Table of Contents

Preface xiii

Foreword xv
Paolo CORONA

Introduction xix

Chapter 1. Position of the Reverberation Chambers in Common Electromagnetic Tests 1

1.1. Introduction 1
1.2. Electromagnetic fields and plane waves 2
1.2.1. Definition and properties of plane waves 3
1.2.2. General plane wave representation 7
1.2.3. Assimilation of the far-field to a local plane wave 8
1.2.4. Induction phenomena produced by plane waves 9
1.3. Electromagnetic tests in confined areas 13
1.3.1. Emission of a small rectangular loop 14
1.3.2. Tests carried out in a TEM cell 16
1.3.3. Measurements carried out in an anechoic shielded chamber 22
1.3.4. Position of the reverberation chambers in tests carried out in a confined space 23
1.4. Discussion 26
1.4.1. On the use of the plane wave concepts 26
1.4.2. On the uncertainty margin of the measurements carried out in a reverberation chamber 27
1.5. Bibliography 28

Chapter 2. Main Physical Features of Electromagnetic Cavities 29

2.1. Introduction 29
2.2. Reduction of the modes in a 1D cavity 30
2.2.1. Description of the 1D cavity 30
2.2.2. Solutions of the 1D waves equation 31
2.2.3. Eigenmodes computation 33
2.2.4. Comparison of a cavity to a network of LC resonators 35
2.2.5. Contribution of the quality factor to the cavity 38
2.2.6. Optimal coupling of the energy on an eigenmode 41
2.2.7. Deviation of the modal frequencies produced by an obstacle 42
2.2.8. Implementation of mode stirring 44
2.3. Physical features of an empty rectangular cavity 44
2.3.1. Geometrical description of the reverberation chamber 44
2.3.2. Calculation of the eigenmodes' frequencies 45
2.3.3. The first eigenmode 48
2.3.4. Higher order modes 49
2.3.5. Mode spacing and mode density 52
2.3.6. Quality factor of the 3D cavity 54
2.3.7. Regarding the excitation conditions of the cavity 59
2.3.8. Plane wave spectrum 64
2.3.9. Influence of the energy losses on the plane wave spectrum 67
2.4. The 3D cavity operating in stirred modes 69
2.4.1. Role given to mode stirring 69
2.4.2. Mechanical mode stirring 70
2.4.3. Experimental proof of the modal excursion 74
2.5. Discussion 77
2.5.1. On the geometry of reverberation chambers 77
2.5.2. On the use of the RLC resonators 78
2.5.3. On the contribution of the modal interferences 79
2.6. Bibliography 80

Chapter 3. Statistical Behavior of Stirred Waves in an Oversized Cavity 83

3.1. Introduction 83
3.2. Descriptions of the ideal random electromagnetic field 84
3.2.1. The electromagnetic field assumed as a random variable 84
3.2.2. Statement of the postulate of an ideal random field 87
3.2.3. Presentation conventions of the random variables 88
3.2.4. χ^2 probability distribution 90
3.2.5. Probability density function of the absolute field amplitude 91
3.2.6. Probability density function of the power variable 92

3.3. Simulation of the properties of an ideal random field 93
3.3.1. Construction of the plane wave spectrum 94
3.3.2. Construction of the interferences by random trials 98
3.3.3. Use of the central limit theorem 101
3.4. Contribution of the statistical tests 104
3.4.1. Role given to the size N of the statistical sampling 104
3.4.2. Assessment of the experimental data to the probability distributions 108
3.4.3. Estimate of the variances and means 112
3.4.4. Kolmogorov–Smirnov test 115
3.5. Balance of power in a reverberation chamber 121
3.5.1. Review of the main features of antennas 121
3.5.2. Receiving antenna immersed in an ideal random field 123
3.5.3. Measurement of the power radiated by a device in a reverberation chamber 128
3.6. Discussion 130
3.6.1. On the hypothesis of the ideal random field 130
3.6.2. On the simulation of the disordered field by plane waves trials 131
3.7. Bibliography 132

Chapter 4. Impact of the Physical and Technological Parameters of a Reverberation Chamber 135

4.1. Introduction 135
4.2. Main parameters for reverberation chamber design 136
4.2.1. List of the main building parameters 136
4.2.2. Impact of the geometrical and physical parameters of the chamber 137
4.2.3. Factors influencing the quality factor of a chamber 140
4.2.4. Space correlation of an ideal random electromagnetic field distribution 149
4.3. The usual techniques of mode stirring 153
4.3.1. Mechanical mode stirring 153
4.3.2. Frequency agitation of the modes or electronic stirring 157
4.3.3. Stirring by switching the transmitting antennas 161
4.3.4. Mode stirring by dimensional modulation of the chamber 162
4.4. The characterization of reverberation chambers 164
4.4.1. Aims of the characterization of reverberation chambers 164
4.4.2. Characterization of the efficiency of mode stirring 165
4.4.3. Test of the stationary random electromagnetic field distribution 169
4.4.4. Measurements of the quality factor 177

