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Full-waveform inversion using a stepped-frequency GPR to characterize the tack coat in hot-mix asphalt (HMA) layers of flexible pavements

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Abstract

The use of tack coats in the construction of road structures is a technique that ensures pavement layer bonding. Unfortunately, existing techniques commonly used in France to estimate tack coat conditions require coring structures for *ad hoc* characterization in the laboratory. This paper investigates a non-destructive approach to characterize changes in geometric and dielectric properties of the tack coats present inside the hot-mix asphalt (HMA) layers of flexible pavements, with the use of a stepped-frequency radar combined with a mono-static, off-ground, ultra-wideband Vivaldi antenna. The principle of this method is to consider the flexible pavement as a multi-layered medium with changing properties (thicknesses, dielectric susceptibilities and dispersion parameters). Then a full-waveform inversion is applied, which allows for the extraction of the dielectric and geometric parameters of each layer composing the structure. Following numerical validations, the multi-layered forward model, namely, a Green's function model integrating the 2-parameter variant of Jonscher's model, combined with Lambot's *et al.* radar full-wave method was experimentally validated using calibrating media (up to three layered media). Then, the link between both the dielectric and the geometric parameters of the tack coats and the emulsion quantity (bonding) was analyzed. The results showed good agreement between measured and modeled radar data. Radar data inversions showed in particular that the dielectric susceptibility and thickness of the transition zone increase with the emulsion quantity. Future research will focus on the establishment of a reference database of calibration curves linking dielectric susceptibility and tack coat characteristics.

Keywords: *Stepped-frequency radar, Green's function, Jonscher's model, tack coat, pavements.*

1. INTRODUCTION

Bonding conditions at the interface between pavement layers (Figure 1) are known to modify the distribution of stresses and strains in flexible or rigid pavement structures and to influence their resistance to cyclic loading. Poor adhesion between layers can lead to premature degradation of the pavement, then to cracks. Although the tack coat technique is a common practice in road works in France, it is qualitatively poorly defined in terms of contractor obligations. Indeed, to this day, tack coats are only considered from a quantitative point of view in the linear setting, where the only homogeneity guarantee corresponds to the performance of the implementation machinery.

To better characterize these layers, various methods are under development or normalization. Thus, since Europe has undertaken standard works in the field of road building, some "Technical Specifications" have been proposed to deal with bonding tests in static and dynamic on asphalt cores (standards EN 12697-48 and TS 12697-51 [1, 2]). All these tests require on-site pavement coring, which presents several drawbacks. Indeed, in addition to limiting the diagnosis to restricted areas of the structure, coring imposes a prolonged exposure of operators to pollutants (asbestos, ionizing radiation, dust, etc.) and to the multiple hazards related to the worksites (road traffic, risks of collapses, reduced and unsecured accessibility, etc.). Limiting operator time on site is also an economic issue because it is to avoid infrastructure service outages in the transport domain.

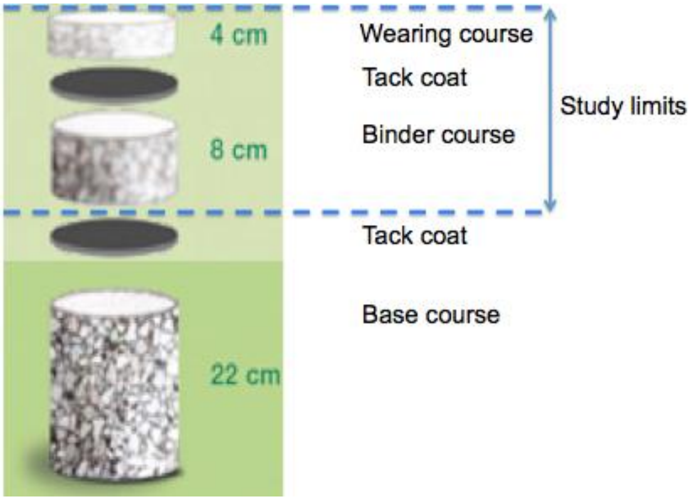

Figure 1: Tack coat positioning in a pavement structure.

Generally speaking, there are additional non-destructive (ND) or semi-destructive methods considered as references for the characterization of pavement layers in the laboratory and on-site (but not for tack coat characterization) that use gammadensimetry devices to estimate the density of road structures. Unfortunately, the restrictive legislation in many countries imposes ever stricter constraints on the storage, transportation and use of nuclear sources. Consequently, developing alternative techniques is a major concern for controlling newly-paved roads. The use of ND methods based on the propagation of electromagnetic (EM) waves represents an adequate solution to this problem.

Ground-penetrating radar (GPR) based on EM wave propagation, is a rising non-destructive technique for measuring the dielectric and geometric characteristics of materials. It is a common technique for geometrical applications (rebar detection [3, 4], road thickness estimation [5, 6], etc.) in civil engineering domain, and remains under study for material characterization (water and chloride content in concrete [7, 8], asphalt compaction [9, 10], etc.). Moreover, GPR techniques constitute a powerful tool for monitoring the condition of dispersive civil engineering materials. Wave propagation is entirely governed by the dielectric response, which reflects the interaction between propagating EM waves and the tested material. Along these lines, several methods and models have been implemented, with varying degrees of success, in order to describe the frequency dependence of the dielectric permittivity of geological and civil engineering materials [11-17].

To estimate dielectric and geometric characteristics for civil engineering materials and multi-layered media, most researchers use the travel time delay (TTD) approach [18], which is limited in terms of forward modelling adequacy and information content. Full-waveform inversion (FWFI), which is based on an accurate forward model and an inversion method, has demonstrated to be a powerful technique for material characterization [11, 12, 19, 20]. Although air-coupled GPR has been more often used in FWFI compared to the more complex ground-coupled GPR configurations [11, 21], ground-coupled GPR can now be accurately modeled as well [12, 22]. Ground-coupled GPR permits deeper characterization and finer resolution compared to air-coupled radars.

