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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.*

34

1. INTRODUCTION

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

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



Figure 1: Tack coat positioning in a pavement structure.

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

66 Ground-penetrating radar (GPR) based on EM wave propagation, is a rising non-destructive
67 technique for measuring the dielectric and geometric characteristics of materials. It is a
68 common technique for geometrical applications (rebar detection [3, 4], road thickness
69 estimation [5, 6], etc.) in civil engineering domain, and remains under study for material
70 characterization (water and chloride content in concrete [7, 8], asphalt compaction [9, 10],
71 etc.). Moreover, GPR techniques constitute a powerful tool for monitoring the condition of
72 dispersive civil engineering materials. Wave propagation is entirely governed by the dielectric
73 response, which reflects the interaction between propagating EM waves and the tested

74 material. Along these lines, several methods and models have been implemented, with varying
75 degrees of success, in order to describe the frequency dependence of the dielectric permittivity
76 of geological and civil engineering materials [11-17].

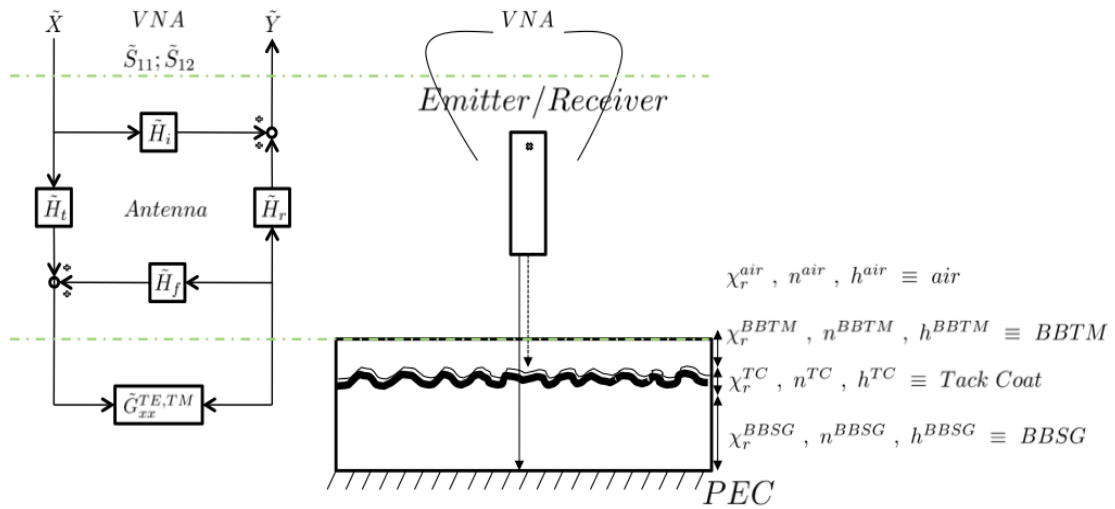
77 To estimate dielectric and geometric characteristics for civil engineering materials and
78 multi-layered media, most researchers use the travel time delay (TTD) approach [18], which is
79 limited in terms of forward modelling adequacy and information content. Full-waveform
80 inversion (FWFI), which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

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

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

102 2. PHENOMENOLOGICAL ASPECTS AND EXPERIMENTAL DESIGN

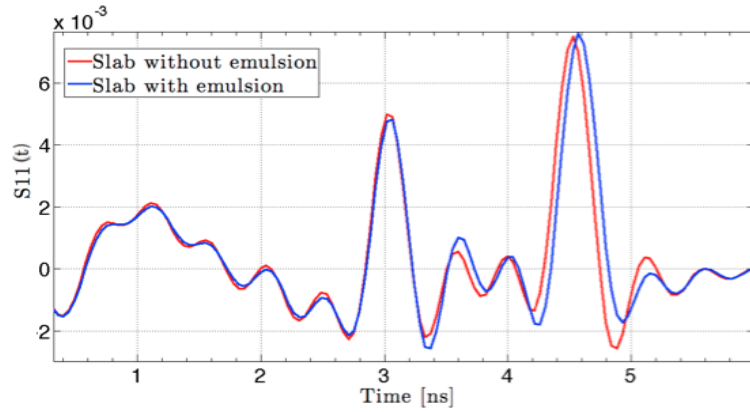
103 In this study, we focused solely on tack coats linking the wearing course and the binder
 104 course (Figure 1). We developed a SFR that integrates a PC-piloted FieldFox Microwave
 105 vector network analyzer (Agilent N9928A) and various Vivaldi antennas in mono-static, near-
 106 field configuration (Figure 2) for measuring a wide range of HMA layers (slabs). The details of
 107 this experimental device are presented in Section IV. A preliminary study was performed to
 108 assess the sensitivity of such a device (using its raw data expressed in the time domain) to the
 109 presence or absence of tack coat emulsion. To do this, 2 two-layer slabs were designed. The
 110 first one did not contain any emulsion at the interface between the wearing course (BBTM - 3
 111 cm thick HMA corresponding to very thin layers) and the binder course (BBSG - 6 cm thick).
 112 The second contained emulsion up to 600 g/m². Figure 3 shows the time variations of the real
 113 part of the SFR reflection coefficients S_{11} on the slabs, laid on a Perfect Electrical Conductor
 114 (PEC), with (blue curve) and without (red curve) emulsion.