4.4.5. Localization of the lowest usable frequency of the chamber 184
4.5. Discussion 188
4.5.1. Regarding the law of large numbers 188
4.5.2. On the impact of the volume of the large devices under test. 188
4.6. Bibliography 190

Chapter 5. Radiated Immunity Tests in a Reverberation Chamber 193

5.1. Introduction. 193
5.2. The calibration process 194
5.2.1. Measurement methods of the statistical uniformity of the field distribution 195
5.3. Examples of calibration results 206
5.4. Implementing of the immunity test for a piece of equipment 210
5.4.1. The loading effect of the device under test 211
5.4.2. Incidence on the statistical uniformity of the field 215
5.4.3. Observation of possible malfunctioning of the device under test. 216
5.4.4. An example of immunity tests 216
5.5. Immunity test in reverberation and anechoic chambers 220
5.5.1. The conventional approach of illumination in an anechoic chamber 221
5.5.2. Illumination in a reverberation chamber 223
5.6. Rectangular components of the electric field and the total electric field 226
5.7. Discussion 228
5.7.1. The limits of statistical uniformity from one standard to another 228
5.7.2. The choice of the number of stirrer positions from one standard to another 229
5.7.3. The nature of immunity tests in reverberation chambers. 229
5.8. Bibliography 230

Chapter 6. Emissivity Tests in Reverberation Chambers 233

6.1. Introduction. 233
6.2. A few notions on electromagnetic radiation and antennas 234
6.2.1. Origin of electromagnetic radiation 234
6.2.2. Properties of the electromagnetic field at a distance from the radiation source 234
6.2.3. Intensity and directivity of the electromagnetic radiation 236
6.2.4. Polarization and partial directivities 238
6.2.5. Efficiency and gain of an antenna 239

6.2.6. Effective area of an antenna 242
6.2.7. Transmission balance between two antennas – Friis expression 243
6.2.8. Formulation and properties of the radiation in a spherical graph 243
6.3. Measurement of the total radiated power in free space 249
6.3.1. Definitions 249
6.3.2. Conventional measurement methods of the total radiated power 251
6.4. Measurement of the unintentional emission of a device under test 252
6.4.1. Calibration and evaluation of the total radiated power in reverberation chambers 256
6.5. Measurement examples of the total radiated power 262
6.5.1. The calibration phase 263
6.5.2. The measurement phase of the device under test 266
6.6. Total radiated power and radiated emissivity 269
6.7. Measurement of the efficiency and of the diversity gain of the antennas 272
6.7.1. Measurement of the antenna efficiency 272
6.7.2. Measurement of the diversity gain of the antennas 274
6.8. Discussion 275
6.8.1. On the measurement of the radiated emissivity of a device in a reverberation chamber 275
6.8.2. On the measurements of radiofrequency devices in a reverberation chamber 276
6.9. Bibliography 276

Chapter 7. Measurement of the Shielding Effectiveness 279

7.1. Introduction 279
7.2. Definitions of the shielding effectiveness 280
7.2.1. Shielding effectiveness of cables and connectors 281
7.2.2. Attenuation of the shielded enclosures 284
7.2.3. Shielding effectiveness of the materials 285
7.3. Measurement of the effectiveness of shielded cables and connectors in reverberation chambers 287
7.3.1. Electromagnetic coupling on wires placed in a reverberation chamber 287
7.3.2. The effective area of a cable or a shielded connector 291
7.3.3. Relationship between the reference power and the current induced on a device under test 295

7.3.4. Conversion of the shielding attenuation into a transfer impedance . . . 297
7.3.5. Examples of the measurements of the shielding effectiveness of the connectors . . . 298
7.4. Measurement of the attenuation of the shielded enclosures . . . 302
7.4.1. Expected electromagnetic coupling mechanisms . . . 302
7.4.2. Example of attenuations measured on a shielded enclosure . . . 303
7.5. Measurement of the shielding effectiveness of the materials . . . 307
7.5.1. On the size of the devices under test with respect to the wavelength . . . 307
7.5.2. Examples of attenuation measurements carried out on a material . . . 311
7.6. Discussion . . . 316
7.6.1. The accuracy of the measurement of the shielding attenuation of the materials . . . 316
7.6.2. The recorded curves of shielding attenuation . . . 318
7.7. Bibliography . . . 318

