

PROPAGATION OF SHORT RADIO WAVES

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

RADIATION LABORATORY SERIES

Board of Editors

LOUIS N. RIDENOUR, *Editor-in-Chief*

GEORGE B. COLLINS, *Deputy Editor-in-Chief*

BRITTON CHANCE, S. A. GOUDSMIT, R. G. HERR, HUBERT M. JAMES, JULIAN K. KNIPP,
JAMES L. LAWSON, LEON B. LINFORD, CAROL G. MONTGOMERY, C. NEWTON, ALBERT
M. STONE, LOUIS A. TURNER, GEORGE E. VALLEY, JR., HERBERT H. WHEATON

1. RADAR SYSTEM ENGINEERING—*Ridenour*
2. RADAR AIDS TO NAVIGATION—*Hall*
3. RADAR BEACONS—*Roberts*
4. LORAN—*Pierce, McKenzie, and Woodward*
5. PULSE GENERATORS—*Glasoe and Lebacqz*
6. MICROWAVE MAGNETRONS—*Collins*
7. KLYSTRONS AND MICROWAVE TRIODES—*Hamilton, Knipp, and Kuper*
8. PRINCIPLES OF MICROWAVE CIRCUITS—*Montgomery, Dicke, and Purcell*
9. MICROWAVE TRANSMISSION CIRCUITS—*Ragan*
10. WAVEGUIDE HANDBOOK—*Marcuvitz*
11. TECHNIQUE OF MICROWAVE MEASUREMENTS—*Montgomery*
12. MICROWAVE ANTENNA THEORY AND DESIGN—*Silver*
13. PROPAGATION OF SHORT RADIO WAVES—*Kerr*
14. MICROWAVE DUPLEXERS—*Smullin and Montgomery*
15. CRYSTAL RECTIFIERS—*Torrey and Whitmer*
16. MICROWAVE MIXERS—*Pound*
17. COMPONENTS HANDBOOK—*Blackburn*
18. VACUUM TUBE AMPLIFIERS—*Valley and Wallman*
19. WAVEFORMS—*Chance, Hughes, MacNichol, Sayre, and Williams*
20. ELECTRONIC TIME MEASUREMENTS—*Chance, Hulsizer, MacNichol,
and Williams*
21. ELECTRONIC INSTRUMENTS—*Greenwood, Holdam, and MacRae*
22. CATHODE RAY TUBE DISPLAYS—*Soller, Starr, and Valley*
23. MICROWAVE RECEIVERS—*Van Voorhis*
24. THRESHOLD SIGNALS—*Lawson and Uhlenbeck*
25. THEORY OF SERVOMECHANISMS—*James, Nichols, and Phillips*
26. RADAR SCANNERS AND RADOMES—*Cady, Karelitz, and Turner*
27. COMPUTING MECHANISMS AND LINKAGES—*Svoboda*
28. INDEX—*Henney*

PROPAGATION OF SHORT RADIO WAVES

Edited by

DONALD E. KERR

ASSISTANT PROFESSOR, DEPARTMENT OF PHYSICS
JOHNS HOPKINS UNIVERSITY

OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT
NATIONAL DEFENSE RESEARCH COMMITTEE

FIRST EDITION



NEW YORK · TORONTO · LONDON
McGRAW-HILL BOOK COMPANY, INC.

1951

TK 6573

M 41

U. 13

35

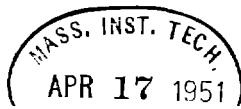
PROPAGATION OF SHORT RADIO WAVES

COPYRIGHT, 1951, BY THE
MCGRAW-HILL BOOK COMPANY, INC.