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

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

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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).

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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:

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

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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:

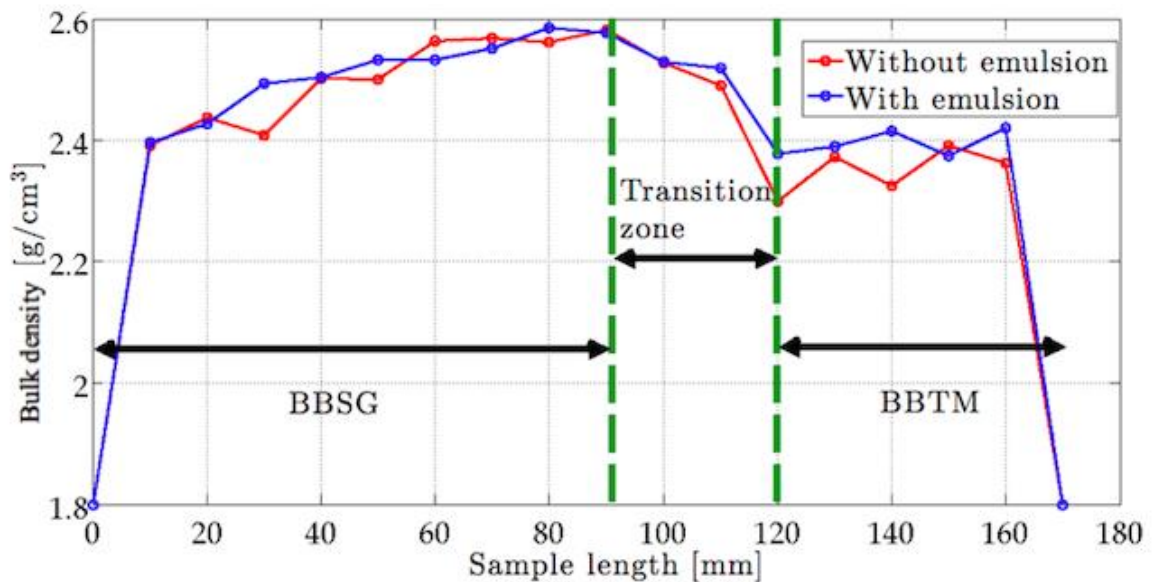
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$$\rho = -\frac{1}{z\mu_0 x} \ln\left(\frac{N_o}{N}\right), \quad (2)$$

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

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



148 **Figure 4: Bulk density variations according to slab thickness with and without**
149 **emulsion.**
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156 The HMA layer nomenclature used in the experimental design is as follows:

157 • BBTM – Very thin bituminous concrete: the target average thickness ranges from 2 to
158 2.5 cm. The binder content is 5.5% and the aggregate size fraction is 0/10 mm with a
159 discontinuity between 2 mm and 6 mm;

160 • BBSG – Semi-coarse HMA: used for surface layers (wearing and/or binder courses) in
161 roadways with medium to high traffic. The target average thickness ranges from 5.5 to 6 cm,
162 the binder content is 5.2% and the aggregate size fraction is 0/10 mm;

163 • GB – bituminous gravel used for the base course. The target average thickness ranges
164 from 10.5 to 11.5 cm, the binder content is 4% and the aggregate size fraction is 0/14 mm.

