Contents

List of Symbols xiv

1 / Historical Introduction 1

1.1 Early Work 1
1.2 The Development of Ionospheric Research 3
1.3 Development of Theoretical Work on Radio Propagation 7

2 / Theory of Wave Propagation 11

2.1 Introduction 11
2.2 Derivation of Maxwell's Equations 11
2.3 A Solution of Maxwell's Equations 14
2.4 Hertz's Experiments 15
2.4.1 Early experiments 15
2.4.2 Later experiments 17
2.5 Some Properties of Plane Waves in an Isotropic Medium 19
2.6 Some Properties of Waves in an Anisotropic Medium 23
2.7 Phase Direction and Ray Direction 26
2.8 Group Propagation 30
2.9 Ray Velocity and Group Ray Velocity 32
2.10 Phase and Group Paths 34
2.11 Ray Theory and Wave Theory 36

3 / The Ionosphere, Geomagnetism, and the Sun 39

3.1 Regions and Layers 39
3.2 The Chapman Layer 42
3.2.1 Introduction 42
3.2.2 Hydrostatic equilibrium 43

3.2.3 Rate of ion production 44
3.2.4 Electron-density distribution 46
3.2.5 Model layers 48
3.3 Radio Soundings of the Ionosphere 52
3.3.1 Ionosondes and ionograms 52
3.3.2 Solar control of the ionosphere 54
3.4 The Geomagnetic Field 64
3.4.1 The dipole approximation 64
3.4.2 The real field 66
3.4.3 Magnetic variations 70
3.4.4 Magnetic indices 71
3.5 The Auroral Zones 72
3.6 Solar Phenomena 72
3.6.1 The visible sun 72
3.6.2 The invisible sun 76

4 / Radio Waves in Ionized Media 83

4.1 Propagation in Isotropic Plasma 83
4.1.1 Introduction 83
4.1.2 The refractive index 84
4.1.3 Properties of the refractive index formula 87
4.2 Magnetoionic Theory 87
4.2.1 The gyromagnetic frequency 88
4.2.2 The constitutive relations of a magnetoplasma and the refractive index formula 89
4.2.3 Some properties of characteristic waves 92
4.2.4 Relative motions of the electrons 97
4.2.5 Magnitude of electron oscillations 103

5 / Dispersion 113

5.1 Introduction 113
5.2 Dispersion in the Absence of a Magnetic Field and Collisions 113
5.3 Dispersion Curves for Longitudinal and Transverse Propagation 114
5.3.1 Longitudinal propagation 114
5.3.2 Transverse propagation 116
5.4 Dispersion Curves for Propagation at Any Angle 117
5.5 Approximate Formulas 118
5.6 The Refractive Index When Collisions Are Included 126
5.6.1 With no magnetic field 126

5.6.2 *With magnetic field* 128
5.7 *Effects of Collisions on the Approximate Formulas* 128
5.8 *The Group Index* 130
5.8.1 *The group index without collisions* 130
5.8.2 *The group index for longitudinal and transverse propagation* 133
5.9 *Approximate Formulas for the Group Index Near the Reflection Levels* 137
5.10 *Effect of Collisions on the Group Index* 137

6 / Absorption 143

6.1 *Physical Causes of Absorption* 143
6.2 *Importance of Absorption* 143
6.3 *Absorption in the Absence of a Magnetic Field* 144
6.3.1 *Expression for the absorption index* 144
6.3.2 *Nondeviative absorption* 145
6.3.3 *Deviative absorption* 148
6.4 *The Absorption Index with Magnetic Field* 148
6.4.1 *The quasilongitudinal approximation for the absorption index* 148
6.4.2 *The quasitransverse approximation for the absorption index* 150
6.5 *The Total Absorption* 151
6.5.1 *The apparent reflection coefficient* 151
6.5.2 *Absorption in model layers* 151
6.5.3 *Absorption in terms of group and phase heights* 154
6.6 *Methods of Measuring Absorption* 155
6.6.1 *The A1 or pulse method* 155
6.6.2 *The A2 or riometer method* 157
6.6.3 *The A3 or continuous-wave method* 159
6.6.4 *The $f_{\min}$ method* 160
6.6.5 *The sweep-frequency method* 160
6.6.6 *Comparison of the various methods* 161