PRINTED IN THE UNITED STATES OF AMERICA

*All rights reserved. This book, or
parts thereof, may not be reproduced
in any form without permission of
the publishers.*

SCIENCE LIBRARY



PROPAGATION OF SHORT RADIO WAVES

EDITORIAL STAFF

DONALD E. KERR LEON B. LINFORD
S. A. GOUDSMIT ALBERT M. STONE

CONTRIBUTING AUTHORS

ARTHUR E. BENT
RICHARD A. CRAIG
WILLIAM T. FISHBACK
JOHN E. FREEHAFFER
WENDELL H. FURBY
HERBERT GOLDSTEIN
ISADORE KATZ
DONALD E. KERR
R. B. MONTGOMERY
EDWARD M. PURCELL
PEARL J. RUBENSTEIN
A. J. F. SIEGERT
J. H. VAN VLECK

Foreword

THE tremendous research and development effort that went into the development of radar and related techniques during World War II resulted not only in hundreds of radar sets for military (and some for possible peacetime) use but also in a great body of information and new techniques in the electronics and high-frequency fields. Because this basic material may be of great value to science and engineering, it seemed most important to publish it as soon as security permitted.

The Radiation Laboratory of MIT, which operated under the supervision of the National Defense Research Committee, undertook the great task of preparing these volumes. The work described herein, however, is the collective result of work done at many laboratories, Army, Navy, university, and industrial, both in this country and in England, Canada, and other Dominions.

The Radiation Laboratory, once its proposals were approved and finances provided by the Office of Scientific Research and Development, chose Louis N. Ridenour as Editor-in-Chief to lead and direct the entire project. An editorial staff was then selected of those best qualified for this type of task. Finally the authors for the various volumes or chapters or sections were chosen from among those experts who were intimately familiar with the various fields and who were able and willing to write the summaries of them. This entire staff agreed to remain at work at MIT for six months or more after the work of the Radiation Laboratory was complete. These volumes stand as a monument to this group.

These volumes serve as a memorial to the unnamed hundreds and thousands of scientists, engineers, and others who actually carried on the research, development, and engineering work the results of which are herein described. There were so many involved in this work and they worked so closely together, even though often in widely separated laboratories, that it is impossible to name or even to know those who contributed to a particular idea or development. Only certain ones who wrote reports or articles have even been mentioned. But to all those who contributed in any way to this great cooperative development enterprise, both in this country and in England, these volumes are dedicated.

L. A. DuBRIDGE

Preface

Most of the volumes of the Radiation Laboratory Series are devoted to specific radar subjects such as components, systems and their applications, or measurement techniques. This volume, however, treats the phenomena associated with the propagation of short radio waves between terminal points, whether they be the radar antenna serving a dual purpose or the antennas of a communications system. The intention is to present a summary of the state of knowledge in the microwave-propagation field at the close of the war. There has been no attempt to produce either a handbook or textbook, but only an interim report on a rapidly changing subject. An attempt has been made to survey all relevant information that was available, from whatever source, and to summarize as much of it as was feasible.

The preparation of the book was undertaken primarily by the Propagation Group (Group 42), and all of its thirty-odd members contributed either directly or indirectly to the material given here. In addition, substantial contributions have been made by authors who were not members of this group but who worked closely with the group during the war. The division of authorship was to a certain extent arbitrary. The principal criterion was, of course, familiarity with the subject matter, and where possible the people who had made original contributions were favored. There were limiting factors, however, such as the degree of availability of possible authors and the fact that it was impractical to have a large number of writers. Unfortunately, it is impossible to give adequate recognition to all those who have contributed directly or indirectly or even to represent the correct proportion of the contributions of those whose names appear here.

A vast amount of material was available for consideration—much more than could have been presented in one volume. Consequently, some topics have been omitted completely, as, for example, diffraction by trees, hills, and obstacles other than the earth or objects used as radar targets. In this case, as in some others, no significant original work on the subject was done at the Radiation Laboratory, and reviewing work done entirely by others did not appear desirable. Other subjects that have been omitted are the numerous attempts at application of radio-meteorology to forecasting of radio and radar propagation performance and the climatological studies needed to make such knowledge useful on

a world-wide scale. In this case, authors were not available to undertake the work. In choosing the meteorological material that was to be presented, it was decided that in the limited time available it was feasible to present only the material considered to have the soundest fundamental background and to eliminate material that involved an appreciable amount of speculation or that would require reworking or further research to put it into the desired form. In general, throughout the book when similar decisions were necessary, they were nearly always made in favor of an exposition of selected material rather than a sketchy, uncritical report of a large amount. We are aware that despite our attempts to include data from many sources our own work tends to predominate; knowing it most thoroughly, we have treated it in greatest detail.

