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# Simply Time Domain Reflectometry system for food analysis

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**Abstract**—Effectiveness of a simple Time Domain Reflectometry instrumental chain was tested by using different sodium chloride concentration.

The layout is quite simple and economic, the software user friendly and the measurements rapid.

An innovative approach for the statistical analysis of these kind of signals was implemented, accounting for multivariate analysis of the waveform, replacing the traditional mathematical theory.

Good results in terms of coefficient of determination for sodium chloride estimation were obtained with  $R^2$  0.942 (RMSE 0.18 g/100ml) for simple linear regression and  $R^2$  0.983 (RMSE 0.10 g/100ml) for PLS analysis.

The results obtained show how a cheap, rapid, and easy to use instrumental chain can be very promising for determinations of foodstuff parameters.

**Keywords**—Multivariate analysis, economic TDR instrumental chain, sodium chloride concentration, rapid non-destructive measurement

## I. INTRODUCTION

Time domain reflectometry (TDR) is a technique based on the dielectric behaviour of a material in a variable electric field [1]. It is based on the generation of a fast rise time step covering different frequency ranges and is a recognised technique for field monitoring of water content in soil and soil bulk electrical conductivity [2].

The signal propagation velocity along a known length probe embedded in a matrix allows parameters estimation as a function of the response dependent on dielectric permittivity of the material under test. The analysis of the travel time of the produced reflection figure out waveform's changes [3].

Effectiveness depends on factors such as temperature, pressure, and physical and chemical characteristics of the product under test. In food manufacturing industry the production chain accounts for several operation steps, each one should be controlled to preserve quality since final product. Additionally, food industry required fast measurements that are crucial for decision along the production process [4].

TDR has high versatility and accuracy and allows to perform measurements in real time presenting a valid alternative for sensing in line measurement. Concerning food applications, TDR was explored in order to determine water content starting from dielectric properties measurements of solid and liquid foods as granular materials [4], vegetables, meat foods and alcoholic beverages [5], extra virgin olive oils [6] and coffee grains [7].

The objective of the present research is to analyse the performance of a rapid and inexpensive tool based on TDR spectroscopic technique by assessing sodium chloride concentration. Water content is commonly recognized as the main component influencing dielectric permittivity, traduced in signal modification. Likewise, sodium chloride influences electromagnetic field due to its high reactivity to electric charges.

In the traditional way to elaborate time domain signals, the travel time of the reflection is geometrically extrapolated from the reflection coefficient waveform and is used to calculate the dielectric constant. Even if, not always a high precision is used to convert the signal displacement traducing in eventual errors [6].

In this work we propose multivariate analysis, in addition to simple linear regression, for rapid understanding of the system under study. The analysis considers the whole acquired signal and could overcome limits shown by the geometrical approach. Furthermore, multivariate analysis can be adapted to noisy and highly collinear dataset [9].

Actually, multivariate analysis can be easily implemented to a computer for simultaneous data processing.

## II. MATERIAL AND METHODS

### A. Time Domain Reflectometry Instrumental chain

The instrumental chain showed in figure 1A is composed by a rod probe, a fast time rise pulse generator, a digital oscilloscope for repetitive signals with bandwidth up to 11 GHz, and a power splitter. The rod probe is made by two silver-plated copper wires of 30 mm length, with a diameter of 0.75 mm, spaced 5.0 mm inserted in a nylon support.

The sample holder is a cuvette and an SMA type socket connect the probe to the circuit. To guarantee a constant volume filling of the sample holder cuvette a special device is made with a pre-set height correspondent to 3.5 ml of liquid, shown in figure 1B, as previously reported by [88].

The device is connected to the PC via USB, and the software has an intuitive graphic interface. The oscilloscope used is economic compared to the customary counterparts. The power splitter (Weinschel model 15151, USA) is used to distribute the impulse signal both to the trigger of the oscilloscope and to the TDR probe.

