

# Contents

1.1 History and Applications of Radar	1
1.2 Basic Radar Functions	3
1.3 Elements of a Pulsed Radar	6
1.3.1 Transmitter and waveform generator	7
1.3.2 Antennas	10
1.3.3 Receivers	16
1.4 Review of Selected Signal Processing Concepts and Operations	21
1.4.1 Resolution	21
1.4.2 Spatial frequency	23
1.4.3 Fourier transforms	24
1.4.4 The sampling theorem and spectrum replication	27
1.4.5 Vector representation of signals	32
1.4.6 Data integration	33
1.4.7 Correlation	35
1.5 A Preview of Basic Radar Signal Processing	37
1.5.1 Radar time scales	39
1.5.2 Phenomenology	40
1.5.3 Signal conditioning and interference suppression	41
1.5.4 Imaging	45
1.5.5 Detection	47
1.5.6 Postprocessing	49
1.6 Radar Literature	49
1.6.1 Radar systems and components	50
1.6.2 Radar signal processing	50
1.6.3 Advanced radar signal processing	50
1.6.4 Current radar research	51
References	51
<b>Chapter 2. Signal Models</b>	<b>53</b>
2.1 Components of a Radar Signal	53
2.2 Amplitude Models	54

2.2.1 Simple point target radar range equation	54
2.2.2 Distributed target forms of the range equation	57
2.2.3 Radar cross section	64
2.2.4 Radar cross section for meteorological targets	66
2.2.5 Statistical description of radar cross section	67
2.2.6 Swerling models	79
<b>2.3 Clutter</b>	<b>82</b>
2.3.1 Behavior of $\sigma^0$	83
2.3.2 Signal-to-clutter ratio	84
2.3.3 Temporal and spatial correlation of clutter	85
2.3.4 Compound models of radar cross section	86
<b>2.4 Noise Model and Signal-to-Noise Ratio</b>	<b>88</b>
<b>2.5 Jamming</b>	<b>92</b>
<b>2.6 Frequency Models: The Doppler Shift</b>	<b>92</b>
2.6.1 Doppler shift	92
2.6.2 Simplified approach to Doppler shift	95
2.6.3 The “stop-and-hop” assumption and spatial Doppler	97
<b>2.7 Spatial Models</b>	<b>100</b>
2.7.1 Variation with angle or cross-range	103
2.7.2 Variation with range	106
2.7.3 Projections	107
2.7.4 Multipath	108
<b>2.8 Spectral Model</b>	<b>109</b>
<b>2.9 Summary</b>	<b>111</b>
References	112
 <b>Chapter 3. Sampling and Quantization of Pulsed Radar Signals</b>	 <b>115</b>
<b>3.1 Domains and Criteria for Sampling Radar Signals</b>	<b>115</b>
3.1.1 Time and frequency samples	116
3.1.2 Spatial samples	118
3.1.3 Sampling criteria	119
<b>3.2 Sampling in the Fast Time Dimension</b>	<b>121</b>
<b>3.3 Sampling in Slow Time: Selecting the Pulse Repetition Interval</b>	<b>123</b>
<b>3.4 Sampling the Doppler Spectrum</b>	<b>128</b>
3.4.1 The Nyquist rate in Doppler	129
3.4.2 Straddle loss	131
<b>3.5 Sampling in the Spatial and Angle Dimensions</b>	<b>136</b>
3.5.1 Phased array element spacing	137
3.5.2 Antenna beam spacing	138
<b>3.6 Quantization</b>	<b>140</b>
<b>3.7 I/Q Imbalance and Digital I/Q</b>	<b>145</b>
3.7.1 I/Q imbalance and offset	145
3.7.2 Correcting I/Q errors	149
3.7.3 Digital I/Q	152
References	157
 <b>Chapter 4. Radar Waveforms</b>	 <b>159</b>
<b>4.1 Introduction</b>	<b>159</b>
<b>4.2 The Waveform Matched Filter</b>	<b>161</b>
4.2.1 The matched filter	161

