MICROWAVE INSPECTION OF CIVIL STRUCTURES

F. Volgyi
Budapest University of Technology and Economics, Budapest, Hungary

Abstract: This paper is devoted to microwave moisture-measurement (aquametry) and composition estimation of civil structures. In recent years considerable efforts have been made in applying microwave technique to test dielectric materials and metals. The first part of this "invited talk" is an overview of the work done by researchers (all over the World) involved in using microwave (or high frequency electromagnetic-) signals for non-destructive testing and evaluation (NDT&E) mainly of concrete (in place and fresh).
In the second part of this paper will be introduced three new instruments developed at Budapest University of Technology and Economics (BUTE). The first item is a/ direct- contact sensor (DCS), for use in bins of raw materials (such as sand-, crushed stone) and in concrete mixers. B/ a particle- board monitoring instrument (PBM), using free- space technique. And c/ a non- contact moisture sensor (NCS), for use in concrete mixers above the moving mix.
Some innovative solutions are introduced to these instruments. The DCS uses three-frequency integrated micro-strip antennas (MSA) and a protecting hard ceramic cap transformer for sensing reflections at the near- field. To reach a high accuracy and density- independent operation, a back propagation artificial neural network (ANN) was developed. Code- modulated-, passive back- scatters are applied at PBM, using circularly- polarized MSA-s. This complex permittivity monitoring system gives us information about moisture distribution, abnormal density or glue- overdose or presence of air inclusions in the board (having dimensions of 3m by 17m), at the moment of its occurrence. A cross- polarized, active back- scatter, and also an ANN is applied at NCS, which is based on a microwave free- space/ double transmission/ reflection type-, two-parameter complex vector measurement.

Introduction: Nowadays, microwave and radio frequency signals are employed for a wide variety of applications. It includes wireless communication systems, mobile phone, radar, telemetry, medicine, biology, agriculture, industrial process control, etc. Electromagnetic (EM) energy can be used efficiently in these applications only if its interaction behavior with associated substance is known. This, in turn, depends on the EM properties of that material. Therefore, the material characteristics can be deduced by analyzing the EM signals interacting with it. One of the most important parameter of materials is the water content, or moisture content (MC). Many damages in buildings are caused by moisture. They can be of various forms, 24% because of penetration of rain- water, 18% cracks, 17% combined damages, 16% are due to condensed water, 15% flaking of plaster, 5% moisture rising from ground. Damage caused by moisture required expenses of maintenance (in the year of 1996) of ca. $28 billion [1]. Low intensity microwave radiation is applied for microwave moisture measurement was called "microwave aquametry" by Kraszewski [2], [3].

Concrete is one of the major materials used in construction globally. It is comprised of cement, water, fine aggregate and coarse aggregate. The cement and water combine into a cement paste binder. The compressive strength of concrete is determined mainly by its water-to-cement w/c ratio, which can be measured by near-field microwave techniques [4]. Changes of moisture in aggregates in the range of 2 - 6% MC reduce the compression strength of concrete up to 25% [5]. Reinforcing steel bars are applied in concrete bridge decks and columns. Chloride intrusion into concrete can lead to depassivation of the steel and initiation of corrosion, which can be detected by microwaves [6]. Reinforcing steel corrosion is the cause of damage in the majority of reinforced concrete bridges in the United States.

It is essential to insert control points into modern automated manufacturing processes to ensure homogeneous product quality. Particleboard PB, chipboard, oriented strand board OSB manufacturing also needs a reliable control method that is able to monitor large size composite boards continuously [7]. The uneven density and MC distribution, voids and fissures, the uneven spreading of the glue on the particles and other less important factors have great effect on the quality of the boards. The majority of these factors can be related to the change of the properties of microwaves as they penetrate through the board [8].

Earliest reports on the concrete moisture measurement appeared in the second half of 1980's [9-12], with some patents [13-15]. Intensive R&D programs have started in 1990's at the Colorado State University, Fort Collins [16], continued in 2003 at the University of Missouri, Rolla [6,17]. There were solved some NDT&E problems of cement based materials by this research group, namely, evaluation of water-to-cement ratio and compressive strength of hardened cement paste [18,19]; evaluation of fresh concrete w/c [20]; evaluation of porosity and sand-to-cement ratio (s/c) in mortar [21]; evaluating mortar permittivity using a combined microwave near-field and modulated scattering technique [22]; evaluation of coarse aggregate-to-cement ratio (ca/c), cure-state and material properties of concrete [4, 23, 24, 25]; detection of grout in masonry bricks [26]. Near-field microwave NDT techniques have also been extensively used in evaluating chloride contamination in cement based materials [27], [28].

After studying more than 150- papers, we could mention some authors and research groups who are active on this field: Bosisio [29] in Canada; King [56], Kraszewski [2, 3], Nelson [30], Trabelsi [31], Zoughi [16, 18, etc.] and his research group in the United States; Stelzer [32] in Austria; Nyfors [33] in Finland; Bolomey [57] and Lasri [34] in France; Brandelik [35], Kupfer [1, 5, 15], Leschnik [37] in Germany, Volgyi [7,8,50-55,58-62] in Hungary; Gentili [38], Paletta [9] in Italy, Kalinski [10] in Poland, Berentsev [14] in Russia, Lenngren [39] in Sweden, Akay [25] in Turkey, Kent [40] and Wang [41] in the UK; Hayashi [42] and Okamura [43] in Japan; Khalid [44] in Malaysia, Van der Berg [45] in South Africa; Bialkowski [46] and Cutmore [47] in Australia; Holdem [48] and Lovell-Smith [49] in New Zealand.