Much of the wartime work was necessarily done in haste without adequate preliminary planning, care in execution, or sufficient analysis of results. If we appear to be overly critical or pedantic here, the reader is asked to understand that this arises, at least in part, from the reaction of the authors to the nature of much of the source material from which the following chapters are formed. We have not hesitated to point out the need for critical examination of the data reviewed here, for such an examination must certainly be one of the first steps in further research in the field. We have also made numerous suggestions for future investigations.

The methods employed in recent propagation research are, we believe, rather important, and we have described them in some detail when it appeared that the description would aid others in future plans. Apparatus details involving radio-frequency techniques are omitted, as most of them are covered in other volumes of this series, but methods of planning experiments and of analyzing results are emphasized. The meteorological instrumentation and new measurement techniques are also emphasized, as they are of utmost importance in investigations of the effects of atmospheric refraction on microwave transmission.

Nomenclature and symbols were matters about which positive decisions were necessary if the book was to be readable. The present choice is the result of considerable deliberation and compromise among several well-established but highly conflicting systems. It embodies as much as possible of the best or of the most firmly established features of each system. A serious attempt has been made to avoid undue overlapping use of symbols but at the same time to adhere to uniform usage throughout the book; some inconsistencies appear inevitable, however.

We have attempted to acknowledge the sources of all our information, even though, unfortunately, these sources are frequently in the form of reports that possibly will never be generally available. Some of the reports cited here are beginning to appear in the literature as this material goes to press, however, and the appropriate footnote references have been inserted wherever possible. When the source of experimental material is not specifically stated, it may be assumed to be the Radiation Laboratory,

but because of the high mobility of ideas, it is not always possible to be certain of their origin. Except for the measurements on oxygen and water-vapor absorption, ship and aircraft cross sections, and a few miscellaneous items, almost all of the Radiation Laboratory material is the work of the Propagation Group or of its close associates.

The information summarized here represents a large investment of effort by many persons and agencies, and it is impossible to acknowledge fully our indebtedness to all of them. Our principal indebtedness is to the remainder of the Propagation Group, whose work contributed so much to this volume. Second, we must acknowledge particular indebtedness to the several authors who at considerable inconvenience to themselves contributed their services long after the termination of the activities of the Radiation Laboratory Office of Publications.

We should like to acknowledge specifically the very great assistance rendered by the several branches of the armed services, who contributed generously in both man power and in equipment such as boats, aircraft, housing facilities, and the many other items necessary to carry on field operations on a large scale. We should like to thank the members of the U.S. Weather Bureau and its several branch offices, whose personnel not only contributed information but in some cases participated in our research program. We are also greatly indebted to Dr. Charles Brooks of the Blue Hill Observatory of Harvard University for his meteorological advice. Most of the aircraft soundings in Chapter 3 were obtained by Robert H. Burgoyne and Earl G. Boardman, who contributed his aircraft and his services as skillful pilot. This work deserves special mention because of its hazardous and highly exacting nature.

In an attempt to ensure accuracy in reporting the work of other groups, we have submitted portions of the manuscript for review to several individuals and organizations. Particular thanks are due to the following people: Sir Edward Appleton, Dr. R. L. Smith-Rose, and the other members of the Tropospheric Wave Propagation Committee in England; Dr. John B. Smyth of the U.S. Navy Electronics Laboratory; A. B. Crawford of the Bell Telephone Laboratories; Professor Paul A. Anderson of Washington State College; Dr. H. H. Beverage of RCA Laboratories; K. A. Norton and Dr. T. J. Carroll of the Central Radio Propagation Laboratory, Bureau of Standards; and Professor C. R. Burrows of Cornell University. The corrections and suggestions offered by these men have been of great value in integrating the descriptions of the work with which they are most familiar. Thanks are also due Norma W. Donelan for her aid in final preparation of the manuscript.

