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Antipodal Vivaldi antennas dedicated to in-situ broadband microwave permittivity measurements

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Abstract — **In the context of the ESA's SMOS and the ESA's BIOMASS space mission, the data processing algorithms require precise permittivity models of the different wood species. To develop the models, in situ sensors that could be easily deployed on the site dedicated to calibration/validation studies would be truly relevant. Microwave volume analysis can be a very useful tool to monitor material properties. There are very few commercial equipment dedicated to in-situ measurements and none of them is developed in order to leave the instrument on site for automatic measurements with specific constraints such as communication, low power consumption, frequency broadband, non-invasive measurement and cheap price. The main objective of the study presented is to develop an equipment to meet these challenges.**

In this article we will present the study that we conducted to design the broadband antennas needed by the device to perform efficient in situ measurements. Preliminary results on a concrete structure demonstrate the possibility to perform quality B scan despite the strict imposed specifications.

***Keywords* — Microwave analysis, permittivity, antenna, in-situ measurements, remote sensing.**

I. INTRODUCTION

The ESA's SMOS (Soil Moisture and Ocean Salinity) [1] [2] [3] space mission is based on a satellite carrying a L-band radiometer (1.4 GHz), which provided since 2009 unprecedented time series of global soil moisture and the oceans salinity maps. More recently, related studies also demonstrate the capabilities of SMOS data to map forest above ground biomass at continental scale [4].

At the same time, the ESA's BIOMASS mission [1] [5] is in preparation for a planned launch in 2020. The on-board instrument will be a P-Band Radar (432-438 MHz) designed to map forest above ground biomass at a global scale.

For these two space-borne missions, the data processing algorithms require precise permittivity models of the different wood species. The latter models are key components of the retrieval algorithms of the SMOS and BIOMASS missions.

Laboratory studies of the permittivity of wood sample has already been done [6] [7] [8] [9]. Unfortunately these data are not sufficiently representative of the properties of "living" wood. Moreover, the existing in-situ permittivity measurement instruments are often inserted within the wood, modifying its properties. So that the development of in situ sensors that could be easily deployed on the site dedicated to calibration/validation studies would be truly relevant.

In this context, microwave volume analysis can be relevant because it is a very useful tool to monitor material (non-destructive testing of building materials for example). GPR (Ground Penetrating Radar) [10] [11] [12] [13] systems allow A scan and B scan (1D and 2D sections) representing the echoes of electromagnetic waves in these structures. The collected data mainly allow to detect defects. The available commercial devices can carry out measurements in reflection and / or in transmission. The wave generation techniques are multiple (pulse, step frequency, frequency modulation) but the measurement frequency band is limited. Thus specifications of apparatus are selected according to the application or structure to be studied.

Available commercial devices are often cumbersome (moving on a cart), expensive and used for limited measurement campaigns.

There are very few equipment dedicated to in-situ measurements [14] and none of them is developed in order to leave the instrument on site for automatic measurements with specific constraints such as communication, low power consumption, , frequency broadband, non-invasive measurement and cheap price.

The main objective of the studies presented is to develop an equipment to meet these challenges.

The major specification of the instrument we designed is to measure in-situ data continuously. The measurements will be nonintrusive to avoid properties modification of material under test. The data will be sent from the device to a remote server. The measurements may be performed in frequency and / or time, reflection and / or transmission mode. The broad measurement frequency range selected will vary from 100 MHz to 3GHz. Some applications will need to focus on particular frequencies or frequency ranges. So the global frequency range can be split by the user as needed. This broadband frequency range for measurement will make it possible to recover temporal responses. The user will be able to view A scan and B scan of the structure. From this data we also expect to be able to provide the user with detailed information depending on the variations of the permittivity in the structure. The manufacturing cost of the instrument should be moderate (e.g. less than 500 euros) in order to allow device networks to be deployed.

Due to these constraints, technological choices on each element of the system must be done.

The device that we present has been developed to study properties of trunks in forest (permittivity profile, sap rise, density change, disease ...). The dielectric properties recorded by several instruments positioned on different tree species will permit the development of a database monitoring a full season of the permittivity of the vegetation. These data will be used to create models of the wood permittivity.

It will be possible to estimate, thanks to permittivity measurements, the variation of other wood properties (humidity, density ...) that we can relate to the permittivity.

The in-situ data collected by our instruments will be therefore very useful to evaluate and calibrate the permittivity models and eventually to improve the algorithms of the SMOS and BIOMASS space-borne missions.