165 The 4 degrees of freedom for this statistic experimental design are as follows: emulsion
166 quantity (0, 200, 400 and 600 g/m²), nature of the layers (BBTM above BBSG and BBSG
167 above GB), their thicknesses (BBTM / 3cm, BBSG / 6cm and GB / 11cm) and their
168 compaction (between 75% and 96%) (Table 1).

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

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

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

178

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/m ²	14/11/14
Ech2	BBSG10 LT C96	BBTM10 N C75	200 g/m ²	17/12/14
Ech3	BBSG10 LT C91	BBTM10 N C90	200 g/m ²	03/03/15
Ech4	BBSG10 LT C96	BBTM10 N C90	200 g/m ²	04/12/14
Ech5	GB14 N C88	BBSG10 LT C91	200 g/m ²	2016-2017
Ech6	GB14 N C96	BBSG10 LT C91	200 g/m ²	2016-2017
Ech7	GB14 N C88	BBSG10 LT C96	200 g/m ²	2016-2017
Ech8	GB14 N C96	BBSG10 LT C96	200 g/m ²	2016-2017
Ech9	BBSG10 LT C91	BBTM10 N C75	600 g/m ²	25/11/14
Ech10	BBSG10 LT C96	BBTM10 N C75	600 g/m ²	07/01/15
Ech11	BBSG10 LT C91	BBTM10 N C90	600 g/m ²	27/03/15
Ech12	BBSG10 LT C96	BBTM10 N C90	600 g/m ²	11/12/14
Ech13	GB14 N C88	BBSG10 LT C91	600 g/m ²	2016-2017
Ech14	GB14 N C96	BBSG10 LT C91	600 g/m ²	2016-2017
Ech15	GB14 N C88	BBSG10 LT C96	600 g/m ²	2016-2017
Ech16	GB14 N C96	BBSG10 LT C96	600 g/m ²	2016-2017
Ech17	BBSG10 LT C91	BBTM10 N C75	0 g/m ²	06/11/14
Ech18	BBSG10 LT C96	BBTM10 N C75	0 g/m ²	16/12/14
Ech19	BBSG10 LT C91	BBTM10 N C90	0 g/m ²	27/01/15
Ech20	BBSG10 LT C96	BBTM10 N C90	0 g/m ²	02/12/14
Ech21	GB14 N C88	BBSG10 LT C91	0 g/m ²	2016-2017
Ech22	GB14 N C96	BBSG10 LT C91	0 g/m ²	2016-2017
Ech23	GB14 N C88	BBSG10 LT C96	0 g/m ²	2016-2017
Ech24	GB14 N C96	BBSG10 LT C96	0 g/m ²	2016-2017
Ech25	BBSG10 LT C91	BBTM10 N C75	400 g/m ²	21/11/14
Ech26	BBSG10 LT C96	BBTM10 N C75	400 g/m ²	06/01/15
Ech27	BBSG10 LT C91	BBTM10 N C90	400 g/m ²	06/03/15
Ech28	BBSG10 LT C96	BBTM10 N C90	400 g/m ²	10/12/14
Ech29	GB14 N C88	BBSG10 LT C91	400 g/m ²	2016-2017
Ech30	GB14 N C96	BBSG10 LT C91	400 g/m ²	2016-2017
Ech31	GB14 N C88	BBSG10 LT C96	400 g/m ²	2016-2017
Ech32	GB14 N C96	BBSG10 LT C96	400 g/m ²	2016-2017

180 ⁽¹⁾LT = Le Tronc quarry, ⁽²⁾ C91 = Compaction at 91%, ⁽³⁾N = Noubleau quarry

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

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

187 3. EM WAVE PROPAGATION MODEL

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

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

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

215 3.1. Effective permittivity

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

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

229 The effective permittivity can be expressed as follows:

$$230 \quad \varepsilon_e = \varepsilon_o \chi_r \left(\frac{f}{f_r} \right)^{n-1} \left(1 - j \cot \left(\frac{n\pi}{2} \right) \right), \quad (3)$$

231

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

234 3.2. Green's function

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

$$237 \quad G(\kappa) = \frac{1}{8\pi} \left(\frac{\gamma_1 R_1^{TM}}{j\omega\varepsilon_{e1}} - \frac{j\omega\mu_1 R_1^{TE}}{\gamma_1} \right) e^{-2\gamma_1 h_1} \quad (4)$$

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

246 3.3. Return loss S_{11}

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

$$250 \quad S_{11}(f) = R_i(f) + T_s(f)(1 - G(f)R_s(f))^{-1}G(f)T_i(f) \quad (5)$$

