

Contents

Preface *XV*

List of Contributors *XIX*

| | | |
|----------|---|-----------|
| 1 | Ultra-Wideband Sensing – An Overview | 1 |
| 1.1 | Introduction | 1 |
| 1.2 | Ultra-Wideband – Definition and Consequences of a Large Bandwidth | 7 |
| 1.2.1 | Basic Potentials of Ultra-Wideband Remote Sensing | 9 |
| 1.2.2 | Radiation Regulation | 10 |
| 1.2.2.1 | Implication of UWB Radiation on Biological Tissue | 14 |
| 1.3 | A Brief History of UWB Technique | 16 |
| 1.4 | Information Gathering by UWB Sensors | 17 |
| | References | 27 |
| 2 | Basic Concepts on Signal and System Theory | 31 |
| 2.1 | Introduction | 31 |
| 2.2 | UWB Signals, Their Descriptions and Parameters | 32 |
| 2.2.1 | Classification of Signals | 32 |
| 2.2.1.1 | Types of Stimulus Signals | 32 |
| 2.2.1.2 | Random Process | 33 |
| 2.2.1.3 | Analogue and Digital Signals | 34 |
| 2.2.2 | Signal Description and Parameters of Compact Signals in the Time domain | 35 |
| 2.2.2.1 | Basic Shape Parameters | 35 |
| 2.2.2.2 | L_p -norm | 38 |
| 2.2.2.3 | Shape Factors | 40 |
| 2.2.2.4 | Time Position | 41 |
| 2.2.2.5 | Integral Values of Pulse Duration | 42 |
| 2.2.3 | Statistical Signal Descriptions | 43 |
| 2.2.3.1 | Probability Density Function and Its Moments | 43 |
| 2.2.3.2 | Individual Signal | 44 |
| 2.2.3.3 | Random Process | 45 |
| 2.2.4 | Signal Description of Continuous Wave (CW) UWB Signals | 49 |

| | | |
|---------|---|-----|
| 2.2.4.1 | Auto-Correlation Function | 50 |
| 2.2.4.2 | Cross-Correlation Function | 52 |
| 2.2.5 | Frequency Domain Description | 54 |
| 2.2.5.1 | The Fourier Series and Fourier Transformation | 55 |
| 2.2.5.2 | Some Properties and Parameters of a Spectrum | 59 |
| 2.2.5.3 | Time-Bandwidth Products | 61 |
| 2.2.6 | Doppler Scaling and Ambiguity Function | 65 |
| 2.3 | Some Idealized UWB Signals | 71 |
| 2.3.1 | Rectangular Unipolar and Bipolar Pulse Trains | 72 |
| 2.3.2 | Single Triangular Pulse | 72 |
| 2.3.3 | Sinc Pulse | 73 |
| 2.3.4 | Gaussian Pulses | 75 |
| 2.3.5 | Binary Pseudo-Noise Codes | 79 |
| 2.3.6 | Chirp | 86 |
| 2.3.7 | Multi-Sine | 88 |
| 2.3.8 | Random Noise | 91 |
| 2.4 | Formal Description of Dynamic Systems | 94 |
| 2.4.1 | Introduction | 94 |
| 2.4.2 | Time Domain Description | 96 |
| 2.4.2.1 | Linearity | 96 |
| 2.4.2.2 | The Impulse Response Function or the Time Domain Green's Function | 97 |
| 2.4.2.3 | Extraction of Information from the Impulse Response Function | 103 |
| 2.4.3 | The Frequency Response Function or the Frequency Domain Greens Function | 107 |
| 2.4.3.1 | Properties of the Frequency Response Function and the Utility of the Frequency Domain | 109 |
| 2.4.3.2 | Parameters of the Frequency Response Function | 111 |
| 2.4.4 | Parametric System Descriptions | 112 |
| 2.4.4.1 | Differential Equation | 112 |
| 2.4.4.2 | The Laplace Transform | 114 |
| 2.4.4.3 | Transfer Function | 115 |
| 2.4.4.4 | State Space Model | 118 |
| 2.4.5 | Time Discrete Signal and Systems | 124 |
| 2.4.5.1 | Discrete Fourier Transform | 125 |
| 2.4.5.2 | Circular Correlation and Convolution | 126 |
| 2.4.5.3 | Data Record Length and Sampling Interval | 127 |
| 2.5 | Physical System | 132 |
| 2.5.1 | Energetic Interaction and Waves | 132 |
| 2.5.2 | N-Port Description by IV-Parameters | 135 |
| 2.5.3 | N-Port Description by Wave Parameters | 138 |
| 2.5.4 | Determination of N-Port Parameters | 142 |
| 2.6 | Measurement Perturbations | 146 |
| 2.6.1 | Additive Random Noise and Signal-to-Noise Ratio | 146 |

