a Slowly Fluctuating Point Target	238
	9.2		Bandpass Noise	244
	9.3	Color	ed Bandpass Noise	247
	9.4	Color	ed Noise with a Finite State Representation	251
		9.4.1	Differential-equation Representation of the Opti-	
			mum Receiver and Its Performance: I	252
		9.4.2	Differential-equation Representation of the Opti-	
			mum Receiver and Its Performance: II	253
	9.5	Optin	nal Signal Design	258
	9.6	Sumn	nary and Related Issues	260
	9.7	Probl	ems	263
	Refe	erences		273

10	Para Targ	meter Estimation: Slowly Fluctuating Point ets	275
	10.1	Receiver Derivation and Signal Design	275
	10.2	Performance of the Optimum Estimator	294
		10.2.1 Local Accuracy	294
		10.2.2 Global Accuracy (or Ambiguity)	302
		10.2.3 Summary	307
	10.3	Properties of Time-Frequency Autocorrelation Func-	
		tions and Ambiguity Functions	308

Contents	xvii
Contents	λνιι

	10.4	Coded	Pulse Sequences	313
		10.4.1	On-off Sequences	313
		10.4.2	Constant Power, Amplitude-modulated Wave-	
			forms	314
		10.4.3	Other Coded Sequences	323
	10.5	Resolut	tion	323
		10.5.1	Resolution in a Discrete Environment: Model	324
		10.5.2	Conventional Receivers	326
		10.5.3	Optimum Receiver: Discrete Resolution Prob-	
			lem	329
		10.5.4	Summary of Resolution Results	335
	10.6	Summa	ary and Related Topics	336
		10.6.1	Summary	336
		10.6.2	Related Topics	337
	10.7	Problem	ms	340
	Refer	ences		352
	2			
11	Dop	pler-S	pread Targets and Channels	357
	11.1	Model	for Doppler-Spread Target (or Channel)	360
	11.2		ion of Doppler-Spread Targets	365
			Likelihood Ratio Test	366
		11.2.2	Canonical Receiver Realizations	367
		11.2.3	Performance of the Optimum Receiver	370
			Classes of Processes	372
		11.2.5	Summary	375
	11.3		unication Over Doppler-Spread Channels	375
		11.3.1		
			Receiver and Performance	376
		11.3.2	Performance Bounds for Optimized Binary	
			Systems	378
		11.3.3		385
		11.3.4	-	396
		11.3.5		
			spread Channels	397

11.4	Parameter Estimation: Doppler-Spread Targets	398
11.5	Summary: Doppler-Spread Targets and Channels	401
	Problems	402
References		411

xviii Contents

12	Rang	ge-Spre	ead Targets and Channels	413
	12.1	Model	and Intuitive Discussion	415
	12.2	Detecti	ion of Range-Spread Targets	419
	12.3		Frequency Duality	421
		12.3.1	Basic Duality Concepts	422
		12.3.2	Dual Targets and Channels	424
		12.3.3	Applications	427
	12.4	Summa	ary: Range-Spread Targets	437
	12.5	Problem	ms	438
	Refer	ences		443
13	Dou	bly-Spi	read Targets and Channels	444
	13.1		for a Doubly-Spread Target	446
		13.1.1	Basic Model	446
		13.1.2	Differential-Equation Model for a Doubly-	
			Spread Target (or Channel)	454
		13.1.3	Model Summary	459
	13.2	Detecti	on in the Presence of Reverberation or Clutter	
		(Resolu	ution in a Dense Environment)	459
		13.2.1	Conventional Receiver	461
		13.2.2	Optimum Receivers	472
		13.2.3	Summary of the Reverberation Problem	480
	13.3 Detection of Doubly-Spread Targets and Commun			
		tion ov	er Doubly-Spread Channels	482
		13.3.1	Problem Formulation	482
		13.3.2	Approximate Models for Doubly-Spread Tar-	
			gets and Doubly-Spread Channels	487
		13.3.3	Binary Communication over Doubly-Spread	
			Channels	502
		13.3.4	Detection under LEC Conditions	516
		13.3.5	Related Topics	521
		13.3.6	Summary of Detection of Doubly-Spread	
			Signals	525
	13.4	Parame	eter Estimation for Doubly-Spread Targets	525
		13.4.1		527
			Amplitude Estimation	530
		13.4.3	Estimation of Mean Range and Doppler	533
		13.4.4	Summary	536