In addition, this device can be used in the field of in-situ monitoring of the construction materials properties (corrosion of engineering structures, monitoring of wood quality, etc.).

In this article we will present the study that we conducted to design the broadband antennas needed by the device to perform efficient in situ measurements.

Preliminary results on a concrete structure in which is inserted an aluminium sheet will be presented.

II. Device Description

The measurement device consists of one or two antennas (reflection or transmission mode) connected to a 2-port VNA card that flowed data into a data storage memory that are transferred to a Sigfox communication module. The VNA card was designed to reduce costs and meet our specifications. We present here our approach of the antenna design and the first obtained measurement results

A. Antenna design

1) Specifications

The antennas must be lightweight and not bulky (15cm x 15 cm maximum). So we chose printed antenna technologies. The manufacturing cost must be low so we decided to use epoxy substrates. The directivity of the antenna must permit the transfer of energy into the structure to be studied. We set at -10 dB the maximum reflection losses (S_{11}) and to -20dB the minimum modulus of the transmission coefficient for antennas 10 cm away (S_{21}). This condition must be respected over a bandwidth from 100 MHz to 5 GHz. Given the limited cost we will not integrate adaptation systems (Balun type).

We selected Vivaldi antennas. These are antennas printed on a substrate with a progressive transition slot (Tapered Slot Antennas TSA). These antennas are adapted over a very wide frequency band. Their radiation pattern is unidirectional in the plane of the substrate and has a low level of cross polarization. Their directivity increases with frequency. There are several types of Vivaldi antennas. We worked on the antipodal Vivaldi antenna which proposes a transition from a micro-strip waveguide which allows a direct connexion to a coaxial cable. This antenna is printed on each of the face of the substrate.

2) Antipodal antenna design

The Vivaldi antipodal antenna [15] offers, like the classic Vivaldi, a transition from a micro-strip line allowing to have a power supply to a coaxial cable. While the opening of the classic Vivaldi transition slot is linear, that of the antipodal Vivaldi is curved. In addition this antenna is printed on each face of the substrate unlike the classic Vivaldi.

To size the antenna we started using an online tool specific to this type of antenna [16].

The first study led us to realize antennas whose dimensions are (Fig. 2.):

- Dielectric material property use for the substrate: 4.7
- Thickness of the substrate [mm]: 3mm
- Impedance: 50 ohms
- Width W [mm]:126.93
- Length L [mm]:152.32
- Width of the waveguide [mm]: 5.217
- Length [mm]: 25.39
- Great axe S1 [mm]:126.93
- Small axe R1 [mm]:66.07
- Radius R2 [mm]: 60.86

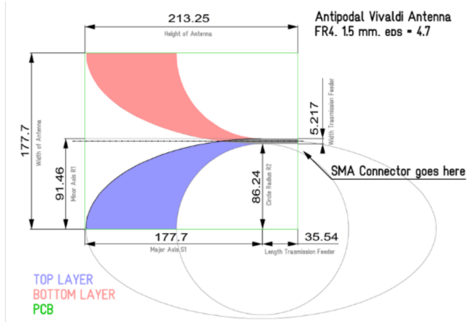

Fig. 1. Antenna Layout (size in mm)

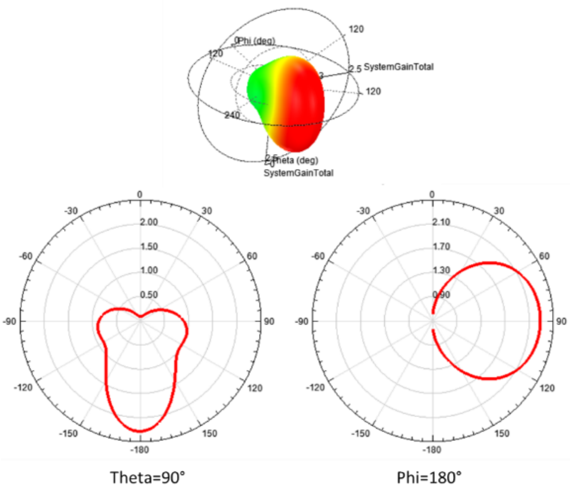

Fig. 2. Computed radiation patterns (1.5 GHz)

The first results obtained show a suitable directivity allowing a good energy transfer in the structure to study. Furthermore, it shows a suitable frequency band (Fig. 3). In particular, transmission measurements S_{21} between two antennas allowed measurements from 500 MHz to 4.5 GHz (Fig. 4.). Using the HFSS software we tried to optimize this antenna, modifying the curvatures of the opening slot, but the improvements were poor.