251 where, R_i is the free space response of the antenna. T_i and T_s are the global transmission
 252 coefficients of the antenna for fields incident from the radar reference plane onto the source
 253 point and vice-versa, R_s is the global reflection coefficient for fields incident from the field
 254 point onto the radar reference plane, and G is the spatial domain Green's function, deduced
 255 from the spectral domain Green's function in (4).
 256

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

$$261 \quad R_i = S_{air} \quad (6)$$

$$262 \quad R_s = \frac{\frac{S_{pec5}-S_{air}}{G_{pec5}} - \frac{S_{pec3}-S_{air}}{G_{pec3}}}{S_{pec5}-S_{pec3}} \quad (7)$$

$$263 \quad T_i T_s = \frac{S_{pec5}-S_{air}}{G_{pec5}} - (S_{pec5} - S_{air})R_s \quad (8)$$

264

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

270 3.4. Inversion objective function

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

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

280 The amplitude-weighted average distance between analytical and reference return loss S_{II}
 281 complex values at each frequency was considered as objective function (9).

282
$$O(m) = \frac{1}{NF} \sum_{i=1}^{NF} \frac{|S_{mod}(f_i, m) - S_{ref}(f_i, m)|}{|S_{ref}(f_i, m)|} \quad (9)$$

283
 284 Here, $S_{mod}(f_i, m)$ and $S_{ref}(f_i, m)$ are the analytical and reference return loss S_{II} at the
 285 frequency f_i . m corresponds to the model parameter vector. NF is the number of frequencies.
 286 There is a return value $O(m)$ for each try of model parameter. The best parameter is reached
 287 once $O(m)$ is minimized using genetic algorithm.

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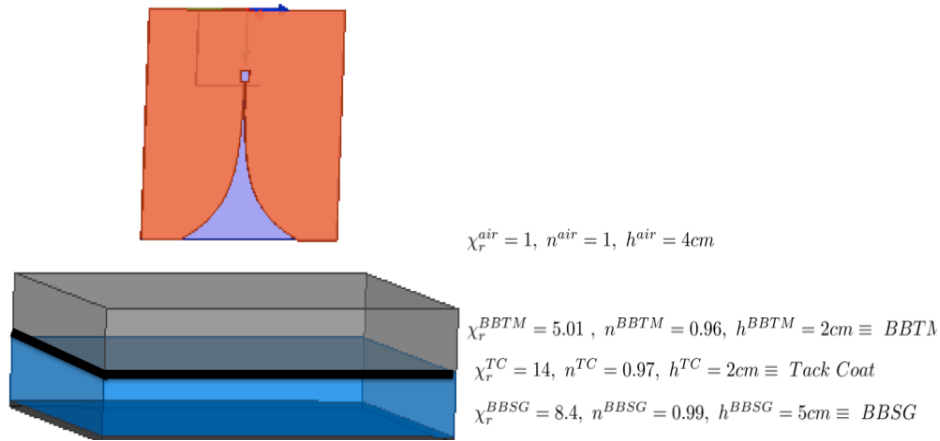
4. NUMERICAL VERIFICATION OF THE FORWARD MODEL

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

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

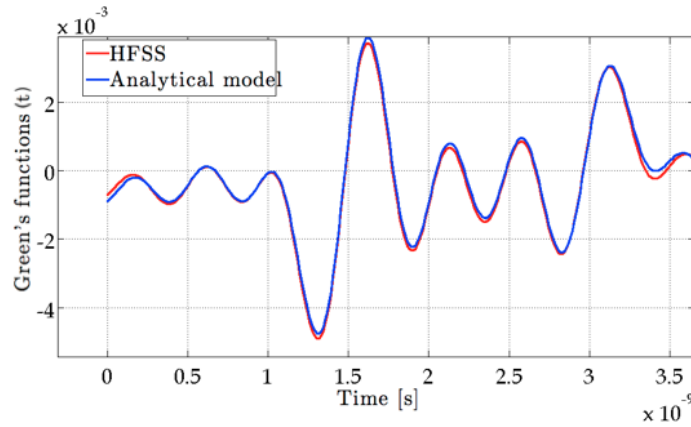
299 The model configuration is shown in Figure 5. The height of the antenna (distance between
 300 the antenna aperture and the upper surface of the BBTM layer) was set to 4 cm, meaning a
 301 near-field case simulation [26]. The thickness, the dielectric susceptibility and the loss
 302 exponent for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