Some measurement methods-, microwave circuit elements are given in the next references. Calibration (density independent): [31]; detection (of rebars in concrete): [16]; free space technique: [9,25,50,59,60]; GPR: [39]; homodyne system: [56]; instruments: [9,13,14,15,33,40,47,51,52,58-61]; MSA: [36,51,55,59,60,61]; MST (modulated scattering technique): [7,8,21,51,52,57,58,59,61]; multi- (and swept-) frequency technique: [2,47,48] references (overview): [3,6,12,43]; reflection measurement: [11,32,50,53,58, etc.]; six-ports: [29,32,46]; spread spectrum technique: [52]; transmission measurement: [11,13,15,31,40,46,47,50,58,60]; transmission line technique (S-parameters): [41]. Materials; sand: [1,10,12,23,53]; water: [2,9,20,53]; wood: [2,7,8,43,44,51,59].

Results and discussion for three instruments designed at BUTE (Hungary) are given next.

Results: Theoretical result [53] of the DCS for use in bins of raw materials and concrete mixers are given first. The radiating element is a 3-frequency integrated micro-strip antenna (IMA). Important part of the direct contact microwave reflection sensor [54] is a ceramic cap (Figure 1), a faceplate material, which protects the microwave units and makes a significant transformation of S-parameters. In this context the distance d_1 between antenna and ceramic cap is an essential dimension, which was optimized to obtain high sensitivity for the variation of the moisture content (MC).

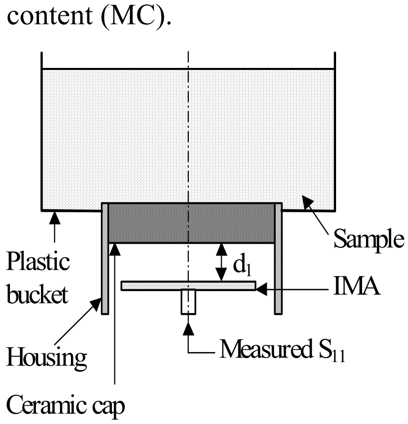

Figure 1. Cross- section view of the DCS.

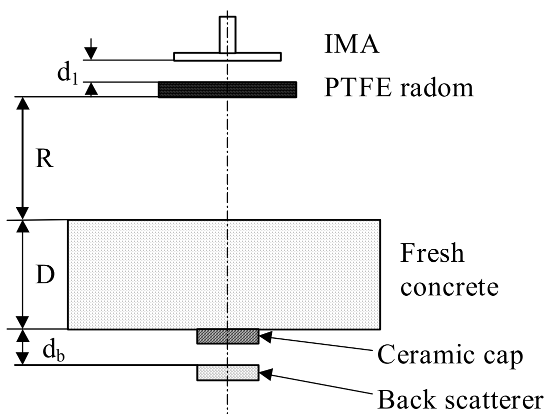

Figure 4. Model of the NCS

The direct-problem of the moisture sensing in the near field is analyzed using scattering matrix representation and signal flow graph shown in Figure 2. The thickness of sample is supposed high enough, so only the input surface reflection Γs of the sample is taken into account [53].

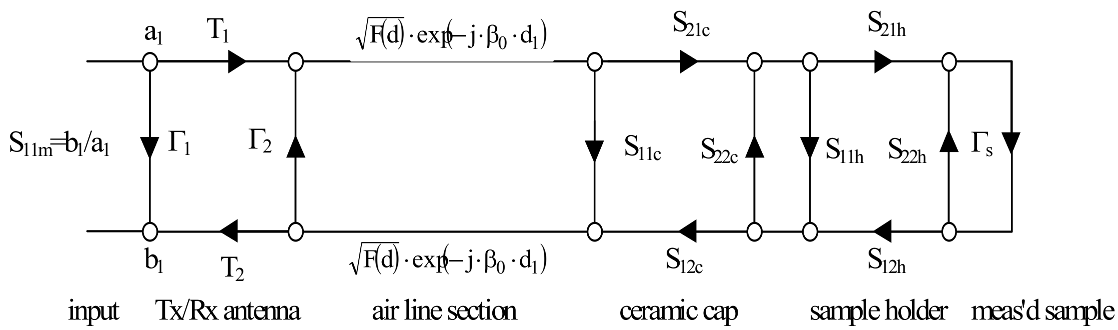

Figure 2. Signal flow graph model for the DCS.