7 / Ray Paths in the Ionosphere 168

7.1 *Need for Ray Tracing* 168
7.2 *Some Methods of Ray Tracing* 169
7.2.1 *Bremmer's rules for ray tracing* 169
7.2.2 *Booker's quartic* 172
7.2.3 *Hazelgrove's equations* 173
7.3 *Ray Paths with Vertical Propagation* 174
7.3.1 *Ray paths on frequencies greater than the gyrofrequency* 174
7.3.2 *Ray paths on frequencies lower than the gyrofrequency* 181

7.4 *Ray Paths with Oblique Propagation* 183
7.4.1 *Propagation in a magnetic meridian* 183
7.4.2 *East-west ray paths with oblique incidence* 187
7.5 *Influence of Electron Collisions on Ray Paths* 190
7.6 *Integration Along Ray Paths* 191

8 / **Virtual Height** 197

8.1 *Importance of Virtual Height* 197
8.2 *Definition of Virtual Height* 198
8.3 *Virtual Heights in Model Layers (No Magnetic Field)* 198
8.4 *Virtual Heights in Model Layers (Longitudinal Propagation)* 200
8.5 *Virtual Heights in Arbitrary Electron-Density Profiles* 204
8.6 *Some Experimental Observations of Virtual Heights* 206
8.7 *Determination of Real Heights* 209
8.7.1 *Inversion of virtual-height curves* 209
8.7.2 *True heights without magnetic field* 210
8.7.3 *True heights with magnetic field* 210
8.8 *Some Difficulties in the Determination of True Heights* 215
8.8.1 *Limiting factors* 215
8.8.2 *The problem of discontinuities* 215
8.8.3 *The height of maximum electron density* 216
8.8.4 *The valley problem* 216
8.8.5 *The unobserved ionization* 222

9 / **Phase and Frequency Variations** 226

9.1 *Importance of Phase* 226
9.2 *Phase Variations* 227
9.2.1 *Method of measurement* 227
9.2.2 *Theory of phase variations* 229
9.2.3 *Effect of including the geomagnetic field* 230
9.2.4 *Some ionospheric results obtained from phase measurements* 232
9.3 *Frequency Variations* 233
9.3.1 *Method of measurement* 233
9.3.2 *Basic theory* 237
9.3.3 *Vertical and oblique equivalence* 240
9.3.4 *Frequency shifts in model layers* 242
9.3.5 *Frequency changes during solar flares* 244
9.3.6 *Other causes of frequency deviations* 248
9.4 *Faraday Rotation* 250
9.4.1 *Rotation of the plane of polarization* 250

9.4.2 Rotation with quasilongitudinal propagation 255
9.4.3 Rotation with quasitransverse propagation 257
9.4.4 Use of Faraday rotation to find the electron content of the ionosphere 259
9.4.5 Some results of Faraday rotation studies 263

10 / Whistler Propagation 269

10.1 Introduction 269
10.2 Frequency Dispersion of Whistlers 271
10.3 Guiding of Whistlers 275
10.4 Group Velocity 276
10.5 Wave and Ray Surfaces 279
10.6 Effects of Heavy Ions on Whistler Propagation 282
10.7 Effects of Collisions on Whistler Propagation 282

11 / Generalized Magnetoionic Theory 287

11.1 Limitations of the Appleton Formula 287
11.2 Experimental Data 288
11.3 Collisions in an Ionized Gas 288
11.4 Distribution of Electron Velocities 291
11.5 The Boltzmann Equation for Momentum Transfer 294
11.6 The Generalized Refractive Index with no Magnetic Field 296
11.7 The Generalized Refractive Index with Longitudinal Propagation 298
11.8 The Generalized Formulas under Limiting Conditions 300
11.9 Frequency Dependence of the Generalized and Classical Formulas 301
11.9.1 Frequency dependence of the real refractive indices 301
11.9.2 Frequency dependence of the absorption indices 303
11.10 Height Variation of the Effective Collision Frequency 304

