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Assessment of food compositional parameters by means of a *Waveguide Vector Spectrometer*

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ABSTRACT

A Waveguide Vector Spectrometer (WVS), operating in the frequency range 1.6–2.7 GHz, was designed, set up and tested for rapid assessment of main chemical-physical properties of a plurality of food products. The system, completely integrated, includes a waveguide, a control unit, a signal generator, a gain/phase comparator, a power supply, and a USB port (for control and data transfer). The information contained in the gain and phase waveforms related to the product dielectric properties are exploited for the prediction of different compounds characterising both simple liquid solutions and more complex food products.

By processing spectral data with Partial Least Square Regression (PLS) algorithm, high levels of prediction accuracy were observed for all the tested products (R^2 values from 0.940 to 0.999, in validation). Generally, both gain and phase waveforms appeared to be effective, for the selected foods, in terms of prediction accuracy. On the whole, the proposed system seems able to assess the content of varied substances both on simple and complex matrices. Simple prospective changes of the sample holder make the equipment potentially suitable for on-line monitoring of the quality of food products.

1. Introduction

Compositional and structural characteristics of an agricultural product can be estimated through the analysis of its interaction with an electromagnetic wave (Barbosa-Cánovas et al., 2006; Ragni et al., 2006, 2007). This interaction is affected by the product dielectric properties, influenced in turn by its electric conduction, dipoles, electronic, ionic and Maxwell-Wagner mechanisms. Dielectric properties are expressed in terms of complex permittivity, characterised by a real and an imaginary component named, respectively, dielectric constant and loss factor. In particular, the product capability in storing energy is associated to the dielectric constant while the absorption and attenuation phenomena are linked to the loss factor (Nelson, 1999). The dielectric constant is responsible of a "phase" shift between an incident wave and a transmitted wave caused by the rotation of molecules; the loss factor is related to the energy dissipation involved in a loss, "gain", in the wave amplitude.

Geometry and temperature of the product under test and frequency of the electromagnetic wave have been demonstrated to affect the dielectric properties characterisation (Sipahioglu et al., 2003; Nelson, 2003). For agricultural products, the factors having a role in the interaction are also the moisture content (Sipahioglu and Barringer, 2003), the composition (Berardinelli et al., 2013), the density (Kim et al., 1998), the physical structure (Ragni et al., 2016), and the water activity (Iaccheri et al., 2015). Generally, by increasing the water content, an increment in the dielectric constant and in the loss factor can be observed but the effect is conditioned to the particular state of the water in the product (Komarov et al., 2005).

Several works were carried out in order to estimate the main qualitative attributes of the agricultural products through a spectroscopic analysis of the sole information contained in the "gain" waveforms. These researches were conducted by means of an instrumental chain composed by an aluminium rectangular waveguide, a sweeper oscillator and a spectrum analyser and through of the exploration of the potentiality of multivariate data

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analysis tools. The product, which is located between vertical transmitting and receiving antennas placed in the waveguide, generates a perturbation in the electromagnetic field propagation (transmission and reflection) that can be read as a relative variation in the voltage amplitude ("gain").

Freshness parameters of shell eggs were estimated through the information contained in the waveforms by means of the artificial neural network (ANN) statistical tool. In the frequency range from 10.5 to 11.5 GHz, R^2 values of 0.918, 0.854 and 0.912 were observed in validation mode for the prediction of the air cell, the thick albumen height and the yolk index, respectively (Ragni et al., 2010).

Soluble solids content (°Brix) and Magness–Taylor flesh firmness of "Hayward" kiwifruits were predicted from the acquired waveforms in combination with Partial Least Squares (PLS) regression analysis; in cross validation, values of the coefficient of determination R^2 up to 0.818 and 0.842 were respectively obtained for the two maturity indices in the frequency range from 2.0 to 2.2 GHz and from 2.9 to 3.0 GHz (Ragni et al., 2012).

The waveguide system was also explored to discriminate between Parmigiano–Reggiano cheese samples according to the rind percentage and respect to three competitors samples by using Principal component analysis (PCA) and Soft Independent Modelling of Class Analogy (SIMCA). Prediction of the rind percentage, months of ripening and moisture content were obtained, via PLS regression (cross validation), with R^2 values respectively up to 0.944 (2–3 GHz), 0.973 (16–17 GHz) and 0.822 (17–18 GHz) (Cevoli et al., 2012).