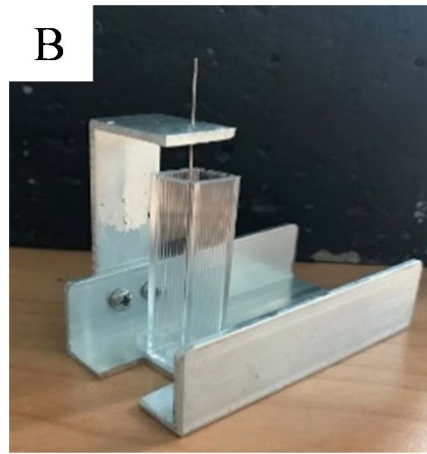
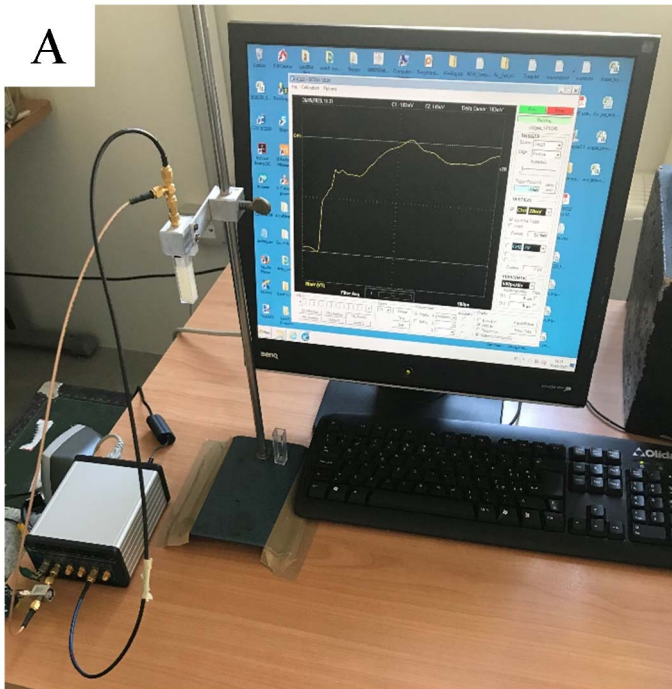


Figure 1. Instrumental chain set up (A) and system for constant volume filling (B).

### B. Sample tested

Analyses were conducted on several solutions of sodium chloride in deionized water.

Several increasing concentrations of sodium chloride were considered: 0.05, 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2, 1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.9, 2.0, 2.1, 2.2, 2.3, 2.4 and 2.5 % (g/100 ml). For each concentration three signal replications were acquired.

As example two waveforms in the time dominion are showed in figure 2. It is possible to detect graphically the start point (air/water interface) from which the data for the statistical analysis were taken into account for the analysis.

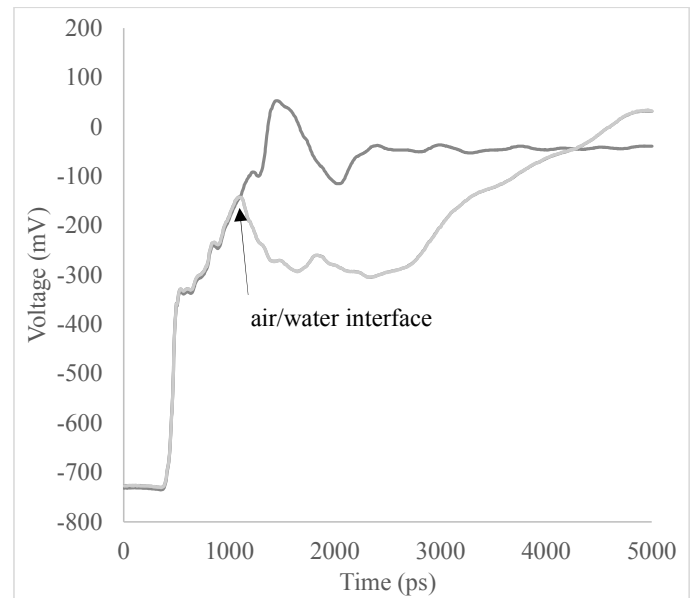


Figure 2. Two waveform, light grey acquired in water, grey in air. Graphically is detected the start point of the signal analysis.

### C. Statistical analyses

Time domain waveforms were processed by using simple linear regression and a multivariate approach. Each used waveform point was used to create a linear regression with sodium chloride concentration.

The goodness of fitting was evaluated by means of the determination coefficient ( $R^2$ ), adjusted  $R^2$  and Root Mean Square Error (RMSE, calculated as reported in equations (1, 2)).

$$\text{Adjusted } R^2 = 1 - \frac{(1-R^2)(N-1)}{N-p-1} \quad (1)$$

$R^2$  is the determination coefficient,  $p$  is the number of predictors, and  $N$  is the number of observation.