12 / Oblique Propagation 307

12.1 Characteristics of Oblique Propagation 307
12.2 Equivalence Theorems 308
12.2.1 The secant law 308
12.2.2 Breit and Tuve's theorem 308
12.2.3 Martyn's equivalent path theorem 308
12.3 Transmission Curves for a Flat Ionosphere 310
12.4 Parabolic Layer Theory for a Flat Ionosphere 313

12.4.1 Introduction 313
12.4.2 Virtual height in a parabolic layer 313
12.4.3 Oblique propagation in a plane parabolic layer 314
12.5 Conversion of a Vertical h'f Curve to an Oblique P'f Curve 317
12.6 Inclusion of the Magnetic Field 319
12.7 Effect of Earth Curvature on Oblique Propagation 322
12.7.1 Oblique propagation with thin layers 322
12.7.2 Oblique propagation with thick layers 325
12.8 Experimental Oblique Ionograms 333
12.9 Oblique Ray Paths 336
12.9.1 Ray paths involving sporadic E *and layer tilts* 336
12.9.2 Guided paths 338
12.9.3 Magnetospheric ducting 339
12.9.4 Effect of underlying layer 340

13 / The Amplitudes of Radio Waves 346

13.1 Factors Affecting the Amplitude 346
13.2 Concept of Power Loss 346
13.3 Spatial Losses 347
13.3.1 Inverse distance loss 347
13.3.2 Concept of effective distance 348
13.3.3 Focusing by a spherically stratified ionosphere 348
13.4 Ionospheric Absorption 352
13.4.1 Nondeviative absorption in middle latitudes 352
13.4.2 Martyn's absorption theorem 353
13.5 Polarization Matching 354
13.5.1 Importance of polarization 354
13.5.2 Limiting polarization 354
13.5.3 Illustrations of polarization matching with vertical propagation 355
13.5.4 Illustrations of polarization matching with oblique propagation 356
13.5.5 Division of power 358
13.5.6 Coupling losses 360
13.5.7 Frequency dependence of limiting polarization 362
13.5.8 Effects of collisions 363
13.6 Fading of Radio Waves 365
13.6.1 Meaning of fading 365
13.6.2 MUF fading 365
13.6.3 Polarization fading 367
13.6.4 Interference fading 370

13.6.5 *Scintillations* 378
13.7 *Reciprocity and Nonreciprocity* 381
13.7.1 *Meaning of reciprocity* 381
13.7.2 *Reciprocity of path and power* 381
13.7.3 *Some nonreciprocal phenomena* 381
13.7.4 *Nonreciprocal effects on transverse propagation of very long waves* 384

14 / Topside Sounding 396

14.1 *Introduction* 396
14.2 *Satellite Sounders and Their Orbits* 396
14.3 *Ray Paths from a Topside Sounder* 401
14.4 *Alouette Ionograms* 404
14.5 *Scattering and Ducting in the Topside* 406
14.5.1 *Scattered echoes* 406
14.5.2 *Ducted echoes* 408
14.6 *Plasma Resonances* 411
14.7 *Electron-Density Analysis for the Topside* 415
14.8 *Some Geophysical Discoveries of Topside Sounders* 415
14.9 *Conclusion* 418

15 / Nonlinear Processes in the Ionosphere 421

15.1 *Meaning of a Nonlinear Process* 421
15.2 *Cross Modulation or Wave Interaction* 423
15.2.1 *The Luxemburg effect* 423
15.2.2 *Fejer's experiment* 424
15.2.3 *Theory of electron heating* 428
15.3 *Gyrointeraction* 433
15.4 *Self-Distortion* 434

APPENDIX I 439
APPENDIX II 440
APPENDIX III 442
AUTHOR INDEX 449
SUBJECT INDEX 451