Our task is converting complex dielectric constant of the sample to complex reflection coefficient measured at the input of the transmit - receive antenna. Using lower case indices for sample s, holder h, ceramic cap c, the thickness of sections d_i , and shifting the reference plane of S_{22c} , the ceramic cap is characterized as:

(1) $$S_{11c} = \frac{1-\sqrt{\varepsilon_{rc}}}{1+\sqrt{\varepsilon_{rc}}}$$ $$S_{21c} = S_{12c} = \sqrt{1-S_{11c}^2} \cdot \exp\left(-j \cdot \beta_0 \cdot \sqrt{\varepsilon_{rc}} \cdot d_c\right)$$ (2)

$$S_{22c} = -S_{11c} \cdot \exp\left(-j \cdot 2 \cdot \beta_0 \cdot \sqrt{\varepsilon_{rc}} \cdot d_c\right)$$ (3)

where β_0 is the phase constant of air. The scattering parameters of the sample holder are written as:

(4) $$S_{11h} = \frac{\sqrt{\varepsilon_{rc}}-\sqrt{\varepsilon_{rh}}}{\sqrt{\varepsilon_{rc}}+\sqrt{\varepsilon_{rh}}}$$ $$S_{21h} = S_{12h} = \sqrt{1-S_{11h}^2} \cdot \exp\left(-j \cdot \beta_0 \cdot \sqrt{\varepsilon_{rh}} \cdot d_h\right)$$ (5)

$$S_{22h} = -S_{11h} \cdot \exp\left(-j \cdot 2 \cdot \beta_0 \cdot \sqrt{\varepsilon_{rh}} \cdot d_h\right)$$ (6)

The surface reflection of the sample, relative to the holder and the result at the input plane of the ceramic cap are given as:

(7) $$\Gamma_s = \frac{\sqrt{\varepsilon_{rh}}-\sqrt{\varepsilon_{rs}}}{\sqrt{\varepsilon_{rh}}+\sqrt{\varepsilon_{rs}}}$$ $$S_{11v} = S_{11c} + S_{12c} \cdot S_{21c} \cdot \left(\frac{S_{11h}}{1-S_{22c} \cdot S_{11h}} + \frac{S_{12h} \cdot S_{21h} \cdot \Gamma_S}{1-S_{22h} \cdot \Gamma_S}\right)$$ (8)

The complex reflection coefficient at the input of the antenna, using a near field amplitude function $F(d_1)$ is:

$$S_{11m} = \Gamma_1 + \left(T_1 \cdot T_2 \cdot S_{11v}\right) / \left[F\left(d_1\right)^{-1} \cdot \exp\left(j \cdot 2 \cdot \beta_0 \cdot d_1\right) - \Gamma_2 \cdot S_{11v}\right]$$ (9)

In this expression, the reflection coefficients Γ_1 , Γ_2 and transmission coefficients T_1 and T_2 constitute a calibration two-port that takes into account the antenna and the part of space including an equivalent phase center of the antenna. The calculated input return loss and the phase of the input reflection are shown in Fig. 3.

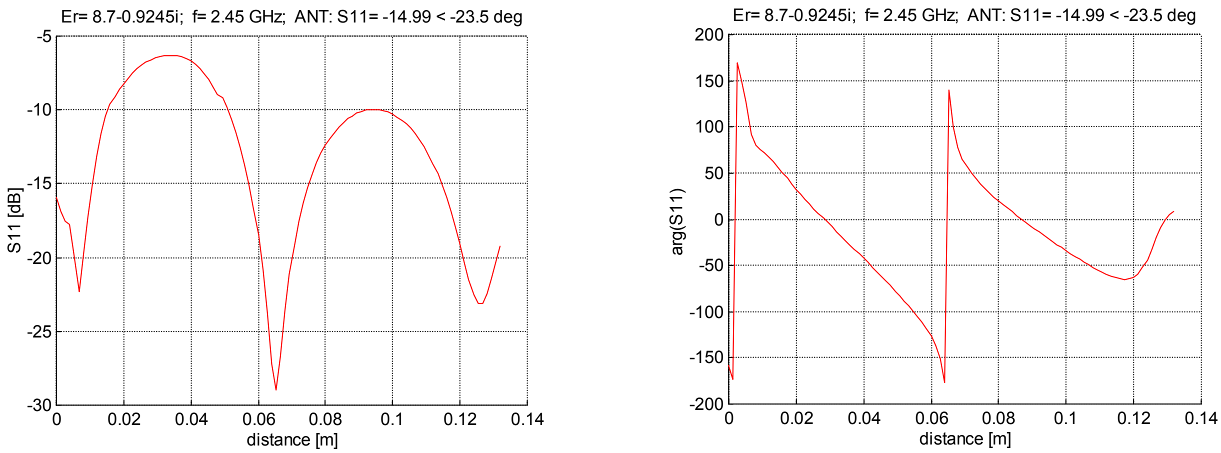

Figure 3. Simulation of the input complex reflection coefficient for moist sand versus d1 distance.

Using these equations, taking into account the dielectric mixing formula [53] and the moisture content versus complex permittivities of composite samples (moist sand, mortar, concrete, etc.), we made some calculations using our program has been implemented in MatLab. Optimization at near field with regard to the selection of the material of the hard ceramic cap and distance d1 between IMA and ceramic cap were also executed.
The model of the non-contact sensor for use in concrete mixers above the moving mix is shown in Fig. 4 (p.3). A simple analysis of the double transmission -attenuation for NCS is written next. In Figure 5 a representation of the attenuation process is shown, neglecting the multiple- reflections.

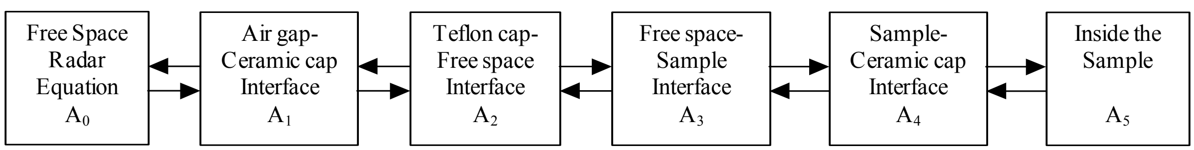

Figure 5. Double-path attenuation process for NCS.

