Contents

1 Historical and Technical Overview of SLF/ELF Electromagnetic Wave Propagation ................................................. 1
   1.1 Medium Characteristics of SLF/ELF Wave Propagation .... 1
   1.2 The VLF Waveguide Propagation Theory and Its Applications in Submarine Communication ....................... 2
   1.3 SLF Communication System and SLF/ELF Propagation Theory . 4
   1.4 SLF/ELF Emission as Earthquake Precursor and Field on and near the Ground by Underground SLF/ELF Source . 7
   1.5 ELF Wave Propagation Along the Ocean Floor and the Marine Controlled Source Electromagnetics (mCSEM) Method . 8
   1.6 VLF/SLF/ELF Field on Sea Surface Excited by Space Borne Transmitter ....................................................... 9
   1.7 Atmospheric Noise in SLF/ELF Ranges ......................... 11
References ........................................................................... 12

2 Excitation and Propagation of SLF/ELF Electromagnetic Waves in the Earth–Ionosphere Waveguide/Cavity .................. 17
   2.1 Introduction ................................................................ 17
   2.2 SLF/ELF Field of VED in the Earth–Ionosphere Waveguide/Cavity ................................................................. 18
      2.2.1 Formulations of the Problem ................................. 18
      2.2.2 Determination of the Excitation Coefficients $A_s$ ...... 25
      2.2.3 Approximated Formulas of SLF Field .................... 26
      2.2.4 New Algorithm for ELF Field .............................. 28
   2.3 SLF/ELF Field of VMD in the Earth–Ionosphere Waveguide/Cavity ................................................................. 33
   2.4 SLF/ELF Field of HED in the Earth–Ionosphere Waveguide/Cavity ................................................................. 39
   2.5 Effect of Phase Velocity and Attenuation Rate by Gradual Inhomogeneous Anisotropic Ionosphere in SLF/ELF Ranges . 45
2.6 SLF/ELF Fields of Ground-Based Horizontal Transmitting Antenna

2.6.1 SLF Field in Far-Field Region

2.6.2 SLF Field in the Near-Field Region

2.6.3 The Field in ELF Range and the Lower End of SLF Range

References

3 Spherical Harmonic Series Solution for SLF/ELF Field in the Earth–Ionosphere Waveguide/Cavity

3.1 Introduction

3.2 SLF/ELF Fields of VED in the Earth–Ionosphere Waveguide/Cavity

3.2.1 Spherical Harmonic Series Solution for SLF/ELF Field of VED in the Earth–Ionosphere Cavity

3.2.2 Speed-up Numerical Convergence Algorithm

3.2.3 Evaluations for $\hat{J}_n(v)$, $\hat{H}_n(v)$, $P_n(v)$, and $P^1_n(v)$

3.2.4 Computations and Discussions

3.3 SLF/ELF Fields of HED in the Earth–Ionosphere Waveguide/Cavity

3.3.1 Spherical Harmonic Series Solution for SLF/ELF Fields of HED in the Earth–Ionosphere Waveguide/Cavity

3.3.2 Speed-up Numerical Convergence Algorithm

3.3.3 Evaluations for $\hat{J}_n(v)$, $\hat{H}_n(v)$, $P_n(v)$, and $P^1_n(v)$

3.3.4 Numerical Results and Discussions

References

4 SLF/ELF Field in Air and Ionosphere Generated by Earthquake Radiation Source

4.1 Introduction

4.2 Formulation of Problem

4.3 Analytical Formulas of the Field Components

4.3.1 Evaluation for the Electric-Type Field

4.3.2 Evaluation for the Magnetic-Type Field

4.3.3 Final Formulas for SLF/ELF Fields in Air and Ionosphere

4.4 Comparison and Analysis for Planar and Spherical Models

4.5 Computations and Conclusions

References

5 Propagation of SLF/ELF Waves in Anisotropic Ionosphere

5.1 Introduction

5.2 Propagation of SLF/ELF Waves in Homogeneous Anisotropic Ionosphere

5.2.1 SLF/ELF Wave Propagation in Homogeneous Anisotropic Ionosphere

5.2.2 Computations and Discussions
5.3 Propagation of SLF/ELF Waves in Inhomogeneous Anisotropic Ionosphere ........................................ 149
  5.3.1 SLF/ELF Wave Propagation in Stratified Anisotropic Ionosphere ........................................ 152
  5.3.2 Computations and Discussions .......................... 157

