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# Moisture content measurements through TDR: a metrological assessment for industrial applications

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***Abstract-*** In this paper a metrological assessment on the accuracy provided by a Time Domain Reflectometry (TDR)-based method for the estimation of moisture content of granular materials is proposed. In particular, comparative moisture content measurements are carried out through two different TDR instruments: an inexpensive portable unit and a high-performance unit. The main goals are first to assess a robust procedure for TDR moisture monitoring (in particular for sand-like materials), and second to provide a deep metrological analysis for minimizing and characterizing error contributions. This feature is particularly important when considering the proposed measurement procedures for industrial applications, where both accuracy and low cost must be guaranteed.

***Keywords-*** time domain reflectometry, moisture measurements, metrological characterization, quality control.

## I. Introduction

Microwave-based sensing techniques are increasingly becoming an attractive alternative for various monitoring purposes in laboratory, as well as in industrial fields. This success is fostered by the need of reliable, continuous, and accurate quality controls: all requirements that microwave sensing meets. In particular, Time Domain Reflectometry (TDR)-based measurements are now considered as a standard approach for moisture content monitoring of materials. As a matter of fact, the simplicity of the scientific principles of TDR, the considerable level of accuracy achieved, and, most importantly, the versatility are the key-features that have contributed to the popularity of TDR [1-5]. In previous papers, the Authors have explored the practical implementation of TDR-based monitoring system for different industrial applications. The main goal of this work is to demonstrate that the performance provided by the proposed monitoring method is such that an averagely-performing TDR instrument guarantees definitely adequate measurement accuracy [6-8]. In this regard, moisture content measurements are carried out on a test-material (sand), using two different TDR units: one is an inexpensive portable unit, whereas the other is a more performing (and expensive) laboratory unit. Results are compared in terms of the provided accuracy. Furthermore, the uncertainty associated with water content measurements is calculated through the evaluation of confidence interval derived from a non-linear regression method. The aim is to show that the uncertainty associated with measurement carried out through a non-expensive piece of equipment remains acceptably good even when compared to measurements obtained through its more expensive counterpart. These results are achieved thanks to some suitable strategies proposed herein, in particular a specific preliminary calibration procedure that makes the approach extremely robust, and the compensation of residual error contributions. It is worth mentioning that, although in related literature several papers deal with TDR-based method for soil moisture evaluation, a rigorous metrological characterization that allows extending the obtained results to different experimental conditions is nowhere to be found.

## II. Experimental set-up

The considered monitoring system has been fully described in previous work [6-8]: basically, an electromagnetic step pulse, generated by TDR instruments, reaches a metallic probe immersed in the material to monitor. By analyzing the reflected signal, one can gather information on the dielectric behaviour of the material under test, strictly related to the water content level. As aforementioned, the TDR instruments considered for the metrological comparative analysis are a Campbell Scientific TDR100 and a Tektronix ® DSA8200, equipped with a TDR 80E04 module. The former is a portable low-cost TDR (signal rise time of 200 ps), whereas the TDR 80E04 is a more sophisticated and expensive laboratory unit (signal rise time of 17.5 ps). The used probe, shown in Figure 1, is a 15 cm-long three-rod probe [9].

## III. Proposed approach

As well known, all measurements are affected by systematic and random effects on the global error. A suitable calibration of the used probe is carried out in order to strongly reduce the contributions of systematic error effects. On the other hand, random fluctuations are taken into account through a statistical approach.

For the proposed metrological characterization, comparative measurements on sand are carried out first using the TDR 100 and then using the TDR80E04. It is worth noting that the moisture levels are the same for the measurements with both instruments: in fact, measurements are performed connecting the probe alternately to the two considered instruments.

All the values of the dielectric constant reported in this paper are the average values of a 10-measurement set: the acquired data are used to extrapolate a calibration curve for the material under test, thus evaluating the $\theta$-$\varepsilon$ dependence and the resulting confidence interval associated to the final moisture data.

### A. Probe calibration

As largely reported in related literature [4, 5, 10, 11], the dielectric constant of the material under test is calculated through the following equation:

$$\varepsilon_r = \left(\frac{L_a}{L_p}\right)^2 \qquad (1)$$

where $L_p$ is the nominal probe length (which is 15 cm in this case), and $L_a$ is the apparent probe length in the medium under test. However, to obtain a more accurate value of the actual probe length (Figure 1), it is necessary to accurately individuate the sections corresponding to the beginning and to the end of the probe (points 1 and 2 in Figure 1, respectively). For this reason, a probe calibration is carried out and the exact value of $L_{p,actual}$, to which refer $L_a$, is established. The calibration of the probe consists of a set of ten measurements performed on two well-referenced materials (de-ionized water at a fixed temperature and air) [9].