The energy reflected at the boundaries of different materials and with it the energy due to unwanted reflections of the environment is definitely lost. That is due to the fact that those waves are not modulated by the back- scatter (BSC) and then not detected by the receiver. Setting off the radar equation (10), which accounts for free space attenuation, neglecting the air gaps d_l and d_b

$$A_0 = (4 \cdot \pi)^3 \cdot (R + D)^4 / \left(\lambda^2 \cdot \sigma \cdot G^2 \cdot \Gamma^2 \cdot M\right) \qquad (10)$$

it has to be added to attenuation due to the energy reflected inside the round path. In (10) λ is the free space wavelength, σ is the radar cross- section of the back- scatter antenna, G is the gain of the Tx and Rx antennas (IMA) when equal, Γ is the reflection coefficient of the BSC (passive or active, using amplifier), and M is a modulation efficiency at BSC. The loss of the boundary between air gap and the ceramic cap is:

$$(11) \quad A_{lac} = \left\{1 - \left[\left(1 - \sqrt{\varepsilon_{rc}}\right)/\left(1 + \sqrt{\varepsilon_{rc}}\right)\right]^2\right\}^{-1} \quad \text{and} \quad A_{lca} = \left\{1 - \left[\left(\sqrt{\varepsilon_{rc}} - 1\right)/\left(\sqrt{\varepsilon_{rc}} + 1\right)\right]^2\right\}^{-1} = A_{lac} \quad (12)$$

The attenuation inside the material due to ε_{rs}'' and the total attenuation of the double transmission path are then:

$$(13) \quad A_5 = \exp\left(\pi \cdot \varepsilon_{rs}'' \cdot 2 \cdot D / \lambda \cdot \sqrt{\varepsilon_{rs}'}\right) \quad \text{and} \quad A_T = A_0 \cdot A_5 \cdot \prod_{i=1}^{4} A_i^2 \quad (14)$$

Having neglected the attenuation inside the PTFE- and ceramic cap. Calculated results [62] for industrial planetary countercurrent mixers with yield concrete of 0.3 - 4.8 m^3, with MC = 6% are: at the frequency of 0.915 GHz, A_T = 54 - 67 dB, at the frequency of 2.45 GHz, A_T = 71 - 93 dB. For twin shaft mixers (2.1 - 7.5 m^3), the calculated total attenuation is A_T (0.915) = 62 - 75 dB, A_T (2.45) = 92 - 117 dB. To handle this large attenuation in industrial environment, a sophisticated code- modulation will be applied at BSC.

Discussion: Near- field microwave nondestructive testing techniques, namely the measurement of reflection coefficient in direct contact with dielectric materials, employing MSA [55] or OERW probes, have shown tremendous potential for evaluating concrete constituent make-up [23]. Recognizing the advantages of a multi-frequency measurement system, we have designed a three- band DCS (Figure 6). First a frequency synthesizer was developed, using a crystal oscillator as its base to give excellent frequency stability over a wide temperature range and giving an output at the lowest of the three operating frequencies. Frequency multipliers generate the other two frequencies. Standard microwave circuits: band- pass filters, amplifiers, PIN-diode switches, splitters and modulators are used in the measurement system. The application of cascaded-, or four-port drop-in circulators gives excellent isolation between the transmitter and the receiver [54]. Homo-dyne receivers [56], [57] are used, because high dynamic range and measurement accuracy are needed. These receivers supply the in-phase (I) and quadrature-phase (Q) components of the reflection coefficients. Each receiver consists of a Wilkinson-hybrid, a quadrature-hybrid, two balanced mixers, band- pass filters and post amplifiers. High level mixers are used, decreasing the non-linear distortions.

For NDT of chipboards and for monitoring their parameters, MSA-s and micro-strip sensors [51, 52, 58] can be advantageously applied. The basic measurement set-up for monitoring particle- boards PBM [59] is shown in Figure 7. This is a free- space, reflection / double transmission system in which the attenuation (ΔA) and phase ($\Delta \Phi$) are measured by the receiver. The microwave transmitter (Tx), which is working in one of the industrial-scientific-medical (ISM) frequency bands, radiates a continuous wave (CW) during the measurement. After passing through the measured moist substance, this wave is reflected by one of the PDB-s. At the microwave

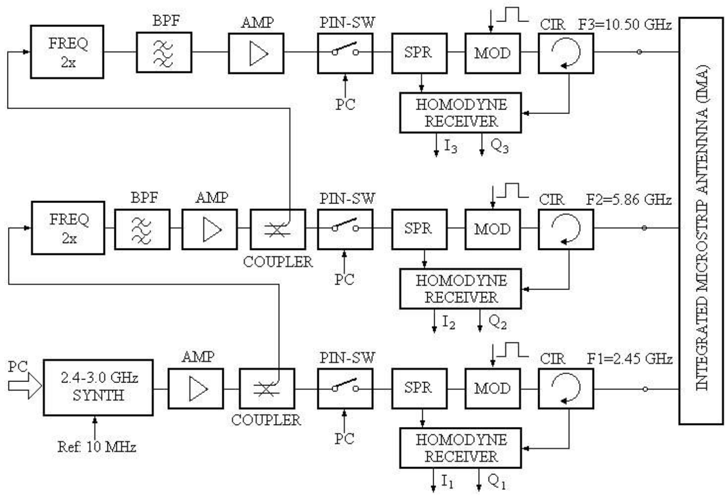

Figure 6. Block diagram of the microwave DCS for use in bins of raw materials and in concrete mixers.