References .................................................. 160

6 ELF Wave Propagation Along Sea-Rock Boundary and mCSEM Method ............................................. 161
  6.1 Introduction .............................................. 161
  6.2 ELF Field of HED on the Boundary Between Sea Water and Ocean Floor .................................... 162
    6.2.1 The Integrated Formulas of the Field in Sea Water and Ocean Floor .................................... 162
    6.2.2 Computations and Discussions .......................... 170
    6.2.3 Poynting Vector and Its Trajectory in Ocean Floor .............................................. 172
  6.3 ELF Wave Excited by HED in the Three-Layered Region .................................................. 179
    6.3.1 Analytical Formulas for EM Field in the Three-Layered Region ........................................ 180
    6.3.2 Computations and Discussions .......................... 185
  6.4 ELF Wave Propagation Along the Boundary Between Sea Water and One-Dimensionally Anisotropic Rock ........................................ 187
    6.4.1 Formulations of the Problem .............................. 188
    6.4.2 Approximated Formulas for the Field Components .............................................. 195
    6.4.3 Computations and Discussions .................................. 198
    6.4.4 Comparisons with Measurements .......................... 198
  6.5 The Electromagnetic Field Generated by HED for \( n \)-Layered Subbed ........................................ 201
    6.5.1 The Integrated Formulas for the Electromagnetic Field Generated by HED for \( n \)-Layered Subbed ........................................ 201
    6.5.2 Speeding Numerical Convergence Algorithm .............................................. 204
    6.5.3 Computations and Discussions on the Normalized Surface Impedance .......................... 207
  6.6 The mCSEM Method and Its Applications ........................................ 208
    6.6.1 The Electric Field Relative Anomaly Versus the Target’s Depth ........................................ 210
    6.6.2 The Relative Anomaly of Electric Field Versus Target Thickness, Conductivity, and Operating Frequency .............................................. 212
    6.6.3 The Effect of Air Waves ...................................... 214
  6.7 Summary .................................................. 219

References .................................................. 219

7 Radiation and Propagation of SLF/ELF Electromagnetic Waves of Space Borne Transmitter .......................... 223
  7.1 Introduction .............................................. 223
7.2 Radiation of an SLF/ELF Electric Dipole in an Infinite Homogeneous Anisotropic Plasma ........................................... 224
  7.2.1 Radiation of a SLF/ELF Electric Dipole in an Infinite Homogeneous Anisotropic Plasma ......................... 224
  7.2.2 The Approximation of the Far Field .......................... 230
  7.2.3 Analyses, Discussions, and Computations ................. 232
7.3 Electromagnetic Field on Sea Surface Generated by Space Borne SLF Transmitter ............................................ 237
  7.3.1 The Representations of the Field Components in the Ionosphere ......................................................... 238
  7.3.2 The Representations of the Field Components in the Air ................................................................. 242
7.4 The Quasi-Longitudinal Approximation ........................... 243
  7.4.1 SLF Field on the Sea Surface .................................. 245
  7.4.2 SLF Field on the Sea Surface for Several Special Cases ............................................................. 247
7.5 Computations and Discussions ......................................... 248
References ...................................................................... 250
8 Atmospheric Noises in SLF/ELF Ranges ............................... 253
  8.1 Introduction ................................................................ 253
  8.2 The Distribution of SLF/ELF Noise Sources and Its Statistical Properties ...................................................... 254
  8.3 Atmospheric Noise Data in HF and VLF Ranges ............... 255
  8.4 Speculation of Global Atmospheric Noise Distributions in SLF/ELF Ranges .................................................... 257
  8.5 Statistical Distributions of Atmospheric Noise in SLF/ELF Ranges ............................................................ 260
References ...................................................................... 261
Index ............................................................................ 263