The general objective of this paper is to investigate FWFI of radar waves to remotely estimate both the dielectric and geometric properties of tack coats in pavement structures based on the full-wave radar method of Lambot *et al.* [11, 12, 22] (patented) combined with Jonscher's model of frequency-dependent medium properties. The adopted approach was validated in the laboratory on a wide range of materials and pavement layers representing a sample of existing road structures in France. From a durability point of view, this work aimed at demonstrating (before quantifying) the relationship between ND observables (permittivity, susceptibility, dispersion parameter, etc.) and the emulsion quantities used in the bonding of pavement layers. Concerning this main objective, three specific scientific issues were addressed in this paper: (1) Establishment of a laboratory experimental design including a significant number of controlled specimens (various emulsion quantities, thicknesses, etc.) intended for dielectric and geometric characterization with a Stepped-Frequency Radar - SFR (Section II); (2) Validation of the forward approach integrating the 2-parameter variant of

Jonscher's model on numerical data (Sections III); and (3) SFR data processing on samples in the laboratory to link dielectric characteristics with emulsion quantities for various specimens (Section IV).

2. PHENOMENOLOGICAL ASPECTS AND EXPERIMENTAL DESIGN

In this study, we focused solely on tack coats linking the wearing course and the binder course (Figure 1). We developed a SFR that integrates a PC-piloted FieldFox Microwave vector network analyzer (Agilent N9928A) and various Vivaldi antennas in mono-static, near-field configuration (Figure 2) for measuring a wide range of HMA layers (slabs). The details of this experimental device are presented in Section IV. A preliminary study was performed to assess the sensitivity of such a device (using its raw data expressed in the time domain) to the presence or absence of tack coat emulsion. To do this, 2 two-layer slabs were designed. The first one did not contain any emulsion at the interface between the wearing course (BBTM - 3 cm thick HMA corresponding to very thin layers) and the binder course (BBSG - 6 cm thick). The second contained emulsion up to 600 g/m^2. Figure 3 shows the time variations of the real part of the SFR reflection coefficients S_{11} on the slabs, laid on a Perfect Electrical Conductor (PEC), with (blue curve) and without (red curve) emulsion.

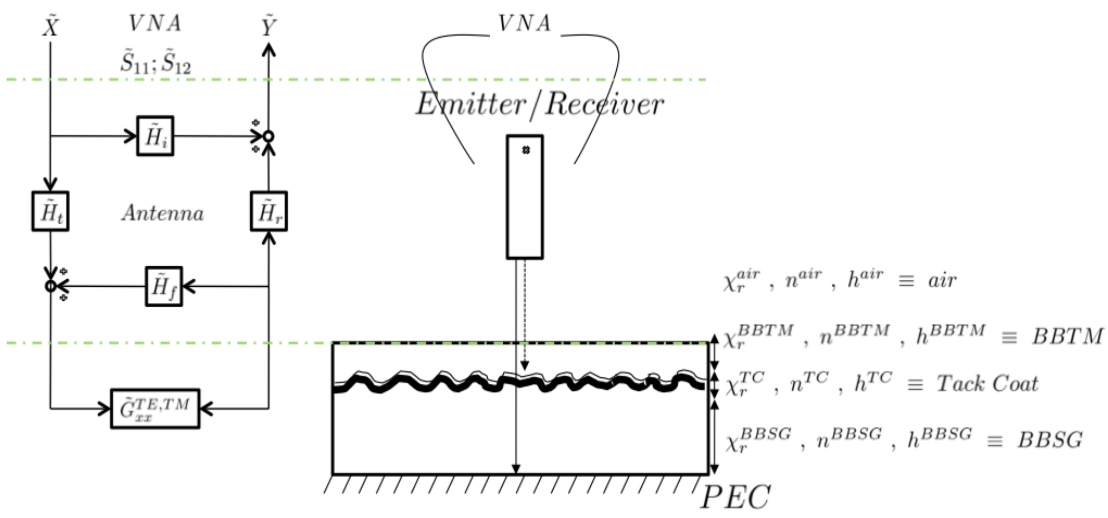

Figure 2: SFR schematic modeling diagram [11, 12, 22] and experimental setup.

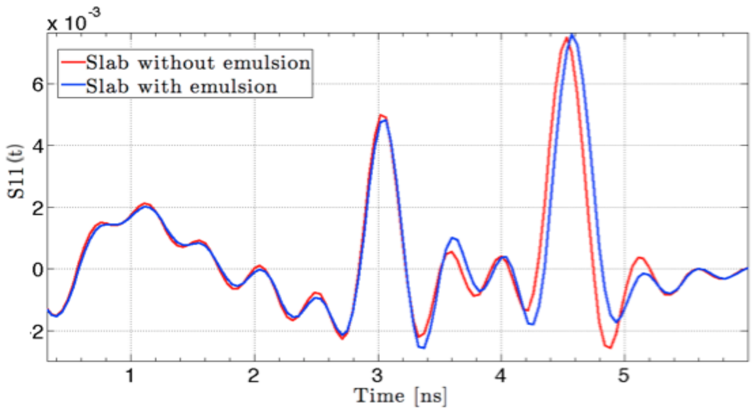

Figure 3: Time signals through similar slabs without (red line) and with (blue line) emulsion.

The presence of emulsion at the BBTM / BBSG interface decreased the wave propagation velocity, implying a time delay in the second echo corresponding to reflection at the bottom of the slabs (BBSG/PEC). This phenomenon is explained by the fact that the emulsion filled the empty pores at the BBTM/BBSG interface, compared to an air gap, which increases the dielectric permittivity of the transition zone between the two layers. This transition zone is also visible in the gammadensimetry results (Figure 4).

As a reminder **[23]**, the gammadensimetry method is based on the absorption of gamma photons emitted by a radioactive source of Cesium C137 S, with energy 0.662 MeV, after passing through the material. This absorption follows Lambert's law:

$$N = N_o \exp(-z\mu_0 \rho x), \qquad (1)$$

where N_o is the number of incident photons and N is the number (in counts per second) of collected photons, μ_0 (cm^2/g) is the mass absorption coefficient of the tested material, ρ (g/cm^3) is the density, x the thickness of the material and z is the correction coefficient defined by the geometry of the device. The density can therefore be given by the equation:

$$\rho = -\frac{1}{z\mu_0 x} ln\left(\frac{N_o}{N}\right), \qquad (2)$$

Knowing z, μ_0 and the thickness of the material x makes it possible to calculate the density ρ.

