CONTENTS

Preface to the Second Edition Preface to the First Edition		xix	
		xxi	
1	1 Introduction and Historical Review		1
	1.1	Applications of Radio Interferometry 1	
	1.2	Basic Terms and Definitions 3	
		Cosmic Signals 3	
		Source Positions and Nomenclature 9	
		Reception of Cosmic Signals 10	
	1.3	Development of Radio Interferometry 12	
		Evolution of Synthesis Techniques 12	
		Michelson Interferometer 13	
		Early Two-Element Radio Interferometers 16	
		Sea Interferometer 18	
		Phase-Switching Interferometer 18	
		Optical Identifications and Calibration Sources 21	
		Early Measurements of Angular Width 21	
		Survey Interferometers and the Mills Cross 24	
		Centimeter-Wavelength Solar Mapping 26	
		Measurements of Intensity Profiles 27	
		Spectral Line Interferometry 28	
		Earth-Rotation Synthesis Mapping 28	
		Development of Synthesis Arrays 31	
		Very-Long-Baseline Interferometry 33	
		VLBI Using Orbiting Antennas 37	
	1.4	Quantum Effect 39	
2	Introd	uctory Theory of Interferometry and Synthesis Imaging	50

- 2.1 Planar Analysis 50
- 2.2 Effect of Bandwidth 53

2.3	One-Dimensional Source Synthesis 57	
	Interferometer Response as a Convolution 58	
	Convolution Theorem and Spatial Frequency 60	
2.4	Example of One-Dimensional Synthesis 61	
2.4	Two-Dimensional Synthesis 64	
	Projection-Slice Theorem 65	
3 Analys	is of the Interferometer Response	
3.1	Fourier Transform Relationship between Intensity and	
	Visibility 68	
3.2	Cross-Correlation and the Wiener–Khinchin Relation 77	
3.3	Basic Response of the Receiving System 78	
	Antennas 78	
	Filters 79	
	Correlator 80	
	Response to the Incident Radiation 80	
Appendix 3.1	Mathematical Representation of Noise-Like Signals 82	
	Analytic Signal 82	
	Truncated Function 84	
4 Geometric Relationships and Polarimetry		
4.1	Antenna Spacing Coordinates and (u, v) Loci 86	
4.2	(u', v') Plane 90	
4.3	Fringe Frequency 91	
4.4	Visibility Frequencies 92	
4.5	Calibration of the Baseline 93	
4.6	Antenna Mounts 94	
4.7	Beamwidth and Beam-Shape Effects 96	
4.8	Polarimetry 97	
	Parameters Defining Polarization 97	
	Antenna Polarization Ellipse 99	
	Stokes Visibilities 102	
	Instrumental Polarization 105	
	Matrix Formulation 109	
	Calibration of Instrumental Polarization 112	
Appendix 4.1	Conversion Between Hour Angle–Declination and	
	Azimuth–Elevation Coordinates 117	
Appendix 4.2	Leakage Parameters in Terms of the Polarization Ellipse 117	
	Linear Polarization 118	

Circular Polarization 119

68

86

x CONTENTS

5	Anteni	nas and Arrays 122
	5.1	Antennas 122
	5.2	Sampling the Visibility Function 126
		Sampling Theorem 126
		Discrete Two-Dimensional Fourier Transform 128
	5.3	Introductory Discussion of Arrays 129
		Phased Arrays and Correlator Arrays 129
		Spatial Sensitivity and the Spatial Transfer Function 132
		Meter-Wavelength Cross and T Arrays 137
	5.4	Spatial Transfer Function of a Tracking Array 138
		Desirable Characteristics of the Spatial Transfer Function 140
		Holes in the Spatial Frequency Coverage 141
	5.5	Linear Tracking Arrays 142
	5.6	Two-Dimensional Tracking Arrays 147
		Open-Ended Configurations 148
		Closed Configurations 150
		VLBI Configurations 155
		Orbiting VLBI Antennas 158
		Planar Arrays 159
	5.7	Conclusions on Antenna Configurations 161
	5.8	Other Considerations 162
		Sensitivity 162
		Long Wavelengths 163
		Millimeter Wavelengths 163
6	Respo	nse of the Receiving System 168
	6.1	Frequency Conversion, Fringe Rotation, and Complex Correlators 168
		Frequency Conversion 168
		Response of a Single-Sideband System 169
		Upper-Sideband Reception 171
		Lower-Sideband Reception 172
		Multiple Frequency Conversions 173
		Delay Tracking and Fringe Rotation 173
		Simple and Complex Correlators 174
		Response of a Double-Sideband System 175
		Double-Sideband System with Multiple Frequency Conversions 178
		Fringe Stopping in a Double-Sideband System 180
		Relative Advantages of Double- and Single-Sideband Systems 181