4.2.2	Matched filter for the simple pulse	163
4.2.3	All-range matched filtering	165
4.2.4	Range resolution of the matched filter	166
4.3	Matched Filtering of Moving Targets	167
4.4	The Ambiguity Function	169
4.4.1	Definition and properties of the ambiguity function	169
4.4.2	Ambiguity function of the simple pulse	173
4.5	The Pulse Burst Waveform	176
4.5.1	Matched filter for the pulse burst waveform	177
4.5.2	Pulse-by-pulse processing	178
4.5.3	Range ambiguity	180
4.5.4	Doppler response of the pulse burst waveform	181
4.5.5	Ambiguity function for the pulse burst waveform	183
4.5.6	Relation of slow-time spectrum to ambiguity function	187
4.6	Frequency-Modulated Pulse Compression Waveforms	188
4.6.1	Linear frequency modulation	188
4.6.2	The principle of stationary phase	192
4.6.3	Ambiguity function of the LFM waveform	194
4.6.4	Range-Doppler coupling	197
4.6.5	Stretch processing	198
4.7	Range Side Lobe Control for FM Waveforms	201
4.7.1	Matched filter frequency response shaping	202
4.7.2	Waveform spectrum shaping	204
4.8	The Stepped Frequency Waveform	206
4.9	Phase-Modulated Pulse Compression Waveforms	211
4.9.1	Biphase codes	212
4.9.2	Polyphase codes	218
4.10	Costas Frequency Codes	222
	References	223

## Chapter 5. Doppler Processing

5.1	Alternate Forms of the Doppler Spectrum	226
5.2	Moving Target Indication (MTI)	228
5.2.1	Pulse cancellers	230
5.2.2	Vector formulation of the matched filter	234
5.2.3	Matched filters for clutter suppression	235
5.2.4	Blind speeds and staggered PRFs	239
5.2.5	MTI figures of merit	244
5.2.6	Limitations to MTI performance	251
5.3	Pulse Doppler Processing	253
5.3.1	The discrete time Fourier transform of a moving target	255
5.3.2	Sampling the DTFT: the discrete Fourier transform	258
5.3.3	Matched filter and filterbank interpretations of pulse Doppler processing with the DFT	261
5.3.4	Fine Doppler estimation	264
5.3.5	Modern spectral estimation in pulse Doppler processing	270
5.3.6	Dwell-to-dwell stagger	272
5.4	Pulse Pair Processing	273
5.5	Additional Doppler Processing Issues	279
5.5.1	Combined MTI and pulse Doppler processing	279
5.5.2	Transient effects	279
5.5.3	PRF Regimes and Ambiguity Resolution	280

5.6 Clutter Mapping and the Moving Target Detector	284
5.6.1 Clutter mapping	284
5.6.2 The moving target detector	286
5.7 MTI for Moving Platforms: Adaptive Displaced Phase Center Antenna Processing	287
5.7.1 The DPCA concept	287
5.7.2 Adaptive DPCA	289
References	293
<b>Chapter 6. Detection Fundamentals</b>	<b>295</b>
6.1 Radar Detection as Hypothesis Testing	296
6.1.1 The Neyman-Pearson detection rule	297
6.1.2 The likelihood ratio test	298
6.2 Threshold Detection in Coherent Systems	308
6.2.1 The Gaussian case for coherent receivers	308
6.2.2 Unknown parameters and threshold detection	312
6.2.3 Linear and square-law detectors	319
6.2.4 Other unknown parameters	319
6.3 Threshold Detection of Radar Signals	321
6.3.1 Coherent, noncoherent, and binary integration	322
6.3.2 Nonfluctuating targets	324
6.3.3 Albersheim's equation	329
6.3.4 Fluctuating targets	331
6.3.5 Shnidman's equation	336
6.4 Binary integration	338
6.5 Useful Numerical Approximations	342
6.5.1 Approximations to the error function	342
6.5.2 Approximations to the magnitude function	344
References	345
<b>Chapter 7. Constant False Alarm Rate (CFAR) Detection</b>	<b>347</b>
7.1 The Effect of Unknown Interference Power on False Alarm Probability	347
7.2 Cell-Averaging CFAR	349
7.2.1 The effect of varying $P_{FA}$	349
7.2.2 The cell-averaging CFAR concept	350
7.2.3 CFAR reference windows	352
7.3 Analysis of Cell-Averaging CFAR	353
7.3.1 Derivation of CA CFAR threshold	353
7.3.2 Cell-averaging CFAR performance	354
7.3.3 CFAR loss	357
7.4 CA CFAR Limitations	358
7.4.1 Target masking	359
7.4.2 Clutter edges	363
7.5 Extensions to Cell-Averaging CFAR	364
7.6 Order Statistic CFAR	370
7.7 Additional CFAR Topics	374
7.7.1 Adaptive CFAR	374
7.7.2 Two-parameter CFAR	375
7.7.3 Clutter map CFAR	377
7.7.4 Distribution-free CFAR	379
7.7.5 System-level control of false alarms	381
References	382