The result of these gammadensimetry measurements is of major importance to the developed FWFI that aims to invert the parameters of the transition zone (i) considered in the presented approach as a dielectric layer in the forward model, and (ii) whose dielectric properties are directly proportional to emulsion quantity. Thus, to establish the link between the emulsion quantity used in the tack coat and the dielectric characteristics derived from SFR measurements, 32 two-layer slabs (three-layers if we consider the transition zone as a layer) were designed and built. To reach 64 samples, the 32 slabs were upturned during the SFR measurements.

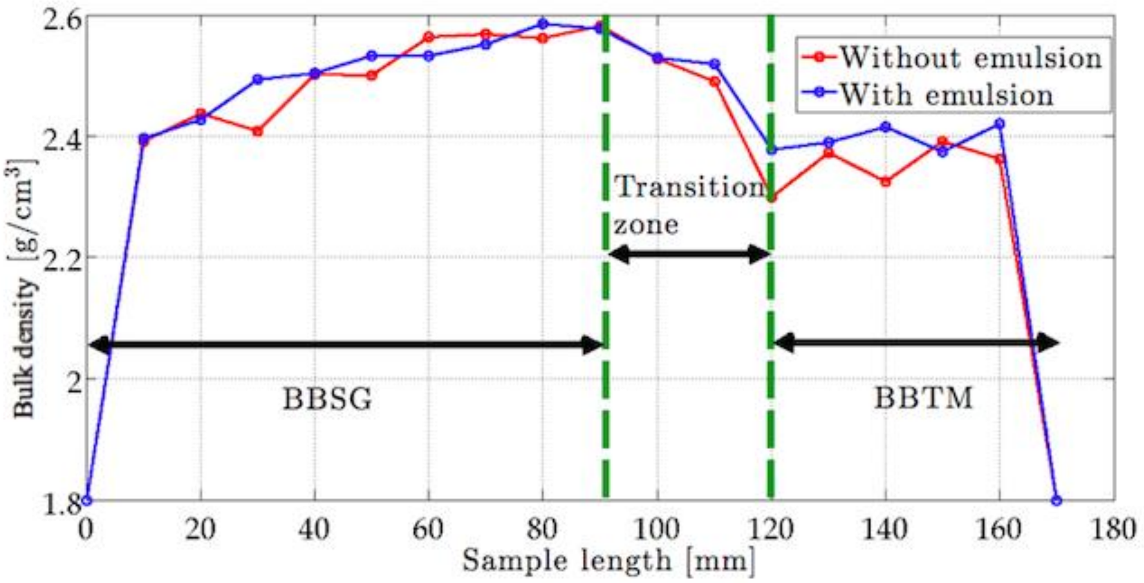

Figure 4: Bulk density variations according to slab thickness with and without emulsion.

The HMA layer nomenclature used in the experimental design is as follows:

- BBTM – Very thin bituminous concrete: the target average thickness ranges from 2 to 2.5 cm. The binder content is 5.5% and the aggregate size fraction is 0/10 mm with a discontinuity between 2 mm and 6 mm;
- BBSG – Semi-coarse HMA: used for surface layers (wearing and/or binder courses) in roadways with medium to high traffic. The target average thickness ranges from 5.5 to 6 cm, the binder content is 5.2% and the aggregate size fraction is 0/10 mm;
- GB – bituminous gravel used for the base course. The target average thickness ranges from 10.5 to 11.5 cm, the binder content is 4% and the aggregate size fraction is 0/14 mm.

The 4 degrees of freedom for this statistic experimental design are as follows: emulsion quantity (0, 200, 400 and 600 g/m^2), nature of the layers (BBTM above BBSG and BBSG above GB), their thicknesses (BBTM / 3cm, BBSG / 6cm and GB / 11cm) and their compaction (between 75% and 96%) (Table 1).

Two aggregate mineralogical types (Diorite and Gneiss) from two different quarries (Noubleau - N and Le Tronc - LT) were used in order to have two different dielectric permittivities for aggregates (between 5 and 7 for diorite and between 8 and 15 for gneiss).

Calibration slabs were also carried out for each layer of the experimental design necessary to initialize the FWFI procedure (allowing the determination of dielectric characteristics of BBTM, BBSG and GB layers considering their thicknesses).

With respect to manufacturing, all samples were made in the laboratory using the MLPC plate compactor and the RETEX texture reproduction module with compaction verification by gammadensimetry measurements.

Table 1: Experimental design characteristics.

