

PRINCIPLES OF RADAR

PREFACE

This volume, like the two preceding editions, deals with the basic principles of pulse radar. It differs from the other editions, however, in a number of ways. The order of presentation of the subject matter has been completely reorganized, and nearly all the material has been rewritten to introduce improved techniques of presentation and to bring about better continuity of articles and chapters. The subject matter has also been expanded by approximately twenty per cent, and more than half of the illustrations are new.

The book is intended primarily for those interested in the basic concepts and techniques of radar. A good deal of the material has been made sufficiently general, however, to render it useful to those working in other fields employing similar techniques. For most efficient use of the book, the reader should have prior knowledge of vacuum-tube behavior and the basic principles of direct- and alternating-current circuits. Ability to carry out simple differentiation and integration is also assumed.

In the frequency domain, radar components divide themselves naturally into low-frequency and high-frequency groups, and it is on this basis that the subject matter is organized. Thus the fore part of the book, which includes the first six chapters, pertains, in general, to pulse circuits and their application to radar modulators, indicators, and receivers. Synchro and servomechanism control circuits are also worked into their logical place in this section. The latter part of the book is devoted to the radio-frequency aspects of radar. Basic concepts are developed in the chapters on transmission lines, waveguides, and resonant cavities, and the techniques of their employment in radar are presented in the remaining chapters.

It is recognized that the concepts presented in a number of articles evolved, either directly or indirectly, from the ideas and thoughts of contributors to other editions of the book. Acknowledgment of the influence of these contributors on the present manuscript is gratefully made. Some of the material from the preceding edition has also been retained essentially intact. In this category is the chapter on propagation, which was originally written for the second edition by Prof. Henry J. Zimmermann of the Department of Electrical Engineering, M.I.T.

In carrying out the project, the authors received the support and encouragement of Dean Harold L. Hazen, and of Prof. Carlton E. Tucker, Executive Officer of the Department of Electrical Engineering and

PREFACE

viii

Director of the Radar School from 1943 to 1949. Professor William H. Radford also took an active part in guiding the project to completion, and Prof. Marcy Eager rendered valuable assistance through his criticisms and proofreading of the manuscript. The cooperation received from Frederick G. Fassett, Jr. and Prof. Gordon S. Brown of the Technology Press is gratefully acknowledged.

Most of the new illustrations were prepared by the M.I.T. Illustration Service. Appreciation is expressed to everyone in this group who participated in the project, and in particular to Gloria B. Williams who was primarily responsible for the work. Appreciation is also expressed to Dorothy Young who typed nearly all the manuscript and assisted in the editing. Thanks are extended to the General Electric Company, Radio Corporation of America, and the Bell Telephone Laboratories for their cooperation in supplying photographs.

*J. Francis Reintjes
Godfrey T. Coate*

CAMBRIDGE, MASS.
May, 1952

CONTENTS

FOREWORD

v

PREFACE

vii

CHAPTER I. *Pulsed Radar*

1

1. Radar Determination of Range	2
2. Radar Direction Indication	7
3. Data Presentation	12
4. Discernment of Signals and Noise	16
5. Radar Range Equation	18
6. Limitations of Radar	22
7. Radar Frequencies	32
8. Types of Radar Equipment	39
9. Block Diagram of a Radar Set	46

CHAPTER II. *Timing Circuits*

54

A. CLIPPING CIRCUITS

54

1. Clipping with Diodes	54
2. Clipping with Amplifiers	56
3. Clipping with Cathode Followers	61

66

B. R-C CIRCUITS

67

4. Transients in R-C Circuits	67
5. Saw-tooth Generator	69
6. Decoupling Filters and Bias Circuits	73
7. R-C Peaker	75
8. Sloping Wavefront Applied to Peaker	78
9. R-C Coupling Circuit	79
10. Signal Bias and Clampers	82
11. Effect of Grid Return	83
12. Step Generator	86
13. Free-running Plate-coupled Multivibrator	92
14. Driven Plate-coupled Multivibrator	97
15. Cathode-coupled Multivibrator	99
16. Phantastron Delay Circuit	104
17. Tube and Wiring Capacitances	110