Contents

FOREWORD	vii
PREFACE	ix
CHAP. 1. ELEMENTS OF THE PROBLEM	1
(JOHN E. FREEHAFFER AND DONALD E. KERR)	
EVOLUTION OF THE PRESENT PROBLEMS	1
1-1. The Ionosphere and the Transmission of Long Waves	1
1-2. Optical Properties of Short Waves	3
TROPOSPHERIC REFRACTION	9
1-3. The Effects of Variable Gradients of Refractive Index	9
1-4. The Meteorological Elements and the Modified Index	12
1-5. The Modified Index and Field-strength Distribution	15
ATMOSPHERIC SCATTERING AND ATTENUATION	22
1-6. Radar Echoes from Precipitation	22
1-7. Scattering and Absorption by Particles	23
1-8. Absorption by Gases	25
CHAP. 2. THEORY OF PROPAGATION IN A HORIZONTALLY STRATIFIED ATMOSPHERE	27
(JOHN E. FREEHAFFER, WILLIAM T. FISHBACK, WENDELL H. FURRY, AND DONALD E. KERR)	
FUNDAMENTAL CONCEPTS	27
2-1. Transmission in Free Space	27
2-2. The Transmission Medium and the Pattern-propagation Factor	34
GEOMETRICAL OPTICS	41
2-3. Ray-tracing Formulas	41
2-4. The Modified Index	50
2-5. Limitations of Ray Methods	53
PHYSICAL OPTICS	58
2-6. The Field from a Dipole in a Stratified Atmosphere near the Earth	58
2-7. The Fundamental Theorem	65
2-8. Phase-integral Methods	70
THE LINEAR MODIFIED-INDEX PROFILE	87
2-9. The Properties of Solutions of $d^2y/d\xi^2 + \zeta y = 0$	87
2-10. The Field Integral	95
2-11. The Interference Region	98
2-12. The Diffraction Region	109
METHODS FOR CALCULATING FIELD STRENGTH WITH STANDARD REFRACTION	112
2-13. The Interference Region	113
2-14. The Diffraction Region	122

2-15. The Intermediate Region	125
2-16. Contours of Constant Field Strength	130
THE BILINEAR MODIFIED-INDEX PROFILE	140
2-17. Definition of the Problem and Preliminary Formulation	140
2-18. Methods for Calculating Characteristic Values	146
2-19. Behavior of Characteristic Values and Characteristic Functions for the First Mode	161
2-20. The Problem of Calculating Field Strength for the Bilinear Profile	168
NONLINEAR MODIFIED-INDEX PROFILES	174
2-21. The Linear-exponential and Power-law Profiles	174
CHAP. 3. METEOROLOGY OF THE REFRACTION PROBLEM	181
(RICHARD A. CRAIG, ISADORE KATZ, R. B. MONTGOMERY, AND PEARL J. RUBENSTEIN)	
HUMIDITY AND REFRACTIVE INDEX	181
3-1. Vapor Pressure and Saturated Vapor	182
3-2. Water-vapor Concentration	184
3-3. Saturation Temperatures on Isobaric Cooling	186
3-4. Refractive Index of Air at Radio Frequencies	189
VERTICALLY HOMOGENEOUS AIR AND ADIABATIC CHANGES	193
3-5. Adiabatic Temperature Lapse Rate and Potential Temperature	194
3-6. Humidity Lapse in Homogeneous Air	196
3-7. Gradient of Refractive Modulus in Homogeneous Air, Potential Modulus	198
3-8. Characteristic Curves and Mixing	200
REPRESENTATION AND DESCRIPTION OF SOUNDINGS	202
3-9. Approximate Formula for Refractive Modulus	203
3-10. Representation of Soundings	206
EDDY DIFFUSION	208
3-11. Eddy Viscosity and Eddy Diffusivity	208
3-12. Layer of Frictional Influence in Neutral Equilibrium	213
3-13. Logarithmic Distributions in the Turbulent Boundary Layer	215
VERTICAL DISTRIBUTIONS IN NEUTRAL AND UNSTABLE EQUILIBRIUM	219
3-14. Heating from Below	220
3-15. Application of Logarithmic Distribution	223
3-16. Rate of Modification of Unstable Air	226
VERTICAL DISTRIBUTIONS IN STABLE EQUILIBRIUM	228
3-17. Cooling from Below	228
3-18. Shear in Stable Equilibrium	234
3-19. Initially Homogeneous Warm Air over Cold Water	237
3-20. Complex Over-water Modifications	250
3-21. Nocturnal Cooling and Diurnal Cycles	253
OTHER ATMOSPHERIC PROCESSES AND THEIR EFFECT ON M-PROFILES	260
3-22. Subsidence and Subsidence Inversions	260
3-23. Fronts and Frontal Inversion	263
3-24. Sea-breeze Circulations	264