Samples	Lower layer (upturned = Upper layer)	Upper layer (upturned = Lower layer)	Emulsion quantity	Manufacturing date
Ech1	BBSG10 LT[1] C91[2]	BBTM10 N[3] C75	200 g/m²	14/11/14
Ech2	BBSG10 LT C96	BBTM10 N C75	200 g/m²	17/12/14
Ech3	BBSG10 LT C91	BBTM10 N C90	200 g/m²	03/03/15
Ech4	BBSG10 LT C96	BBTM10 N C90	200 g/m²	04/12/14
Ech5	GB14 N C88	BBSG10 LT C91	200 g/m²	2016-2017
Ech6	GB14 N C96	BBSG10 LT C91	200 g/m²	2016-2017
Ech7	GB14 N C88	BBSG10 LT C96	200 g/m²	2016-2017
Ech8	GB14 N C96	BBSG10 LT C96	200 g/m²	2016-2017
Ech9	BBSG10 LT C91	BBTM10 N C75	600 g/m²	25/11/14
Ech10	BBSG10 LT C96	BBTM10 N C75	600 g/m²	07/01/15
Ech11	BBSG10 LT C91	BBTM10 N C90	600 g/m²	27/03/15
Ech12	BBSG10 LT C96	BBTM10 N C90	600 g/m²	11/12/14
Ech13	GB14 N C88	BBSG10 LT C91	600 g/m²	2016-2017
Ech14	GB14 N C96	BBSG10 LT C91	600 g/m²	2016-2017
Ech15	GB14 N C88	BBSG10 LT C96	600 g/m²	2016-2017
Ech16	GB14 N C96	BBSG10 LT C96	600 g/m²	2016-2017
Ech17	BBSG10 LT C91	BBTM10 N C75	0 g/m²	06/11/14
Ech18	BBSG10 LT C96	BBTM10 N C75	0 g/m²	16/12/14
Ech19	BBSG10 LT C91	BBTM10 N C90	0 g/m²	27/01/15
Ech20	BBSG10 LT C96	BBTM10 N C90	0 g/m²	02/12/14
Ech21	GB14 N C88	BBSG10 LT C91	0 g/m²	2016-2017
Ech22	GB14 N C96	BBSG10 LT C91	0 g/m²	2016-2017
Ech23	GB14 N C88	BBSG10 LT C96	0 g/m²	2016-2017
Ech24	GB14 N C96	BBSG10 LT C96	0 g/m²	2016-2017
Ech25	BBSG10 LT C91	BBTM10 N C75	400 g/m²	21/11/14
Ech26	BBSG10 LT C96	BBTM10 N C75	400 g/m²	06/01/15
Ech27	BBSG10 LT C91	BBTM10 N C90	400 g/m²	06/03/15
Ech28	BBSG10 LT C96	BBTM10 N C90	400 g/m²	10/12/14
Ech29	GB14 N C88	BBSG10 LT C91	400 g/m²	2016-2017
Ech30	GB14 N C96	BBSG10 LT C91	400 g/m²	2016-2017
Ech31	GB14 N C88	BBSG10 LT C96	400 g/m²	2016-2017
Ech32	GB14 N C96	BBSG10 LT C96	400 g/m²	2016-2017

[1]LT = Le Tronc quarry, [2] C91 = Compaction at 91%, [3]N = Noubleau quarry

In the context of this paper, we focused only on four series for a total of 32 slabs (BBTM / BBSG and BBSG / BBTM) with the four emulsion quantities (total of 16 slabs that we upturned).

Slab size was determined from a parametric study (not detailed in this paper) associated with the radiation pattern of the Vivaldi antenna used in order to avoid edge effects that are not included in the forward model, which assumes infinite horizontal layers.

3. EM WAVE PROPAGATION MODEL

The aim of this section is to present the fast calculation time model describing an air-coupled radar wave propagation through multi-layered media, taking into account the frequency-dependence of electromagnetic properties. As shown in the Figure 2, this problem can be described as EM wave propagation through a three-layer planar and lossless medium (BBTM/Tack coat/BBSG). The considered transceiver (emitter/receiver) simulates a mono-static stepped-frequency radar, giving high effective bandwidth with plural narrow instantaneous bandwidth.

Lambot *et al*. [11] proposed a closed-form, intrinsic antenna model combined with zero-offset Green's function to describe radar propagation in planar-layered media. This model holds when the distribution of the backscattered field over the antenna aperture is constant, which in particular occurs in far-field conditions (homogeneous field in that later case). Afterwards, this antenna model was generalized to near-field conditions [12, 22], for which the field distribution over the antenna aperture is variable. In that case, multi-offset Green's functions are used. Furthermore, both a linear model and Debye's model were used by the authors to describe the frequency dependence of dielectric permittivity of dispersive materials. However, a previous study [24] showed the advantages of using a two-parameter (2p) variant of Jonscher's model [25], which has proven its efficiency in describing the dielectric response of civil engineering materials with a constant quality factor Q. Therefore, in this paper, we used this Jonscher's model with a limited number of parameters (2) to describe the frequency dependence of the material EM properties.

In the following sub-sections, the theoretical Jonscher's model is reminded. It describes the frequency dependence of the effective permittivity by means of 2 parameters, susceptibility and loss exponent. The model of Lambot *et al*. [11, 12, 22] is then applied to relate the total return loss S_{11} to Jonscher's parameters and is parameterized with a single point source and receiver, which provides sufficient accuracy for our model configuration [20] (the antenna is at sufficient distance from the medium). The overall model is numerically studied and then experimentally validated in the next sections.

3.1. **Effective permittivity**

The effective permittivity is a complex and frequency-dependent quantity in dispersive materials. The 2p variant of Jonscher's model is chosen instead of the universal model because the association BBTM / Tack Coat / BBSG is considered as a *Q*-constant dielectric medium, thereby reducing the number of unknown parameters by two over the whole frequency band.

Jonscher's model is based on universality in the form of dielectric response. The model states that, above the peak loss, should one exist, the dielectric susceptibility $\chi = \chi' - j\chi''$ of all dielectric systems follows a frequency power law $\chi'(f) \propto \chi''(f) \propto f^{n-1}$ where *f* is the frequency and *n* a parameter ranging from 0 to 1. The dielectric susceptibility can be defined as a quantity characterizing the capability of a material to be polarized. Quantitatively, it equals the proportionality coefficient relying the intensity of the applied electric field and the polarization of the material (the dipole moment per unit volume of the dielectric). Generally speaking, the dielectric properties of a material are characterized by dielectric susceptibility, as well as by its dielectric permittivity.

The effective permittivity can be expressed as follows:

$$\varepsilon_e = \varepsilon_o \chi_r \left(\frac{f}{f_r}\right)^{n-1} \left(1 - jcot\left(\frac{n\pi}{2}\right)\right), \qquad (3)$$

where χ_r is the reference susceptibility, n is the loss exponent, ε_o is the permittivity of vacuum and f_r is the reference frequency arbitrarily chosen.