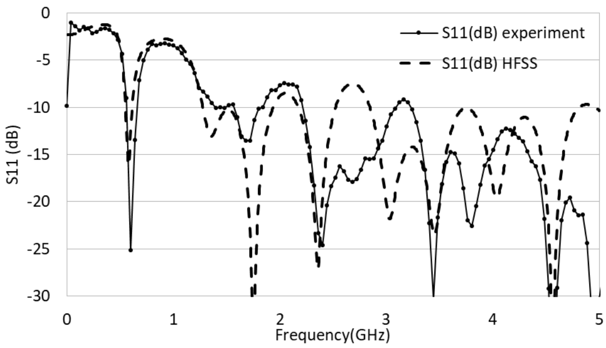

Fig. 3. S_{11} Magnitude vs frequency.
Experimental measurements and numerical computation

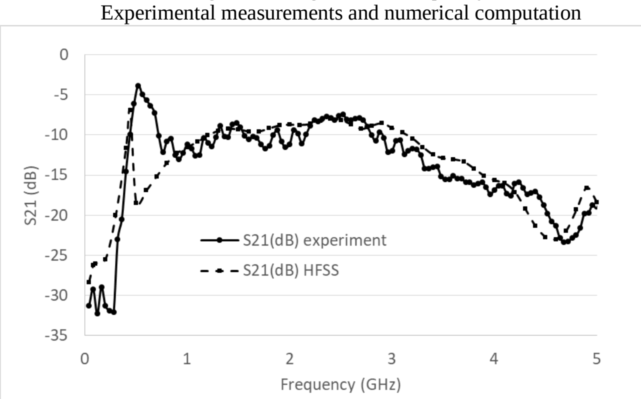

Fig. 4. S_{21} Magnitude vs frequency.
Experimental measurements and numerical computation

Finally, the antenna we obtained was optimized by changing the substrate thickness (3mm). The frequency band now extends from 300 MHz to 6GHz (Fig. 5.).

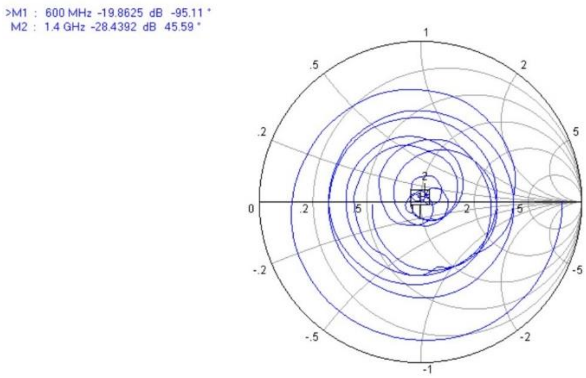

Fig. 5. S11 Smith diagram

III. Preliminary results

A. Experiment description

An aluminium thin film (thickness 0.02 mm) was placed between two concrete slabs as shown in the following figure. The system includes an air-concrete interface, a concrete-air-concrete interface (there is a poor contact between the two concrete slabs due to concrete roughness so there is a thin layer of air between the two slabs), a concrete-aluminium interface, and a concrete-table interface (support of the experiment) (Fig. 6.).

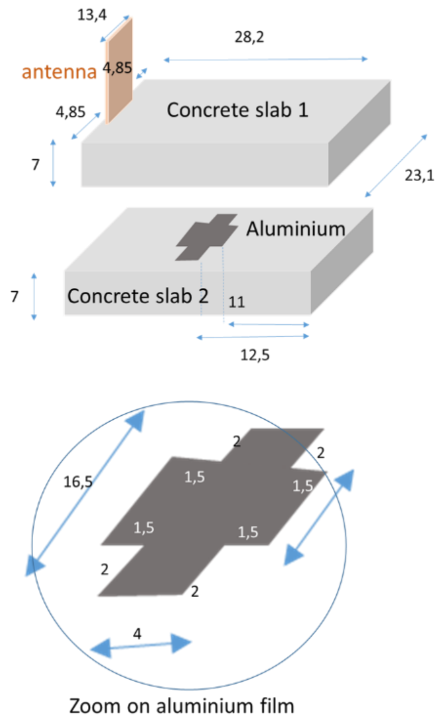

Fig. 6. Experiment description (sizes in cm)

The antenna is moved along the X axis, in the middle of the concrete slab, every 1 cm (see Fig. 7).