The probe calibration is performed for each of the used instruments. The actual probe length $L_{p,actual}$ of the used probe is 15.16± 0.03 cm for the TDR100 and 15.74 ± 0.01 cm for the TDR80E04.

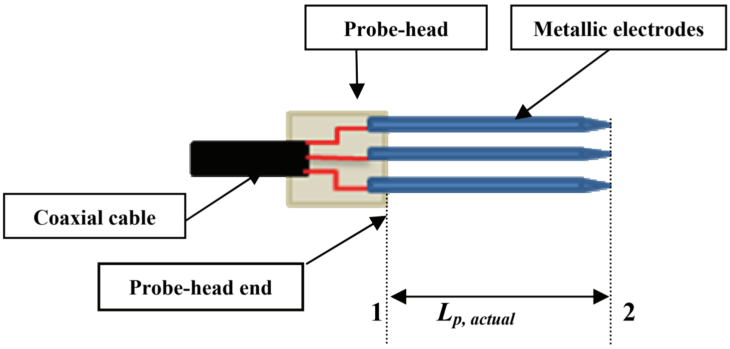


Figure 1.Cross section of the three-rod probe

In order to further assess the accuracy of the proposed method, an appropriate simulation of the measurement system has been performed, comparing the measured TDR waveforms with the ideal ones. In particular, the simulation has been performed implementing a transmission line model through AWR Microwave Office (MWO) circuit simulator. The model consists of three transmission line sections: the connecting cable, the TDR probe-head embedded in teflon, and the TDR probe immersed in the material under test.

The characteristic impedance of the TDR probe sections has been derived based on the formulation suggested in [12]. As an example, TDR curves obtained by inverse transformation of MWO-derived frequency responses for the probe immersed in dry sand are shown in Figure 2: the comparison shows a good agreement between measurement and simulation.

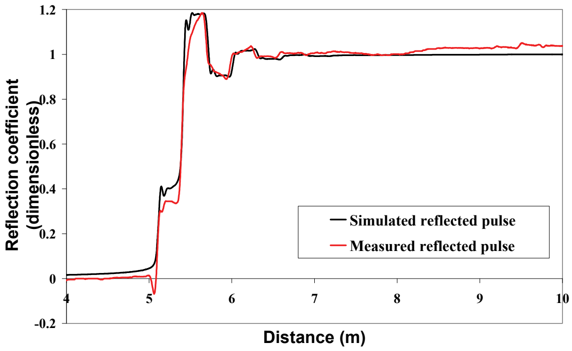


Figure 2. Comparison between measured and simulated TDR waveforms in sand

### B. Uncertainty evaluation for the dielectric constant

As aforementioned, each data point of the dielectric constant is derived as the average of ten measurements performed on the same sample (in turn, each measurement is the result of twelve automatically-repeated acquisitions). Successively, the uncertainty in $\varepsilon$ is evaluated through the traditional uncertainty propagation theory [13]. Furthermore, in order to verify whether the error distribution is appropriately described by a normal distribution, a *t*-Student distribution is applied to the data.

### C. Confidence band evaluation for the calibration curve

As reported in literature [10, 11] and in previous works of the Authors, the experimental data are best fitted by a third-order polynomial. This way, the following equation represents the calibration curve; in correspondence of each measured dielectric constant value $\varepsilon$, the model gives the corresponding moisture level ($\theta$):

$$\theta = B_0 + B_1 \cdot \varepsilon + B_2 \cdot \varepsilon^2 + B_3 \varepsilon^3 \tag{2}$$

where $B_0$, $B_1$, $B_2$ and $B_3$ are the regression coefficients.
In order to characterize the extrapolated value of $\theta$ from a metrological point of view, the associated uncertainty is evaluated through the non-linear regression theory [13]. Hence, the variance analysis for the single values expected from the previous equation, is conducted according to the formula:

$$\mathrm{var}[\theta] = \sigma^2 \left( 1 + \frac{1}{n} + \sum_i \left( \frac{\partial \theta}{\partial B_i} \right)^2 \mathrm{var}[B_i] + 2 \sum_{ij} \left( \frac{\partial \theta}{\partial B_i} \frac{\partial \theta}{\partial B_j} \right) \mathrm{cov}[B_i, B_j] \right) \tag{3}$$

where var[$\theta$] is the variance of the moisture level, $\sigma^2$ is the variance between experimental and fitted data, $n$ is the number of experimental points, $i, j = 0, 1, 2, 3$ and cov[$B_i$, $B_j$], is the covariance of the $B_i$ parameter with respect to the $B_j$ parameter.
In correspondence of a confidence level of 95%, the equations associated to the lower and upper confidence limits for the calculated regression curve are given by the following equations (where $\alpha$ is the significance level of 5%):

$$L_{low} = (B_0 + B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3) - t_{n-4,1-\frac{\alpha}{2}} \sqrt{\mathrm{var}[\theta]} \tag{4}$$