| | | |
|----------|---|------------|
| 2.6.1.1 | Signal-to-Noise Ratio (SNR) | 148 |
| 2.6.1.2 | Sliding Average | 149 |
| 2.6.1.3 | Synchronous Averaging | 151 |
| 2.6.1.4 | Matched Filter/Correlator | 152 |
| 2.6.1.5 | Device Internal Noise | 157 |
| 2.6.1.6 | Quantization Noise | 158 |
| 2.6.1.7 | IRF and FRF Estimation from Noisy Data | 166 |
| 2.6.2 | Narrowband Interference | 168 |
| 2.6.3 | Jitter and Phase Noise | 170 |
| 2.6.3.1 | Trigger Jitter | 170 |
| 2.6.3.2 | Phase Noise | 173 |
| 2.6.3.3 | Cycle Jitter | 175 |
| 2.6.3.4 | Oscillator Stability | 177 |
| 2.6.4 | Linear Systematic Errors and their Correction | 178 |
| 2.6.5 | Non-Linear Distortions | 189 |
| 2.6.6 | Dynamic Ranges | 191 |
| 2.7 | Summary | 195 |
| | References | 195 |
| 3 | Principle of Ultra-Wideband Sensor Electronics | 199 |
| 3.1 | Introduction | 199 |
| 3.2 | Determination of the System Behaviour by Pulse Excitation | 201 |
| 3.2.1 | Basic Principle | 201 |
| 3.2.2 | Pulse Sources | 203 |
| 3.2.2.1 | Monolithically Integrated Pulse Sources | 203 |
| 3.2.2.2 | Tunnel Diode | 204 |
| 3.2.2.3 | Avalanche Transistor | 204 |
| 3.2.2.4 | Step Recovery Diode (Snap-Off Diode) | 206 |
| 3.2.2.5 | Non-Linear Transmission Line | 206 |
| 3.2.3 | Voltage Capturing by Sub-Sampling (Stroboscopic Sampling) | 207 |
| 3.2.3.1 | Preliminary Remarks | 207 |
| 3.2.3.2 | Principles of Voltage Sampling | 208 |
| 3.2.3.3 | Timing of Data Capturing by Sub-Sampling | 223 |
| 3.2.4 | Voltage Capturing by 1 bit Conversion | 236 |
| 3.2.5 | Peculiarities of Sensors with Pulse Excitation | 240 |
| 3.3 | Determination of the System Behaviour by Excitation with Pseudo-Noise Codes | 243 |
| 3.3.1 | Generation of Very Wideband PN-Codes | 243 |
| 3.3.2 | IRF Measurement by Wideband Correlation | 247 |
| 3.3.3 | The Sliding Correlator | 248 |
| 3.3.4 | Basic Concept of Digital Ultra-Wideband PN-Correlation | 251 |
| 3.3.4.1 | Digital Impulse Compression | 255 |
| 3.3.4.2 | Transformation into the Frequency Domain | 257 |
| 3.3.4.3 | Removal of Stationary Data | 258 |