114

C. R-L-C CIRCUITS

115

18. Transients in Parallel R-L-C Circuits	115
19. Ringing Circuit	120

20. Pulse Transformers	123
21. Blocking Oscillator	134
22. Traveling Waves on Artificial Transmission Lines	139
23. Switching Operations in Transmission-line Circuits	143
24. Reflections at Line Terminals	145
25. Applications of Artificial Transmission Lines	150

153

CHAPTER III. *Modulators*

A. PULSE FORMATION BY NETWORKS AND SWITCHES	154
1. Charging an Open-end Line	154
2. Pulse Formation by Discharge of an Open-end Line	158
3. Pulse Formation by a Shorted-end Line	159
4. Pulse-forming Networks	160
5. Characteristics of Loads for Pulse-forming Networks	164
6. Switching Devices for Discharging Pulse-forming Networks	166
B. LINE-PULSING MODULATORS	169
7. Charging Methods	170
8. Rotary-spark-gap Modulator	176
9. Modulator with Saturable-core Inductor and Inductive-impulse Charging	183
C. DRIVER-POWER-AMPLIFIER MODULATORS	186
10. R-C-coupled Power Amplifier	187
11. Transformer-coupled Power Amplifier	196
12. Bootstrap Drive	200
13. Line-controlled Blocking-oscillator Driver	204
14. Delay-line-controlled Driver	209
15. Driver Using Shorted-end Line	210
16. Blocking-oscillator Modulator	214

CHAPTER IV. *Indicators*

215

A. CATHODE-RAY TUBES	215
1. Electrostatic Cathode-ray Tubes	216
2. Magnetic Cathode-ray Tubes	221
3. Designations and Ratings of Cathode-ray Tubes	225
4. Data Presentation by Means of Cathode-ray Tubes	225
B. SWEEP-VOLTAGE CIRCUITS	227
5. Basic Type A Indicator	227
6. Methods of Improving the Linearity of Sweep Voltages	229
7. Phase-inverter Circuits	234
8. Delayed Sweeps and Expanded Sweeps	239
9. Indicators Used with Antenna Switching	240
10. Type J Presentation	242

CONTENTS

xi

11. Ringing Circuit for Type J Presentation	244
12. Crystal-controlled Oscillator for Type J Presentation	248
C. SWEEP-CURRENT CIRCUITS	252
13. Basic Magnetic-deflection Indicator	252
14. Current-Voltage Relations for Deflection Coil	253
15. Grid Voltage for Deflection-coil Driver Tube	255
16. R-C Trapezoidal-voltage Generator	258
17. Rectangular Grid-voltage Pulse for Driver Tube	260
18. Feedback-amplifier Sweep Circuit	262
19. Azimuth Sweep Circuit for Type B Presentation	265
20. Rotating-coil Plan-position Indicator	267
21. Methods of Positioning the Sweep Trace	269
22. Fixed-coil Plan-position Indicator	271
CHAPTER V. <i>Synchros and Servomechanisms</i>	277
A. SYNCHROS	277
1. Construction and Connection of Synchro Motors and Generators	277
2. Operation of Generator—Electrical Zero	280
3. Operation of Motor	284
4. Torque-Angle Curve	287
5. Oscillation Dampers	288
6. Synchro Control Transformer	289
7. Differential Synchro	292
8. Designations of Synchros	295
9. Synchro Capacitors	296
10. The Electrical-zero Autotransformer	298
11. Geared Synchro Systems	298
12. Applications of Synchros	300
B. SERVOMECHANISMS	305
13. Components of Servo Systems	306
14. Servo Using Ward-Leonard Control System	308
15. Direct-current Servo Motor	309
16. Phase-sensitive Rectifiers	312
17. Amplidyne Servomechanism	316
18. Two-phase Induction Motor	319
19. Servomechanisms Using Two-phase Induction Motor	322
20. Transient Oscillations in Servomechanisms	324
21. Sustained Oscillations in Servomechanisms	325
22. Antihunt Devices	328
23. Applications of Servomechanisms	336
	338
CHAPTER VI. <i>Receivers</i>	338
A. GENERAL PRINCIPLES	338
1. Block Diagram	341
2. Sine-wave Analysis	