By performing PLS (cross validation), the water content of green and roasted coffee samples was estimated from the acquired waveforms with values of the coefficient of determination R^2 up to 0.998 (5–6 GHz) and 0.999 (17–18 GHz), respectively; best predictions of the a_w were obtained in the 17–18 GHz frequency range for both green ($R^2 = 0.996$) and roasted ($R^2 = 0.998$) coffee samples (Iaccheri et al., 2015).

Although the analysed configuration was proven to be useful in terms of non-destructive estimation of chemical–physical properties of agricultural products, the system is quite complicate to use (instrumental chain assembling), expensive and cumbersome.

The present paper aims at exploring the potentiality of a prototype instrument, named *Waveguide Vector Spectrometer* (WVS), in the estimation of main compositional parameters of simple and complex food matrices through the measurement of the electromagnetic field perturbation due to the sample under test confined in a waveguide. The device, operating in the low region of the microwave spectrum, is an Italian patent of the Alma Mater Studiorum, University of Bologna, Italy (N. 1421744, 2016; international application: WO2015/107455A1, 2015) and was set up with the purpose to provide a comprehensive cheap and simply to use tool for the assessment of the main qualitative attributes of the agricultural products. In addition, differently from the above researches, the apparatus integrates in a single instruments the sensor (waveguide) and measuring system by extracting in a vector fashion both "gain" and "phase" shifts occurring through the sample. All these features make the prototype a new instrument for the determination of physical-chemical properties of foods. The results of measurements conducted on a plurality of substances

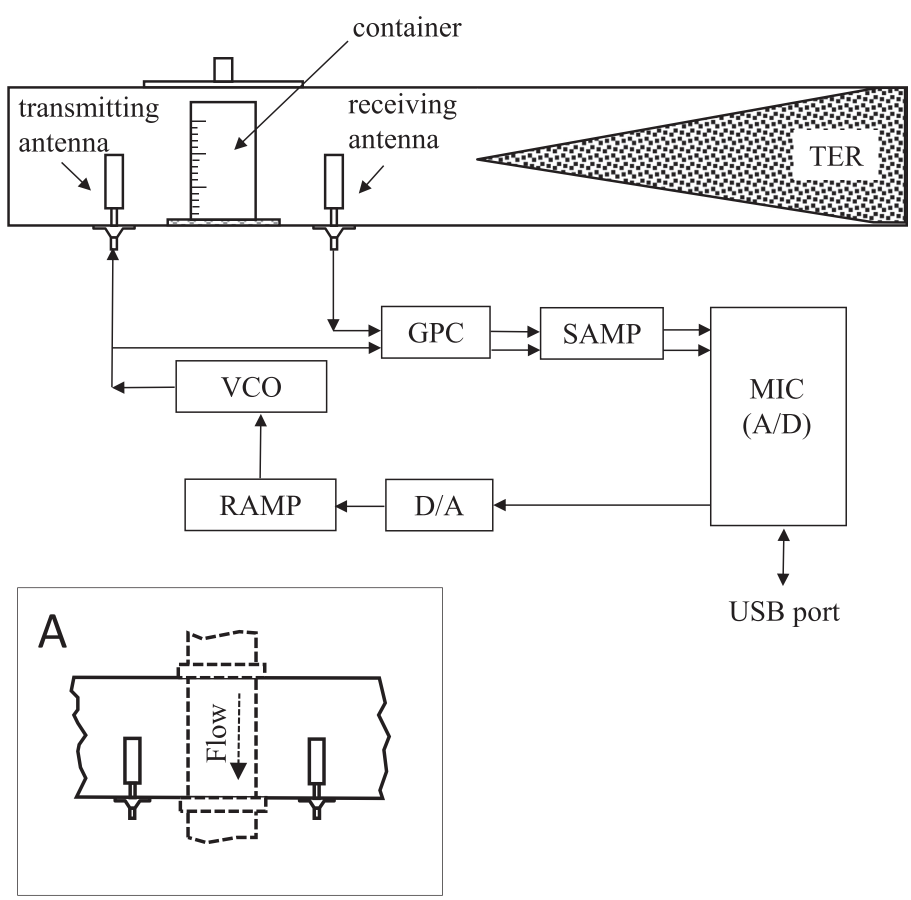

Fig. 1. Schematic of the waveguide vector spectrometer (side view). In the A inset: potential set up for on-line measurements. TER, waveguide termination; VCO, voltage controlled oscillator; GPC, gain-phase comparator; SAMP, signal amplifier; MIC, micro controller; D/A, digital to analog converter for the voltage ramp generation; RAMP, ramp amplifier.