| | | |
|----------|--|------------|
| 3.3.5 | Some Particularities of PN-Sequence Devices | 262 |
| 3.3.6 | System Extensions of Digital PN-Correlator | 266 |
| 3.3.6.1 | Improving the Sampling Efficiency | 266 |
| 3.3.6.2 | MiMo-Measurement System | 275 |
| 3.3.6.3 | Up-Down-Conversion | 278 |
| 3.3.6.4 | Equivalent Time Oversampling | 283 |
| 3.3.6.5 | Beam Steering and Doppler Bank | 287 |
| 3.3.6.6 | Transmitter-Receiver Separation | 293 |
| 3.4 | Determination of the System Behaviour by Excitation with Sine Waves | 296 |
| 3.4.1 | Introduction | 296 |
| 3.4.2 | Measurement of the Frequency Response Functions | 297 |
| 3.4.2.1 | Homodyne Receiver | 297 |
| 3.4.2.2 | Heterodyne Receiver | 299 |
| 3.4.3 | Sine Wave Sources of Variable Frequency | 302 |
| 3.4.4 | Operational Modes | 306 |
| 3.4.4.1 | Stepped Frequency Continuous Wave (SFCW) | 306 |
| 3.4.4.2 | Continuous Frequency Variation | 317 |
| 3.5 | The Multi-Sine Technique | 323 |
| 3.6 | Determination of the System Behaviour with Random Noise Excitation | 330 |
| 3.6.1 | Time Domain Approaches | 334 |
| 3.6.2 | Frequency Domain Approaches | 338 |
| 3.7 | Measuring Arrangements | 341 |
| 3.7.1 | Capturing of Voltage and Current | 341 |
| 3.7.2 | Basic Measurement Circuit | 343 |
| 3.7.3 | Methods of Wave Separation | 347 |
| 3.7.3.1 | Wave Separation by Time Isolation | 347 |
| 3.7.3.2 | Wave Separation by Directional Couplers | 351 |
| 3.7.3.3 | Wave Separation by Voltage Superposition | 351 |
| 3.7.3.4 | Capturing of E- and H-Field | 353 |
| 3.8 | Summary | 354 |
| | References | 356 |
| 4 | Ultra-Wideband Radar | 363 |
| 4.1 | Introduction | 363 |
| 4.2 | Distributed System – the Measurement Problem | 363 |
| 4.3 | Plane Wave and Isotropic Waves/Normalized Wave | 368 |
| 4.4 | Time Domain Characterization of Antennas and the Free Space Friis Transmission Formula | 379 |
| 4.4.1 | Introduction | 379 |
| 4.4.2 | Antenna as Transmitter | 382 |
| 4.4.3 | Antenna as Receiver | 384 |
| 4.4.4 | Transmission Between Two Antennas – The Scalar Friis Transmission Formula | 385 |