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^n (y_{\text{predicted}} - y_{\text{observed}})^2}{n}} \quad (2)$$

$Y_{\text{predicted}}$  is the predicted value,  $y_{\text{observed}}$  is the observed value,  $n$  is the number of observations.

The best point in terms of maximum  $R^2$  and lower RMSE was herein presented.

Multivariate approach is quite innovative in this kind of measurements. Partial Least Square regression was applied on the whole signal ( $X$  dataset) in order to build a model able to predict the tested parameter ( $Y$  dataset) by using Unscrambler software (version 9.7, CAMO, Oslo, Norway). The three replications of the TDR acquisitions were averaged. Segmented cross validation was used to validate the model by considering segments (six samples randomly selected).

### III. RESULTS AND DISCUSSION

Figure 2 shows the average waveforms of the water and sodium chloride solutions at different concentrations (pulses of about 800 mV). As it can be possible to observe, changes in the concentration of sodium chloride produce a change in the signal over the time domain.

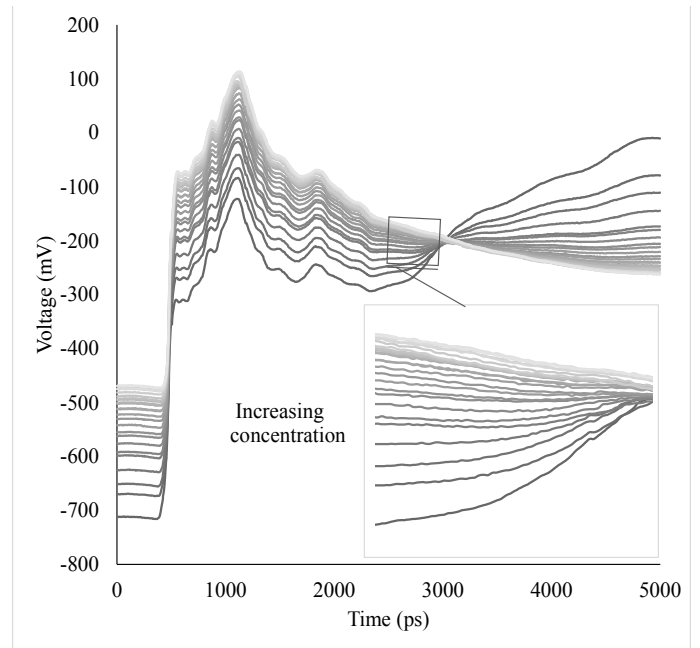


Fig. 2 Waveforms (mV) acquired in the time domain (ps) averaged, for different concentrations of salt in solution (g/100 ml).

The analysis of the waveform was not devoted to defining permittivity parameters in the mostly accurate way, but indirectly exploit spectral differences to relate food parameters for calibration model building.

Actually, the spectral points were used as variables for building a simple linear regression model to estimate sodium chloride concentration.

Figure 3 shows  $R^2$  values for each spectral point and a signal at a concentration of 2.5% sodium chloride, as an example, to figure out which part of the waveform had the greatest estimation contribute.

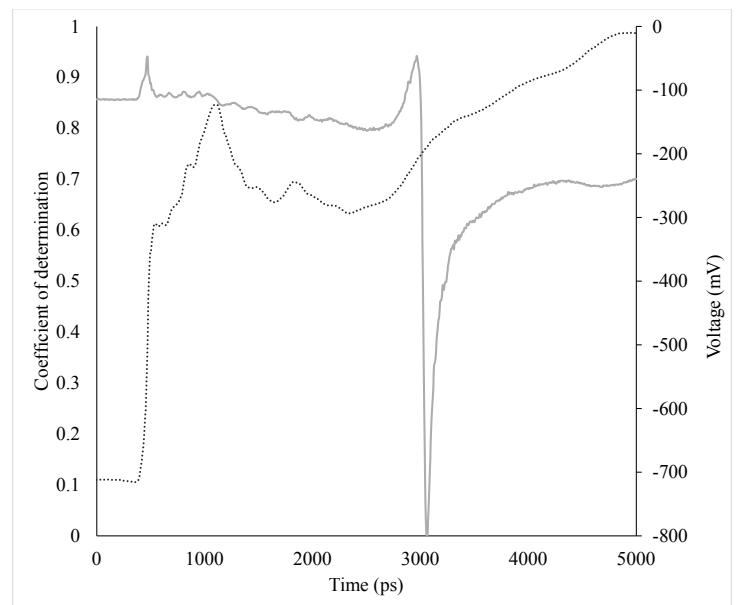


Fig. 3 Trend of the coefficient of determination for simple linear regression for all spectral points (grey line). Voltage over time of the solution with 2.5% sodium chloride shown as an example (dashed line).