254

6.2	Sideband Separation 181 Response to the Noise 183 Signal and Noise Processing in the Correlator 183 Noise in the Measurement of Complex Visibility 188 Signal-to-Noise Ratio in a Synthesized Map 189 Noise in Visibility Amplitude and Phase 192
	Relative Sensitivities of Different Interferometer Systems 193
6.2	System Temperature Parameter α 199 Effect of Pandwidth 100
0.3	Mapping in the Continuum Mode 200
	Wide-Field Manning with a Multichannel System 204
64	Effect of Visibility Averaging 205
0.4	Visibility Averaging Time 205
	Effect of Time Averaging 206
Appendix 6.1	Partial Rejection of a Sideband 208
7 Design	of the Analog Receiving System 212
7.1	Principal Subsystems of the Receiving Electronics 212
	Low-Noise Input Stages 212
	Noise Temperature Measurement 214
	Local Oscillator 217
	IF and Signal Transmission Subsystems 218
	Optical Fiber Transmission 218
	Delay and Correlator Subsystems 220
7.2	Stability 221
	Round-Trip Phase Measuring Schemes 221
	Swarup and Yang System 222
	Frequency-Offset Round-Trip System 223
	Automatically Correcting System 228
	Fiberoptic Transmission of LO Signals 229
	Phase-Locked Loops and Reference Frequencies 230
	Phase Stability of Filters 232
	Effect of Phase Errors 233
7.3	Frequency Responses of the Signal Channels 233
	Optimum Response 233
	Interances on Variation of the Frequency Response:
	Tolerances on Variation of the Frequency Response:
	Gain Errors 235

	Delay-Setting Tolerances 238
	Implementation of Bandpass Tolerances 239
7.4	Polarization Mismatch Errors 240
7.5	Phase Switching 240
	Reduction of Response to Spurious Signals 240
	Implementation of Phase Switching 241
	Interaction of Phase Switching with Fringe Rotation and Delay
	Adjustment 246
7.6	Automatic Level Control and Gain Calibration 248
Appendix 7.1	Sideband-Separating Mixer 248
Appendix 7.2	Dispersion in Optical Fiber 249
	Signal Decoopie
	Signal Processing
8.1	Bivariate Gaussian Probability Distribution 255
8.2	Periodic Sampling 256
	Nyquist Rate 250
0.2	Correlation of Sampled but Unquantized Waveforms 257
8.3	Sampling with Quantization 260
	Two-Level Quantization 261
	Four-Level Quantization 264
	Infee-Level Quantization 2/1
	Quantization with Eight of More Levels 273
	Quantization Correction 276
	Comparison of Quantization Schemes 2//
0.4	System Sensitivity 2/8
8.4	Accuracy in Digital Sampling 278
	Principal Causes of Error 2/8
0 -	Tolerances in Three-Level Sampling 2/9
8.5	Digital Delay Circuits 282
8.6	Quadrature Phase Shift of a Digital Signal 283
8.7	Digital Correlators 283
	Correlators for Continuum Observations 283
	Principles of Digital Spectral Measurements 284
	Lag (XF) Correlator 289
	FX Correlator 290
	Comparison of Lag and FX Correlators 293
	Hybrid Correlator 297
	Demultiplexing in Broadband Correlators 297
Appendix 8.1	Evaluation of $\sum_{q=1}^{\infty} R_{\infty}^2(q\tau_s)$ 298
Appendix 8.2	Probability Integral for Two-Level Quantization 299