| | | |
|---------|--|-----|
| 4.5 | Indirect Transmission Between Two Antennas – The Scalar Time Domain Radar Equation | 388 |
| 4.5.1 | Wave Scattering at Planar Interfaces | 388 |
| 4.5.2 | Wave Scattering at Small Bodies | 391 |
| 4.6 | General Properties of Ultra-Wideband Antennas | 405 |
| 4.6.1 | Canonical Minimum-Scattering Antenna | 409 |
| 4.6.2 | Spectral Domain Antenna Parameters | 412 |
| 4.6.3 | Time Domain Antenna Parameters | 417 |
| 4.6.3.1 | Effective Centre of Radiation | 420 |
| 4.6.3.2 | Boresight Direction and Canonical Position | 424 |
| 4.6.3.3 | Time Domain Directive Gain Pattern | 425 |
| 4.6.3.4 | Spherical Deformation Pattern | 425 |
| 4.6.3.5 | Fidelity and Fidelity Pattern | 425 |
| 4.6.3.6 | Structural Efficiency Pattern | 426 |
| 4.6.4 | Parametric Description of Antenna and Scatterer | 427 |
| 4.6.5 | Distance and Angular Dependence of Antenna Functions and Parameters | 430 |
| 4.6.6 | The Ideal Short-Range UWB Radar Equation | 435 |
| 4.6.7 | Short-Range Time Domain Antenna Measurements | 440 |
| 4.6.7.1 | Transmission Measurement Between Two Antennas | 440 |
| 4.6.7.2 | Direct Measurement of Antenna Impulse Response | 443 |
| 4.6.7.3 | Impulse Response Measurement by Backscattering | 445 |
| 4.6.7.4 | Measurement of Antenna Backscattering | 446 |
| 4.7 | Basic Performance Figures of UWB Radar | 446 |
| 4.7.1 | Review on Narrowband Radar Key Figures and Basics on Target Detection | 446 |
| 4.7.2 | Range Resolution of UWB Sensors | 455 |
| 4.7.3 | Accuracy of Range Measurement | 459 |
| 4.7.3.1 | Statement of the Problem | 459 |
| 4.7.3.2 | Noise- and Jitter-Affected Ultra-Wideband Signals | 463 |
| 4.7.3.3 | Noise and Jitter Robustness of Various UWB Sensor Concepts | 468 |
| 4.7.3.4 | Short-Pulse Excitation and Dual Ramp Sampling Control | 469 |
| 4.7.3.5 | Analogue Short-Pulse Correlation and Dual Sine Timing | 470 |
| 4.7.3.6 | Ultra-Wideband CW Stimulation and Dual Pulse Timing | 471 |
| 4.7.3.7 | Random Uncertainty of Time Position Estimation | 473 |
| 4.7.3.8 | Time Position Error Caused by Drift and Its Correction | 483 |
| 4.8 | Target Detection | 487 |
| 4.8.1 | Preliminary Remarks | 487 |
| 4.8.2 | Target Detection Under Noisy Conditions | 489 |
| 4.8.2.1 | Detections Based on a Single Measurement | 490 |
| 4.8.2.2 | Detection Based on Repeated Measurements | 496 |
| 4.8.3 | Detection of Weak Targets Closely Behind an Interface | 507 |
| 4.8.3.1 | Modelling of the Receiving Signal | 509 |

| | | |
|----------|---|------------|
| 4.8.3.2 | Hidden Target Detection | 510 |
| 4.8.3.3 | Blind Range Reduction | 512 |
| 4.9 | Evaluation of Stratified Media by Ultra Wideband Radar | 519 |
| 4.9.1 | Measurement arrangement and Modelling of Wave Propagation | 519 |
| 4.9.2 | Reconstruction of Coplanar Layer Structure | 526 |
| 4.10 | Ultra-Wideband Short-Range Imaging | 530 |
| 4.10.1 | Introduction | 530 |
| 4.10.2 | The Basic Method of Short-Range Imaging | 531 |
| 4.10.3 | Array-Based Imaging | 535 |
| 4.10.3.1 | Ultra-Wideband Radar Array | 538 |
| 4.10.3.2 | Point Spread Function and Image Resolution | 539 |
| 4.10.3.3 | Steering Vector Design | 544 |
| 4.10.3.4 | Sparse Scene Imaging | 552 |
| 4.10.3.5 | Array Configurations and Remarks on UWB Radar Imaging | 562 |
| 4.10.4 | Shape Reconstruction by Inverse Boundary Scattering | 565 |
| 4.10.4.1 | Shape Reconstruction by Quasi-Wavefront Derivation | 565 |
| 4.10.4.2 | Shape Reconstruction Based on Tangent Planes | 568 |
| 4.10.4.3 | Planar Interface Localization by Mono-Static Measurements | 568 |
| 4.10.4.4 | Bi-Static Measurement | 572 |
| 4.10.4.5 | Estimation of Reconstruction Errors | 574 |
| | References | 578 |
| 5 | Electromagnetic Fields and Waves in Time and Frequency | 585 |
| 5.1 | Introduction | 585 |
| 5.2 | The Fundamental Relations of the Electromagnetic Field | 586 |
| 5.2.1 | Maxwell's Equations and Related Relations | 587 |
| 5.2.2 | Boundary Conditions | 592 |
| 5.2.3 | Energy Flux of Electromagnetic Radiation | 593 |
| 5.2.4 | Radiation Condition | 594 |
| 5.2.5 | Lorentz Reciprocity | 594 |
| 5.3 | Interaction of Electromagnetic Fields with Matter | 596 |
| 5.4 | Plane Wave Propagation | 601 |
| 5.4.1 | The Electromagnetic Potentials | 602 |
| 5.4.2 | Time Harmonic Plane Wave | 604 |
| 5.4.3 | fp-Space Description and Dispersion Relation | 606 |
| 5.4.4 | Propagation in Arbitrary Direction | 608 |
| 5.4.5 | Time Domain Description of Wideband Plane Wave | 611 |
| 5.4.6 | Scattering of a Plane Wave at a Planar Interface | 614 |
| 5.5 | The Hertzian Dipole | 617 |
| 5.5.1 | The Dipole as Transmitter | 618 |
| 5.5.2 | Far-Field and Normalized Dipole Wave | 622 |
| 5.5.3 | The Dipole as Field Sensor and Self-Reciprocity | 624 |

