## **Table of Contents**

1 Recent Developments in Electromagnetic Aquametry	1
1.1 Introduction	1
1.2 Principles and Definitions	3
1.3 Instrumentation	6
1.3.1 Metrological Enhancements	6
1.3.2 New Sensors and Transducers	9
1.4 Summary	11
References	12

## **Dielectric Properties of Water and Moist Substances**

2 Electromagnetic Wave Interactions with Water and Aqueous Solutions	15
2.1 Introduction: Water, the Omnipresent Liquid	15
2.2 The Architecture of the Water Molecule and	
the Unique Hydrogen Network	16
2.2.1 The Isolated Water Molecule	16
2.2.2 Liquid Water	17
2.3 Hydrogen Network Fluctuations and Polarization Noise	19
2.4 The Dielectric Properties of Water	21
2.4.1 Complex Permittivity Spectrum	21
2.4.2 Static Permittivity	23
2.4.3 High Frequency Properties	25
2.4.4 Principal Relaxation Time	26
2.5 Aqueous Solutions	28
2.5.1 Solute Contributions to Dielectric Spectra	28
2.5.2 Solvent Permittivity Contribution Aspects	33
2.6 Conclusions: Microwave Aquametry, an Inverse Problem	36
References	37
3 Water in Polymers and Biopolymers Studied by Dielectric Techniques	39
3.1 Introduction	39
3.2 Hydration Properties	41
3.3 Dielectric Techniques and Dielectric Properties	42
3.4 Overall Behaviour	44
3.5 Effects of Water on Secondary Relaxations and Relaxation	
in a Separate Water Phase	50

3.6 Effects of Water on Glass Transition and Primary $\alpha$ -Relaxation	55
3.7 Effects of Water on Electrical Conductivity	60
3.8 Conclusions	63
References	65
4 Thermal and Geometrical Effects on Bulk Permittivity	
of Porous Mixtures Containing Bound Water	71
4.1 Introduction	71
4.1.1 Dielectric Mixing Theory	71
4.1.2 Geometrical Effects	72
4.1.3 Bound Water	73
4.2 Theoretical Considerations	74
4.2.1 Water-Phase Permittivity	74
4.2.2 Water-Phase Temperature-Dependence	75
4.2.3 Particle Shape Effects	76
4.2.4 Three-Phase Dielectric Mixture Model	77
4.3 Measurements and Modeled Results	77
4.3.1 Permittivity Measurements in Porous Mixtures	78
4.3.2 Thermal Effects of Bound Water	78
4.3.3 Modeling the Total Water-Phase Permittivity	80
4.3.4 Modeling Geometrical Effects	82
4.3.5 Modeling Porosity and Density	84
4.3.6 Constituent-Phase Configuration Influence on Bulk Permittivity	87
4.4 Summary	89
References	90
5 Model Systems for Materials with High Dielectric Losses in Aquametry	93
5.1 Introduction	93
5.2 Classical Two-Phase Mixing Formulas	94
5.3 Interfacial Polarization in Aquatic Mixtures	97
5.3.1 Interfacial Polarization and Dispersion	97
5.3.2 Effective Permittivity of a Layered Structure	97
5.3.3 Enhancement Effect	100
5.4 Analysis of the Enhancement Effect in High-Loss Mixtures	101
5.4.1 Peculiarities in High-Loss Mixing	101
5.4.2 Maxwell Garnett Formula for Lossy Mixtures	102
5.4.3 Discussion on the Enhancement Effect	105
5.5 Critical Parameters for Enhancement	106
5.5.1 Mixing Rules for Varying Inclusion Shapes	107
5.5.2 Example of the Critical Case	108
5.6 Discussion	110
References	111