3. B. Sine-wave Components of Video Pulses	343
4. Sine-wave Components of Carrier-frequency Pulses	346
5. Sine-wave Response of $R-C$ Circuits	349
6. Sine-wave Response of Parallel $R-L-C$ Circuit	352
7. Reproduction of Video Pulses	356
8. Reproduction of Carrier-frequency Pulses	359
9. Linear Equivalent Circuits for Tubes	364
10. Grid Loading Caused by Cathode-lead Inductance	367
11. Transit-time Grid Loading	369
12. Silicon Crystals	371
13. Characteristics of Noise	376
14. Noise in Linear Passive Circuits	379
15. Antenna Noise	383
16. Vacuum-tube and Crystal Noise	384
17. Noise Figure	392
18. Receiver Frequencies and Bandwidths	396
B. COMPONENT CIRCUITS	401
19. Typical Video Amplifier	401
20. Video-pulse Amplification	404
21. Compensated Video Amplifiers	409
22. Single-tuned Intermediate-frequency Amplifier	412
23. Double-tuned Coupling Circuits	419
24. Stagger-tuned Amplifier	424
25. Intermediate-frequency Input Stages	427
26. Diode Detectors	432
27. Triode and Pentode Detectors	439
28. Crystal Mixers	441
29. Vacuum-tube Mixers	449
30. Automatic-frequency-control Circuits	452
31. Anti-interference Circuits and Signal Discernibility	461
CHAPTER VII. Radio-frequency Transmission Lines	468
1. Types of Transmission Lines	469
2. Traveling Waves	471
3. Lines Terminated in a Short Circuit	477
4. Lines Terminated in an Open Circuit and in a Reactance	483
5. Lines Terminated in a Resistance	486
6. Lines Terminated in a Complex Impedance	490
7. Graphical Determination of Reflection Coefficient	493
8. Input Impedance of Transmission Lines	495
9. Transmission-line Charts	499
10. Input Admittance	505
11. Transient and Steady-state Operation of Transmission Lines	506
12. Power and Power Capacity	510

13. Losses and Attenuation	514
14. Impedance of Lines Having Small Losses	521
15. Impedance-changing Devices	523
16. Transmission-line Capacitance	531
17. Transmission-line Inductance	535
18. Transmission-line Resistance	539
19. Characteristic Resistance, Propagation Speed, and Attenuation	541

CHAPTER VIII. *Waveguides*

545

1. Applications and Advantages of Waveguides	545
2. Basic Electromagnetic-wave Concepts—The Parallel-strip Transmission Line	547
3. Types of Electromagnetic Waves	554
4. Normal Reflection of Plane Transverse Waves	556
5. Oblique Reflection of Plane Transverse Waves	560
6. Field Patterns Obtained by Oblique Reflection	564
7. The $TE_{1,0}$ Wave in a Rectangular Waveguide	570
8. Phase Velocity and Group Velocity	577
9. Power and Attenuation	580
10. Higher Order Wave Types in Rectangular Waveguides	587
11. Rectangular-waveguide Dimensions	590
12. Waveguide Fields for Frequencies below Cutoff	591
13. Waveguide Impedances	596
14. Impedance-changing Devices	601
15. Circular Waveguides	608

613

CHAPTER IX. *Resonant Lines and Cavities*

613

1. Resonant Modes of Networks	617
2. The Quality Factor Q	619
3. Transmission-line Resonators	625
4. Rectangular-waveguide Resonators	633
5. Cavity Resonators	639
6. Impedance of One-entry Resonators	645
7. Coupling to One-entry Resonant Networks	649
8. Equivalent Circuits for Transmission-line Resonators	654
9. Coupling to Transmission-line Resonators	658
10. Transmission Lines Terminated by Resonators	665
11. Two-entry Resonators	668
12. Coupling Devices for High-frequency Resonators	670
13. Parallel Connections at High Frequency	674
14. Coupling Loops	677
15. Wavemeters	682
16. Coupling Probes	