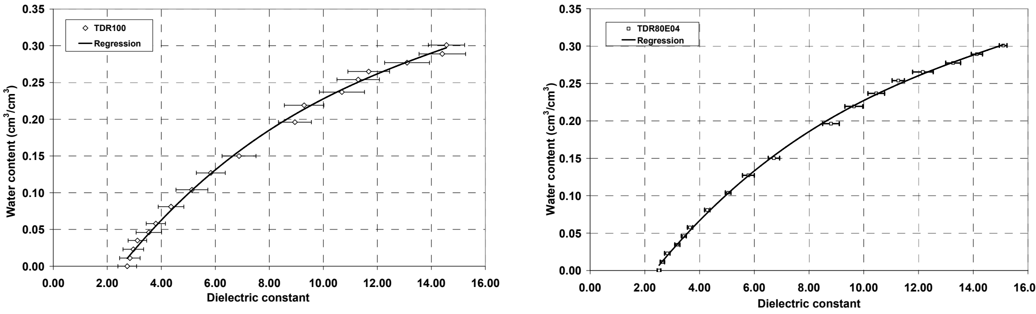
$$L_{up} = (B_0 + B_1\varepsilon + B_2\varepsilon^2 + B_3\varepsilon^3) + t_{n-4,1-\frac{\alpha}{2}} \sqrt{\mathrm{var}[\theta]} \tag{5}$$

### D. Preparation of the samples

For the TDR measurements, the sand is placed inside an open-top “large box” (1 m X 1 m X 0.3 m) and is homogeneously moistened, at room temperature at pre-established levels, according to the volumetric method reported in [14]. Successively, a sample is removed from the box, placed inside a cylindrical sample holder (with a diameter of 7 cm, graduated up to 2000 ml) and characterized. Preliminary measurements confirmed that boundary effects due to the used holder are negligible. Indeed, this is a major advantage over other well-known moisture content measurement methods, such as capacitive method or ultrasonic sensor. In fact, in the last two cases, the involved low-frequency range requires the use of large boxes intended to prevent interferences caused by boundary effects.

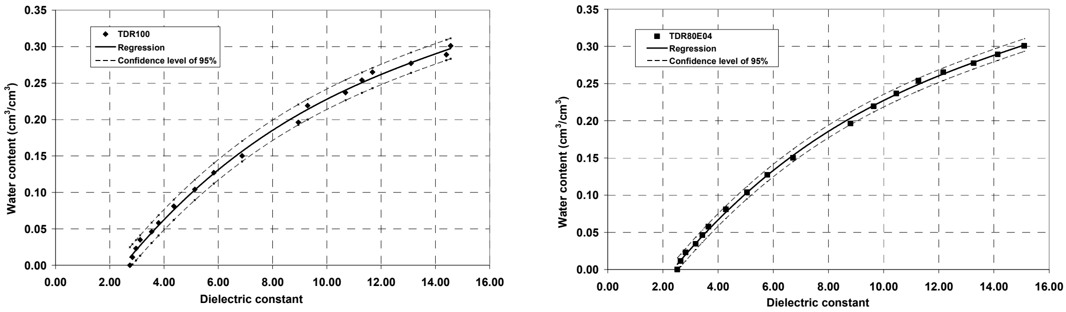
## IV. Results and discussion

In Figure 3 a), b) the calibration curves related to measurements performed with the two instruments are reported. The experimental points in the plot correspond to 18 pre-established different moisture levels to which the sand is sequentially moistened. The uncertainty for the 18 moisture levels (in the worst case) has been evaluated and is less than 0.02 %. Figure 3 also shows that, being the TDR80E04 a more performing instrument, the bars related to the dielectric constant uncertainties are narrower than the ones corresponding to the TDR100 measurements.



a) b)

Figure 3. Calibration curves for sand for measurements performed a) through TDR100, b) through TDR80E04. Uncertainty bars are also reported



a) b)

Figure 4. Confidence intervals of the fitted regression curves for measurements performed through a) TDR100, b) TDR80E04