<b>Chapter 8. Introduction to Synthetic Aperture Imaging</b>	<b>385</b>
<b>8.1 Introduction to SAR Fundamentals</b>	<b>390</b>
8.1.1 Cross-range resolution in radar	390
8.1.2 The synthetic aperture viewpoint	392
8.1.3 Doppler viewpoint	399
8.1.4 SAR coverage and sampling	401
<b>8.2 Stripmap SAR Data Characteristics</b>	<b>404</b>
8.2.1 Stripmap SAR Geometry	404
8.2.2 Stripmap SAR data set	407
<b>8.3 Stripmap SAR Image Formation Algorithms</b>	<b>410</b>
8.3.1 Doppler beam sharpening	411
8.3.2 Quadratic phase error effects	416
8.3.3 Range-Doppler algorithms	421
8.3.4 Depth of focus	426
<b>8.4 Spotlight SAR Data Characteristics</b>	<b>428</b>
<b>8.5 The Polar Format Image Formation Algorithm for Spotlight SAR</b>	<b>433</b>
<b>8.6 Interferometric SAR</b>	<b>436</b>
8.6.1 The effect of height on a SAR image	436
8.6.2 IFSAR processing steps	439
<b>8.7 Other Considerations</b>	<b>444</b>
8.7.1 Motion compensation and autofocus	444
8.7.2 Autofocus	447
8.7.3 Speckle reduction	455
<b>References</b>	<b>458</b>
<b>Chapter 9. Introduction to Beamforming and Space-Time Adaptive Processing</b>	<b>461</b>
<b>9.1 Spatial Filtering</b>	<b>461</b>
9.1.1 Conventional beamforming	461
9.1.2 Adaptive beamforming	465
9.1.3 Adaptive beamforming with preprocessing	469
<b>9.2 Space-Time Signal Environment</b>	<b>471</b>
<b>9.3 Space-Time Signal Modeling</b>	<b>475</b>
<b>9.4 Processing the Space-Time Signal</b>	<b>479</b>
9.4.1 Optimum matched filtering	479
9.4.2 STAP metrics	480
9.4.3 Relation to displaced phase center antenna processing	484
9.4.4 Adaptive matched filtering	488
<b>9.5 Computational Issues in STAP</b>	<b>491</b>
9.5.1 Power domain solution	492
9.5.2 Computational load of the power domain solution	493
9.5.3 Voltage domain solution and computational load	495
9.5.4 Conversion to computational rates	496
<b>9.6 Reduced-Dimension STAP</b>	<b>497</b>
<b>9.7 Advanced STAP Algorithms and Analysis</b>	<b>499</b>
<b>9.8 Limitations to STAP</b>	<b>501</b>
<b>References</b>	<b>502</b>