113
113
113
114
116
118
119
120
120
120
121
123
126
130
131
133

### Measurement Methods and Sensors in Frequency Domain

7 Methods of Density-Independent Moisture Measurement	135
7.1 Introduction	135
7.2 Density Variations in One-Parameter-Methods	136
7.3 Density Determination by Using Gamma Rays	137
7.4 Density Compensation using Model Equations in RF and MW Range	139
7.4.1 Multiparameter-Multifrequency Method According to Chope	139
7.4.2 Two-Parameter Method According to Kraszewski and Stuchly	141
7.4.3 Two-Parameter Method According to Meyer and Schilz	142
7.4.3.1 Transmission Measurement	142
7.4.3.2 Resonator Measurement	144
7.4.4 Methods in the RF Range	146
7.4.4.1 Parallel Plate Capacitor	146
7.4.4.2 Coaxial Sample Container	147
7.4.4.3 Stray-Field Capacitor	148
7.4.5 The A-Φ-Diagram	151
7.4.5.1 Transmission Measurements of Anorganic Materials	151
7.4.5.2 Transmission Measurements of Organic Materials	154
7.4.5.3 The A-Φ-Diagram Transformed	
onto a Resonator System	155
7.4.6 Density-Independent Measurement with an	
Open Dielectric Resonator Pair	157
7.4.7 Density-Independent Measurement Using	
Frequency Swept-Transmission	158

7.4.8 Microwave Free-Space Technique at Two Frequencies 7.4.9 Methods of Density-Independent Measurement for	159
Grain in the Microwave Range	160
7.4.9.1 Artificial Neural Network	161
7.4.9.2 Argand-Diagram According to Trabelsi,	
Kraszewski and Nelson	162
7.4.9.3 Comparison of Density-Independent Functions	163
7.5 Summary	164
References	165
8 Microwave and RF Resonator-Based Aquametry	169
8.1 Introduction	169
8.2 Traditional and New Types of Resonator Sensors	169
8.2.1 Basic Types of Resonator-Based Moisture/Humidity Sensors	169
8.2.2 New Types of Resonator Sensors and Applications	170
8.2.2.1 Waveguide-based Resonators	170
8.2.2.2 RF TEM Line-Based Resonator Sensors	175
8.2.2.3 Multiple-Probe Moisture Sensors	178
8.2.2.4 Split-Cavity Moisture Sensors	181
8.2.2.5 Waveguide Resonator Moisture Sensors	184
8.3 Dielectric Permittivity/Density-Independent	
Resonator-Based Aquametry	184
8.4 Conclusion	189
References	189
9 Density and Moisture Measurements Using Microwave Resonators	193
9.1 Introduction	193
9.2 Resonators	194
9.2.1 Cavity Resonators	195
9.2.1.1 E-Type Resonators	195
9.2.1.2 H-Type Resonators	197
9.2.2 Planar Resonant Structures	198
9.2.3 Overview Resonators	199
9.3 Density Independent Moisture Determination	200
9.4 Moisture Independent Density Determination	202
9.5 Measurement Devices	203
9.6 Temperature Compensation	206
9.7 Calibration	207
9.8 Industrial Applications	209
9.8.1 Moisture Measurement in Coffee Beans	210
9.8.2 On Site Moisture Measurement of Concrete	211
9.8.5 Density Measurement in Cigarettes	212
	014
9.9 Conclusions	214

10 Microwave Semisectorial and Other Resonator Sensors	
for Measuring Materials under Flow	217
10.1 Introduction	217
10.2 Implementing a Resonator Sensor in a Pipe	218
10.3 Sectorial and Semisectorial Waveguides	219
10.3.1 TM Modes in Semisectorial Waveguides	220
10.3.2 TE Modes in Semisectorial Waveguide	222
10.3.3 Values for $p_{1m}$ and $p'_{1m}$ for Waveguide Modes	
in Semisectorial Waveguide	225
10.3.4 Discussion on Semisectorial and Sectorial Waveguide Modes	227
10.4 Cylindrical Fin Resonator (CFR) Sensor	229
10.5 End Grid Resonator Sensor	231
10.6 Wet Gas Meter Based on a V-Cone Resonator	234
10.7 Watercut Meter for Measuring Downhole in an Oil Well	238
References	241
11 Microstrin Transmission, and Reflection, Type Sensors	
Used in Microwave Aquametry	243
11.1 Introduction	243
11.1.1 Microstrin Sensors Used in Microwave Aquametry	243
11.1.1 Microstrip Sensors Osed in Microwave Aquaneury	245
11.2 Transmission-Type Microstrip Sensors	249
11.2.1 Free-Space Set-up Using Modulated Backscatter Technology	249
11.2.2 Bi-static Sensors for On-line Control	249
11.2.3 Emerging MSA and Sensor Technologies	250
11.3 New Results Using Reflection-Type Sensors	251
11.3.1 New Concept for Near-Field Sensing	251
11.3.2 A Calibration Method Using Scattering Parameters	253
11.3.3 Experimental Results	253
11.4 Conclusions	254
References	255
12 A Blind Deconvolution Approach for Free-Space Moisture Profile	
Retrieval at Microwave Frequencies	257
12.1 Introduction	257
12.2 Free-Space Characterization Method	258
12.2.1 Reflection Coefficient Modeling for a Two-Layer Material	258
12.2.2 Construction of a Subsurface Moisture Profile	261
12.3 Blind Deconvolution Approach	262
12.3.1 Simulation of Reflection Coefficient Profiles	263
12.3.2 Profile Estimate Results	266
12.4 Reconstruction Method of a Moisture Profile	268