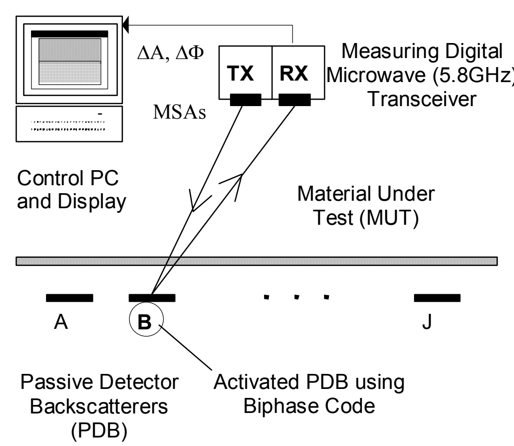

Figure 7. The basic measurement set-up for PBM (particle- board monitoring system).

receiver (Rx) the signal is converted to IF stage and then sampled by the DSP unit, which carries out the code correlation. The two parameters (ΔA and $\Delta \Phi$) can be measured, and the relative complex permittivity, MC, wet and dry densities, etc., can be calculated from the measured data. Circularly polarized MSA-s are used in the system, eliminating the disturbing effects of the reflected wave from the air-slab interface. More details of this system are given in [7], [8], [59], [60] and [61].

Microwave non-contact transmission and double- transmission sensors are advantageously applied e.g. for control of hen-eggs [50], or for use in concrete mixers [62] and inspection of civil structures. We have designed a NCS for this purpose using cross-polarized-, active BSC. A preliminary measurement set-up [62] is shown in Figure 8. The dual- polarized, single MSA- patch receives the co- polarized signal, which is amplified (14 dB) by a low noise amplifier, modulated and re-radiated in cross polarization. This double-transmission signal is received by the Rx-MSA. The experiment with fresh concrete show linear function of the attenuation versus moisture content, namely: A [dB] = 24.1 + 1.2 MC [%], at the frequency of F_0 = 2.457 GHz. The measurement is independent of the density and the distance- variation between transmit / receive antennas and material, because two additional frequencies are used around F_0 (e.g. ± 40 MHz). The new instrument, developed, will also apply the 0.9 GHz frequency- band.

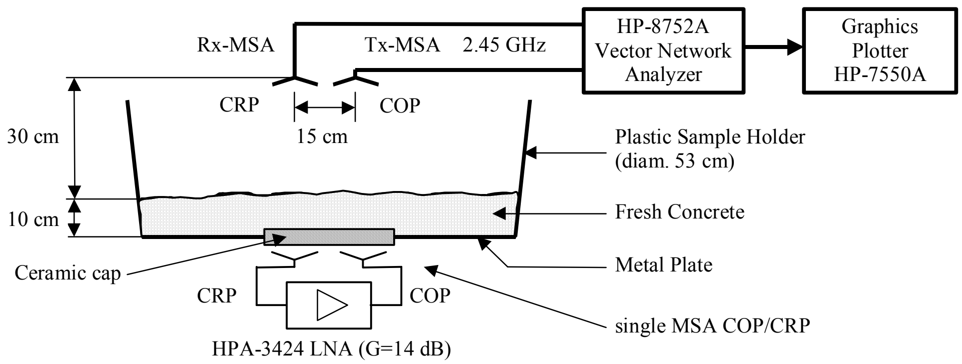

Figure 8. Measurement setup for NCS using active-BSC.

Conclusions: In recent years, microwave NDT&E techniques, mostly in the near field using open- ended rectangular waveguide probes, coaxial mono-pole antennas, microstrip antennas, have been extensively used to interrogate a wide variety of cement based materials for their important physical and structural properties. Some examples of these R&D projects were mentioned in the Introduction of this paper.

Three microwave instruments developed at BUTE (Hungary) had been introduced for inspection of civil structures and materials of building industries. New microwave moisture sensors presented show some significant advantages for water content determination in bins of raw materials and in concrete mixers. The reflection type DCS is being used on-line, density-independent, improved measurement speed and is able to measure moisture content accurately in materials with large granule size, due to the multi-frequency operation (2.45-5.85-10.50 GHz) and the application of ANN.

A free-space arrangement was applied at PBM, using the modulated scattering technique. This microwave NDT of particle- boards gives us information about moisture content, abnormal density or glue overdose or presence of air inclusions in the board at the moment of its occurrence. Industrial tests showed that the developed measurement system is suitable for on-line, real-time quality monitoring of large boards (3m x 17m). Our software can display graphically the surface distribution of these parameters on the whole board, so its quality could be judged simply at a glance.

The double frequency (0.9 and 2.45 GHz) NCS is designed for use in concrete mixers above the moving mix, or for inspection of civil structures with large wall-thickness, because of the high dynamic range in attenuation measurement. The active BSC is independent of the Tx/Rx unit, so the arrangement is practically single-sided. The density-independent operation will be provided by an ANN with self-learning by presenting samples of different moisture and density.