Appendix 8.3 Correction for Four-Level Quantization 300

9 Very-Long-Baseline Interferometry

9.2 Differences Between VLBI and Conventional Interferometry 306 304

- 9.3 Basic Performance of a VLBI System 308 Time and Frequency Errors 308 Retarded Baselines 315 Noise in VLBI Observations 316 Probability of Error in the Signal Search 319 Coherent and Incoherent Averaging 323
 9.4 Fringe Fitting for a Multielement Array 326 Global Fringe Fitting 326 Relative Performance of Fringe Detection Methods 329
- Triple Product, or Bispectrum 330
- Fringe Searching with a Multielement Array 331
- Multielement Array with Incoherent Averaging3319.5Phase Stability and Atomic Frequency Standards332
 - Analysis of Phase Fluctuations 332

Oscillator Coherence Time 340

- Precise Frequency Standards 342
- Rubidium and Cesium Standards 346
- Hydrogen Maser Frequency Standard 348
- Local Oscillator Stability 351
- Phase Calibration System 352 Time Synchronization 353
- 9.6 Recording Systems 353
- 9.7 Processing Systems and Algorithms 357 Fringe Rotation Loss (η_R) 358 Fringe Sideband Rejection Loss (η_S) 361 Discrete Delay Step Loss (η_D) 363 Summary of Processing Losses 365
- 9.8 Bandwidth Synthesis 366 Burst Mode Observing 368
- 9.9 Phased arrays as VLBI Elements 369
- 9.10 Orbiting VLBI (OVLBI) 373

10 Calibr	ation and Fourier Transformation of Visibility Data	383
10.1	Calibration of the Visibility 383	
	Corrections for Calculable or Directly Monitored Effects	384
	Use of Calibration Sources 385	
10.2	Derivation of Intensity from Visibility 387	
	Mapping by Direct Fourier Transformation 387	
	Weighting of the Visibility Data 388	
	Mapping by Discrete Fourier Transformation 392	
	Convolving Functions and Aliasing 394	
	Aliasing and the Signal-to-Noise Ratio 398	
10.3	Closure Relationships 399	
10.4	Model Fitting 401	
	Basic Considerations for Models 402	
	Cosmic Background Anisotropy 404	
10.5	Spectral Line Observations 404	
	General Considerations 404	
	VLBI Observations of Spectral Lines 406	
	Variation of Spatial Frequency over the Bandwidth 409	
	Accuracy of Spectral Line Measurements 409	
	Presentation and Analysis of Spectral Line Observations	410
10.6	Miscellaneous Considerations 411	
	Interpretation of Measured Intensity 411	
	Errors in Maps 412	
	Hints on Planning and Reduction of Observations 413	
Appendix 10.1	The Edge of the Moon as a Calibration Source 414	
Appendix 10.2	Doppler Shift of Spectral Lines 417	
Appendix 10.3	Historical Notes 421	
	Maps from One-Dimensional Profiles 421	
	Analog Fourier Transformation 422	
11 Decon	volution, Adaptive Calibration, and Applications	426
11.1	Limitation of Spatial Frequency Coverage 426	
11.2	The Clean Deconvolution Algorithm 427	
	CLEAN Algorithm 427	
	Implementation and Performance of the CLEAN Algorithm 429	
11.3	Maximum Entropy Method 432	
	MEM Algorithm 432	
	Comparison of CLEAN and MEM 434	
	Other Deconvolution Procedures 435	