		Contents	xix
	13.5 -13.6 <i>Refer</i>	Problems	536 538 553
14	Disc	ussion	558
	14.1 14.2 14.3 <i>Refer</i>	Epilogue	558 563 564 564
	Appe	ndix: Complex Representation of Bandpass Signals, Systems, and Processes	565
	A.1 A.2 A.3	 Bandpass Linear Systems A.2.1 Time-Invariant Systems A.2.2 Time-Varying Systems A.2.3 State-Variable Systems Bandpass Random Processes A.3.1 Stationary Processes A.3.2 Nonstationary Processes 	566 572 572 574 574 576 576 576
	A.4 A.5 Refer	A.3.3 Complex Finite-State Processes Summary Problems rences	589 598 598 603
	Glossary		605
	Auth	or Index	619
	Subje	ect Index	623

Accuracy, local, 294 global, 302 Ambiguity function, cross, 339, 350, 481 definition, 279 Doppler-spread, 400, 409 examples, 280, 283, 285, 292, 308 generalized spread, 401 ideal, 282 properties, 290, 341 reverberation problem, 462 Amplitude estimation, doubly-spread targets, 530 spectrum, 191, 204, 211, 214 Array processing, 563 Asymptotic results, 112 Autocorrelation function, time-frequency, 279

Bandlimited spectrum, 108, 116

Bandpass detection problems, 74, 77 Barker codes, 316 Bayes test, 10 Bernoulli sequences, 319 Bhattacharyya distance, 180 Binary communication, 69, 74, 79, 111, 375, 484 Binary detection, simple, 8, 100, 244, 366, 419,482 general, 56, 80, 110 Binary FSK, 377 Binary symmetric detection problem, 68 Bound, Barankin, 184 bias, 198 binary error probability, 380 Chernoff, 153 ellipses, 298 error, 160

mean-square error, 183, 201 performance of suboptimum receivers, 390 variance, 177 Butterworth spectrum, 104

Canonical receiver realizations, Dopplerspread targets, 367 No. 1, Estimator-Correlator, 15 No. 2, Filter-Correlator, 16 No. 3, Filter-squarer-integrator, 17 No. 4, Optimum realizable filter, 19 No. 4S, State-variable realization, 23 Characterizations, doubly-spread targets, 451 point targets, 238 Channels, Doppler-spread, 375 dual, 424 equivalent, 522 multiplicative, 26 Nakagami, 243 range-spread, 413 Rayleigh, slowly-fluctuating, 238 Rician, 243 tapped-delay line models, 488 Chernoff bounds, 153 Classification, of Gaussian detection problems, 57 Coded pulse sequences, 283, 313, 344 Colored bandpass noise, detection in, 247, 267, 329 Comb filters, 264 Communication, binary, 69, 74, 79, 111, 375, 484 Doppler-spread channels, 375, 406 doubly-spread channels, 482 M-ary, 396, 523

624

range-spread channels, 432 Complex, envelope, 569 finite-state processes, 589 Gaussian random variable, 584 Gaussian processes, 583 representation, linear systems, 572 random processes, 576, 600 signals, 566, 598 state-variables, 574 sufficient statistic, 244 white processes, 582 Composite, hypothesis tests, 219 signals, 73 Correlator, 121, 245

Delay-spread targets, 412

Detection, binary, 8, 100, 244, 366, 419, 482 Gaussian signals in white noise, 8 M-ary, 147, 159 range-spread targets, 419, 438 stationary processes, 99 target with unknown parameters, 339 vector processes, 52, 91 Differential equation, 252, 253 model for doubly-spread target, 454 Discrete resolution, 323, 324, 346 Dispersive targets, 413 Distributed state-variables, 454, 473 Diversity, explicit, 381 eigenvalue, 117 frequency, 126 implicit, 381 minimum, 510 optimum, 130, 381, 510 system, 510 time, 122 Doppler estimation, 275 Doppler shift, 241 Doppler-spread channels, 375 Doppler-spread targets, 357 optimum receivers, 367 state-variable model, 365 Doubly-spread targets, 444 Dual channels, 424 Dual targets, 424 Duality, applications, 428 concepts, 422 time-frequency, 421

Edgeworth series, 39

Efficiency factor, 115, 118 Equivalent channels, 522 Error expressions, approximate, 38 Estimates, truncated, 194 Estimation, amplitude, 191, 204, 211, 214, 530 Doppler, 275 mean Doppler, 533 mean range, 533 parameters of process, 167, 188 range, 275 velocity, 275 Estimator-correlator, Class B_w, 65 simple binary, 15, 101

Fading, frequency-selective, 415 time-selective, 357 Feedback shift register, 319, 345

Filter-squarer receiver, Class B_W, 65 parameter estimation, SPLOT, 189 parameter estimation, 174, 278 simple binary, 17, 246, 249, 367 suboptimum, 154, 390
Filters, mismatched, 338
Finite-state processes, 209, 227, 251, 270, 372, 389
Fredholm, determinant, 23, 71, 150, 154, 371, 391, 396
Frequency-selective fading, 415
Frequency-spread targets, 357
Functional square root, 18