12.4.1 Moisture Profile Simulation	268
12.4.2 Moisture Profile Measurement	270
12.5 Conclusion	273
References	274
13 Sensors for Soil, Substrates, Concrete Based on the MCM100 Microchip	277
13.1 Introduction	277
13.2 A Microchip for Impedance Monitoring	279
13.2.1 Operation of the Chip	281
13.2.2 Calibration Procedure and Computation of Dielectric Properties	283
13.2.3 Temperature Corrections	285
13.3 FD Sensor for Water Content and Bulk EC in Soil	285
13.4 A Pore Water Conductivity Sensor for Growing Substrates	291
13.5 Monitoring the Strength of Young Concrete	296
13.6 A Dielectric Tensiometer to Measure Soil Matric Potential	300
13.7 An FD Sensor Auto-Calibration Method for Volumetric Water Content	308
References	312

#### **Measurement Methods and Sensors in Time Domain**

#### 14 Advanced Measurement Methods in Time Domain Reflectometry for Soil Moisture Determination

317

14.1 Introduction	317
14.2 Dielectric Properties of Soils	318
14.3 Transmission Lines	321
14.3.1 Resistance R and Inductance L	322
14.3.2 Capacitance C and Conductance G	323
14.3.3 Transient Analysis	325
14.4 Reconstruction Algorithm	326
14.4.1 The Telegraph Equations	327
14.4.2 The Optimization Approach	328
14.4.3 Exact Expression for the Gradient of the Cost Function	329
14.4.4 Reconstruction of the Parameters	330
14.4.5 Reconstruction Examples	330
14.4.5.1 Lossless Case	331
14.4.5.2 Lossy Case	332
14.5 A Novel TDR Measurement Principle	333
14.5.1 The "Binary Sampler", a Delta Modulator	
in Equivalent-Time Sampling	333
14.5.2 Slope Overload, Amplitude Range, and Quantization Noise	336
14.5.3 Equivalent-Time Sampling	337
14.5.4 "Observer", a Novel TDR Instrument	338

Table of Contents X	IX

14.5.5 Application and Comparison to Other Instruments	339
14.6 Experimental Results	341
14.6.1 Measuring of Soil Water on a Full-Scale Levee Model	341
14.6.2 Monitoring of Levees and Dams	344
14.7 Conclusion	346
References	3/16
References	540
15 Simulations and Experiments for Detection of Moisture Profiles	
with TDR in a Saline Environment	349
15.1 Introduction	349
15.2 Fundamentals of Time Domain Reflectometry	350
15.3 Simulation of the Measurement Set-up	354
15.4 Calibrations	359
15.5 Moisture Profiles	360
15.6 Bentonite in a Pressure Test Stand	362
15.7 Summary	364
References	365
	000
16 Combined TDR and Low-Frequency Permittivity Measurements	
for Continuous Snow Wetness and Snow Density Determination	367
16.1 Introduction	367
16.2 Dielectric Properties of Snow	369
16.3 Measurement Principle	371
16.4 Flat Band Cable Sensor	371
16.5 Field Experiment Set-up	373
16.6 Experimental Results	376
16.7 Conclusion	381
References	382
17 Dringinlag of Liltra Widshand Sangar Flagtronias	202
17 Principles of Oltra-wideband Sensor Electronics	202
17.1 Introduction	383
17.2 Basics of UWB System Theory	385
17.3 Practical Constraints of UWB Measurements	389
17.4 Measurement Errors	393
17.4.1 Additive Random Noise	393
17.4.2 Jitter	397
17.4.3 Drift	398
17.4.4 Systematic Errors	399
17.5 Architecture of UWB Systems	400
17.5.1 Down-Conversion	401
17.5.2 Sliding Correlation	404
17.5.3 Bandwidth Compression by Under-Sampling	404
17.5.4 UWB Principles for Volume Application	407