11.4	Adaptive Calibration and Mapping With Amplitude Data Only 438	
	Hybrid Mapping 438	
	Self-Calibration 440	
	Mapping with Visibility Amplitude Data Only 444	
11.5	Mapping With High Dynamic Range 445	
11.6	Mosaicking 446	
	Methods of Producing the Mosaic Map 449	
	Some Requirements of Arrays for Mosaicking 451	
11.7	Multifrequency Synthesis 453	
11.8	Non-Coplanar Baselines 454	
11.9	Further Special Cases of Image Analysis 459	
	Use of CLEAN and Self-Calibration with Spectral Line Data 459	
	Low-Frequency Mapping 459	
	Lensclean 461	
12 Interfe	rometer Techniques for Astrometry and Geodesy	467
12.1	Requirements for Astrometry 467	
	Reference Frames 469	
12.2	Solution for Baseline and Source-Position Vectors 470	
	Connected-Element Systems 470	
	Measurements with VLBI Systems 472	
	Phase Referencing in VLBI 476	
12.3	Time and the Motion of the Earth 480	
	Precession and Nutation 481	
	Polar Motion 482	
	Universal Time 482	
	Measurement of Polar Motion and UT1 484	
12.4	Geodetic Measurements 485	
12.5	Mapping Astronomical Masers 485	
Appendix 12.1	Least-Mean-Squares Analysis 490	
13 Propag	ation Effects	507
13.1	Neutral Atmosphere 508	
	Basic Physics 508	
	Refraction and Propagation Delay 513	
	Absorption 518	
	Origin of Refraction 524	
	Smith–Weintraub Equation 528	
	Phase Fluctuations 530	

	Kolmogorov Turbulence 534
	Anomalous Refraction 539
	Water Vapor Radiometry 541
13.2	Atmospheric Effects at Millimeter Wavelengths 543
	Site Testing by Opacity Measurement 543
	Site Testing by Direct Measurement of Phase Stability 546
	Reduction of Atmospheric Phase Errors by Calibration 550
13.3	Ionosphere 554
	Basic Physics 555
	Refraction and Propagation Delay 559
	Calibration of Ionospheric Delay 560
	Absorption 562
	Small- and Large-Scale Irregularities 562
13.4	Scattering Caused by Plasma Irregularities 564
	Gaussian Screen Model 564
	Power-Law Model 569
13.5	Interplanetary Medium 571
10.0	Refraction 571
	Interplanetary Scintillation 574
13.6	Interstellar Medium 576
	Dispersion and Faraday Rotation 576
	Diffractive Scattering 579
	Refractive Scattering 580
Van Ci	ttert-Zernike Theorem, Spatial Coherence, and Scattering 594
14.1	Van Cittert–Zernike Theorem 594
	Mutual Coherence of an Incoherent Source 596
	Diffraction at an Aperture and the Response of an Antenna 597
	Assumptions in the Derivation and Application of the Van Cittert–Zernike Theorem 600
14.2	Spatial Coherence 602
	Incident Field 602
	Source Coherence 603
	Completely Coherent Source 606
14.3	Scattering and the Propagation of Coherence 607
Dadia	Interference
15 1	General Considerations 613
15.1	Short- and Intermediate-Reseline Arrays 615
	 13.2 13.3 13.4 13.5 13.6 Van Ci 14.1 14.2 14.2 14.3 Radio 15.1 15.2

15.2 Short- and Intermediate-Baseline Arrays 615 Fringe-Frequency Averaging 616

xviii CONTENTS

Decorrelation of Broadband Signals 620 15.3 Very-Long-Baseline Systems 621 15.4 Interference From Airborne and Space Transmitters 624 Appendix 15.1 Regulation of the Radio Spectrum 625 16 Related Techniques 627 16.1 Intensity Interferometer 627 16.2 Lunar Occultation Observations 632 16.3 Measurements on Antennas 636 16.4 Optical Interferometry 641 Modern Michelson Interferometer 642 Sensitivity of Direct Detection and Heterodyne Systems 644 Optical Intensity Interferometer 646 Speckle Imaging 647 **Principal Symbols** 655 **Author Index** 667

Subject Index 677