Chapter 8. Mode Stirring Reverberation Chamber: A Research Tool . . . 321

8.1. Introduction . . . 321
8.2. A non-ideal random electromagnetic field . . . 324
8.2.1. An estimate of the statistics of a rectangular component of an electric field in an effective reverberation chamber . . . 325
8.2.2. Resorting to a replacement distribution: the Weibull distribution . . . 332
8.3. Studying the correlation of a set of measurements . . . 336
8.3.1. Outline of the link between correlation and statistical uncertainty . . . 336
8.3.2. Measurement of the correlation . . . 337
8.3.3. Study of the linear correlation during experimental estimates . . . 338
8.3.4. Statistical distribution of the coefficient of linear correlation . . . 339
8.3.5. Approximation of a normal distribution for the estimate of the first order correlation function . . . 342
8.3.6. Residual correlation and impact on the reproducibility of the measurements in reverberation chambers . . . 345
8.4. Quantization of the scattered and coherent fields in a reverberation chamber . . . 349
8.4.1. Coherent residual field in a reverberation chamber and the Rice statistics . . . 349
8.4.2. Goodness-of-fit test of a Rice distribution in a reverberation chamber . . . 351

8.4.3. Example of evaluation of a Rice channel in a reverberation chamber . . . 353
8.5. Discussion . . . 356
8.6. Bibliography . . . 358

APPENDICES . . . 361

Appendix 1. Notion of Probability . . . 363

A1.1. The random variable concept . . . 363
A1.2. Probability concept from intuition . . . 363
A1.3. Probability density function (pdf). . . . 364
A1.4. Computation of moments . . . 365
A1.4.1. Computation of the moment of the x random variable . . . 365
A1.4.2. Computation of the moment of the x squared random variable. . . . 366
A1.5. Centered and normalized variables . . . 366
A1.5.1. Centered variables . . . 366
A1.5.2. Normalized variables . . . 366
A1.6. Computation of the variance and standard deviation . . . 367
A1.6.1. Definition of the variance . . . 367
A1.6.2. Definition of the standard deviation . . . 367
A1.7. Probability distributions . . . 367
A1.7.1. Uniform probability distribution . . . 368
A1.7.2. Normal probability distribution . . . 368
A1.8. The cumulative distribution function (cdf) . . . 369
A1.9. The ergodism notion . . . 369
A1.9.1. Intuitive definition of the ergodic property . . . 369
A1.9.2. Use of ergodism to the calculation of the autocorrelation function . . . 370
A1.10. Features of the random stationary variables . . . 372
A1.11. The characteristic function . . . 373
A1.12. Summary of the main probability distributions . . . 375
A1.12.1. Uniform distribution . . . 375
A1.12.2. Normal distribution . . . 375
A1.12.3. Chi-squared distribution . . . 376
A1.12.4. Weibull distribution . . . 376
A1.12.5. Exponential distribution . . . 377
A1.12.6. Rayleigh distribution . . . 377
A1.13. Tables of numerical values of the normal distribution integrals. . . . 378
A1.13.1. Calculation of the integral . . . 378

A1.13.2. Solution to the integral equation 378
A1.14. Bibliography 379

Appendix 2. Formulas of the Quality Factor of a Rectangular Cavity . . . 381

A2.1. Quality factor of the $\mathsf{TM}_{\mathrm{m\ n\ p}}$ mode 381
A2.2. Calculation of the average $\tilde{Q}$ quality factor 382
A2.3. Bibliography 384

Appendix 3. Total Field and Total Power Variables 385

A3.1. Total field variables 385
A3.2. χ^2 variable attached to the total field 386
A3.3. Total field probability density function 386
A3.3.1. The pdf related to the total "e_t" normalized field variable 386
A3.3.2. The pdf related to the absolute amplitude of the total field "E_t" 387
A3.4. Calculation of the mean of the total field 387
A3.4.1. Mean of the normalized "e_t" amplitude 387
A3.4.2. Mean of the absolute "E_t" amplitude 387
A3.5. The pdf of the total power 388
A3.5.1. Variables of total power "p_t" variable 388
A3.5.2. Computation of the pdf related to the total power 388
A3.5.3. The pdf of the normalized total power variable "p_{tr}" 388
A3.5.4. Computation of the pdf of the total normalized power 389
A3.6. Calculation of the mean total powers 389
A3.6.1. Mean of the total normalized power "p_{tr}" 389
A3.6.2. Mean of the total power "p_t" 389

Appendix 4. Calculation of the Variances of υ_φ, υ_η, υ_θ 391

A4.1. Variance of the υ_φ and υ_η variables 391
A4.2. Variance of the υ_θ variable 392

Appendix 5. Electric Dipole Formulas 395

A5.1. Complete formulas of the electric dipole 395
A5.2. Near-field formulas of the electric dipole 397
A5.3. Far-field formulas of the electric dipole 397
A5.4. Bibliography 398

Index 399