3-25. Horizontal Gradients	267
3-26. Local Variations with Time	268
INSTRUMENTS TO MEASURE TEMPERATURE AND HUMIDITY IN THE LOWER ATMOSPHERE	272
3-27. Psychrograph	272
3-28. Wired Sonde	283
3-29. Aircraft Psychrometers	287
3-30. Resistance Thermometer and Humidiometer	289
3-31. Thermocouples	290
3-32. General Problems Associated with Low-level Soundings	291
METEOROLOGICAL CONSTANTS	292
3-33. Useful Meteorological Constants	292
CHAP. 4. EXPERIMENTAL STUDIES OF REFRACTION	294
(PEARL J. RUBENSTEIN, DONALD E. KERR, AND WILLIAM T. FISHBACK)	
ONE-WAY TRANSMISSION OVER WATER	294
<i>Transmission over Massachusetts Bay</i>	
4-1. Radio Measurements Program	296
4-2. Meteorological Measurements and Analysis	297
4-3. General Characteristics of Transmission	301
4-4. Comparison with Theory	307
4-5. Transmission under Complex Conditions	315
4-6. Some Statistical Results	319
<i>Transmission Experiments in the British Isles</i>	
4-7. The Irish Sea Experiment	322
4-8. South Wales to Mt. Snowdon	328
<i>Transmission along the California Coast</i>	
4-9. San Diego to San Pedro	328
<i>Transmission over an Inland Lake</i>	
4-10. Flathead Lake	335
ONE-WAY TRANSMISSION OVER LAND	336
4-11. Early Experiments	336
4-12. Summary of General Characteristics	340
4-13. Additional Observations	343
4-14. Discussion	350
RADAR TRANSMISSION	353
4-15. New England Coast	354
4-16. California Coast	361
4-17. Welsh Coast	363
4-18. The English Channel Region	367
4-19. Other Regions	369
SPACE VARIATIONS IN FIELD STRENGTH	373
4-20. Shallow Surface <i>M</i> -inversions	374
4-21. Deep Surface <i>M</i> -inversions	378
4-22. Elevated <i>M</i> -inversions	382
ANGLE MEASUREMENTS ON SHORT OPTICAL PATHS	385
4-23. Measurements of Angle of Arrival	386
4-24. Theoretical Discussion	391