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



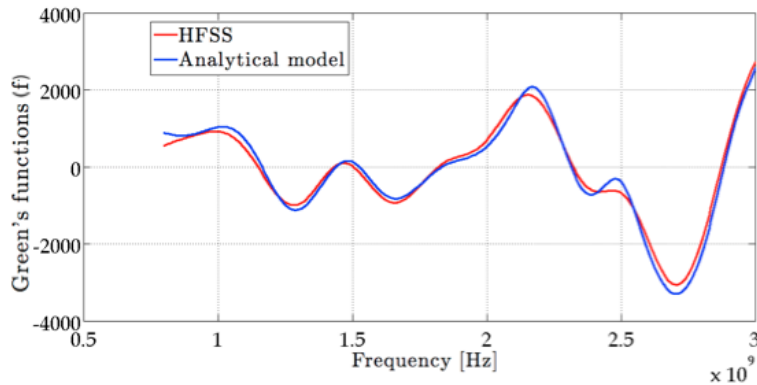
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Figure 5: HFSS- based numerical model.



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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.



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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.

318 The values of the Green's analytical model integrating 2p variant of Jonscher's model
319 perfectly match the reference theoretical values (HFSS) after the near-field calibration of the

320 antenna. The small differences between the two model curves are partly due to the single point
321 source and receiver approximation for this near-field configuration (the field distribution over
322 the antenna aperture slightly changes between 3 and 5 cm height).

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

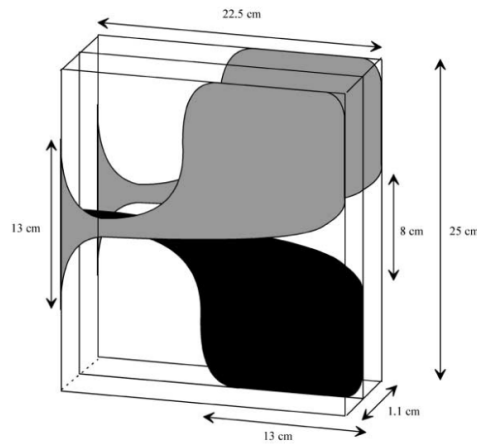
326 5. EXPERIMENTAL VALIDATION

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

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

340 The first SFR measurements were performed on two series of four BBTM / tack coat /
341 BBSG slabs (dimensions 40 cm \times 30 cm \times 9.5 cm) placed on a metal plate of similar
342 dimensions. The SFR measurement configuration is shown in Figure 10, wherein the Vivaldi

343 antenna is placed 4 cm above the slabs. It should be noted that the rear aerial EM echoes from
344 the metallic antenna-holder are accounted for by the antenna calibration process.

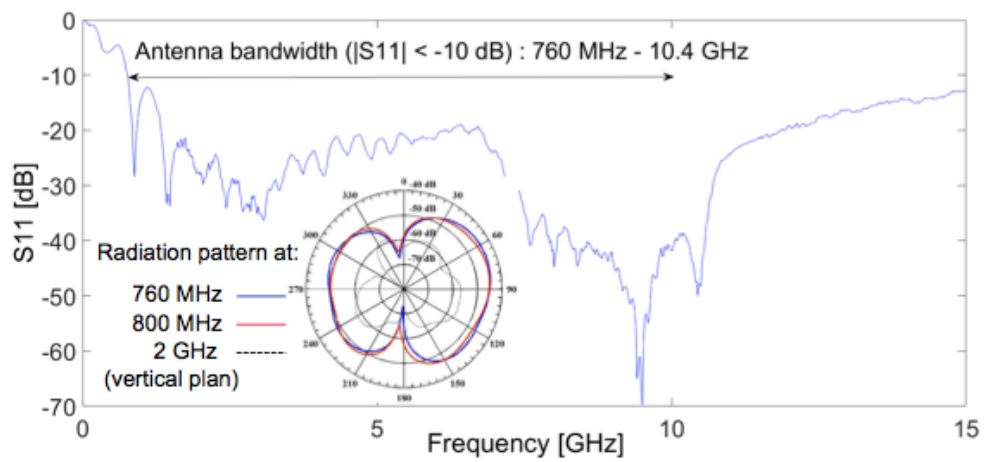


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Figure 8: Structure of the Vivaldi antenna [28].