The range between 3000 and 4000 ps is characterized by high  $R^2$  highlighting that a high portion of the signal contain the latent information's. More than one point contributes to explain the samples variability and, in this way, could be an opportunity to evaluate a multivariate approach.

According to this, the instrument shows a good ability to read sodium chloride concentration.

Within this area we represent in figure 4 the model of the signal point with the highest  $R^2$  (0.942), with a RMSE value equal to 0.18 g/100 ml is shown.

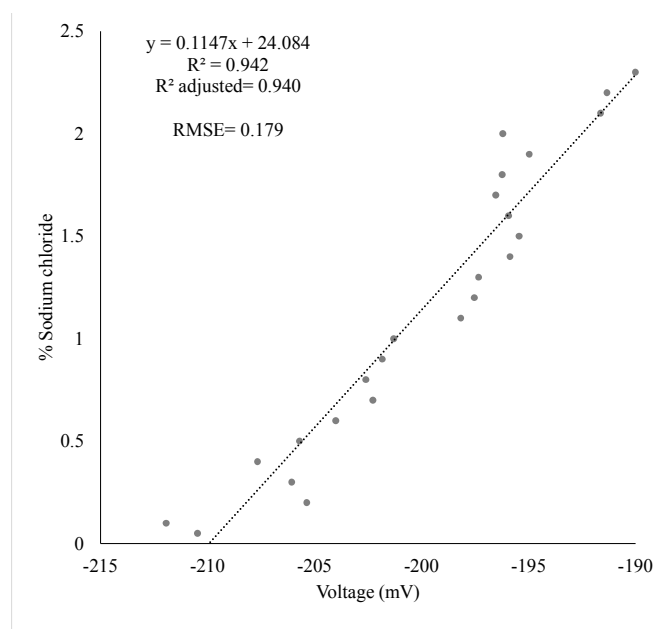


Fig. 4 Sodium chloride percentage solution in relation to the voltage (spectral point 3144 ps) and related  $R^2$  and  $R^2$  adjusted.

The whole signals were then elaborated with multivariate PLS regression. Test set validation give a higher  $R^2$  value (0.975, 5 PLS components) (RMSE 0.18 g/100ml) than that of simple linear regression (figure 5).

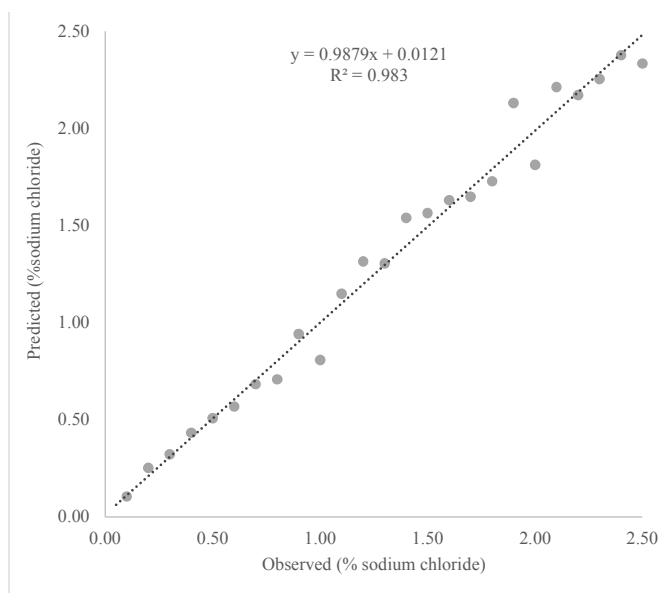


Figure 5. Predicted vs observed values for PLS regression.

Considering the opportunity to estimate sodium chloride in more complex system like food, a more complex analysis as PLS, which analyses all the spectral points, could be a very useful opportunity to overcome the possible influences operated by different constituents.