References:

[1] Kupfer, K., ”Radio-frequency and Microwave Moisture Sensing of Building Materials”, *Sensors Update*, Wiley-VCH, Weinheim, GE, ISBN 3-527-29821-5, vol. 7, pp. 27-50, 2000.

[2] Kraszewski, A. (ed): *Microwave Aquametry*, IEEE Press, New York, ISBN-0-7803-1146-9, 484 p, 1996.

[3] Kraszewski, A., "Microwave aquametry: an effective tool for nondestructive moisture sensing" Subsurface Sensing Technologies and Applications (SSTA), An Int. Journal, 2(4) pp. 347- 362, October 2001.

[4] Bois, K.J., A. D. Benally, P.S. Nowak and R. Zoughi, "Cure-State Monitoring and Water-to-Cement Ratio Determination of Fresh Portland Cement-Based Materials Using Near Field Microwave Techniques”, *IEEE Trans.Instrum.Meas*., v. 47, pp. 628-637, June 1998

[5] Kupfer, K., "RF & microwave instrumentation for moisture measurements in process and civil engineering", Proc. Conf. SSTA-1, Denver, SPIE Vol. 3752, pp. 39-46, July 1999.

[6] Peer, S., J.T. Case, E. Gallaher, K.E. Kurtis and R. Zoughi, "Microwave Reflection and Dielectric Properties of Mortar Subjected to Compression Force and Cyclically Exposed to Water and Sodium Chloride Solution", *IEEE Trans.Instrum.Meas*., v.52, pp. 111--8, 2003

[7] Volgyi, F., ”Microwave NDT of Particle-boards”,*12th Int.Symp. Nondestructive Testing of Wood*, pp. 357-365, Sopron, HU, Sep 2000

[8] Volgyi, F., and Zombori, B.,”A New Application of WLAN-Concept: Complex Permittivity Monitoring of Large-Sized Composite Boards”, *2nd Intern. Conf. Electromagnetic Wave Interact. Water and Moist Subst.*, pp. 119-122, San Francisco, 17-21 June 1996.

[9] Paletta, F., A.M. Ricca, "Concrete moisture evaluation by microwaves", Alta Frequenza, vol. LV- N.4, pp. 255-264, July-Aug 1986.

[10] Kalinski, J., "On-line MC monitoring of building materials using microwaves" 8th MICROCOLL, Budapest, pp. 171-172, Aug 1986