CHAP. 5. REFLECTIONS FROM THE EARTH'S SURFACE	396
(DONALD E. KERR, WILLIAM T. FISHBACK, AND HERBERT GOLDSTEIN)	
THEORY OF SPECULAR REFLECTION	396
5-1. Fresnel's Equations for a Smooth Plane Surface	396
5-2. Geometrical Interpretation of the Divergence Factor	404
5-3. Effects of Reflections on Field Strength	406
5-4. Surface Roughness	411
REFLECTION COEFFICIENT OF THE OCEAN	418
5-5. Measurements of Short-time Variations	419
5-6. Interference Measurements over Long Ranges	421
5-7. Interference Measurements at Short Ranges	427
5-8. Interpretation of Measurements	429
REFLECTION COEFFICIENT OF LAND	430
5-9. Measurements over Long Ranges	430
5-10. Measurements at Short Ranges	433
5-11. Measurements of Time Variations	434
5-12. Interpretation of Measurements	435
ERRORS IN RADAR HEIGHT MEASUREMENTS	436
5-13. Qualitative Discussion	437
5-14. Illustrative Examples	441
CHAP. 6. RADAR TARGETS AND ECHOES	445
(DONALD E. KERR AND HERBERT GOLDSTEIN)	
THE RADAR CROSS SECTION OF ISOLATED TARGETS	445
6-1. Scattering from a Sphere	445
6-2. Vector Form of Huygens' Principle	454
6-3. Scattering from Planes and Curved Surfaces	456
COMPLEX TARGETS	469
6-4. Radar Cross Section of Aircraft	470
6-5. Radar Cross Section of Ships	472
SEA ECHO	481
6-6. Nature of the Problem	481
6-7. Nature of the Sea Surface	486
6-8. Validity of the Fundamental Assumptions	490
6-9. Frequency Dependence of Sea Echo	494
6-10. Measurements of the Properties of Sea-echo Cross Section	499
6-11. The Fluctuation of Sea Echo	514
6-12. Theories of Sea Echo	518
THE ORIGINS OF ECHO FLUCTUATIONS	527
6-13. The Limitations of System Stability	527
6-14. Atmospheric Variations	531
6-15. Fluctuations in the Space Interference Pattern	535
6-16. Isolated Moving Targets	539
6-17. Interference Phenomena in Complex Targets	547
THE FLUCTUATIONS OF CLUTTER ECHOES	550
6-18. The Nature of Clutter Echoes	550
6-19. The Theory of Clutter Fluctuations	553

6-20. Experimental Techniques in the Study of Clutter Fluctuations	562
6-21. Experimental Results	571
CHAP. 7. METEOROLOGICAL ECHOES	588
(HERBERT GOLDSTEIN, DONALD E. KERR, AND ARTHUR E. BENT)	
ORIGIN OF THE ECHO	588
7-1. The Echo from Incoherent Scatterers Distributed in Volume	589
7-2. Evidence of Direct Correlation between Meteorological Echoes and Precipitation	591
7-3. The Approximate Magnitude of Rain Echoes on the Drop Theory	596
7-4. Possible Alternative Theories to Scattering by Drops	598
7-5. Modifications of the Drop Theory	604
THE INTENSITY OF METEOROLOGICAL ECHOES	607
7-6. The Radar Cross Section of Single Drops	608
7-7. Drop-size Distribution	615
7-8. Echoes from Solid Precipitation	618
GENERAL PROPERTIES OF PRECIPITATION ECHOES	621
7-9. Identifying Characteristics	621
7-10. Confusion and Masking of Other Echoes	625
PRECIPITATION ECHO PROPERTIES AND METEOROLOGICAL STRUCTURE	626
7-11. Classification of Echo Types	626
7-12. Thunderstorms	627
7-13. Other Forms of Localized Precipitation	632
7-14. Widespread Precipitation	633
7-15. Cyclonic Storms of Tropical Origin	636
CHAP. 8. ATMOSPHERIC ATTENUATION	641
(J. H. VAN VLECK, E. M. PURCELL, AND HERBERT GOLDSTEIN)	
8-1. Properties of the Complex Dielectric Constant	641
THEORY OF ABSORPTION BY UNCONDENSED GASES	646
8-2. Oxygen	648
8-3. Uncondensed Water Vapor	656
MEASUREMENT OF ATMOSPHERIC ABSORPTION	664
8-4. Direct Measurement of Absorption by Oxygen	665
8-5. Measurements of Water-vapor Absorption	666
ATTENUATION BY CONDENSED WATER	671
8-6. Phenomenology of Attenuation by Precipitation	671
8-7. Calculation of Attenuation by Water Drops	674
8-8. Calculation of Attenuation by Precipitation in Solid Form	685
8-9. Measurements of Attenuation by Rain	688
APPENDIX	693
(DONALD E. KERR, A. J. F. SIEGERT, AND HERBERT GOLDSTEIN)	
Application of the Lorentz Reciprocity Theorem to Scattering	693
Coherent and Incoherent Scattering from Assemblies of Scatterers	699
NAME INDEX	707
SUBJECT INDEX	713