3.2. **Green's function**

The planar multi-layered medium Green's function in the frequency and spectral domains is calculated for the one-point source-receiver using (4).

$$G(\kappa) = \frac{1}{8\pi}\left(\frac{\gamma_1 R_1^{TM}}{j\omega\varepsilon_{e1}} - \frac{j\omega\mu_1 R_1^{TE}}{\gamma_1}\right) e^{-2\gamma_1 h_1} \qquad (4)$$

In this equation, ω is the angular frequency; subscript 1 refers to the upper half-space (free-space); h_1 is the distance between transceiver points and the first material interface; R_1^{TM} and R_1^{TE} are respectively the transverse magnetic (TM) and transverse electric (TE) global reflection coefficients concerning all reflections in layered material; γ_1 is the complex vertical wavenumber defined as $\gamma_1 = \sqrt{\kappa^2 - j\omega\mu_1\eta_1}$, where μ_1 and η_1 are, respectively, the magnetic permeability and complex conductivity of air. The spatial-domain Green's function is obtained from its spectral counterpart using Sommerfeld's integration [26].

3.3. **Return loss *S_{11}***

Return loss S_{11}, the output of the radar equation, is the ratio of reflected and emitted EM electric fields. Assuming a single point source and receiver as approximation to describe our near-field radar data, it is defined by the following equation [12, 22]:

$$S_{11}(f) = R_i(f) + T_s(f)\big(1 - G(f)R_s(f)\big)^{-1} G(f)T_i(f) \qquad (5)$$

where, R_i is the free space response of the antenna. T_i and T_s are the global transmission coefficients of the antenna for fields incident from the radar reference plane onto the source point and vice-versa, R_S is the global reflection coefficient for fields incident from the field point onto the radar reference plane, and G is the spatial domain Green's function, deduced from the spectral domain Green's function in (4).

The transmission and reflection coefficients are determined by solving equations (6-8) for two near-field measurements on a PEC with two different antenna heights S_{pec3} and S_{pec5} (3 cm and 5 cm), by measuring the open-air impedance S_{air}, and by calculating the corresponding Green's functions G_{pec3} and G_{pec5} for these two antenna heights [11].

$$R_i = S_{air} \quad (6)$$

$$R_s = \frac{\frac{S_{pec5}-S_{air}}{G_{pec5}} - \frac{S_{pec3}-S_{air}}{G_{pec3}}}{S_{pec5}-S_{pec3}} \quad (7)$$

$$TiTs = \frac{S_{pec5}-S_{air}}{G_{pec5}} - \left(S_{pec5} - S_{air}\right)R_s \quad (8)$$

Once the global transmission and reflection coefficients (R_i, T_iT_s, R_s) are determined, the return loss *S11* is directly calculated using the zero-offset, single-point Green's function. It is worth noting that these antenna transfer functions may be slightly different from those which would be obtained in farer conditions, but they correspond to the field distribution over the antenna aperture occurring in that height range [20, 27].

3.4. **Inversion objective function**

Given the analytical forward model, EM wave propagation through the radar-antenna-layered medium is described. However, we need to solve the inverse problem. The objective of inversion is to have the best group of model parameters that minimizes the difference between analytical *S11* and reference (numerical or experimental) *S11*, assuming that this group of parameters to correspond to the right configuration.

There are three main kinds of inversion methods. FWFI reliability has been well demonstrated [11, 12, 19, 20]. As time gating was not necessary in our study, we performed inversion in the frequency domain in order to avoid the inverse Fourier transform calculation, and hence, minimize processing time.

The amplitude-weighted average distance between analytical and reference return loss *S11* complex values at each frequency was considered as objective function (9).

$$O(m) = \frac{1}{NF}\sum_{i=1}^{NF}\frac{|S_{mod}(f_i,m)-S_{ref}(f_i,m)|}{|S_{ref}(f_i,m)|} \qquad (9)$$

Here, $S_{mod}(f_i, m)$ and $S_{ref}(f_i, m)$ are the analytical and reference return loss S_{11} at the frequency f_i. m corresponds to the model parameter vector. NF is the number of frequencies. There is a return value $O(m)$ for each try of model parameter. The best parameter is reached once $O(m)$ is minimized using genetic algorithm.

4. Numerical verification of the forward model

High Frequency Electromagnetic Field Simulation (HFSS) is a commercial electromagnetic simulation software based on the finite element method. The aim of this section is to present an HFSS-based numerical verification approach, in order to evaluate the stability and robustness of our analytical model when estimating the dielectric and geometric characteristics of a multi-layered medium representing road structures with a tack coat equivalent layer.

Thus, a Vivaldi ultra-wideband antenna was designed and activated from 0.8 to 3 GHz with a frequency step of 5 MHz. The phase center of this antenna was fixed at a distance of 10.53 cm inward from its aperture. Following the procedure described in Section 3.3, we performed the calibration process to obtain the global, frequency-dependent transmission and reflection coefficients of the antenna.

The model configuration is shown in Figure 5. The height of the antenna (distance between the antenna aperture and the upper surface of the BBTM layer) was set to 4 cm, meaning a near-field case simulation [26]. The thickness, the dielectric susceptibility and the loss exponent for each layer are reported in Figure 5, considering that they are used as inputs for both numerical and analytical models.

Figures 6 and 7 correspond to examples of time and frequency variations of the real parts of the HFSS Green's functions (red curves) and those of our model including the 2p variant of Jonscher's model (blue curves).

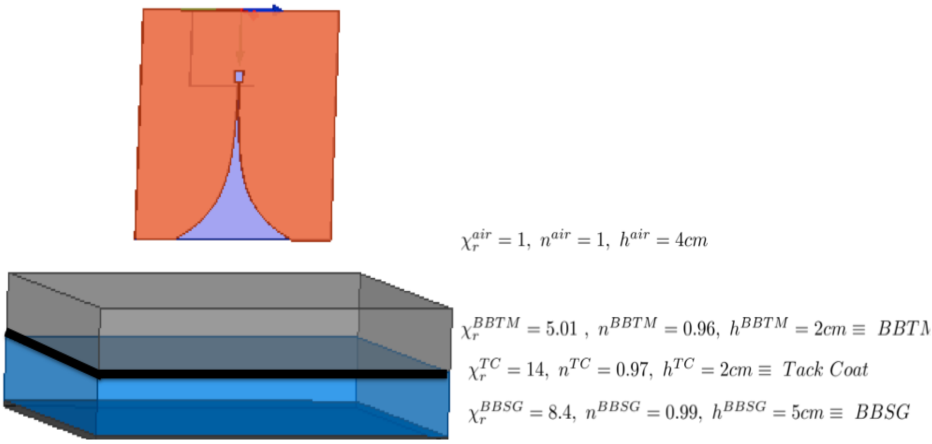

Figure 5: HFSS- based numerical model.