[11] Clemena, G.G., "Determining water content of fresh concrete by microwave reflection or transmission measurement", Final report PB88-120548, Virginia Transportation Research Council, 15 pp, August 1987.
[12] Rose, M., "Nonintrusive Moisture Analyzer for Concrete", Tech. Innovation., Cleveland, OH, Report, NSF/ISI-88156, 25 Aug 1988
[13] Schmidt, J., and B. Wunderlich, "Moisture content measurer for bulk goods uses hollow body shaping part between waveguides for microwaves; concrete admixed material", German Patent, DD-242487, Jan. 28, 1987.
[14] Berentsev, R.A., V.K. Benzar, and Y.U.M. Mamontov, "Porous materials moisture microwave meter - has calculator, transformer and load for improving measurements precision", Soviet Union Patent, SU-1337746, Sept. 15, 1987.
[15] Kupfer, K., G. Fuchs, B. Beutler, E. Wilhelm, and K. Morgeneier, "Microwave moisture content measuring circuit for bulk materials has computer to form quotient of attenuation and phase shift in measuring and reference path", GE -Patent, DD-288229, Sept. 29, 1989
[16] Zoughi, R., G.L. Cone and P.S. Nowak, "Microwave Nondestructive Detection of Rebars in Concrete Slabs", *Mater. Eval.,* vol. 49, no. 11, pp. 1385-1388, Nov 1991.
[17] Peer, S., K.E. Kurtis, and R. Zoughi, "An Electromagnetic Model for Evaluating Temporal Water Content Distribution and Movement in Cyclically Soaked Mortar", *IEEE Trans. Instrum. Meas*., vol. 53, April 2004.
[18] Zoughi, R., S. D. Gray and P.S. Nowak, "Microwave Nondestructive Estimation of Cement Paste Compressive Strength", *ACI Mater. J.,* vol. 92, no. 1, pp. 64-70, Jan.-Feb. 1995.
[19] Shalaby, W. and R. Zoughi, "Microwave Compressive Strength Estimation of Cement Paste Using Monopole Probes", *Res. Nondestruct. Eval.,* vol. 7, no. 2/3, pp. 101-115, 1995.
[20] Mubarak, K., K.J. Bois and R. Zoughi, "A Simple, Robust, and On-Site Microwave Technique for Determining Water-to-Cement Ratio (w/c) of Fresh Portland Cement-Based Materials", *IEEE Trans. Instrum. Meas*., vol. 50, pp. 1255-1263, October 2001.
[21] Bois, K.J., A. Benally, P.S. Nowak and R. Zoughi, "Microwave Non-destructive Determination of Sand-to-Cement Ratio in Mortar", *Res. Nondestruct. Eval.*, vol. 9, no. 4, pp. 227-238, 1997.
[22] Joisel, A., K.J. Bois, A.D. Benally, J. Bolomey and R. Zoughi, "Embedded Modulating Dipole Scattering for Near-Field Microwave Inspection of Concrete: Preliminary Investigation", *SPIE Conf. SSTA-1*, vol. 3752, pp. 208-214, Denver, Colorado, USA, 19-21 July 1999
[23] Bois, K.J., A.D. Benally and R. Zoughi, "Microwave Near-Field Reflection Property Analysis of Concrete for Material Content Determination", *IEEE Trans. Instrum. Meas*., vol. 49, pp. 49-55, February 2000.
[24] Bois, K. and R. Zoughi, "A Decision Process Implementation for Microwave Near-Field Characterization of Concrete Constituent Makeup", *Subsurface Sensing Technologies and Applications (SSTA) Int. Journal*, vol. 2, pp363-376, Oct 2001
[25] Kharkovsky, S.N., M.F. Akay, U.C. Hasar, C.D. Atis, "Measurement and Monitoring of Microwave Reflection and Transmission Properties of Cement Based Specimens", *IEEE/ IMTC'01*, pp. 513-518, Budapest, Hungary, May 21-23, 2001.
[26] Bois, K.J., H. Campbell, A. Benally, P.S. Nowak and R. Zoughi, "Microwave Non-invasive Detection of Grout in Masonry", *TMS Journal*, vol. 16, no. 1, pp. 49-54, June 1998.
[27] Bois, K., A. Benally and R. Zoughi, "Near-Field Microwave Non-invasive Determination of NaCl in Mortar", *IEE Proc.-Sci., Meas. Technol.,* vol. 148, pp. 178-182, July 2001.
[28] Hu, C., A. Benally, T. Case, R. Zoughi and K. Kurtis, "Influence of Chloride in Mortar Made of Portland Cement Types II, III and V on the Near-Field Microwave Reflection Properties", *SPIE Conf. SSTA-2*, vol. 4129, pp. 31-38, San Diego, California, USA, Aug 2000
[29] Xu, Y., R.G. Bosisio "Six-port engineering applied to signal comparators" SSTA-1, Denver, CO, SPIE v. 3752, 346-354, July 1999
[30] Nelson, S.O., "Determining dielectric properties of coal and limestone by measurements on pulverized samples" Journal of Microwave Power and Electromagnetic Energy, Vol. 31, No. 4, pp. 215-220, 1996.[
[31] Trabelsi, S., A.W. Kraszewski and S.O. Nelson, "New density-independent calibration function for microwave sensing of moisture content in particulate materials", IEEE Transactions on Instrumentation and Measurement, vol. 47, no. 3, pp. 613-622, June 1998.
[32] Stelzer, A., C.G. Diskus, and C. Gamsjager, "Error propagation in a practical six-port device" Subsurface Sensing Technologies and Applications (SSTA), 2(2) pp. 77-97, July 2000.
[33] Fischer, M., P. Vainikainen, and E. Nyfors, "Design aspects of strip-line resonator sensors for industrial applications", Journal of Microwave Power and Electromagnetic Energy, Vol. 30, No. 4, pp. 246-257, 1995.
[34] Glay, D., T. Lasri, A. Mamouni, Y. Leroy, "Free Space Moisture Profile Measurement", *4th Intern. Conf. Electromagnetic Wave Interact. Water and Moist Subst.,* pp. 235-242, Weimar, Germany, May 13-16, 2001.
[35] Brandelik, A., C. Huebner, S. Schlaeger, and M. Stacheder, "Determination of snow density and snow water equivalent for hydro power generation", ISEMA'03, pp. 196-202, Rotorua, NZ, 23-26 March 2003.
[36] Menke, F., R. Knöchel, "Portable Moisture Measurement System", *2nd Intern. Conf. Electromagnetic Wave Interact. Water and Moist Subst.,* pp. 87-90, San Francisco, 17-21 June 1996.
[37] Leschnik, W. and U. Schlemm, "Theoretical and Practical Investigation in the Influence of Inhomogeneities in the Microwave Measurement of the Moisture and Salt Content of Building Materials", *ISHM'02*, pp. 304-309, Taipei, Taiwan, R.O.C. 16-19 Sep. ,2002.
[38] Gentili, G.B., and C. Riminesi, "Full-wave modeling of microwave planar reflection sensors for material moisture testing" Subsurface Sensing Technologies and Applications (SSTA), An Int. Journal, 2(4) pp. 453 - 470, October 2001.
[39] Lenngren, C., J. Bergström and B. Ersson, "Using Ground Penetrating Radar for Assessing Highway Pavement Thickness", *Subsurface Sensing Technol. Appl*., vol. 4129, pp. 474-483, San Diego, 2000
[40] Kent, M., R.H. Christie and A. Lees, "A portable fat meter suitable for live salmonid fish", pp. 387-394, Ch. 27 in book: Kraszewski, A. (ed): "Microwave Aquametry", IEEE Press, New York, ISBN-0-7803-1146-9, 484 p, 1996.
[41] Wang, Q., K. Ahmet, Y. Yue and Ch. Yan, "Dielectric Properties of Gypsum Plaster-Based Materials", *ISEMA'03*, pp. 291-299, Rotorua, New Zealand, 23-26 March 2003.