| | | |
|----------|--|------------|
| 5.5.4 | Interfacial Dipole | 625 |
| 5.6 | Polarimetric Friis Formula and Radar Equation | 631 |
| 5.7 | The Concept of Green's Functions and the Near-Field Radar Equation | 636 |
| | References | 647 |
| 6 | Examples and Applications | 651 |
| 6.1 | Ultra-Wideband Sensing – The Road to New Radar and Sensor Applications | 651 |
| 6.1.1 | Potential of Ultra-Wideband Sensing – A Short Summary | 651 |
| 6.1.2 | Overview on Sensor Principles | 654 |
| 6.1.3 | Application of Ultra-Wideband Sensing | 655 |
| 6.2 | Monolithically Integration of M-Sequence-Based Sensor Head | 663 |
| | <i>Martin Kmec</i> | |
| 6.2.1 | Introduction | 663 |
| 6.2.2 | Technology and Design Issues | 663 |
| 6.2.2.1 | Sensor IC Technology Choice | 663 |
| 6.2.2.2 | Design Flow | 666 |
| 6.2.2.3 | Architecture-Specific Circuit Definitions | 667 |
| 6.2.2.4 | Technology Figure-of-Merits | 667 |
| 6.2.3 | Multi-Chip and Single-Chip Sensor Integration | 668 |
| 6.2.4 | The UWB Single-Chip Head | 672 |
| 6.2.4.1 | Architecture and Design Philosophy | 672 |
| 6.2.4.2 | Implemented Circuit Topology | 674 |
| 6.2.4.3 | Single-Chip Floor Plan | 676 |
| 6.2.5 | Particular Single-Chip Blocks | 678 |
| 6.2.5.1 | Stimulus Generator | 678 |
| 6.2.5.2 | The Synchronization Unit | 679 |
| 6.2.5.3 | Transmitter I/O Buffers | 680 |
| 6.2.5.4 | Ultra-Wideband Receivers | 681 |
| 6.2.6 | Single-Chip Test Prototypes | 685 |
| 6.3 | Dielectric UWB Microwave Spectroscopy | 688 |
| | <i>Frank Daschner, Michael Kent, and Reinhard Knöchel</i> | |
| 6.3.1 | Introduction | 688 |
| 6.3.2 | Time Domain Reflectometer for Dielectric Spectroscopy | 690 |
| 6.3.2.1 | Probe | 690 |
| 6.3.2.2 | Instrument Requirements | 690 |
| 6.3.2.3 | Sequential Sampling | 691 |
| 6.3.2.4 | System Design | 692 |
| 6.3.2.5 | Hardware Effort | 693 |
| 6.3.3 | Signal Processing | 693 |
| 6.3.3.1 | Principal Component Analysis and Regression | 694 |
| 6.3.3.2 | Artificial Neural Networks | 697 |
| 6.3.4 | Summary | 698 |