Figure 4 shows the calibration curves with the related confidence bands, which, in both cases, are extremely narrow. In particular, in the case of TDR100, the absolute uncertainty value (derived from (4) and (5)), for the calculated moisture level is 0.014, whereas for the TDR80E04 it is about 0.008. These values are mainly attributable to the broader dispersion of the TDR100 experimental points, with respect to the dispersion of the TDR80E04 experimental points

## V. Conclusions

In this paper a metrological assessment of TDR measurements of moisture content of granular materials has been made. The goal was to show that TDR-based measurements have achieved a considerable level of accuracy, and that even instrument with non-enhanced performances can provide good reliability: this is particularly useful for practical moisture monitoring in industrial applications, where any implementation should always consider the involved costs. The good level of accuracy achieved is closely related to two aspects, namely to an optimized calibration procedure that de-embed the measurements of the systematic error contributions and to the regression method that has been adopted for statistically processing the data. In particular, for the considered material, the maximum percentage relative uncertainty in dielectric constant estimation is 4% for the TDR80E04 measurements and 12% for the TDR100 measurements, as derived from the application of the uncertainty propagation theory to (1). Although 12% may seem high, it should be underlined that, considering the low costs involved in the used instrumentation, this value appears reasonably acceptable.

In the future, the Authors plan to further explore TDR solutions for industrial applications, in particular a standardized procedure for TDR-based measurements and a rigorous metrological characterization will be thoroughly investigated.

## References

[1] J. R. Andrews, “Time Domain Reflectometry”, *Proc. Symposium and Workshop on Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications (Northwestern University, US, Bureau of Mines)* SP-19-94, pp. 4–13, 1994.

[2] F. N. Dalton, W. N. Herkelrath, D. S. Rawlins, and J. D. Rhoades, “Time domain reflectometry: Simultaneous measurements of soil water content and electrical conductivity with a single probe”, *Science*, vol. 224, pp. 989–990, 1984.

[3] K. Noborio, “Measurement of soil water content and electrical conductivity by time domain reflectometry: a review”, *Computers and Electronics in Agriculture*, vol. 31, pp. 213–237, 2001.

[4] S. Pepin, A. P. Plamondon, and J. Stein, “Peat water content measurement using time domain reflectometry”, *Can. J. For. Res. J.*, vol. 22, pp. 534–540, 1992.

[5] J. Ledieu, P. De Ridder, P. De Clerck, and S. Dautrebande, “A method measuring soil water moisture by time-domain reflectometry”, *J. Hydrol.*, vol. 88, pp. 319–328, 1986.

[6] A. Cataldo, M. Vallone, G. Cannazza, and M. Cipressa, “TDR Moisture Measurement in Granular Materials: from the Siliceous Sand test-case to the Applications for Agro-food Industrial Monitoring”, *submitted for the Special Issue of the Computer Standards and Interfaces on XV IMEKO TC-4 Symposium.*

[7] M. Vallone, A. Cataldo, and L. Tarricone, “TDR Moisture Measurement in Sand-like Materials: a Comparison between Different Calibration Procedures”, *Proc. 15th IMEKO TC4 Symposium on Novelties in Electrical Measurements and Instrumentation (Iasi, Romania, September 2007).*

[8] M. Vallone, A. Cataldo, and L. Tarricone,“TDR Water Content Estimation in Granular Materials by Time Domain Reflectometry: a Key-note on Agro-Food Applications”, *Proc. 24th IEEE-IMTC 2007-Instrumentation and Measurement Technology Conference, (Warsaw, Poland, May 2007).*

[9] 2006 TDR probes instruction manual Campbell Scientific, Inc.

[10] G. C. Topp, J. L. Davis, and A. P. Annan, “Electromagnetic determination of soil water content: Measurements in coaxial transmission lines”, *Water Resources Res.*, vol. 16, pp. 574–582, 1980.

[11] K. Roth, R., Schulin, H. Fluhler, and W. Attinger, “Calibration of time domain reflectometry for water content measurement using a composite dielectric approach”, *Water Resources Res.*, vol. 26, pp. 2267–2273, 1990.

[12] Ball J. A. R., “Characteristic Impedance of Unbalanced TDR Probes”, *IEEE Transactions on Instrumentation and Measurement*, vol. 51, pp. 532-536, 2002.

[13] 1995 Guide to Expression of Uncertainty in Measurement.

[14] K.M. O’Connor, C.H. Dowding, GeoMeasurements by Pulsing TDR Cables and Probe, CRC Press, New York, 1999.