17. Waveguide-to-coaxial-line Junctions	684
18. Aperture Coupling	689
697	
CHAPTER X. <i>High-frequency Triode Oscillators</i>	697
1. Ultrahigh-frequency Triodes	703
2. Sustained Oscillations	706
3. Ultra-audion Oscillators	709
4. Plate-return Oscillators	712
5. Multitube Oscillators	716
6. Analysis of Grid-return Circuits	720
7. Grid-return Oscillators	724
8. Loading of Oscillators	727
9. Output Circuits for Uhf Oscillators	734
10. Effects of Load on Frequency of Oscillation	737
11. Grid-leak Bias in Oscillators	740
12. Pulsed Oscillators	
745	
CHAPTER XI. <i>Klystrons and Magnetrons</i>	745
A. KLYSTRONS	745
1. Two-resonator Klystron	750
2. Reflex Klystrons	755
3. Characteristics of Reflex Klystrons	760
4. Electronic Tuning, Hysteresis, and Load Effects	763
B. MAGNETRONS	763
5. Magnetron Construction and Type Numbers	769
6. Magnetron Resonators	776
7. Electron Motion in Magnetrons	781
8. Magnetron Characteristics	792
9. Performance Charts	795
10. Rieke Diagrams	803
11. Operation and Care of Magnetrons	
806	
CHAPTER XII. <i>Radio-frequency Transmitting and Receiving Systems</i>	806
1. Radio-frequency-system Components	810
2. Choke Joints	812
3. Rotary Joints	816
4. Waveguide Bends, Corners, and Twists	818
5. T Junctions	825
6. Hybrid Junctions	834
7. Directional Couplers	840
8. Attenuators	849
9. Balanced-to-unbalanced Transformers	851
10. Adjustment of Impedance Levels	857
11. Tubes for T-R Devices	

12. Ultrahigh-frequency T-R Systems	860
13. Transmit-Receive Devices for Coaxial-line Microwave Systems	863
14. Transmit-Receive Devices for Waveguide Systems	866
15. Input Circuits for Ultrahigh-frequency Receivers	871
16. Single-ended Crystal Mixers	876
17. Balanced Crystal Mixers	881
18. Test Equipment	886

CHAPTER XIII. *Antennas*

895

1. The Half-wave Antenna	895
2. Input Impedances of Center-fed Antennas of Arbitrary Length	899
3. Radiation Fields of a Half-wave Antenna	903
4. Analysis of Radiation Fields of a Half-wave Antenna	905
5. Patterns of a Half-wave Antenna; Pattern Interpretation	910
6. Radiation Pattern of an Array of Half-wave Antennas Fed in Phase	913
7. Radiation Pattern of an Array of Half-wave Antennas Fed out of Phase	919
8. Examples of the Use of Factors in Obtaining Antenna Patterns	924
9. Elimination of Back Radiation from Broadside Arrays	929
10. Approximate Method of Determining the Beam Angle of a Broadside Array	933
11. Antenna Connections for Broadside Arrays	934
12. Parasitic Antennas	937
13. Antennas with Parabolic Reflectors	942
14. Feeds for Parabolic Antennas	950
15. The Cosecant-squared Antenna	957

91

CHAPTER XIV. *Propagation*

1. Components of Radiation	960
2. Reflection from a Perfectly Conducting Plane	961
3. Reflection Coefficients	964
4. Effect of Earth Reflections on Range	965
5. Divergence	967
6. Standard Atmospheric Refraction	968
7. Vertical-coverage Diagrams	971
8. Nonstandard Refraction	974
9. Atmospheric Reflections	976
10. Character of Radar Echoes	976

INDEX