| | |
|---------|---|
| 6.4 | Non-Destructive Testing in Civil Engineering Using M-Sequence-Based UWB Sensors 700 <i>Ralf Herrmann and Frank Bonitz</i> |
| 6.4.1 | Assessment of Sewer Pipe Embedding 701 |
| 6.4.1.1 | Pipe Inspection Sensor 702 |
| 6.4.1.2 | Test Bed and Data Processing 702 |
| 6.4.1.3 | Measurement Example for the Bedding of a Plastic Pipe 704 |
| 6.4.2 | Inspection of the Disaggregation Zone in Salt Mines 706 |
| 6.4.2.1 | M-Sequence UWB Sensor for Detection of Salt Rock Disaggregation 707 |
| 6.4.2.2 | Data Processing for Detection of Disaggregation 707 |
| 6.4.2.3 | Example Measurement: A 3D View of Salt Rock Disaggregation in an Old Tunnel 709 |
| 6.4.2.4 | Example Measurement: Subsidence Analysis in a Fresh Tunnel Stub 712 |
| | Acknowledgements 714 |
| 6.5 | UWB Cardiovascular Monitoring for Enhanced Magnetic Resonance Imaging 714 <i>Olaf Kosch, Florian Thiel, Ulrich Schwarz, Francesco Scotto di Clemente, Matthias Hein, and Frank Seifert</i> |
| 6.5.1 | Introduction 714 |
| 6.5.2 | Impact of Cardiac Activity on Ultra-Wideband Reflection Signals from the Human Thorax 716 |
| 6.5.3 | Compatibility of MRI and UWB Radar 717 |
| 6.5.3.1 | Measurements on a Stratified Human Thorax Phantom 717 |
| 6.5.3.2 | Design Considerations for MR Compatible Ultra-Wideband Antennas 718 |
| 6.5.4 | Interpretation of Physiological Signatures from UWB Signals 720 |
| 6.5.4.1 | Simultaneous ECG/UWB Measurements 720 |
| 6.5.4.2 | Appropriate Data Analysis and Resulting Multiple Sensor Approach 722 |
| 6.5.4.3 | Physiological Interpretation 722 |
| 6.5.5 | MR Image Reconstruction Applying UWB Triggering 724 |
| 6.5.6 | Outlook and Further Applications 724 |
| | Acknowledgement 726 |
| 6.6 | UWB for Medical Microwave Breast Imaging 726 <i>Marko Helbig</i> |
| 6.6.1 | Introduction 726 |
| 6.6.1.1 | Non-Contact Breast Imaging 727 |
| 6.6.1.2 | Contact-Mode Breast Imaging 728 |
| 6.6.2 | Breast and Body Surface Reconstruction 728 |
| 6.6.2.1 | Method 728 |
| 6.6.2.2 | Detection and Elimination of Improper Wavefronts 732 |