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



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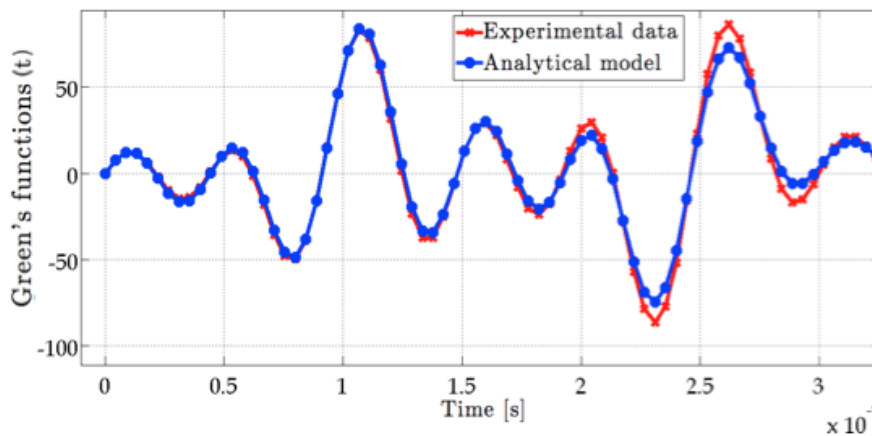
354

Figure 10: Experimental setup.

355

356 The global inversion calculation is initialized with the parameters χ_{rBBTM} , n_{BBTM} ,
357 χ_{rBBSG} and n_{BBSG} determined from a first inversion procedure of SFR measurements made on
358 the calibration slabs (dimensions 40 cm \times 30 cm \times 3 cm for BBTM and 40 \times 30 cm \times 5 cm
359 for BBSG).

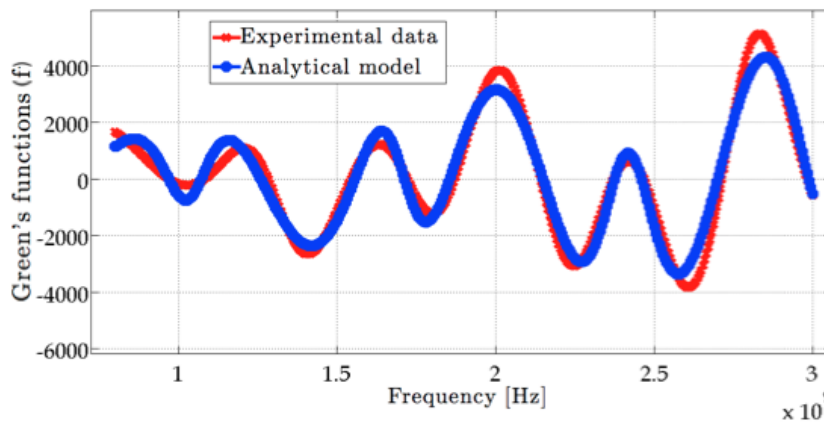
360 Figures 11 and 12 correspond to examples of time and frequency variations of the real parts
361 of the experimental Green's functions (red curves) and those of our model including the 2p
362 variant of Jonscher's model (blue curves) in the case of a tack coat (between BBTM and
363 BBSG layers) with an emulsion quantity equal to 600 g/m².



364

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

368



369

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

373

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

377 These results lead to the following remarks:

378 • the greater the emulsion quantity, the higher the dielectric susceptibility of the
379 transition zone. This confirms the results of the preliminary study in Section 2,

380 • the greater the emulsion quantity, the thicker the transition zone in contrast to BBTM
381 thickness.

382 **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)	$\chi_{rTC}^{inv.}$ (-)	$n_{TC}^{inv.}$ (-)
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

383

384 The presence of some outliers in these results (*i.e.*, sample 3) can be partly explained by the
385 residues of the single point source and receiver approximation for this near-field configuration
386 that does not take into account the changes in the field distribution over the antenna aperture.

387 The second assumption for the origin of these outliers is related to the roughness of the

388 objective function showing a convergence to local minima and the need to use a more time-
389 consuming specific iterative algorithm with more generations.