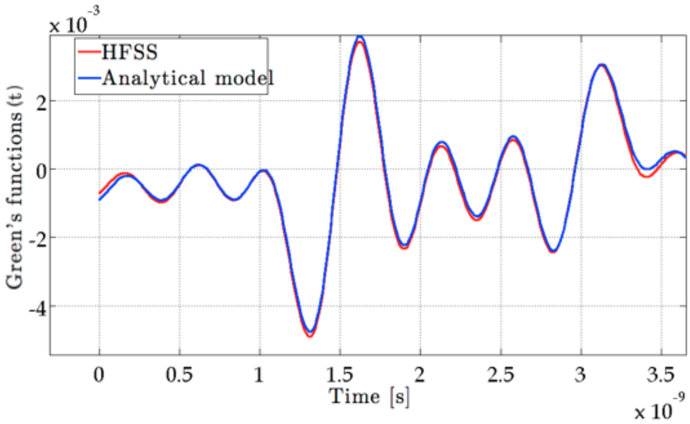

Figure 6: Time variation of the real parts of the HFSS Green's functions (red curve) and of the analytical model (blue curve) after the numerical calibration process.

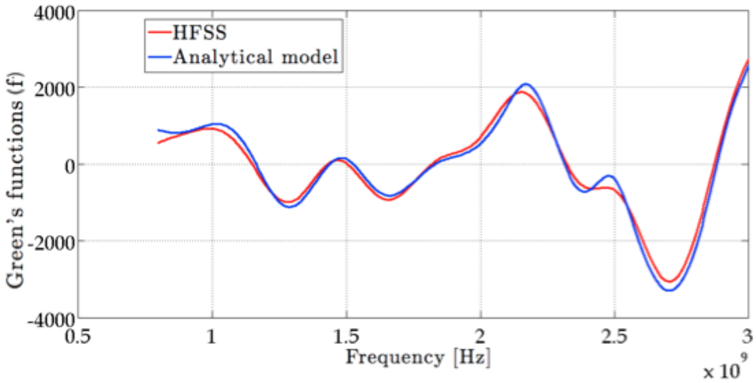

Figure 7: Frequency variation of the real parts of the HFSS Green's functions (red curve) and of the analytical model (blue curve) after the numerical calibration process.

The values of the Green's analytical model integrating 2p variant of Jonscher's model perfectly match the reference theoretical values (HFSS) after the near-field calibration of the antenna. The small differences between the two model curves are partly due to the single point source and receiver approximation for this near-field configuration (the field distribution over the antenna aperture slightly changes between 3 and 5 cm height).

Thus, a generalization of this numerical study (not completely presented in this paper) allowed us to validate the forward and inverse procedures before the transition to the experimental study.

5. Experimental validation

A wide characterization experiment was carried out in order to test our method for estimating the tack coat characteristics. The SFR system consists of a PC-piloted FieldFox Microwave vector network analyzer (Agilent N9928A) connected to the Vivaldi antenna [28], in order to setup the ultra-wideband (UWB), stepped-frequency continuous-wave (SFCW) radar system. The scattering parameters were measured at the VNA reference calibration plane, located at the cable connector to which the antenna is connected. In a mono-static configuration, the frequency-dependent, complex return loss S_{11} from the VNA in the range 0.8 to 3 GHz is the measured variable. Following the procedure described in Section 3.3, the system was calibrated to obtain the antenna transmission and reflection coefficients.

Additionally, fine characterization was carried out in an anechoic chamber in order (i) to determine the radiation pattern of the Vivaldi antenna and (ii) to assess the edge effects that are generated by the samples with a limited size and not considered in the proposed model (Figures 8 and 9).

The first SFR measurements were performed on two series of four BBTM / tack coat / BBSG slabs (dimensions 40 cm × 30 cm × 9.5 cm) placed on a metal plate of similar dimensions. The SFR measurement configuration is shown in Figure 10, wherein the Vivaldi antenna is placed 4 cm above the slabs. It should be noted that the rear aerial EM echoes from the metallic antenna-holder are accounted for by the antenna calibration process.

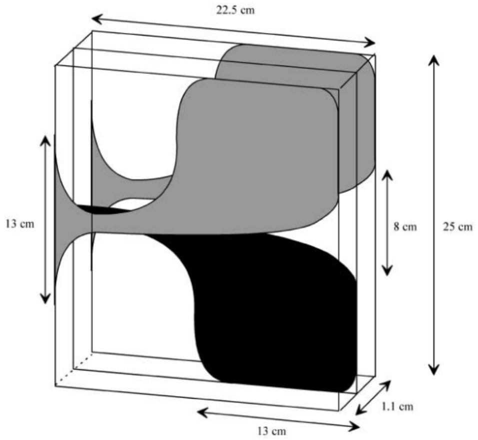

Figure 8: Structure of the Vivaldi antenna [28].

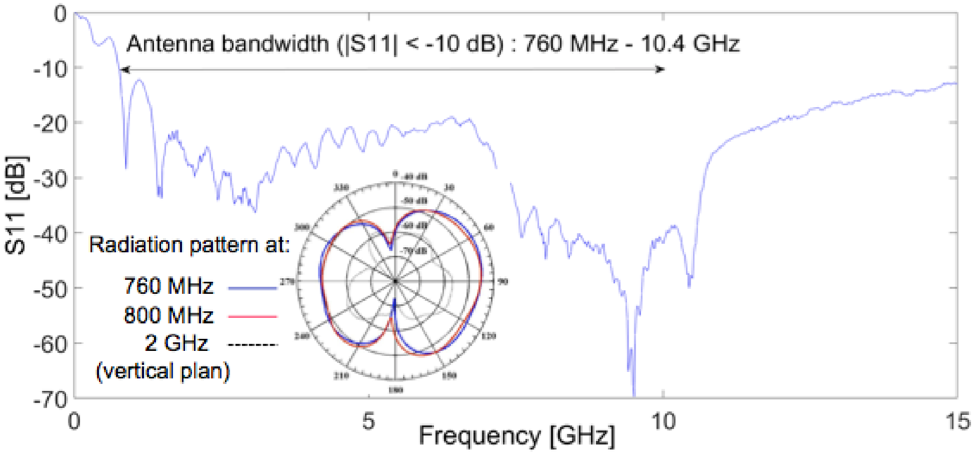

Figure 9: Vivaldi antenna radiation pattern and free space response.