| | | |
|---------|--|-----|
| 6.6.2.3 | Exemplary Reconstruction Results and Influencing Factors | 735 |
| 6.6.3 | Contact-Based Breast Imaging | 740 |
| 6.6.3.1 | UWB Breast Imaging in Time Domain | 740 |
| 6.6.3.2 | Measurement Setup Based on Small Antennas | 741 |
| 6.6.3.3 | Imaging Results of Phantom Trials | 743 |
| | Acknowledgement | 744 |
| 6.7 | M-Sequence Radar Sensor for Search and Rescue of Survivors Beneath Collapsed Buildings | 745 |
| | <i>Egor Zaikov</i> | |
| 6.7.1 | Principle and Challenges | 746 |
| 6.7.2 | The Radar System | 748 |
| 6.7.3 | Pre-Processing and Breathing Detection | 749 |
| 6.7.3.1 | Breathing Enhancement by Its Periodicity | 752 |
| 6.7.3.2 | Signal Enhancement in Propagation Time | 753 |
| 6.7.4 | Non-Stationary Clutter Reduction | 756 |
| 6.7.5 | Localization of Breathing People | 758 |
| 6.7.6 | Conclusions and Future Work | 761 |
| | Acknowledgement | 762 |
| 6.8 | Multiple Moving Target Tracking by UWB Radar Sensor Network | 762 |
| | <i>Dušan Kocur, Jana Rováková, and Daniel Urdzík</i> | |
| 6.8.1 | Introduction | 762 |
| 6.8.2 | Shadowing Effect | 764 |
| 6.8.3 | Basic Concept of UWB Sensor Network for Short-Range Multiple Target Tracking | 765 |
| 6.8.4 | Experimental Results | 767 |
| 6.8.5 | Conclusions | 771 |
| 6.9 | UWB Localization | 772 |
| | <i>Rudolf Zetik</i> | |
| 6.9.1 | Classification of UWB Localization Approaches | 772 |
| 6.9.1.1 | Two-Step Localization versus Imaging | 773 |
| 6.9.1.2 | Active versus Passive Approach | 774 |
| 6.9.1.3 | Time of Arrival versus Time Difference of Arrival | 775 |
| 6.9.2 | Active Localization | 777 |
| 6.9.3 | Passive Localization | 779 |
| 6.9.3.1 | Detection of Targets | 779 |
| 6.9.3.2 | Passive Localization of Targets | 780 |
| 6.9.3.3 | Measured Example | 781 |
| 6.9.4 | Imaging of Targets | 783 |
| 6.9.5 | Further Challenges | 787 |
| | References | 789 |

Appendix 801

Symbols and Abbreviations 803

Symbols 803

| | |
|--|-----|
| Notations | 810 |
| Structure of Multi-Dimensional Data | 811 |
| Abbreviations | 812 |

| | |
|--------------|-----|
| Index | 817 |
|--------------|-----|

Online Annex (available at Wiley homepage)

| | |
|-------|--|
| A | Mathematical Basics |
| A.1 | Some Useful Improper Integrals |
| A.2 | Dirac Delta Function and Doublets |
| A.3 | Some Definitions and Calculation Rules for Statistic Variables |
| A.4 | Coordinate Systems |
| A.5 | Some Vector Operations and Useful Identities |
| A.6 | Some Matrix Operations and Useful Identities |
| A.7 | Quadric Surfaces and Curves |
| A.7.1 | Ellipse |
| A.7.2 | Hyperbola |
| A.7.3 | Intersection of Two Circles |
| B | Signals and Systems |
| B.1 | Fourier and Laplace Transform |
| B.2 | Properties of convolution |
| B.3 | Spectrum of Complex Exponential (FMCW-signal) |
| B.4 | Product Detector |
| B.4.1 | ACF of Band-Limited White Gaussian Noise |
| B.4.2 | CCF between a Perturbed and Unperturbed Version of the same Signal |
| B.4.3 | ACF of a Perturbed Deterministic Signal |
| B.4.4 | IQ-Demodulator |
| B.5 | Shape Factors |
| B.5.1 | Generalised Shape Factors of Triangular Pulse |
| B.5.2 | Generalised Shape Factor of M-Sequence |
| B.6 | Conversion between N-Port Parameters |
| B.7 | Mason Graph |
| B.8 | S-Parameters of Basic Circuits |
| B.9 | M-Sequence and Golay-Sequence |
| B.9.1 | M-Sequence |
| B.9.2 | Complementary Golay-Sequence |
| C | Electromagnetic Field |
| C.1 | Time Domain Reciprocity relation |
| C.2 | Scattering of Plane Waves at a Planar Interface |
| C.3 | Scattering of a Plane Wave at a Sphere |
| D | Colored Figures and Movies |