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

395

396

6. CONCLUSION

397 A model of stepped-frequency radar wave propagation through HMA layers of flexible
398 pavements was investigated using both numerical and experimental experiments. The FWFI
399 was tested in near-field conditions for estimating the dielectric and geometric characteristics of
400 a wide range of materials and pavement layers. In particular, we used a homemade ND
401 technique based on a vector network analyzer combined with a homemade Vivaldi antenna
402 (stepped frequency radar), associated with the radar model and methods of Lambot *et al.* [11,
403 12, 22] combined with Jonscher's parameterization for describing the frequency-dependent
404 medium properties. This first step durability process demonstrated the relationship between
405 ND observables (dielectric susceptibility) and the emulsion quantities used in the pavement
406 layer bonding process.

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

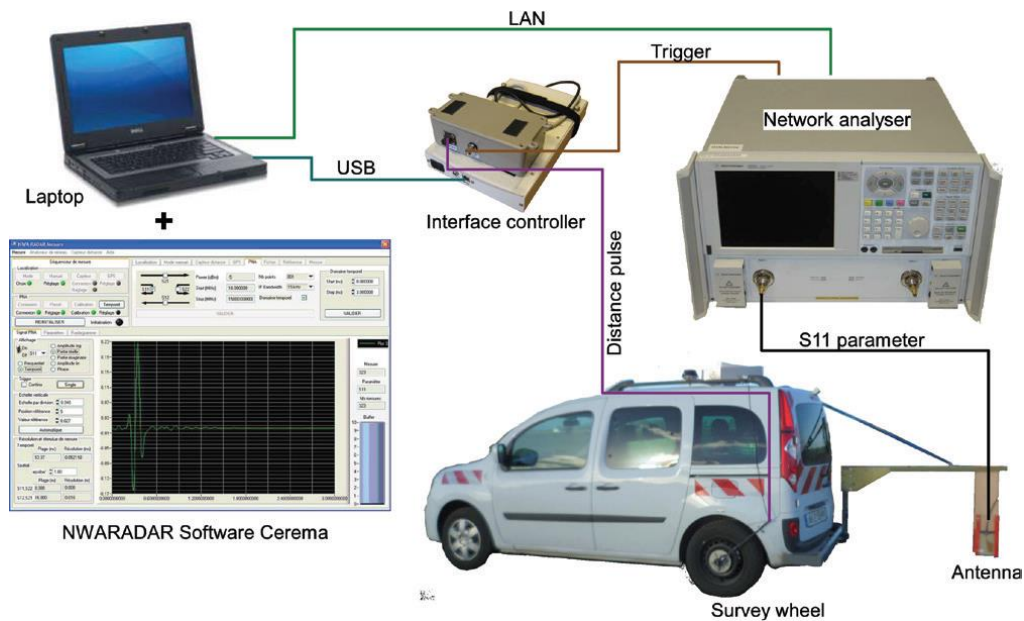
412 Moreover, we noted that the emulsion quantity has an influence on the estimated layer
413 thicknesses. Indeed, the greater the emulsion quantity, the thicker the transition zone in
414 contrast to BBTM thickness.

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

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

429 Generally speaking, the results of these preliminary research works prove that the FWFI
430 approach combined to SFR technique is suitable for describing wave propagation through
431 multi-layered media with a correlation between dielectric susceptibility and emulsion quantity.
432 Thus, the future objective will be to generalize this study to a more complete experimental
433 design for obtaining laboratory calibration curves that will link the ND observable χ_{rTC} to the
434 durability indicator (emulsion quantity). This second inverse problem will be solved
435 statistically by applying a non-deterministic optimization (machine learning) algorithm to the

436 in-lab calibration curves that tie the controlled tack coats in various hot mix asphalt layers with
437 the dielectric susceptibility output by the laboratory EM characterization device.



438
439

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

440

441 Finally, we have already begun the phase of *in situ* deployment of this non-destructive tool
442 (Figure 11) in collaboration with the Vendée Departmental Council (France). The objective is
443 to classify the bonding areas into three categories on a new roadway (basing on test data bases
444 of the machine learning method that uses the in-lab validated kernels). Indeed, the
445 infrastructure owner has made a test area with three partial sections (30 m) oversized in terms
446 of emulsion quantity (600 and 800 g/m²) into a global section (2.5 km) with a usual dosage of
447 400 g/m². At the roadway time zero state (without loading due to traffic), our initial right
448 classification rate was around 70% on all the inverted signals using the current and the small
449 training data base (incomplete and preliminary test). This structure is still considered as an *in*
450 *situ* validation area for our approach. The idea is to integrate in the future works additional
451 structural constraints and evaluate accordingly the accuracy of our SFR device and the stability
452 of our inverse methods.

453

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