Figure 10: Experimental setup.

The global inversion calculation is initialized with the parameters χr_{BBTM}, n_{BBTM}, χr_{BBSG} and n_{BBSG} determined from a first inversion procedure of SFR measurements made on the calibration slabs (dimensions 40 cm × 30 cm × 3 cm for BBTM and 40 × 30 cm × 5 cm for BBSG).

Figures 11 and 12 correspond to examples of time and frequency variations of the real parts of the experimental Green's functions (red curves) and those of our model including the 2p variant of Jonscher's model (blue curves) in the case of a tack coat (between BBTM and BBSG layers) with an emulsion quantity equal to 600 g/m^2.

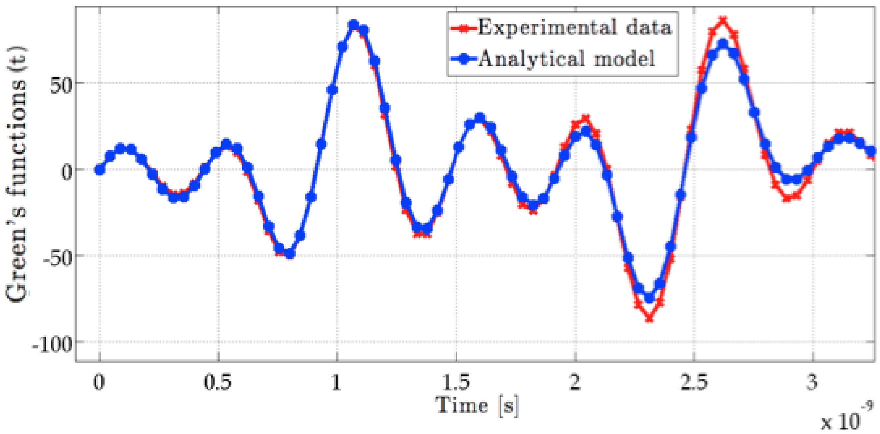

Figure 9: Time variation of the real parts of the experimental Green's functions (red curve) and of the analytical model (blue curve) after the experimental calibration process.

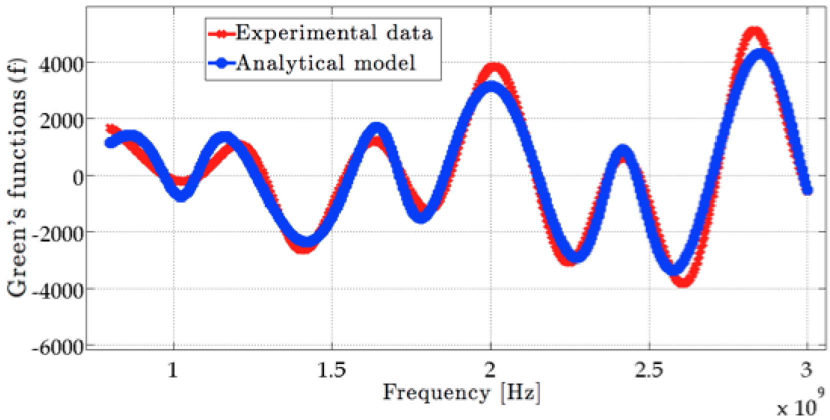

Figure 10: Frequency variation of the real parts of the experimental Green's functions (red curve) and of the analytical model (blue curve) after the experimental calibration process.

These results show a relatively good agreement between the analytical model and experimental data. Thus, all inversion results representing these two series (BBTM / Tack coat / BBSG) are reported in Table 2.

These results lead to the following remarks:

- the greater the emulsion quantity, the higher the dielectric susceptibility of the transition zone. This confirms the results of the preliminary study in Section 2,
- the greater the emulsion quantity, the thicker the transition zone in contrast to BBTM thickness.

Table 2: Full waveform inversion results

Sample number	**Emulsion quantity (g/m^2)**	$h^{inv.}{}_{BBTM}$ **(mm)**	$h^{inv.}{}_{TC}$ **(mm)**	$h^{inv.}{}_{BBSG}$ **(mm)**	$\chi_{r_{TC}}{}^{inv.}$ **(-)**	$n_{TC}{}^{inv.}$ **(-)**
17	0	32.2	12.1	61.4	4.27	0.98
1	200	30.9	12.7	64.9	4.35	0.99
25	400	27.8	13.9	66.6	4.72	0.99
9	600	27.1	14.7	68.1	5.01	0.99
20	0	29.3	11.3	65.3	4.21	0.97
4	200	27.8	12.4	67.2	4.35	0.99
28	400	27.2	12.1	65.1	4.74	0.98
12	600	26.1	13.8	66.2	4.98	0.99
19	0	30.5	11.7	63.7	4.38	0.99
3	200	27.1	13.8	68.4	4.92	0.99
27	400	26.9	13.1	67.5	4.74	0.99
11	600	25.9	14.5	67.8	5.03	0.99
18	0	33.8	13.9	57.3	4.22	0.98
2	200	30.1	15.8	63.8	4.23	0.99
26	400	25.9	12.7	67.8	4.45	0.99
10	600	24.8	12.8	68.2	4.89	0.99

The presence of some outliers in these results (*i.e.*, sample 3) can be partly explained by the residues of the single point source and receiver approximation for this near-field configuration that does not take into account the changes in the field distribution over the antenna aperture. The second assumption for the origin of these outliers is related to the roughness of the objective function showing a convergence to local minima and the need to use a more time-consuming specific iterative algorithm with more generations.