Gaussian, processes, 8, 56, 99, 147 pulse, 283, 290

Hermite polynomials,343

Information matrix, 295 Inverse kernels, 11

Kernels, inverse, 11 separable, 119, 373

Lagrange multipliers, 259

Laguerre polynomials, 343 Large time-bandwidth signals, 339 Likelihood function, 170, 399, 529 Likelihood ratio test, 10, 61, 81, 245, 366, 483 Linear frequency modulation, 290, 292, 466

Local accuracy, 294 Low-energy-choerence (LEC), 131, 213, 373, 431, 516

Matched filter, 121, 245 Maximum likelihood equations, 175 M-ary systems, 396, 523 Mean-square bandwidth, 290, 571 Mean-square duration, 290, 571 MMSE realizable estimate, 24, 103, 183, 369, 483 Moment-generating functions, 34 Multipath, resoluable, 128, 431 Multiple-parameters, 217, 230

Non-Gaussian processes, 156

On-off sequences, 313 Optimal signal design, 258 Optimum linear filters, complex processes, 595 Orthogonal series model, 495 Overspread, channels, 504 targets, 453

Parameter estimation, 167, 188 Doppler-spread targets, 398, 409 doubly-spread targets, 525 finite-state processes, 209, 227 generalized sets, 337 low-energy coherence, 213, 229, 527 range-spread targets, 436 separable kernels, 211, 228 SPLOT, 188, 221 Performance, approximations, 38, 82 bounds, 79, 153, 380, 502 detection of Doppler-spread targets, 370, 380 detection of point target in white noise, 246 general binary, 66, 82, 92 LEC conditions, 136 M-ary, 151 parameter estimation, 177, 194, 294, 400, 436, 531 reverberation, 461 simple binary, 32 typical system, 44 white noise, 32 Phasor diagram, 565

Processes, complex finite-state, 369, 428, 589 complex Gaussian, 360, 415, 446, 583 conditionally Gaussian, 169 finite-state, 209, 227, 251, 369, 428, 589 Gaussian, 8, 56, 99, 147 non-Gaussian, 156 vector, 52, 91, 141, 145, 157, 185, 224 Pseudo-random sequences, 321 Radar, model, 234 Radar uncertainty principle, 309 Radiometer, two-filter, 421 Range estimation, 275 Range-scattering function, 416 Range-spread targets, 413 Rayleigh, channel, 118 Realization, canonical receiver, 15, 16, 17, 19 parallel processing, 63 Receivers, adaptive, 155 conventional, 326, 461 optimum, 9, 63, 65, 101, 102, 103, 109, 114, 245, 278, 367, 421, 430, 431, 477, 493 optimum for discrete resolution, 329 optimum in reverberation, 472 optimum LEC, 135, 421, 519 suboptimum, 151, 162, 205, 263, 385, 433, 519 Resolution, dense, 459 discrete, 323, 346 Reverberation, 459, 539 Reverberation scattering function, 461

Scattering function, Doppler, 361, 382 doubly-spread, 448, 458, 462 range, 416, 438 range-invariant, 465 Separable kernels, 119, 211, 373 Shift-register sequences, 318 Signal design, optimal, 258, 270 Singular tests, 79, 83 Sonar, model, 235 Special situations, 68 SPLOT case, 99, 188, 372 State-variable representation, complex, 251, 574,589 distributed, 454, 473, 495 ordinary, 23, 42, 209, 227 Suboptimum receivers, 151, 162, 205, 263, 385, 433, 519

Summary, detection of point targets, 260 detection theory, 137, 157 discrete resolution, 335 doubly-spread targets and channels, 536 estimation theory, 184, 220 general binary, 88 range-Doppler estimation, 326 range-spread targets, 437 receiver structures, 31 simple binary detection, 46

Tapped-delay models, 487

Targets, degenerate, 452 Doppler spread, 357 doubly-spread, 444 dual, 424 range-spread, 413 slowly-fluctuating point, 238 overspread, 453 underspread, 453 Tests, composite-hypothesis, 219 likelihood ratio, 10, 61, 81, 245, 366, 483 singular, 79 Tilted variables, 38 Time compression, 241 Time-frequency, autocorrelation function, 279 duality, 421, 439 Time-selective fading, 357 Two-filter radiometer, 421 Two-frequency correlation function, 417

Underspread, channels, 503 targets, 453

Vector processes, 157 Volume invariance, 308

White bandpass noise, 244, 263 Whitening, approach, 59 filters, 59, 254

626