[42] Hayashi, Y., M. Asano, N. Shinyashiki, S. Yagihara, M. Shiotsubo, Y. Kato, T. Uomoto, ”Dielectric Measurement for Mortar: Curing Time Dependency of Relaxation Spectra of Hydrated Water and Non-destructive Test”, *4th Intern. Conf. Electromagnetic Wave Interact. Water and Moist Subst.*, pp. 243-250, Weimar, Germany, May 13-16, 2001.
[43] Okamura, S., "Microwave technology for moisture measurement" Subsurface Sensing Technologies and Applications (SSTA), An Int. Journal, 1(2) pp. 205- 227, April 2000.
[44] Khalid, K., M.H. Shari, N.K. Keong, and S.A. Fuad, "Microwave dielectric properties of wooden cross-arms", Proc. Conf. SSTA-1, Denver, Colorado, SPIE Vol. 3752, pp. 146-156, July 1999.
[45] Van der Berg, J., P. Swart and B. Lacquet, ”Microwave Properties of Phosphate Rock”, *Journal on Microwave Power and Electromagnetic Energy*, vol. 27, no. 3, pp. 183-189, 1992.
[46] Robinson, A. and M. Bialkowski, "Single- and multiple-frequency phase change methods for microwave moisture measurement", pp. 413-422, Ch. 30 in book: Kraszewski, A. (ed): "Microwave Aquametry", IEEE Press, New York, ISBN-0-7803-1146-9, 484 pp, 1996.
[47] Cutmore, N.G., and N. Cutmore, "Moisture content measuring appts. for material on conveyor belt - uses averaged phase shifts of microwave signals passed through material at discrete frequencies in combination with mass per unit area", Australian Patent, AU-9061689, April 03, 1991, and WO-9102966, March 07, 1991.
[48] Holdem, J.R., R.B. Keam, and J.A. Schoonees, "Estimation of the number of frequencies and bandwidth for the surface measurement of soil moisture as a function of depth", IEEE Trans. on Instrum. and Meas., vol. 49, no. 5, pp. 964-970, October 2000.
[49] Lovell-Smith, J., M. Cunningham and R. Keey, ”Techniques for the Measurement of Moisture Profiles in Drying Concrete Slabs”, *4th Intern. Symp. Humidity and Moisture 2002 (ISHM’02),* pp. 296-303, Taipei, R.O.C. 16-19 Sep 2002
[50] Volgyi, F., "Specifying the freshness of eggs using microwave sensors", *(SSTA) Int. J.,* 1(1) pp. 119-139, Jan 2000.
[51] Volgyi, F., "Microstrip sensors used in microwave aquametry" in book: Kupfer K, Hubner C (eds), Proceedings of the Fourth Intern. Conference on Electromagnetic Wave Interaction with Water and Moist Substances, Weimar, GE, pp. 135-142, May 13-16, 2001.
[52] Volgyi, F., "Design of an on-line sensor system with spread-spectrum and modulated back-scatter techniques", Proceedings of the Conference SSTA-3, San Diego, CA, USA, 29 July- 3 August 2001.
[53] Volgyi, F., J. Burrows and R. Shepherdson, ”Calibration Methods for Non Density-Sensitive Microwave-Based Moisture Sensors”, 4th International Symposium on Humidity and Moisture, *ISHM’02*, pp. 371-378, Taipei, Taiwan, R.O.C. 16-19 Sept. 2002.
[54] Volgyi, F., R. Shepherdson and J. Burrows, ”New Microwave Moisture Sensors for Use in Bins of Raw Materials and In Concrete Mixers”, *ISEMA’03*, pp. 291-299, Rotorua, New Zealand, 23-26 March 2003.
[55] Volgyi, F. (assoc.ed.), Special issue on WLAN and ISM applications of microstrip antennas, *Telecommunications* (Hiradastechnika), J C^5 L(12), Budapest, 76 pp. 1999.
[56] King, R.J., "Microwave homodyne systems" Peter Peregrinus Ltd., Stevenage, Herts, England, ISBN-0-901223-52-2, 368 pp, 1978.
[57] Bolomey, J.-Ch., and Gardiol, F.E., "Engineering applications of the modulated scatterer technique", Artech House, Boston, ISBN-1-58053-147-4, 255 pp, 2001.
[58] Volgyi, F., "Microstrip transmission- and reflection type sensors used in microwave aquametry" Ch.11 in book: Electromagnetic Aquametry, by Kupfer K (ed), Springer-Verlag GmbH&Co.KG, Berlin/Heidelberg. Will be published in 2004.
[59] Volgyi, F., "Monitoring of the PB-production using microwave sensors", *Sensors Update,,* v.7, Wiley, Weinheim, 249-274, 2000.
[60] Volgyi, F., "Integrated Microwave Moisture Sensors for Automatic Process Control" pp. 223- 238, in Kraszewski, A. (ed): *Microwave Aquametry*, IEEE Press, New York, ISBN-0-7803-1146-9, 484 p, 1996.
[61] Volgyi, F., I. Mojzes, M. Kelemen, L. Racz, R. Seller, A. Sonkoly, F. Divos, B. Zombori "Method and equipment for specifying the parameters of substances, applied mainly for moving multi-layer-, sheet-like materials", Hungarian pat. applicat., P.9601630, June 1996.
[62] Volgyi, F., "Non-contact microwave sensor for use in concrete mixers above the moving mix", Research Report, Scale- Tron Inc., Montreal, Canada, 80 p, May 2003.