The results of this experimental study prove that this analytical model is suitable for describing SFR wave propagation through multi-layered media with a correlation between dielectric susceptibility and emulsion quantity. Thus, the future objective will be to generalize this study to a more complete experimental design for obtaining laboratory calibration curves that will link the ND observable $\chi_{r_{TC}}$ to the durability indicator (emulsion quantity).

6. Conclusion

A model of stepped-frequency radar wave propagation through HMA layers of flexible pavements was investigated using both numerical and experimental experiments. The FWFI was tested in near-field conditions for estimating the dielectric and geometric characteristics of a wide range of materials and pavement layers. In particular, we used a homemade ND technique based on a vector network analyzer combined with a homemade Vivaldi antenna (stepped frequency radar), associated with the radar model and methods of Lambot *et al.* [11, 12, 22] combined with Jonscher's parameterization for describing the frequency-dependent medium properties. This first step durability process demonstrated the relationship between ND observables (dielectric susceptibility) and the emulsion quantities used in the pavement layer bonding process.

Experimental results show a monotone evolution of the emulsion quantity according to the estimated dielectric susceptibility of the transition zone. This tendency is explained by the fact that the emulsion filled the empty pores at the interface, compared to an air gap, which increases the dielectric permittivity of the transition zone between the two layers. This transition zone is also visible in the gammadensimetry results.

Moreover, we noted that the emulsion quantity has an influence on the estimated layer thicknesses. Indeed, the greater the emulsion quantity, the thicker the transition zone in contrast to BBTM thickness.

Concerning the inverse problem, the presence of outliers in the FWFI results can be partly explained by the residues of the single point source and receiver approximation for this near-field configuration that does not take into account the changes in the field distribution over the antenna aperture. For the next step of this research work, we propose that an equivalent Green's function model can be built to describe the border effects and a multi-dipoles Green function model in a simple mathematical form can replace the current single-dipole Green function model to include more accurately the near-field effects.

The second assumption for the origin of these outliers is related to the roughness of the objective function showing a convergence to local minima and the need to use a more time-consuming specific iterative algorithm. An optimization of the objective function can be studied and proposed in the future in order to improve the performance of the inversion method. The genetic algorithm method can be combined with other local minimization method, in order to make a balance between the inversion result performances and the inversion time costs.

Generally speaking, the results of these preliminary research works prove that the FWFI approach combined to SFR technique is suitable for describing wave propagation through multi-layered media with a correlation between dielectric susceptibility and emulsion quantity. Thus, the future objective will be to generalize this study to a more complete experimental design for obtaining laboratory calibration curves that will link the ND observable $\chi_{r_{TC}}$ to the durability indicator (emulsion quantity). This second inverse problem will be solved statistically by applying a non-deterministic optimization (machine learning) algorithm to the in-lab calibration curves that tie the controlled tack coats in various hot mix asphalt layers with the dielectric susceptibility output by the laboratory EM characterization device.

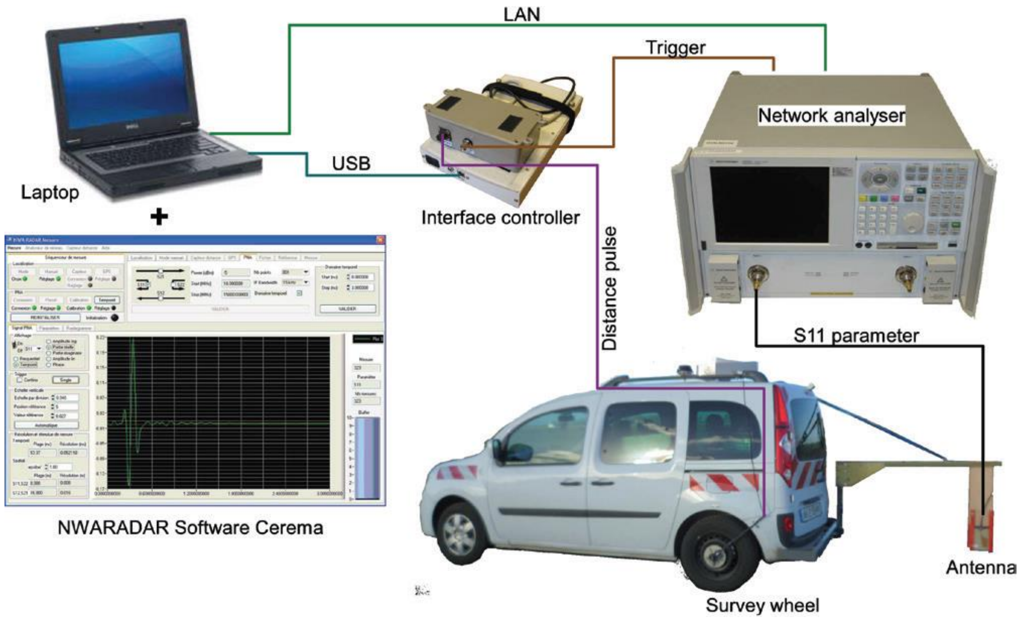

Figure 11: Stepped Frequency Radar system of Cerema for road survey.

Finally, we have already begun the phase of *in situ* deployment of this non-destructive tool (Figure 11) in collaboration with the Vendée Departmental Council (France). The objective is to classify the bonding areas into three categories on a new roadway (basing on test data bases of the machine learning method that uses the in-lab validated kernels). Indeed, the infrastructure owner has made a test area with three partial sections (30 m) oversized in terms of emulsion quantity (600 and 800 g/m^2) into a global section (2.5 km) with a usual dosage of 400 g/m^2. At the roadway time zero state (without loading due to traffic), our initial right classification rate was around 70% on all the inverted signals using the current and the small training data base (incomplete and preliminary test). This structure is still considered as an *in situ* validation area for our approach. The idea is to integrate in the future works additional structural constraints and evaluate accordingly the accuracy of our SFR device and the stability of our inverse methods.

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