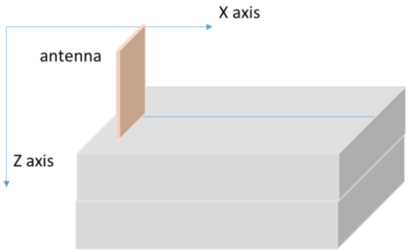

Fig. 7. Antenna position shift

B. Results

Until the end of the design of our VNA card, we used a network analyser (Rohde and Schwartz ZVH). However, we made the experiment in conditions close to our future VNA characteristics (number of points, frequency range ...). For each measurement we measure the frequency reflexion response S_{11} of the structure (Fig. 8.). An inverse Fourier transform (iFFT) allows us to compute the temporal response of the structure (Fig. 9.). An estimation of the permittivity of the concrete material (eps'=5) allows us to determine the velocity of the electromagnetic wave in the material and thus to plot the response of the structure as a function of the Z axis dimension.

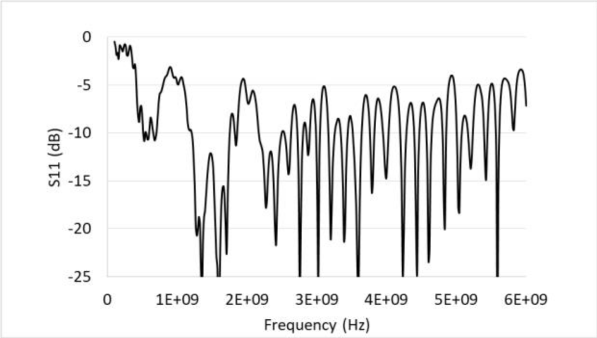

Fig. 8. S_{11}(dB) vs frequency for X=8cm

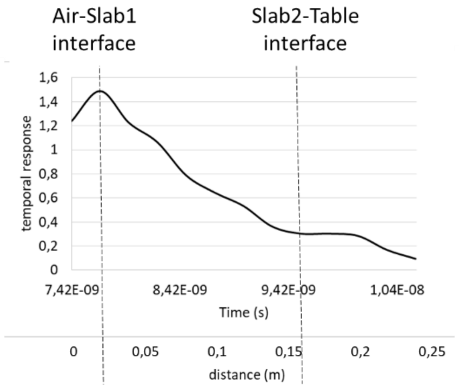

Fig. 9. A Scan for X=8cm vs time and distance

The combination of the all previous data obtained (A scans) allowed us to plot the B scan of the structure (Fig. 10.).

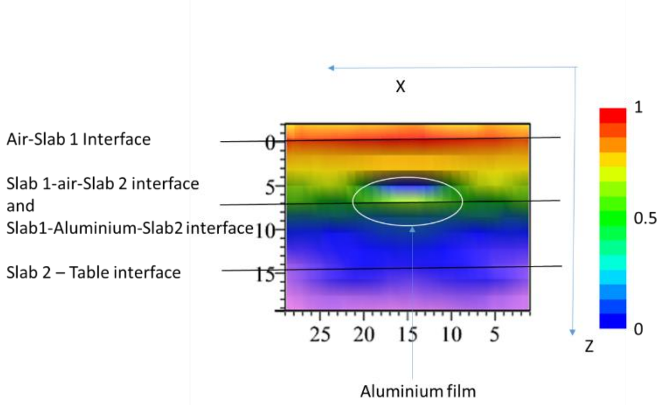

Fig. 10. B scan experimental result

The data collected makes it possible to accurately locate the aluminium film. The different interfaces are clearly visible as well as the edge effects related to the finite dimensions of the concrete slabs.

The spatial resolution can be further improved modifying the frequency measurement step and / or the selected frequency range.

IV. Conclusion

We have demonstrated the possibility to perform quality B scan despite the strict imposed specifications (bandwidth, cost, directivity, gains). In particular we have used for the experiment the VNA card specifications of the future VNA device that will be used for in situ measurements.

We will present further results in order to highlight the additional information (humidity gradient for example) that we will be able to extract from measurements on different frequency ranges. The results showed that we can detect and localized permittivity gradients in structures and demonstrate the ability of the device to detect and analyse tree sap rises.

The further work will focus on the algorithm development to compute permittivity from the B scan measurements obtain.

Acknowledgment

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