17.6 Examples	410
17.7 Summary	416
References	417

# Methods and Sensors for Quality Assesment to Products of Agriculture, Food, and Forestry

18 Permittivity Measurements and Agricultural Applications	419
18.1 Introduction	419
18.2 Permittivity Measurements	420
18.2.1 Measurement Techniques	421
18.2.2 Permittivity Data	422
18.3 Dielectric Heating Applications	426
18.3.1 Product Drying	426
18.3.2 Pest Control	427
18.3.3 Seed Treatment	430
18.3.4 Product Conditioning	431
18.4 Product Quality Sensing	432
18.4.1 Fruit and Vegetable Quality Sensing	432
18.4.2 Grain and Seed Moisture Sensing	432
18.4.3 General Principles	434
18.5 Potential for Further Applications	438
References	439
19 Determination of the Composition of Foodstuffs Using Microwave	
Dielectric Spectra	443
19.1 Introduction	443
19.2 Experiments	444
19.2.1 Preparation of the Samples	444
19.2.2 Dielectric Measurements	444
19.3 Qualitative View on the Influence of the Sample Treatment	445
19.4 Dielectric Modeling	446
19.5 Direct Processing of the Dielectric Data in a MLR	451
19.6 Elimination of the Collinearity using Partial Least Squares Regression	452
19.7 Non-linear Data Processing Using Artificial Neural Networks	455
19.7.1 Training of the Artificial Neural Network	456
19.7.2 Optimal Architecture Found	456
19.7.3 Results Obtained with ANN	457
19.8 Comparison of Methods	460
19.8.1 General Evaluation of the Methods Discussed	460
19.9 Conclusions	463
References	464

20 Microwave Dielectric Properties of Hevea Rubber Latex, Oil Palm Fruit		
and Timber and Their Application for Quality Assessment	467	
20.1 Introduction	467	
20.2 Dielectric Properties	468	
20.2.1 Hevea Rubber Latex	468	
20.2.1.1 Dielectric Properties	468	
20.2.1.2 Mixture Model	472	
20.2.2 Oil Palm Fruit	473	
20.2.2.1 Dielectric Properties	473	
20.2.2.2 Mixture Model	475	
20.2.3 Timber	476	
20.2.3.1 Dielectric Properties	476	
20.2.3.2 Mixture Model	478	
20.3 Application of Dielectric Properties	481	
20.3.1 Latexometer	481	
20.3.2 Microstrip and Conductor-Backed Coplanar Waveguide		
(CBCPW) Moisture Sensors for Oil Palm Fruit	483	
20.3.3 Wood Meter	485	
20.4 Conclusion	488	
References	489	

## Application of Nuclear Magnetic Resonance

21 Moisture Measuring with Nuclear Magnetic Resonance (NMR)	491
21.1 Introduction	491
21.2 Physical Background	492
21.2.1 Basics of Hydrogen NMR	492
21.2.2 NMR Relaxation and Signals	494
21.2.3 Spatially Resolved NMR and MRI	495
21.3 NMR Hardware	496
21.3.1 Basic Components of NMR Instrumentation	496
21.3.2 IBP Instrumentation	496
21.3.3 IZFP Instrumentation One-Sided Access NMR (OSA-NMR)	498
21.4 Potential and Limits	499
21.4.1 Potential of the Method	499
21.4.2 Limits of the Method	500
21.4.3 Accuracy and Spatial Resolution	501
21.4.4 Maximum Specimen Size and Maximum Measuring Depth	501
21.5 Application	502
21.5.1 Foods, Pharmaceuticals and Consumer Products	502
21.5.2 Liquid Transport Coefficients in Building Materials	504

XXII Table of Contents

21.5.2.1 Measuring Procedure	504
21.5.2.2 Results and Discussion	505
21.5.3 Application of OSA-NMR	508
21.5.3.1 On-Site Determination of Moisture Profiles in Buildings	509
21.5.3.2 On-Line Determination of Density and Moisture in Wood	510
21.5.3.3 Monitoring of Concrete Hardening	511
21.6 Summary and Conclusions	513
References	514
1	C 1 7

Index

517