Previous works report time domain reflectometry (TDR) for both in-line and off-line moisture content measurement in the agri-food sector [10].

Non-traditional elaboration approaches were evaluated accounting for empirical models as simple and accurate, as far as multivariate analysis. As authors pointed out, calibration curves are matrix dependent, and in this way different curves must be developed for different materials [4,10, 11, 12].

Despite this, availability of very low-cost TDR instrumentation for food quality evaluation is considered very interesting for agri-food industry.

## CONCLUSION

The instrument developed is relatively simple to assemble, easy to use and economic than the traditional TDR instruments on the market.

The time domain signals obtained with sodium chloride solutions of the different concentrations have been used to build simple linear regression model,  $R^2$  0.942 (RMSE 0.18 g/100 ml).

PLS regression was implemented to improve the comprehension of the signal and segmented cross validated model reported high coefficient of determination,  $R^2$  of 0.983 (RMSE 0.10 g/100 ml, PCs 4).

Further developments could include various foodstuff to test the instrumental chain with different component estimations.

Despite this, the results show that the TDR presented is accurate in the measurement of sodium concentration, therefore

very promising for the rapid and non-destructive analysis of food.

## REFERENCES

- [1] N., Miura, S., Yagihara, and S. Mashimo, "Microwave dielectric properties of solid and liquid foods investigated by time-domain reflectometry," *J. Food Sci.* 68(4), 1396–1403 (2003).
- [2] Robinson, D. A., Jones, S. B., Wraith, J. M., Or, D., Friedman, S. P. (2003). A review of advances in dielectric and electrical conductivity measurement in soils using time domain reflectometry. *Vadose Zone J.*, 2, 444–47.
- [3] Fellner-Feldegg, H., (1969). Measurement of dielectrics in the time domain. *The Journal of Physical Chemistry* 73 (3), 616-623.
- [4] Cataldo, A., Vallone, M., Tarricone, L., Cannazza, G., Cipressa, M.. (2009). TDR moisture estimation for granular materials: application in agro-food industrial monitoring. *IEEE Transactions on Instrumentation and Measurements* 58 (8), 2597-2605.
- [5] Miura, N., Yagihara, S., Mashimo, S. (2003). Microwave dielectric properties of solid and liquid foods investigated by time-domain reflectometry. *J. Food Sci.* 68(4), 1396–1403.
- [6] Ragni, L., Berardinelli, A., Cevoli, C., Valli, E. (2012). Assessment of the water content in extra virgin olive oils by time domain reflectometry (TDR) and partial least squares (PLS) regression methods. *J. Food Eng.*, 111, 66–72.
- [7] Toledo, O. M., Oliveora Filho, D., Zanatta, F. (2008). Moisture content and dielectric constant of coffee grains measurements determination using time domain reflectometry. *Proceedings of the International Conference of Agricultural Engineering, XXXVII Brazilian Congress of Agricultural Engineering, International Livestock Environment Symposium - ILES VIII, Iguassu Falls City, Brazil.*
- [8] Ragni, L., Berardinelli, A., Cevoli, C., Filippi, M., Iaccheri, E., Romani, A. (2017). Assessment of food compositional parameters by means of a Waveguide Vector Spectrometer. *J. Food Eng.* 205. <https://doi.org/10.1016/j.jfoodeng.2017.02.016>
- [9] Eriksson, D. L., Byrne T., Johansson E., Trygg J. and Vikström, C. (2013). *Multi- and Megavariate Data Analysis Basic Principles and Applications*, Volume 1. Umetrics AB. ISBN 9197373052, 9789197373050.
- [10] A., Cataldo, E., De Benedetto, C., Huebner, and D., Trebbels, "TDR Application for Moisture Content Estimation in Agri-Food Materials," *IEEE Instrumentation & Measurement Magazine*, 2017, 1094-6969/17.
- [11] S. Trabelsi, A. Kraszewski, and S. O. Nelson, "A microwave method for on-line determination of bulk density and moisture content of particulate materials," *IEEE Trans. Instrum. Meas.*, vol. 47, pp. 127-132, 1998.
- [12] S. Trabelsi, A. Kraszewski, and S. O. Nelson, "Unified calibration method for nondestructive dielectric sensing of moisture content in granular materials," *Electronics Letters*, vol. 35, pp. 1346-1347, 1999.